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A Comprehensive Framework and Associated Methodology for the Design, Operative Planning, and Operation of District Heating Systems to Facilitate the Transition Towards a Fully Renewable Heat Supply

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Abstract

District heating systems (DHSs) are a mature technology for an efficient heat supply in cities. In the context of the climate crisis and the related goal of a decarbonized heating sector, DHSs play an ambivalent role. As existing DHSs are mostly based on fossil fuels, they are part of the problem. However, as they can also integrate renewable heating plants, DHSs offer a great potential to support the transition towards a fossil-free heat supply.

This transition is hindered by several barriers. For example, low supply temperatures are needed for the economically efficient integration of renewable heating plants. However, since existing fossil heating plants marginally benefit from a reduction of the temperature, a lock-in effect to the established business models exists. In the current research, resolving the barriers is focused either on individual solutions for specific issues or on heat strategies for a general level. Since the barriers are strongly interrelated, district heating (DH) companies require a systemic transition methodology for their specific activities in the different fields of planning and operation. Since such a transition methodology is identified as lacking in the literature, this thesis aims to develop a comprehensive methodology that facilitates the transition in an economically efficient way.

To develop such a transition methodology, this thesis introduces a framework approach that combines new and existing independent concepts and that is built on a newly developed structure of eight "DH scopes." These DH scopes classify the activities in the different fields of DH concerns. To address the planning and operation activities in DH companies, these activities are integrated into the new "framework" that is classified according to the three DH scopes "design," "operative planning," and "operation." The framework summarizes the related activities according to processes and links them using technical and economic mechanisms. These mechanisms are considered in such a way that all activities are incentivized

to facilitate the transition. A new organizational structure is proposed that allows for the introduction of competition while the framework secures so-called suboptimization, abuse of market power, or investment restraint. Independent heat producers are integrated in a system-serving way. The framework integrates the relevant technologies that offer flexibility to the system to compensate for fluctuation in production.

In this thesis, a framework is devised that is suitable for implementing a comprehensive "transition paradigm" to existing or future DHSs. Further, it can be used by policymakers or municipalities to improve existing legal conditions and local heat strategies in relation to a comprehensive overall system. The thesis recommends further investigation for the implementation of the framework and a quantitative evaluation of the introduction of competition to DHSs.

Resumen

Los Sistemas de Distribución de Calor Urbanos (SDCU) son una tecnología madura para el suministro eficiente de calor en las ciudades. En el contexto de la crisis climática y del objetivo de descarbonizar el sector de la calefacción, estos sistemas pueden desempeñar un papel muy importante. En principio, los SDCU existentes actualmente están basados principalmente en el uso de combustibles fósiles, por lo que forman parte del problema. Sin embargo, mediante la integración de plantas de generación de calor renovables, los SDCU pueden ofrecer un gran potencial para apoyar la transición hacia un suministro de calor sin combustibles fósiles.

Esta transición se ve dificultada por diversas barreras. Por ejemplo, la necesidad de bajas temperaturas de suministro para que la integración de las plantas renovables de generación de calor sea rentable. Sin embargo, dado que las plantas de generación de calor fósiles existentes no se benefician de una reducción de la temperatura, existe un efecto de bloqueo en los modelos de negocio establecidos. En la investigación actual, la resolución de las barreras se centra en soluciones individuales para cuestiones específicas y en estrategias de calor para un nivel general. Como las barreras están fuertemente interrelacionadas, las empresas de distribución de calor urbano requieren una metodología de transición sistémica para sus actividades específicas en los diferentes ámbitos de planificación y operación. Tras constatar su ausencia en la bibliografía, la presente tesis pretende desarrollar una metodología integral que facilite dicha transición de forma rentable.

Para la realización de esta tarea, esta tesis introduce un enfoque de marco que combina conceptos independientes nuevos y existentes, construyéndose sobre una estructura diseñada en los ocho «ámbitos» de interés de los SDCU. Estos ámbitos de los SDCU clasifican las actividades en los diferentes campos de las problemáticas de este tipo de sistemas. Para abordar las actividades de planificación y operación en las empresas de distribución de calor urbano, estas actividades se integran en

el nuevo «marco» que se clasifica según los tres ámbitos de los SDCU: «diseño», «planificación operativa» y «operación». Dicho marco resume las actividades relacionadas según los procesos y las vincula mediante mecanismos técnicos y económicos. Estos mecanismos se plantean de forma que todas las actividades se incentiven para facilitar la transición. Se propone una nueva estructura organizativa que permita la introducción de la competencia, al mismo tiempo que el marco asegura la llamada suboptimización, la prevención del abuso de poder en el mercado y la restricción de las inversiones. Además, permite a los productores de calor independientes integrarse en el sistema. Complementariamente, el marco integra las tecnologías más relevantes que ofrecen flexibilidad al sistema para compensar las fluctuaciones de la producción.

En esta tesis se ha desarrollado un marco adecuado para aplicar un «paradigma de transición» global a los SDCU existentes o futuros. Además, puede ser utilizado por los responsables políticos o municipales para mejorar las condiciones legales existentes y las estrategias locales de calor en relación con un sistema global. La tesis recomienda seguir investigando para la implementación del marco y una evaluación cuantitativa de la introducción de la competencia en los SDCU.

Resum

Els Sistemes de Distribució de Calor Urbans (SDCU) són una tecnologia madura per a la provisió eficient de calor a les ciutats. En el context de la crisi climàtica i de l'objectiu de descarbonitzar el sector de la calefacció, aquests sistemes poden exercir un paper molt important. En principi, els SDCU existents actualment estan basats principalment en l'ús de combustibles fòssils, per la qual cosa formen part del problema. No obstant això, mitjançant la integració de plantes de generació de calor renovables, els SDCU poden oferir un gran potencial per a donar suport a la transició cap a una provisió de calor sense combustibles fòssils.

Aquesta transició es veu dificultada per diverses barreres. Per exemple, la necessitat de baixes temperatures de subministrament perquè la integració de les plantes renovables de generació de calor siga fructífera. No obstant això, atés que les plantes de generació de calor fòssils existents no es beneficien d'una reducció de la temperatura, existeix un efecte de bloqueig en els models de negoci establits. En la investigació actual, la resolució de les barreres se centra en solucions individuals per a qüestions específiques i en estratègies de calor per a un nivell general. Com les barreres estan fortament interrelacionades, les empreses de distribució de calor urbana requereixen una metodologia de transició sistèmica per a les seues activitats específiques en els diferents àmbits de planificació i operació. Després de constatar la seua absència en la bibliografia, la present tesi pretén desenvolupar una metodologia integral que facilite aquesta transició de manera profitosa.

Per a la realització d'aquesta tasca, aquesta tesi introdueix un enfocament de marc que combina conceptes independents nous i existents, construint-se sobre una estructura dissenyada en els huit «àmbits» d'interés dels SDCU. Aquests àmbits dels SDCU classifiquen les activitats en els diferents camps de les problemàtiques d'aquest tipus de sistemes. Per a abordar les activitats de planificació i operació en les empreses de distribució de calor urbana, aquestes activitats s'integren en el nou

«marc» que es classifica segons els tres àmbits dels SDCU: «disseny», «planificació operativa» i «operació». Aquest marc resumeix les activitats relacionades segons els processos i les vincula mitjançant mecanismes tècnics i econòmics. Aquests mecanismes es plantegen de manera que totes les activitats s'incentiven per a facilitar la transició. Es proposa una nova estructura organitzativa que permeta la introducció de la competència, al mateix temps que el marc assegura l'anomenada suboptimització, la prevenció de l'abús de poder en el mercat i la restricció de les inversions. A més, permet als productors de calor independents integrar-se en el sistema. Complementàriament, el marc integra les tecnologies més rellevants que ofereixen flexibilitat al sistema per a compensar les fluctuacions de la producció.

En aquesta tesi s'ha desenvolupat un marc adequat per a aplicar un «paradigma de transició» global als SDCU existents o futurs. A més, pot ser utilitzat pels responsables polítics o municipals per a millorar les condicions legals existents i les estratègies locals de calor en relació amb un sistema global. La tesi recomana continuar investigant per a la implementació del marc i una avaluació quantitativa de la introducció de la competència en els SDCU.

Kurzfassung

Fernwärmesysteme sind eine ausgereifte Technologie für eine effiziente Wärmeversorgung in Städten. Im Zusammenhang mit der Klimakrise und dem damit verbundenen Ziel eines dekarbonisierten Wärmesektors spielen Fernwärmesysteme eine ambivalente Rolle. Da die bestehenden Fernwärmesysteme meist auf fossilen Brennstoffen basieren, sind sie Teil des Problems. Jedoch bieten Fernwärmesysteme ein großes Potenzial den Übergang zu einer fossilfreien Wärmeversorgung zu unterstützen, da sie auch erneuerbare Erzeugungsanlagen integrieren können.

Diesem Übergang stehen mehrere Hindernisse entgegen. So sind zum Beispiel niedrige Vorlauftemperaturen für die wirtschaftlich effiziente Einbindung von erneuerbaren Erzeugungsanlagen erforderlich. Da jedoch bestehende fossile Erzeugungsanlagen von einer Absenkung der Temperatur nur marginal profitieren, besteht ein Lock-in-Effekt für die etablierten Geschäftsmodelle. Die aktuelle Forschung konzentriert sich bei der Lösung der Barrieren entweder auf individuelle Lösungen für spezifische Probleme oder auf Wärmestrategien auf einer generellen Ebene. Die Barrieren sind stark miteinander verknüpft, weswegen Fernwärmeunternehmen eine systemische Übergangsmethodik für ihre spezifischen Aktivitäten in den verschiedenen Bereichen der Planung und des Betriebs benötigen. Da eine solche Übergangsmethodik in der Literatur als fehlend identifiziert wurde, zielt diese Arbeit darauf ab, eine umfassende Methodik zu entwickeln, die die Umstellung in einer wirtschaftlich effizienten Weise erleichtert.

Um eine solche Übergangsmethodik zu entwickeln, wurde in dieser Arbeit ein Ansatz gewählt, der auf einem „Rahmenwerk“ basiert. Dieser Ansatz kombiniert neue und bestehende unabhängige Konzepte und baut auf einer neu entwickelten Struktur von acht „Handlungsfeldern“ auf. Diese Handlungsfelder klassifizieren die Aktivitäten in den verschiedenen Bereichen der Fernwärme. Um die Planungs- und Betriebsaktivitäten in Fernwärmeunternehmen zu adressieren, werden diese Aktivitäten in das neue Rahmenwerk integriert, das nach den drei Handlungsfeldern „Auslegung“, „Einsatzplanung“ und „Betrieb“ strukturiert ist. Das Rahmenwerk fasst zusammenhängende Aktivitäten in Prozessen zusammen und verknüpft sie über technische und wirtschaftliche Mechanismen. Diese Mechanismen werden so ausgelegt, dass für alle Aktivitäten Anreize geschaffen werden, um die Wärmewende voranzutreiben. Es wird eine neue Organisationsstruktur vorgeschlagen, die die Einführung von Wettbewerb ermöglicht, während das Rahmenwerk gegen die so genannte Suboptimierung, den Missbrauch von Marktmacht oder die Investitionszurückhaltung absichert. Unabhängige Wärmeproduzenten werden dabei in einer systemdienlichen Weise integriert. Das Rahmenwerk integriert die relevanten Technologien, die dem System Flexibilität bieten, um Schwankungen in der Produktion auszugleichen.

In dieser Arbeit wird ein Rahmenwerk entwickelt, das geeignet ist, ein umfassendes „Übergangsparadigma“ für bestehende oder zukünftige Fernwärmesysteme zu implementieren. Darüber hinaus kann es von politischen Entscheidungsträgern oder Kommunen genutzt werden, um bestehende rechtliche Rahmenbedingungen und Wärmestrategien im Hinblick auf ein umfassendes Gesamtsystem zu verbessern. Die Arbeit empfiehlt weitere Untersuchungen zur Umsetzung des Rahmenwerkes und eine quantitative Evaluierung der Einführung von Wettbewerb in Fernwärmesystemen.

Preface

Dear readers,

I am pleased to present this dissertation to you, which has the goal of developing a comprehensive perspective for the transition of district heating systems. Before starting with the substantive part, I would like to thank for the funding and the numerous support that I have received over the past years and also give a few general remarks about this work.

General remarks

For all readers of the digital document, I recommend the book view, as the arrangement of the graphics has been arranged in such a way that related texts and graphics are placed on a double page, if possible.

In addition, I would like to point out that the references in this work are deliberately set in two different ways. If a source refers to only one sentence, then the reference is placed before the full stop. If the source refers to the entire paragraph, then the reference is after the full stop of the last sentence at the end of the paragraph.

Since there are inaccuracies in the use of terms in the literature about district heating, an attempt has been made to use uniform definitions of terms in this work. For this reason, the most important terms are explained in the glossary (p. xxxiii). In addition, there is a brief presentation of the most important fundamentals in appendix A (p. 309).

Funding sources
This doctorate was financially supported by several grants.

I would like to thank the *Hamburg University of Applied Sciences (HAW Hamburg)* for the grant within the framework of the doctoral funding program, which made this thesis possible in the first place. This grant in turn made it possible to apply for further research projects, which helped to continue the funding of the doctorate.

Within the research project *Smart Heat Grid Hamburg* [03ET1458A] this doctorate could be continued. Furthermore, the research project *Reallabor: Integrierte WärmeWende Wilhelmsburg – Integrierter Wärmemarkt (Living Lab: Integrated Heating Transition Wilhelmsburg—Integrated Heat Market)* [03EWR006MC] emerged from the ideas of this dissertation and in return also co-financed it. These two projects were funded by the *German Federal Ministry for Economic Affairs and Climate Action* to whom I would like to express my gratitude.

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In this long time so many people have supported and encouraged me that it is hardly possible to thank them all adequately. Nevertheless, I will try to do so in the following with the hope that I have thought of everyone.

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Moreover, I would like to thank Cassandra Louw for the helpful and high-quality suggestions for the linguistic improvement of this work, which she provided to me during a professional proofreading of this work.

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I would like to thank Javier Rodriguez Garcia for helping me with the translation of the abstract into Spanish and Valencian, as well as helping with administrative matters at the *UPV*. Also, I would like to thank the whole team in Valencia for the great time during my stay there.

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Carlos Alvarez-Bel, I would like to thank you for the many valuable discussions that made this thesis what it is. Thanks to you I was able to learn a lot about scientific working methods. It is great how much you have been involved in the supervision of this doctorate despite the long distance and the "non-electrotechnical" topic.

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A big thanks goes to the team *Wärme* of the *Competence Center for Renewable Energy and Energy Efficiency* of the *HAW Hamburg*, which are namely Nina, Paul, Jan, Philipp, Philip, Ina, Fabian, Moritz, and Hans, as well as numerous companions. On the one hand, you have always supported me by taking over many topics and keeping my back free in the projects. On the other hand, you have pushed me forward in my doctorate project through the numerous discussions and feedback on the written work. I am very grateful for this support!

Further, I would like to thank all my friends, who understood very well how to get me out of my apartment in times of home office and how to take my mind off in the often-stressful times. I would like to thank my friends Sarah and Michael for their feedback on the dissertation at an earlier stage.

Finally, I would also like to thank my family for their support. Particularly, I want to say thank you to my parents, who have always supported me. Especially during the height of the pandemic, they supported me mentally by making certain "demolition activities" possible.

Thank you all very much!

Now I hope that you enjoy reading and browsing through this dissertation,

Peter Lorenzen

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Acronyms

Notation	Description
1GDH	1^{st} generation district heating.
2GDH	2^{nd} generation district heating.
3GDH	3^{rd} generation district heating.
4GDH	4^{th} generation district heating.
5GDH	5^{th} generation district heating.
ATES	aquifer thermal energy storage.
BTES	borehole thermal energy storage.
CFD	contract for differences.
CHP	combined heat and power.
COP	coefficient of performance.
DH	district heating.
DHC	district heating and cooling.
DHS	district heating system.
DHW	domestic hot water.
DN	norm diameter.
DSM	demand side management.
ENB	Energiebunker.
ENV	Energieverbund.
ETC	evacuated tube collector.
EU	European Union.
FPC	flat plate collector.

Notation	Description
GCV	gross calorific value.
GT	geothermal.
GTW	Geothermie Wilhelmsburg.
HEX	heat exchanger.
HOB	heat only boiler.
HP	heat pump.
ICT	information and communication technology.
ISH	industrial surplus heat.
KPI	key performance indicator.
MILP	mixed integer linear programming.
MINLP	mixed integer nonlinear programming.
MPC	model predictive control.
NCV	net calorific value.
NGB	North German Basin.
P&I	piping and instrumentation.
PCM	phase-changing material.
PLR	part load ratio.
PRC	price revision clause.
PTES	pit thermal energy storage.
PV	photovoltaics.
SB	single buyer.
SCADA	supervisory control and data acquisition.
SOC	state of charge.
ST	solar thermal.
STG	smart thermal grid.
TC	thermocline.
TES	thermal energy storage.
TTES	tank thermal energy storage.
VAT	value added tax.

Nomenclature

Notation	Description	Unit
A	Area	m^2
A_{coll}	Area of solar thermal collector	m^2
a_1	First order solar thermal loss coefficient	$W/(m^2.K)$
a_2	Second order solar thermal loss coefficient	$W/(m^2.K^2)$
α_{air}	Convection heat transfer coefficient for air	$W/(m^2.K)$
b_0	Zero order pressure coefficient	Pa
b_2	Second order pressure coefficient	$Pa/(m^3/s)^2$
$bonus_{management}$	Management bonus for renewable CHP plants	$€/MWh_{el}$
$C_{el,pump}$	Pumping costs	€
COP_{Carnot}	Carnot coefficient of performance	–
$COP_{heating}$	Heating coefficient of performance	–
$COP_{technical}$	Technical coefficient of performance	–
$C_{p, TES}$	Heat capacity of TES at constant pressure	W/K
c_{AV}	Average variable costs for heat	€/MWh
$c_{electricity}$	Specific electricity costs	$€/MWh_{el}$
c_{fuel}	Specific fuel costs	$€/MWh_{GCV}$
c_{others}	Other specific costs	€/MWh
c_p	Specific heat capacity at constant pressure	W/(kg.K)
d_i	Inner diameter	m
$d_{insulation}$	Insulation diameter	m
d_{pipe}	Pipe diameter	m
d_{TES}	TES diameter	m
ΔH_{prim}	Difference of enthalpy on the primary side	J
ΔH_{sec}	Difference of enthalpy on the secondary side	J

Notation	**Description**	**Unit**
Δp	Pressure drop	Pa
Δp_{loss}	Pressure loss	Pa
Δp_{pump}	Pressure difference inducted by pump	Pa
Δp_{tot}	Total pressure change	Pa
$\Delta \dot{Q}$	Discrete difference of heat transfer rate	W
$\Delta T_{\text{HEX, r}}$	Return temperature gradient of heat exchanger	K
$\Delta T_{\text{HEX, s}}$	Supply temperature gradient of heat exchanger	K
ΔT_{loss}	Temperature loss	K
ΔT_{s}	Discrete supply temperature difference	K
Δt	Discrete time difference	s
ΔU_{TES}	Difference of internal energy of TES	J
$\Delta U_{\text{TES, sunk}}$	Difference of sunk internal energy of TES	J
$\Delta \eta_{\text{th}}$	Thermal efficiency correction offset	–
ϵ_{surf}	Surface roughness	mm
ϵ_{TES}	TES effectiveness	–
$\epsilon_{\text{TES, min}}$	Minimum TES effectiveness	–
$\bar{\epsilon}_{\text{TES, min}}$	Minimum mean TES effectiveness	–
$\bar{\epsilon}_{\text{TES, remain}}$	Remaining mean TES effectiveness	–
η_0	Solar thermal zero loss efficiency	–
η_{coll}	Solar thermal collector efficiency	–
η_{el}	Electrical efficiency	–
$\eta_{\text{el, nom}}$	Nominal electrical efficiency	–
$\eta_{\text{pump, nom}}$	Nominal pump efficiency	–
η_{pump}	Pump efficiency	–
η_{TES}	TES efficiency	–
η_{th}	Thermal efficiency	–
$\eta_{\text{th, nom}}$	Nominal thermal efficiency	–
$\eta_{\text{th, PLR}}$	Thermal efficiency in relation to PLR	–
η_{water}	Dynamic viscosity	Pa.s
$f_{\text{COP, PLR}}$	COP factor in relation to PLR	–
$f_{\eta_{\text{el}}, \text{PLR}}$	Electrical efficiency factor in relation to PLR	–
$f_{\eta_{\text{th}}, \text{PLR}}$	Thermal efficiency factor in relation to PLR	–
$f_{\eta_{\text{th}}, \text{T}_\text{s}}$	Thermal efficiency factor in relation to supply temperature	–
f_{Lorenz}	Relation of technical COP to Carnot COP	–
$f_{\text{TES, costs}}$	TES cost factor	–
g	Gravitational acceleration	m/s^2
G_{t}	Total solar irradiance	W/m^2
H	Enthalpy	J
H_{in}	Input enthalpy	J
H_{out}	Output enthalpy	J

Notation	Description	Unit
h	Specific enthalpy	J/kg
k	Thermal conductivity	W/(m.K)
$k_{\text{insulation}}$	Thermal conductivity of insulation material	W/(m.K)
k_{soil}	Thermal conductivity of soil	W/(m.K)
K_{TES}	TES capacity	J
l	Length	m
$l_{\text{insulation}}$	Insulation thickness	mm
λ	(Darcy) friction factor	–
$\dot{m}$	Mass flow rate	kg/s
$P_{\text{el,pump}}$	Electrical power consumption of the pump	W
PI	Geothermal productivity index	$(\text{m}^3/\text{s})/\text{Pa}$
PLR	Part load ratio	–
PY_{buy}	Price for heat purchase	€
PY_{sell}	Price for heat sales	€
p_{in}	Input pressure	Pa
p_{out}	Output pressure	Pa
p	Static pressure	Pa
p_{WH}	Wellhead pressure of a geothermal production well	Pa
$\overline{py}_{\text{reference}}$	Reference mean price for electricity	€/MWh_{el}
py_{sale}	Price for electricity sales	€/MWh_{el}
Q	Heat	J
$\dot{Q}$	Heat transfer rate	W
Q_{loss}	Heat losses	J
$\dot{Q}_{\text{coll}}$	Heat transfer rate of solar thermal collector	W
$\dot{Q}_{\text{loss}}$	Heat transfer rate of heat losses	W
$\dot{Q}_{\text{max}}$	Maximum thermal power	W
$\dot{Q}_{\text{min}}$	Minimum thermal power	W
R	Hydraulic resistance	$(\text{kg.m})^{-1}$
Re	Reynolds number	–
Re_{crit}	Critical Reynolds number	–
$r_{\text{electricity}}$	Specific revenues for electricity production	€/MWh_{el}
ρ	Density	kg/m^3
SOC_{TES}	State of charge	MWh
s_{TC}	Slope of thermocline	–
$s_{\text{TC, standby}}$	Standby slope of thermocline	–
$subsidy_{\text{fixed}}$	Fixed subsidy	€/MWh_{el}
σ_{TES}	Relative state of charge	–

Notation	**Description**	**Unit**
T	Temperature	K
T_{a}	Ambient temperature	K
T_{c}	Cold reference temperature	K
$\overline{T}_{\mathrm{coll}}$	Solar thermal collector mean temperature	K
T_{fluid}	Fluid temperature	K
T_{h}	Hot reference temperature	K
$T_{\mathrm{HP,\,sink}}$	Heat pump internal sink temperature	K
$T_{\mathrm{HP,\,source}}$	Heat pump internal source temperature	K
T_{in}	Input temperature	K
T_{out}	Output temperature	K
T_{r}	Return temperature	K
$T_{\mathrm{r,\,source}}$	Heat source return temperature	K
$T_{\mathrm{r,\,heating\,plant}}$	Heating plant return temperature	K
$T_{\mathrm{r,\,prim}}$	Primary return temperature	K
$T_{\mathrm{r,\,prim,\,max}}$	Maximum primary return temperature	K
$T_{\mathrm{r,\,sec}}$	Secondary return temperature	K
T_{s}	Supply temperature	K
$T_{\mathrm{s,\,heating\,plant}}$	Heating plant supply temperature	K
$T_{\mathrm{s,\,max}}$	Maximum supply temperature	K
$T_{\mathrm{s,\,min}}$	Minimum supply temperature	K
$T_{\mathrm{s,\,nom}}$	Nominal supply temperature	K
$T_{\mathrm{s,\,prim}}$	Primary supply temperature	K
$T_{\mathrm{s,\,sec}}$	Secondary supply temperature	K
$T_{\mathrm{s,\,sec,\,min}}$	Minimum secondary supply temperature	K
T_{surr}	Surrounding temperature	K
$\overline{T}_{\mathrm{TES}}$	Mean TES temperature	K
$\overline{T}_{\mathrm{TES,\,bottom}}$	Mean bottom TES temperature	K
$\overline{T}_{\mathrm{TES,\,max}}$	Maximum mean TES temperature	K
$\overline{T}_{\mathrm{TES,\,min}}$	Minimum mean TES temperature	K
$\overline{T}_{\mathrm{TES,\,remain}}$	Remaining mean TES temperature	K
$\overline{T}_{\mathrm{TES,\,top}}$	Mean top TES temperature	K
t	Time	s
t_0	Starting time	s
t_1	Point of time 1	s
t^*	Dimensionless time	–
Θ	Dimensionless temperature	–
$\overline{\Theta}$	Mean dimensionless temperature	–
$\overline{\Theta}_{\mathrm{TES}}$	Mean TES dimensionless temperature	–
$\Theta_{\mathrm{s,\,sec,\,min}}$	Minimum dimensionless secondary supply temperature	–
ϑ	Temperature	°C
ϑ_{a}	Ambient temperature	°C
ϑ_{r}	Return temperature	°C
ϑ_{s}	Supply temperature	°C

Notation	**Description**	**Unit**
$\vartheta_{\mathrm{s,\,nom}}$	Nominal supply temperature	°C
$\vartheta_{\mathrm{r,\,source}}$	Heat source return temperature	°C
U	Internal energy	J
U_{loss}	Thermal transmittance	$W/(m^2.K)$
U_{TES}	Internal energy of TES	J
$U_{\mathrm{TES,\,max}}$	Maximum internal energy of TES	J
$U_{\mathrm{TES,\,min}}$	Minimum internal energy of TES	J
u	Specific internal energy	J/kg
$\dot{V}$	Volume flow rate	m^3/s
$\dot{V}_{\mathrm{pump,\,nom}}$	Nominal pump flow rate	m^3/s
$\dot{V}_{\mathrm{pump}}$	Pump flow rate	m^3/s
V_{TES}	TES Volume	m^3
v	Fluid velocity	m/s
W	Work	J
$\dot{W}$	Power (rate of energy transfer by work)	W
W_{p}	Pressure work	J
W_{s}	Shaft work	J
Z	Height/depth	m
Z_{DFL}	Dynamic fluid level	m
Z_{SFL}	Static fluid level	m
Z_{TES}	TES height	m
z	Relative height	–
z_{TC}	Relative height of thermocline	–
$z_{\mathrm{TC,\,max}}$	Maximum relative height of thermocline	–
$z_{\mathrm{TC,\,min}}$	Minimum relative height of thermocline	–
$z_{\mathrm{TC,\,remain}}$	Remaining relative height of thermocline	–
ζ	Pressure loss coefficient	–
ζ_{λ}	Pressure loss coefficient of a pipe	–

Glossary

Notation	**Description**
District heating system (DHS) control levels	For control systems, four different *DHS control levels* can be defined: component-level (e.g., a pump), aggregate-level (e.g., a heating plant), subsystem-level (e.g., heating central, customer's building, or network), and the system-level.
Distribution line/network	In DHSs, a network of pipes connects the heating plants and the substations. The smaller and local connections are called *distribution lines*. As most DHSs only have a local scale, it is unusual to differentiate between the transmission and distribution layers. The terms are therefore used synonymously, except for a few instances explicitly outlined in the text.
Energy transfer station	A substation that connects a heating central or a prosumer, is referred to as an *energy transfer station* related to [1].
Heat consumption	*Heat consumption* is the economic description of the thermodynamic process of decreasing the internal energy of a system. The term *consumption* conflicts with the thermodynamic understanding of energy conservation. However, since this term is well understood in both the economic and general context, it is nevertheless used in this work.
Heat production	*Heat production* is the economic description of the thermodynamic process of increasing the internal energy of a system. The term *production* conflicts with the thermodynamic understanding of energy conservation. However, since this term is well understood in both the economic and general context, it is nevertheless used in this work.

Heat source	The term *heat source* is used for primary heat sources.
Heating plant	The term *heating plant* is used for a specific heating plant consisting of a heating plant type and specific parameters.
Heating plant type	The term *heating plant type* is used for the combination of a heat source and a heating technology.
Heating technology	The term *heating technology* is used for a type of machine that converts the primary heat source or the primary energy of a fuel into heat that can be used by the DHS.
Reservoir	The term *reservoir* is used for geological structures that contain water.
Return line	The cold-water pipe is called the *return line* [2, p. 462]. The nomenclature is dependent on the temperature and not on the flow direction.
Smart thermal grids	In contrast to the definition of Lund et al. [3], in this thesis, it is proposed that the utilization of information and communication technology (ICT) is the main difference between a *smart thermal grid* and a non-smart thermal grid. The pipe design and layout are defined as parallel improvements of the fourth generation district heating (DH) besides the smart thermal grid. This is used to distinguish between the generations of DH and the implemented level of ICT.
Storage tank	The term *storage tank* will be used for those thermal energy storages which are (mostly) cylindrical vessels with a constant volume of water and which are built for the purpose of storing heat.
Substation	A *substation* is a connection between the network and the consumer, and it transfers the heat from the DHS to the building's internal heating system [4].
Supply line	The hot-water pipe is called a *supply line* [2, p. 462]. The nomenclature is dependent on the temperature and not on the flow direction. The term *supply* is used in several contexts (e.g., in an economic context).
Thermal energy	The term *thermal energy* is used for the amount of heat delivered at an interface of the DHS. For further discussion, q.v. *thermal power* and [cf. 2, pp. 18–20].
Thermal energy costs	*Thermal energy costs* are the variable costs related to the production of heat such as the cost of fuels.

Thermal energy storage	The term *thermal energy storage (TES)* is used for the technical entity that is built to store heat. There are different types of thermal energy storages (TESs) in the DHS.
Thermal power	The term *power* is frequently used in electrical systems. In thermodynamics, *power* is the rate of energy transfer by work [5, p. 57]. In this thesis, the term *power* in a thermodynamical context is not relevant. For a clear delimitation, the term *electrical power* is used for the electrical context. Further, the term *thermal power* is used to describe the heat flow rate respectively the heat transfer rate at interfaces of the DHS. This is related to the discussion in [2, pp. 18–20] where the term “heat power” is introduced. Such a simplification of the terms is useful because it allows for a simple comparison of electrical and thermal issues. Further, the adjective *thermal* is used instead of *heat* in analogy to *electrical*, which is also an adjective.
Thermal power costs	The *thermal power costs* are the fixed costs in relation to the installed capacity (thermal power). In DHSs, the largest part of the fixed costs is the capital costs. The costs for staff also belong to the fixed costs since they must be paid independently from the operation.
Transmission line/network	In DHSs, a network of pipes connects the heating plants and the substations. The larger connections are called *transmission lines*. As most DHSs have only a local scale, it is unusual to differentiate between the transmission and distribution layers. The terms are therefore used synonymously, with the exception of a few instances explicitly outlined in the text.

Chapter 1

Introduction

District heating systems (DHSs) are centralized heating systems that enable an economically and technically efficient heat supply. In the context of the climate crisis, DHSs have a special role to play. On the one hand, they can be used to integrate renewable heat sources and on the other hand, existing systems use fossil fuels for the current heat supply and need to be transformed. Even though the transition of DHSs towards a fossil-free heat supply is subject to ongoing research, a comprehensive methodology for the transition in the field of design, planning, and operation is still lacking. Therefore, this thesis aims to develop a methodology that facilitates the transition in an economically efficient way. This chapter introduces the thesis by presenting the motivation and background of this research. The research problem and the thesis objectives are introduced, and the structural outline is described.

1.1 Motivation

Global warming is one of the greatest crises of our time [6]. Although the potential risks are known, greenhouse gases continue to be emitted through the burning of fossil fuels [6]. To counter this development, the 196 signatory parties to the Paris Agreement (2015) agreed to limit global warming to preferably 1.5 °C [7]. To achieve this goal, the emissions of greenhouse gases must be drastically reduced.

The heating sector is one of the most relevant emitters of greenhouse gases. According to the International Energy Agency, the heating sector accounted for around 50 % of final energy consumption in 2019 [8]. As the share of renewable energy sources was still low (11 %), heat production based on fossil fuels emitted 40 % of the global CO_2 emissions [8].

DHSs are a promising technology—particularly for urban areas. DHSs are networks of pipes that use water to transmit heat from the heating plants to the heat consumers. In the Environmental Program of the United Nations, district heating (DH) is described as a “best practice approach” [9] for ecologically and economically efficient urban heating [9].

However, DHSs are not renewable per se as they are simply a technology for the distribution of heat. To achieve the climate goals, fossil heat production must be progressively substituted by renewable heating plants in the coming decades. The European Commission described decarbonized DHSs as a supporting component to achieve the European Union (EU) decarbonization objectives for buildings [10]. For example, in 2017 the share of renewable sources of heat production in DHSs in Germany was only 7 % and the share of waste incineration was 14 % [11]. Other sources of heat in DHSs are coal with a share of 28 % [11] which is mostly used in large-scale combined heat and power (CHP) plants, and natural gas with a share of 47 % [11] which is generally used in mid-scale and small-scale CHP plants as well as for peak-load boilers.

Even though renewable heating plants only have a small share of the overall heat production today, several technologies are already mature. Figure 1.1 summarizes the sophisticated renewable heating plants.

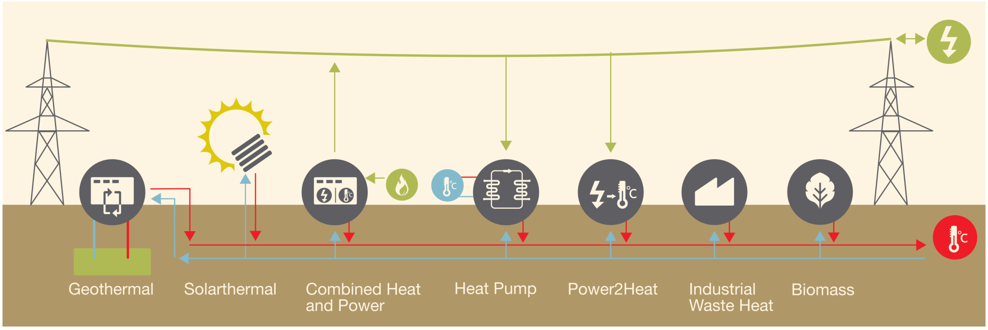

Figure 1.1: Sophisticated technologies for renewable heat production[1]

All new heat sources use different principles to provide heat for DHSs. Geothermal and solar thermal plants directly use environmental heat, industrial waste heat plants utilize surplus heat from industry, and biomass plants directly burn biomass such as wood or other biofuels. Heat pumps are a special type of heating plant

[1]The concept outlined in the figure was developed by the author and previously published in [12].

because they need an additional low-temperature heat source. CHP plants that use biofuels, heat pumps, and direct electrical heating are coupled to the electrical grid.

By this coupling of the heating and electricity sector, CHP plants, heat pumps, and direct electrical heating can also support the energy transition in the electricity sector. In this sector, the transition of electricity production towards renewable energies such as wind power and photovoltaics (PV) creates fluctuations in production that need to be compensated. The share of renewable electricity generation in Germany was already 37.8 % in 2018, whereby the bulk of the supply was provided by wind (18.7 %) and PV (7.7 %) power [13]. For a stable operation of electricity systems, more controllable generators must balance the fluctuating generation and demand. Relevant examples of controllable generators are CHP plants. Due to their high efficiency, they are a prevalent supply technology in DHSs [2, pp. 146, 150]. Induced by the changes in the electricity markets, an increasing number of CHP plants are operated in an electricity-led mode [3]. Other technologies that can be used to compensate for fluctuations in electrical generation include electrical boilers and heat pumps [14].

Figure 1.2 summarizes the two main challenges of the transition in the heating sector, namely the interaction with the electricity sector and the integration of more renewable heat production. The goal to reduce the primary energy demand must be achieved in all three fields of the DHS: production (efficient, renewable, and integrated), distribution (efficient), and demand side (reduced) [12].

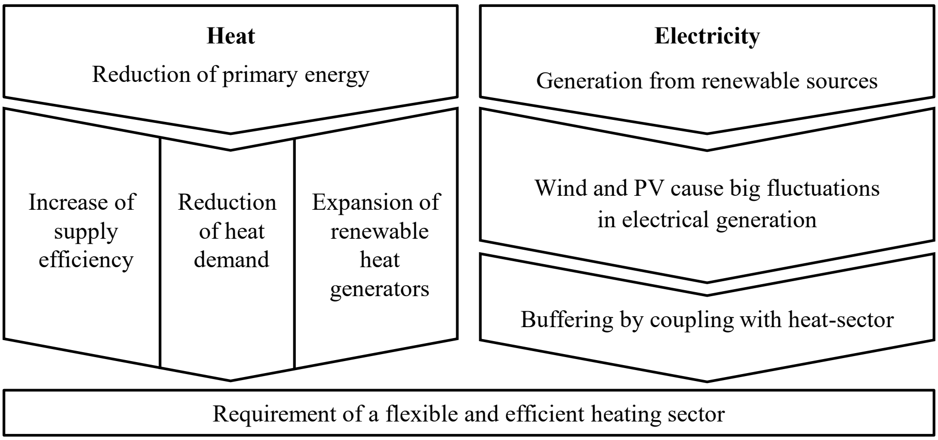

Figure 1.2: Overview of the reasons for the requirement of a flexible and efficient heating sector[2]

[2]An adapted version of this figure was previously published in [12].

1.2 Background

Lund et al. define four generations of DHSs. According to this concept, DHSs are classified in terms of available heat production technology, the system's efficiency, and the temperature level in the supply and return lines. DHSs continuously evolved since the end of the 19^{th} century. This transition up to the present conditions is summarized in [3] and updated by [15]. The *1^{st} generation district heating (1GDH)* was based on coal combustion processes between 1880 and 1930. The medium was steam with a supply temperature of up to 200 °C and a return temperature above 80 °C. The *2^{nd} generation district heating (2GDH)* introduced CHP processes whereby the supply temperature was still high at more than 100 °C and with return temperatures of up to 70 °C. In the period between 1930 to 1980, the technologies of the 2GDH were most commonly available. In the *3^{rd} generation district heating (3GDH)*, renewable heat sources were introduced. Some technologies such as biomass boilers and biomass CHP plants still require combustion, while others such as solar thermal plants and industrial surplus heat plants are not based on combustion processes. The system temperatures are less than 100 °C for supply and less than 45 °C for return. The period for this generation started in 1980 and it is now in the process of being replaced by the 4^{th} generation district heating (4GDH). [3], [15]

In contrast to the first three generations, the *4^{th} generation district heating (4GDH)* can be described as the first generation that is based on a fully renewable heat supply and that interacts with the electricity system. It aims for low grid temperatures with less than 70 °C (ideally less than 60 °C) and a return temperature near to the room temperature of 25 °C. Many different types of heating plants can additionally be integrated into such a DHS: centralized heat pumps, geothermal, surplus heat from data centers, and other low-temperature sources. Furthermore, centralized district cooling plants and cooling grids may also be connected as heat sources to the DHS and, consequently, the heating plants will be highly distributed in the whole system. The integration of a higher share of renewable heating plants results in the need for seasonal thermal energy storages (TESs). While TESs have been used in every generation, they have become increasingly important with the newer generations. The systems' efficiency has constantly increased with every new generation. In 4GDH, the concept of smart thermal grid (STG) can be implemented. By the interaction of electrical smart grids and thermal conversion as well as electricity-oriented CHP production, DHSs can compensate for wind and PV surplus and electricity generation shortage. Especially the participation of the CHP plants in different electricity markets (not only day-ahead spot markets) could increase the economy of the operation. [3], [15]

From a global perspective, *smart electrical* and *smart thermal grids* are part of the infrastructure of future *smart cities* [16]. The combination of the different smart energy grids (electricity, thermal, and gas) is defined as a *smart energy* *system* [17]. The interaction of these different systems allows for the flexibility of each system to be accessed in a comprehensive way which reduces the overall sum of the required storage capacity and allows for the utilization of the cheapest way to store the energy [17]. Smart grids are enhanced with information infrastructure to allow for monitoring and dynamic management of the whole system for the optimization of operation, maintenance, and planning [18]. Their main objective is to facilitate the integration of fluctuating and decentralized renewable energy sources [18]. Lund et al. defined the concept of an STG as a parallel to smart electricity grids [3]. Since DHSs have a high thermal inertia, they can offer much flexibility [19]. The objective of an STG is to integrate renewable heat sources and reduce temperatures [3]. Besides intelligent control and metering, low grid losses and improved pipe design are the main characteristics of an STG [3].

In addition to the definitions proposed by Lund et al., a *5th generation district heating (5GDH)* is defined by Buffa et al. [20]. Here, the distribution temperatures are below the required temperature for domestic hot water (DHW) heating [20]. To meet the temperature requirement, heat pumps are used to lift the temperature in the substations [20]. Lund et al. argued that the label of 5$^{\text{th}}$ generation district heating (5GDH) is misleading since the development of 5GDH requires another technical approach and it thus does not represent a consecutive development [21]. Instead, 4GDH and 5GDH should be seen as parallel developments [21]. As the 5GDH is evaluated as an independent technology, it will not be considered in this thesis.

Since the 4GDH is the first fossil-free generation, it will be used synonymously for fossil-free DH. The 3GDH (as well as previous generations) is at least partly based on fossil fuels and on combustion processes in mostly centralized plants. The transition from 3GDH to 4GDH is part of an ongoing development and is the focus of current research activities [1], [15] whereby the concept of an STG is seen as a supporting element for the transition. In contrast to the definition of Lund et al., in this thesis, it is proposed that the utilization of information and communication technology (ICT) is the main difference between a smart and a non-smart thermal grid. The pipe design and layout are defined as parallel improvements of the 4GDH besides the STG. This is intended to distinguish between the generations of DH and the implemented level of ICT.

For the transition to succeed, several things must change. One condition for the renewable heat supply is the availability of low system temperatures [3]. Further, some of the new heat sources (like surplus heat from industry) are owned by third-party companies, which conflicts with the typical vertical integration of DH companies [22]. Another aspect is that previous generations benefit from the flexibility of burning fossil fuels whereas, in contrast, renewable heat sources such as solar thermal are fluctuating [3]. In addition, fluctuations in the electrical grid that are induced by wind power and PV cause higher fluctuations in electricity prices which impact the heat production if heat pumps or CHP plants are used [3].

Therefore, fluctuations must be compensated by an enhanced management of flexible technologies such as TESs. These effects can be found in many references (q.v. chapter 2). Thus, it can be concluded that there is a consensus in the scientific community on these changes.

More critically, it is discussed how the transition can be supported. In the past, these discussions focused on technical solutions but—as is highlighted by the literature review (q.v. chapter 2)—the newer discussions also include the economic perspective. For example, Lygnerud showed that the *established business logic* is one of the main barriers that hinder the transition [23]. The problem can be described as follows: in the case of heating plants based on combustion processes, lowering the supply temperature only has a minor impact on the efficiency and therefore on the costs [24] whereas, in the case of renewable heating plants that are combustion-free, the impact is significant [24]. These heating plants can therefore not be introduced to DHSs with high temperatures in an economically viable way [24]. However, if there are no renewable heating plants existent in a DHS, there is no significant advantage that results from reducing the temperature. Since vertically integrated companies additionally benefit from the utilization of their existing plants, there is no strong internal incentive to reduce the temperature and to get rid of the existing plants in the short term. This phenomenon is described by the term *lock-in effect* and results from established business models [cf. 23]. As this effect probably cannot effectively be addressed by the current incremental evolution, it can only be overcome by a disruptive change. In contrast to incremental technical changes in the established economic environment, such a disruptive change requires the change of the whole technical and economic environment.

1.3 Research problem, objectives, and limitations

The transition of DHSs to 4GDH is complex since many different fields are interrelated. The review of the state of the art (q.v. chapter 2) showed that there is literature with a systemic perspective on the fields of *policies* and *heat strategies*. These fields define the conditions for the operating companies, whereas the DH companies—mostly monopolists—are responsible for the *design, planning, and operation* of the DHS. In contrast to the fields of policies and heat strategies, a scientifically developed solution with an overall perspective is lacking in these fields. While there is a great deal of existing scientific knowledge about how to solve individual issues in these different fields, the identified solutions only focus on single isolated problems. For example, the introduction of more competition is evaluated as economically inefficient under the present conditions. However, the aspect of whether the introduction of competition has a positive impact on the transition is not considered in these discussions.

Research problem

The literature review (q.v. chapter 2) identifies the research problem, namely that several barriers complicate or even impede the transition towards 4GDH. In the fields of design, operative planning, and operation, existing scientific solutions only focus on resolving single barriers. However, the interaction of the different solutions in a systemic context has not yet been evaluated and thus it cannot be ensured that the independently developed concepts form a comprehensive environment with the objective to support the transition and resolve the existing lock-in effect concerning the established technologies.

Such a comprehensive solution is necessary for the transition to succeed at all and thereby contribute to mitigating the climate crisis. In addition, it requires the acceptance of the heat consumers, which can only be ensured by a transition that is as cost-effective as possible.

Research aim and objectives

To contribute to resolving the research problem, this thesis aims to develop a comprehensive transition methodology to facilitate the district heating transition towards renewable energy sources in an economically efficient way.

This research aim leads to the following four specific objectives:

Objective 1: Identify existing methodologies that aim to facilitate the transition to 4GDH in a comprehensive way. To do so, classify and structure the different activities to identify a possible gap in the research.

Objective 2: Develop a new framework for the activities in the fields of design, operative planning, and operation of DHSs as a transition methodology. Investigate the possibility of new roles or agents, consider the physics of the system, and aim for high economic efficiency. Ensure that the new framework connects all subsystems in a comprehensive way.

Objective 3: Integrate the heating plants into the new framework by evaluating the supply temperature impact on the variable costs of heat production to evaluate the temperature relevance of the new framework.

Objective 4: Develop a concept for the integration of flexibility into the new framework. To do so, identify existing concepts and evaluate their compatibility with the new framework. The final integration should allow for accessing the thermal flexibility to manage the DHS in the most efficient and systemic way.

Limitations

As this thesis focuses on a systemic perspective and since it is limited in time and scope, the development can only take place on a global level. It is therefore not possible to develop and implement all innovations that would be required to fully resolve each of the new questions raised during the development. For example, certain implementations are limited to a specific level of detail. The software that will be needed to implement the framework is not fully developed and presented in this thesis since it would require extensive effort that goes beyond the scope of the research. These open implementations subsequently limit the possibility to validate the proposed concepts under real conditions. Further, evaluations on a macroeconomic scale are made qualitatively based on the literature and fundamentals and, therefore, they are not quantified.

Relevance

Despite the described limitations, a framework is developed in this thesis that does not exist in this comprehensive manner yet. This framework combines the required activities for design, operative planning, and operation to processes that are linked by mechanisms that are a synthesis of existing and newly developed concepts. The application of the framework serves as the transition methodology which has been identified as lacking.

This framework thus contributes to filling the identified gap in the literature and proposes scientifically supported concepts to fill them and, in so doing, it further enhances the scientific knowledge in the field of DH.

In addition, this thesis contributes to the two research projects *Smart Heat Grid Hamburg* [25] and *Reallabor: Integrierte WärmeWende Wilhelmsburg – Integrierter Wärmemarkt* (*Living Lab: Integrated Heating Transition Wilhelmsburg—Integrated Heat Market*) [26]. The projects aim to facilitate the transition to 4GDH by developing innovations and their practical implementation in a DHS in the Wilhelmsburg district of the city of Hamburg in Germany. Since this thesis uses this DHS as a case study site, the developed concepts and the results of their application to the case study contribute directly to these two projects and the operation of the DHS.

Besides these scientific contributions, the developed concepts and tools can be applied in practice and benefit several stakeholders. Firstly, this thesis can be used to implement the proposed framework and tools in a structural way on a company level. Secondly, municipalities could use this thesis as an orientation guide when implementing new DH utilities. Finally, it may help policymakers to improve the regulation for DHSs. On all these levels, the results of this thesis may contribute to supporting the transition to a fossil-free energy supply.

1.4 Structural outline

In chapter 2, relevant scientific literature related to the systematic methodologies for the transition of DHSs is reviewed. Based on the identified contents, eight DH scopes are proposed, which classify the different activities in DH research and practice. By evaluating the literature in relation to its coverage of these DH scopes, the main gap—a lacking transition methodology for design, operative planning, and operation—is identified.

To fill this gap, a new *framework* should be developed. The top level of the framework approach for the development is presented in chapter 3 and includes four steps: the definition of the basic framework structure and the outer conditions (1), the individual framework process development (2), the integration of heating plants (3), and the integration of flexibility (4). In addition to the framework approach, the required standards for the implementations proposed in this thesis are introduced in chapter 3. These are global technical conditions, the modeling tools, and the introduction of a DHS case study.

These steps of the framework approach are applied in chapters 4 to 6. Each of these chapters has been developed as an independent but linked unit with its own problem statement, method, analysis, development, results, and discussion section. In chapter 4, steps 1 and 2 of the framework approach are presented. The definition of the basic framework structure includes the introduction of a new organizational structure as well as several required framework processes. In the subsequent individual framework process development, the relevant activities for design, operative planning, and operation are considered. As a first implementation of the framework, a method is developed in chapter 5 that integrates the heating plants into the operative planning processes of the framework. This method is based on the average variable costs of heat production in correlation to temperature and thermal power. The new method is applied to the heating plants of the DHS case study. Chapter 6 is focused on improving the management of the DHS by using the system's flexibility. In this chapter, the different technologies offering flexibility are analyzed and systematically integrated into the new framework in general and into the operative planning processes specifically. Further, flexibility metrics are developed and implemented as models. These models are applied to storage tanks of the DHS case study.

In the last chapter, the results are summarized and compared to the objectives of the thesis. The main contributions are outlined, limitations are discussed, and recommendations for future research are presented.

Besides the main chapters, further information is provided by this thesis in the following sections:

Due to the non-standardized vocabulary in the DH sector [1] and because of some conflicts of terms of the different disciplines that are relevant for this thesis (e.g., macroeconomics and thermodynamics), some terms require a further clarification, which is provided by the glossary.

For an understanding of the main chapters, a basic knowledge of different disciplines is required. This includes technical basics (district heating, thermodynamics, heat transfer, and hydraulics), economic basics (different types of costs and competition theory), as well as a brief introduction to algorithms (mixed integer programming, evolutionary algorithms, neural networks, and fuzzy logic systems). This basic knowledge is provided in appendix A which can be referred to as needed. Appendix B presents the full interviews with DH companies from Denmark (used in chapter 4). Appendix C presents detailed input data of the case studies used in chapters 5 and 6. Appendix D presents several definitions for the term flexibility, which are discussed in chapter 6.

Chapter 2

State-of-the-art review of DH transition methodologies

The transition to 4th generation district heating (4GDH) is a complex process that affects all fields of district heating (DH) [cf. 3]. It requires changes in all technological parts of the district heating system (DHS), and it often also necessitates changes to the structure and organization of DHSs. This chapter aims to identify the existing methodologies for the transition and presents an analysis to identify the gaps in these methodologies.

In a first step, the requirements for the transition are identified from the literature and then summarized. These are later used for the validation of the developed concepts.

For a systematic evaluation of existing methodologies and the focus they have in the different fields, eight new *DH scopes* are proposed in this chapter. These DH scopes are derived from the findings of the literature review as well as from the author's personal experience in DH research and practice. By making use of these DH scopes, the identified literature and the related methodologies can be classified and, in so doing, existing methodologies can be evaluated according to their coverage of these scopes.

Finally, it can be shown that extensive methodologies are available in the DH scopes of *policies* and *heat strategy*. In contrast, the DH scopes of *design*, *operative planning*, and *operation* lack a coherent and comprehensive methodology for the transition of DH. In this deficit lies the motivation for the development of a new framework and its associated methodology, which together form the core of this thesis.

The chapter is organized into five sections. In the first section, the requirements for the transition of DHSs to renewable heat sources are analyzed. Section 2.2 presents the methodology used for the systematic literature review which aims to identify existing comprehensive methodologies for the transition. The third section presents the results of the literature review by referring to research reports in the first subsection and to articles in the second subsection. In section 2.4, the results are discussed, and a gap in the existing methodology for the transition of DH is identified. This gap affects the DH scopes of design, operative planning, and operation. Finally, the main contributions of the chapter are concluded in section 2.5.

2.1 Requirements for the transition in DHSs

For the later evaluation of existing methodologies, an identification of the requirements for the transition towards 4GDH is necessary. Therefore, the requirements for the transition based on the literature are analyzed in this section.

Transitions can be described as "systems of innovations" [27] which are structural changes in a whole system including social and technical aspects such as technology, policy, and markets [27].

Innovation can be described as a new product or process with considerable differences from those available in the market. Innovation can take place at the component, system, or inter-organizational levels and it can be incremental or radical. By evaluating the transition in DHSs, it is shown that preliminary changes can mostly be characterized as incremental instead of disruptive. [28]

DH is regarded as an economical, safe, and reliable technology for urban areas. However, as the complexity of the heating sector is high the transition to renewable sources is challenging, although a transition is supported by the public if the costs of a new supply are competitive compared to the costs of the current supply. Well-operated DHSs can effectively support the urban poor (e.g., through a better heating quality to prevent mold at low costs). To promote DH, social participation, suitable governmental policies, and municipal activities are important. Further, reliability is another important social requirement that can be improved by new technologies. [29]

2.1.1 Technical requirements

The change from fossil to non-combustion renewable heat sources is identified as a major topic for DH research [28]. Depending on the type of heat source, different constraints and requirements go along with the technologies.

Industrial surplus heat is characterized by variations that are related to the different industries. Another challenge is that demand and supply must be met at the same location. For solar thermal integration, thermal energy storages (TESs) are needed, and low temperatures are required to operate at high efficiency. If they are integrated in a decentralized way, enhanced control strategies are needed. Geothermal plants require large investments, and they would also profit from lower DH temperatures if the available geothermal temperature is low. In some cases, additional heat pumps are needed. Other applications using heat pumps would also benefit from lower temperatures, for example, sea-water heat pumps. The electricity demand of heat pump applications depends on the source temperature. [29]

These examples demonstrate that lower operating temperatures on the customer side are required to improve the efficiency of transport and heat production [30]. Here, the major challenge lies in lowering temperatures in existing buildings [14]. This challenge concerning high temperatures and the reduction in existing systems is the focus of many research articles [28].

The non-combustion technologies have a significant impact on costs related to the system's temperature level as higher temperatures induce higher production costs and vice versa. In contrast, combustion-based technologies do not have such a significant impact. This results in a lock-in effect in existing DHSs with high temperature levels. The combustion technologies do not benefit in the same way from lower temperature and, therefore, lowering the temperature does not yield a significant cost reduction as long these technologies are used. At the same time, non-combustion technologies are not cost-effective at high temperatures as they require lower temperatures. [24]

This lock-in effect of high temperatures will be overcome by the temperature reduction which is introduced in the 4GDH [28].

The 4GDH needs to handle different stages of renovation of the supplied buildings, requires low distribution losses, and must integrate renewable heat sources at low temperatures. It is argued that the transition to sustainable DH requires the transition to 4GDH, which is a system that motivates the integration of renewable heat sources at low temperatures and includes the concept of the smart thermal grid (STG). To fulfill this technological transition, a radical change in the system is required. In addition to lowering the temperature, it is proposed that these DHSs are part of an overall smart energy system that integrates the different energy sectors. For example, the DHSs can be used to compensate for the fluctuation in electricity generation caused by wind and solar generators. [3]

In times of electricity surplus, the DHSs can be supplied by electrical boilers and heat pumps whereas if the electricity demand is high, flexible combined heat and power (CHP) plants can compensate for low power production [14].

The new heat sources correlate with a higher degree of decentralization. The decentralization, as well as the lower temperatures, can cause problems in existing grid layouts e.g., through bottlenecks. [28]

The transition will result in numerous plants with centralized and decentralized connections. In most cases, fossil peak production is still necessary, even though it is the most expensive type. Prosumers will become an important aspect that requires other operational concepts. Such a concept could be a market-price-based selection of the momentary type of heating plant. Heat trading could be introduced compared to the electricity sector. Further, DHSs should be opened for third-party access to integrate surplus heat from industry or prosumers. An example of such an open market is found in Stockholm. [31]

2.1.2 Economic requirements

Long-standing policies can support the transition to non-fossil heat sources. The whole transition benefits from systemic planning that includes the design of the buildings and the urban area for which standardized planning and strategies on a regional level are required. Large investments with high uncertainty (e.g., in the case of industrial surplus heat plants) require public support, and regulations are needed to displace the fossil plants and to handle the monopoly structure of the DHS. [32]

Compared to conventional technologies, most renewable heat sources have a higher demand for capital resulting from a higher share of investments [28]. This challenge leads to a larger gap between short-term and long-term marginal costs [30]. Therefore, it is necessary to provide strategic and operational structures for planning and incentivizing the transformation [3]. For example, the introduction of renewable technologies can be supplemented by new types of organization that should be developed [3].

Related to the local conditions of the non-combustion heat sources, the new technologies are not as generic as fossil technologies [14]. Therefore, specific planning on the municipal level is important, even though this can also lead to interference with politics, which can result in a barrier to successful implementation [28]. As DHSs are influenced by politics, they must be operated under uncertainties due to changing policies [33, p. 14].

Regulations are made on different levels [34, p. 17, Fig. 4]: the first level is the regional and local regulation, the second level is the national regulation, and the third level is the European Union (EU) (supernational) regulation. Through these different levels, local heat strategies will differ depending on their geographical location and the specific regulation. [34, p. 17, Fig. 4]

Experiences from other natural monopolies show that DH companies do not act innovatively without extra incentives from the regulator if they are benefitting from the status quo. Further, the different policies in the EU countries form a heterogenous situation and hinder the application of successful business models from other countries. Another barrier is the long-term investment required in the DH sector. This is “unattractive” [35] compared to other energy sectors with shorter payback times. [35]

Current developments towards the integration of surplus heat from third-party suppliers such as industry, data centers, or supermarkets may require the liberalization of DHSs. For example, the regulation of the Danish DH sector hinders the integration of surplus heat due to the prohibition on profit in DH sectors. In Norway, prices are limited according to the electricity price. In contrast, although Sweden has deregulated the heat market, there are indications that some of the DH companies “behave as price-makers” [22]. [22]

In Sweden, DH companies have deregulated market conditions, which is different from other countries. In this market, the DH sector has managed to drastically reduce the emissions in a deregulated market through the introduction of carbon taxes. In recent decades, some challenges arose due to policy changes with more price regulation, the introduction of the carbon tax, third-party access, and a new DH law. The main challenge is to become independent of fossil fuels while staying competitive in relation to other supply options, mainly individual heat pumps. The impact on the current business model is analyzed using a literature review and interviews with DH companies, whereby a lock-in effect of established business models that focus on centralized large-scale production is identified. A barrier to change is that the established business models are still profitable, and it is, therefore, hard to switch to future business models. Hence, short-term and incremental changes are made instead, with the issue that the step from low emissions to zero emissions would require more drastic changes. The interviews showed that, from the customer side, there is a lack of trust in the DH companies. It is concluded that existing business models conflict with the new requirements for higher efficiency as well as the integration of distributed and low-temperature heat sources. This issue is not solved yet. Instead of supporting large-scale centralized plants, a system is needed that gives incentives for flexibility and the integration of surplus heat to keep DHSs competitive with individual renewable heating. [23]

2.1.3 Summary of requirements

The requirement analysis shows that a transition to a renewable heat supply is needed. DH is a suitable technology to achieve climate goals under acceptable social conditions. To do so, renewable heating technologies must be integrated, which requires a reduction in temperature. Existing systems have a barrier as the conventional (combustion-based) technologies do not have this significant temperature impact. Further, this transition does not only require a technical change but also changes in the business model, planning procedures, and municipal strategies and policies. This transition can benefit from many developments and from research that is currently performed under the umbrella of the 4GDH and STG in conjunction with the digitalization of the DHS. As the complexity of the topics requires an evaluation of comprehensive solutions, the objective of the following literature review is to identify a comprehensive methodology for how to create a system that incentivizes improvements and penalizes activities that are not in line with the transition.

2.2 Method of the state-of-the-art review

The objective of this chapter is to identify existing methodologies from the literature that facilitate the transition of DHSs towards 4GDH in a comprehensive way. These methodologies are evaluated in relation to the coverage of different fields of DH to identify gaps for the further development of such a systemic methodology.

The identified literature is evaluated in two steps. Firstly, an own list of *DH scopes* is proposed that aims to classify activities in the different fields of DH research and practice. Secondly, the identified references are evaluated for their coverage of these DH scopes. The novelty of this method lies in the list of the DH scopes and their systemic combination to present a comprehensive overview of DH activities.

2.2.1 A new classification of DH activities: DH scopes

Table 2.1 presents eight *DH scopes* that are proposed for classifying the activities in research and practice. The scopes represent a hierarchy of the different fields and do not present phases (structure by time). They should be applied in a generic way, and they are technology-independent. The eight scopes are derived from the experiences made by the author in DH planning, operation, and research as well as from the literature that is presented later, and were iteratively developed.

Table 2.1: New DH scopes for the classification of activities in DH research and practice

Scope	Title	Description
I.	Preconditions	include the people's needs as well as technically available sources. They are independent of the existence of a DHS or even a DH strategy.
II.	Policies	form the legal frame for all economic activities (DH as well). In general, it is defined by the legislation.
III.	Heat strategy	is a plan or vision, and in most cases, it is developed by a government or administration.
IV.	Organization	is the first implementation level of a DHS i.e., by defining the legal form of one or more DH companies. It includes specific business mechanisms such as contracts and tariffs.
V.	Design	deals with the technical implementation of the DHS including the specific construction and selection of heating plants.
VI.	Operative planning	focuses on the scheduling of plants after their implementation. The operative planning introduces economic optimizations to existing systems.
VII.	Operation	represents the real-time processes including control and maintenance.
VIII.	Evaluation	includes all activities that are performed post-operation such as evaluation of historical data or billing for customers.

It is hypothesized that such a comprehensive hierarchy has not been published yet and further that it covers all relevant topics in DH research. The literature presented in section 2.3 will be used to evaluate whether such a structure already exists. Further, it should be examined whether the proposed hierarchy can be applied to classify different fields of DH research. Finally, the new classification of the literature is used to identify the missing methodologies in DH research.

2.2.2 Systematic literature review

The systematic literature review is performed with Google Scholar [36] as through the use of this search engine, reports and books are included in addition to papers. The results are sorted by relevance, and the first 100 results of each keyword search are included. The period considered is from January 2000 to April 2021, which is the last month of the working phase of the thesis, before the final documentation is started. Most literature on the transition of DH came up in the last 10 years [cf. 1]. The year 2000 is included to ensure the inclusion of all relevant publications while simultaneously limiting the overall number of publications. The focus of the selected articles is on a comprehensive perspective that considers more than a single DH scope or a single technology to create an overview of the different DH scopes and identify interfaces.

The keywords and the number of results are presented in table 2.2. All keywords are combined with *district heating*. As shown, the number of results related to the different keywords varies between 239 and 168,000. For every keyword combination, the titles of the first 100 publications are read and their relevance is evaluated. Titles that indicate a focus on a single heating technology (e.g., only heat pumps) or a single DH scope are not included. In most cases, a quarter to a third of the 100 evaluated titles is selected for further evaluation. To do so, the abstract is reviewed and again only those that allude to a comprehensive perspective are further evaluated. Finally, the articles of the selected abstracts are read and only a small number of publications are identified as supporting a comprehensive view.

Because it is challenging to present a comprehensive view in the form of a paper, research reports from the project database of *IEA-DHC* [37] and the knowledge hub of *Euroheat & Power* [38] are also considered. In this way, relevant additional publications (reports, guidelines, and books) are identified.

Table 2.2: Keywords used for the systematic literature review

Key words ("District heating" + ...)	**Results**	**Reviewed titles**	**Reviewed abstracts and texts**	**Further processed**
... methodology	127,000	100	34	4
... comprehensive	150,000	100	30	8
... systemic	27,000	100	24	6
... systemic design	239	100	1	0
... holistic	31,000	100	21	0
... framework	168,000	100	33	7
... interfaces	36,000	100	16	1
... phases	95,000	100	22	1
... layer	154,000	100	5	1
... agile	5.400	100	5	4
... scopes	5.800	100	19	2
... transformation	139,000	100	26	2
... transition	139.00	100	24	3

2.3 Evaluation of the coverage of DH scopes

In this section, relevant publications are presented that are identified by the literature research and are evaluated according to their systemic perspective. The content of each publication is presented on an abstract level to identify the coverage of the introduced DH scopes.

Table 2.3 presents an overview of the publications whereby a black cell indicates that the scope is a main aspect of the publication and gray fields indicate that there is information about the scope but it is not the central aspect of the publication in question.

In the review, the most comprehensive views in books, guidelines, and reports (R) are identified and hence these are presented first. Afterward, their results are supplemented by findings in articles (A). Most of the papers are review articles whereby the majority of the reviewed research articles contribute to only one of DH scopes. They thus do not present a comprehensive perspective and are not used in this section. Some of these one-scope articles are referred to in the following chapters when a focus on one scope is required.

Table 2.3: Relevant publications and their coverage of the DH scopes

Reference: (R)eport, (A)rticle	**DH scope I**	**DH scope II**	**DH scope III**	**DH scope IV**	**DH scope V**	**DH scope VI**	**DH scope VII**	**DH scope VIII**
[**34**] (R)		■	■	■				
[**33**] (R)		■	■	■	■		■	
[**39**] (R)		▒	■		▒			▒
[**40**] (R)		■	■	■	▒	▒		
[**41**] (R)		■	■	■	■			
[**42**] (R)			■	■	■		▒	▒
[**29**] (A)	■	■						
[**43**] (A)	■	■	■	■	▒			
[**44**] (A)		■	■					
[**45**] (A)			■	▒				
[**46**] (A)			▒	■				
[**28**] (A)			■		■			
[**47**] (A)	▒			■	▒	▒		
[**23**] (A)	▒			■				
[**48**] (A)				■	■		■	
[**22**] (A)				■		■		
[**49**] (A)					■	■		
[**30**] (A)				▒	■	■		
[**50**] (A)					■	■		
[**19**] (A)						■	■	
[**51**] (A)						■	■	

2.3.1 Reports with a comprehensive perspective on DH

Hotmaps is an EU research project that developed handbooks for strategic heat planning [34]. On an abstract level, the handbooks describe how and why novel technologies often need new business structures [34, p. 14]. Further, it could be necessary that these new business structures require support from new legal conditions. These handbooks focus on heat strategies (III) and give an extensive overview of the measures necessary for policies (II) and the later organization of the DHS (IV).

Another project is the *Governance Models and Strategic Decision-Making Processes for Deploying Thermal Grids* funded by the International Energy Agency [33]. Its report serves as a guide for developers, politicians, real estate owners, and city planners [33, p. 8]. The report presents aspects of the DH scopes II–V and VII although the required interfaces are discussed superficially. From an overall system perspective, an important aspect is that the different activities include feedback loops (e.g., for enhancing the system). The related lifecycle stages are depicted in figure 2.1.

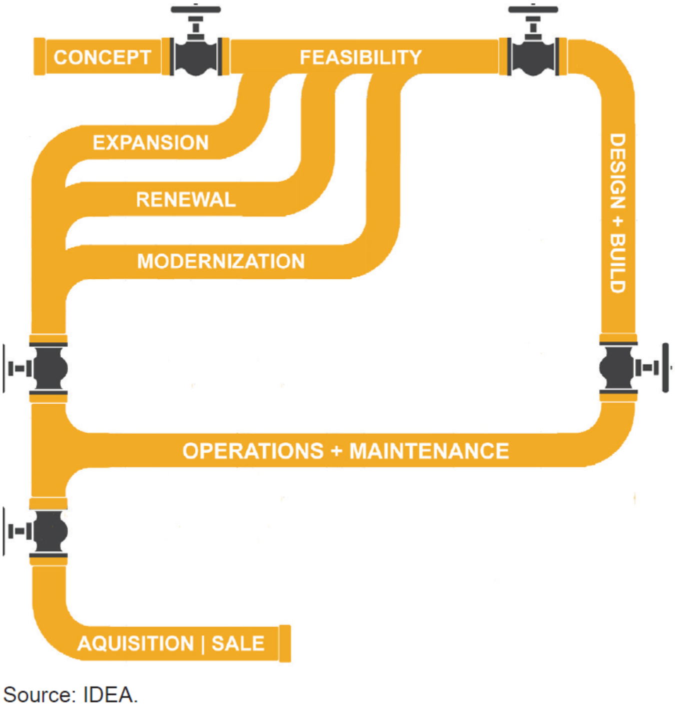

Figure 2.1: Activities during a DHS's lifetime [33, p. 43]

The figure presents different activities that must be undertaken in the lifecycle of a district energy system, and they can be necessary more than once (cyclical) [33, p. 43]. In the concept stage, stakeholders present their development objectives and planners develop an early concept. The feasibility of the measures must be evaluated before the system can be designed and built. After installation, the system is operated, maintained and its performance is optimized. The reasons for the adjustment of the previous concept can be due to the extension, renovation, or modernization that can be necessary during the system's long lifetime. Finally, the system can change ownership while still in operation. [33]

The project *Heat Roadmap Europe* published three reports to give recommendations for DHSs to politicians at different levels (local, national, EU) [39]. All in all, comprehensive planning is required that is evaluated frequently to provide input for policymakers [39, p. 94]. The planning should be continuous and transparent and should include the relevant stakeholders [39, p. 17]. The dependencies of the different activities are emphasized by the management cycle (q.v. figure 2.2).

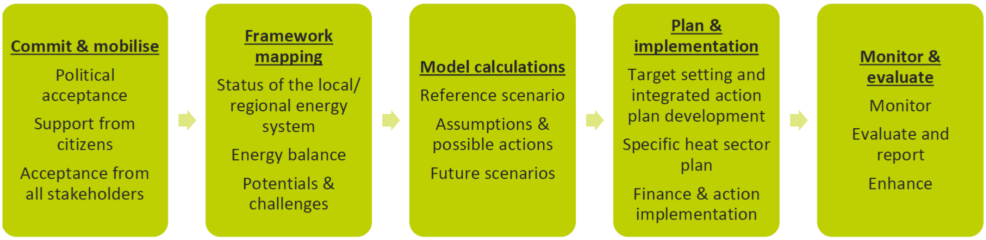

Figure 2.2: The DH management cycle [39, p. 16]

The steps of the cycle are [39, p. 16]: "commit & mobilize" for stakeholder engagement, "framework mapping" to identify the given energy balances, "model calculation" in different scenarios, and "plan & implementation" and "monitor and evaluate" to secure an enhancement of the planning. The report focuses on heat strategies (III) and gives further recommendations for the DH scopes II, V, and VIII.

The study *Efficient district heating and cooling systems in the EU* presents an evaluation of eight district heating and cooling (DHC) systems in the European Member States [40]. It identifies key success factors and gives recommendations for policymakers concerning district heating and cooling (DHC) [40, pp. 123–133]:

1. "Adequate national policy and regulatory environment"
2. "Direct/indirect financial support"
3. "Focused local policy and coherence with urban planning"
4. "Alignment of interests/Cooperation maturity"

5. “Availability and relevance of local resources”
6. “Comprehensive project development”
7. “Price competitiveness against alternative energy solutions”
8. “Flexible heat and cold production”
9. “Combining technical and non-technical innovation”

The key success factors 1–3 are related to the policy scope (II), 4–6 should be part of a heat strategy (III), and 7–9 are general recommendations that contribute to the DH scopes IV–VI. The authors argue that DHC systems must be “periodically re-engineered” [40, p. 7] to ensure a flexible supply in a “smart multi-energy system” [40, p. 7]. DHC systems can balance energy transitions and must be developed in an evolutive way [40, pp. 134–135]. In recent decades, the radical changes in DHC systems affected the DHC systems and thus it is proposed that DHC systems require an open and evolutionary architecture including both competition and cooperation [40, pp. 136–137]. The study focuses on the DH scopes II–IV. It shows that policies provide a framework for the municipal strategy and that the organizational frame (e.g., with or without competition) depends on the superordinated levels. Further, the study gives best practices for designing activities (V) including tendering (case of Barcelona) as well as the innovative scheduling procedure from *Varmelast* in Copenhagen (VI).

The guideline *integrating low-temperature renewables in district energy systems* describes several issues and solutions for politicians with a focus on low temperature and renewable energy in DHC systems [41]. The guideline emphasizes that the integration of low-temperature sources requires a transition in the building stock and also in existing networks. Therefore, low-temperature measures should be integrated into the local heat strategy [41, pp. 78–86]. This guideline clarifies many aspects of the DH scopes II–V and their interrelationship (e.g., new technical designs and their requirements concerning the heat strategy). It also includes the temperature dimension on all levels.

The *London Heat Network Manual* aims to support the development of large-scale DH in London to facilitate the achievement of the city’s climate goals [42]. The manual provides guidelines for technical solutions as well as for the organization of the planning and operation activities. It also provides an overview of the different activities in DHSs with practical advice and standardizations. The DH scopes III–V are identified as the focus of this manual and it provides information on the different approaches for conducting measurements, which both are part of the design and are also related to VIII. Further, standards for operation (VII) are presented. The operative planning (DH scope VI) is not included, and consequently, its integration in an overall context is also lacking.

2.3.2 Articles with a comprehensive perspective of DH

Mazhar et al. present a literature review on the state of the art of DHSs [29]. The main input of this paper to the developed DH scopes is the preconditions and their impact on legislation, technical framework, and policies (DH scopes I and II). The article provides an overview of the different heat sources and their new requirements concerning the overall system as presented in section 2.1. The paper classifies the research fields "technologies," "economics and social aspects," "market leaders [. . .] and the evolution of these grids," and "legislation, technological framework, and policies" [29]. This classification can be regarded as being different compared to the proposed one.

Werner provides a review of the DH sector in Sweden, where a high share of DH exists in general and where the DHSs have a low fossil fuel consumption [43]. The review also presents important developments in Sweden and discusses several aspects of the DH scopes I–IV although the interfaces of the different topics are not explicitly discussed. Werner introduces several contexts ("market," "technical," "supply," "environmental," "institutional," and "future" [43]) to classify the findings. His classification can be regarded as being different compared to the one that is proposed here.

Sperling et al. evaluate the alignment of municipal energy planning and the national energy strategy in Denmark [44]. The paper argues that a comprehensive strategy to meet the climate goals requires strategic planning at the municipal and central levels instead of parallel energy planning activities. Sperling et al. emphasize that the national objectives and the municipal energy planning should be harmonized to create strategic energy planning. Based on these challenges, the authors have developed a "comprehensive picture of all tasks and actors" [44] as depicted in figure 2.3.

The figure presents the dependencies of different strategic heat planning tasks, the different levels (national and municipal), and the actors that are involved. The main tasks are defined with a "national [. . .] energy planning strategy," "[. . .] legislation and support schemes," "framework for strategic municipal energy planning," "strategic municipal energy plans," and the "implementation of strategic municipal energy plans" [44]. The concept is not meant as top-down centralized planning but rather, the idea is to support municipalities by providing guidance. This strategic energy planning benefits from local effectiveness and a centralized framework. Further, it is addressed that this whole planning framework requires a regular evaluation. The proposed framework focuses on the DH scopes II and III and their compatibility with each other.

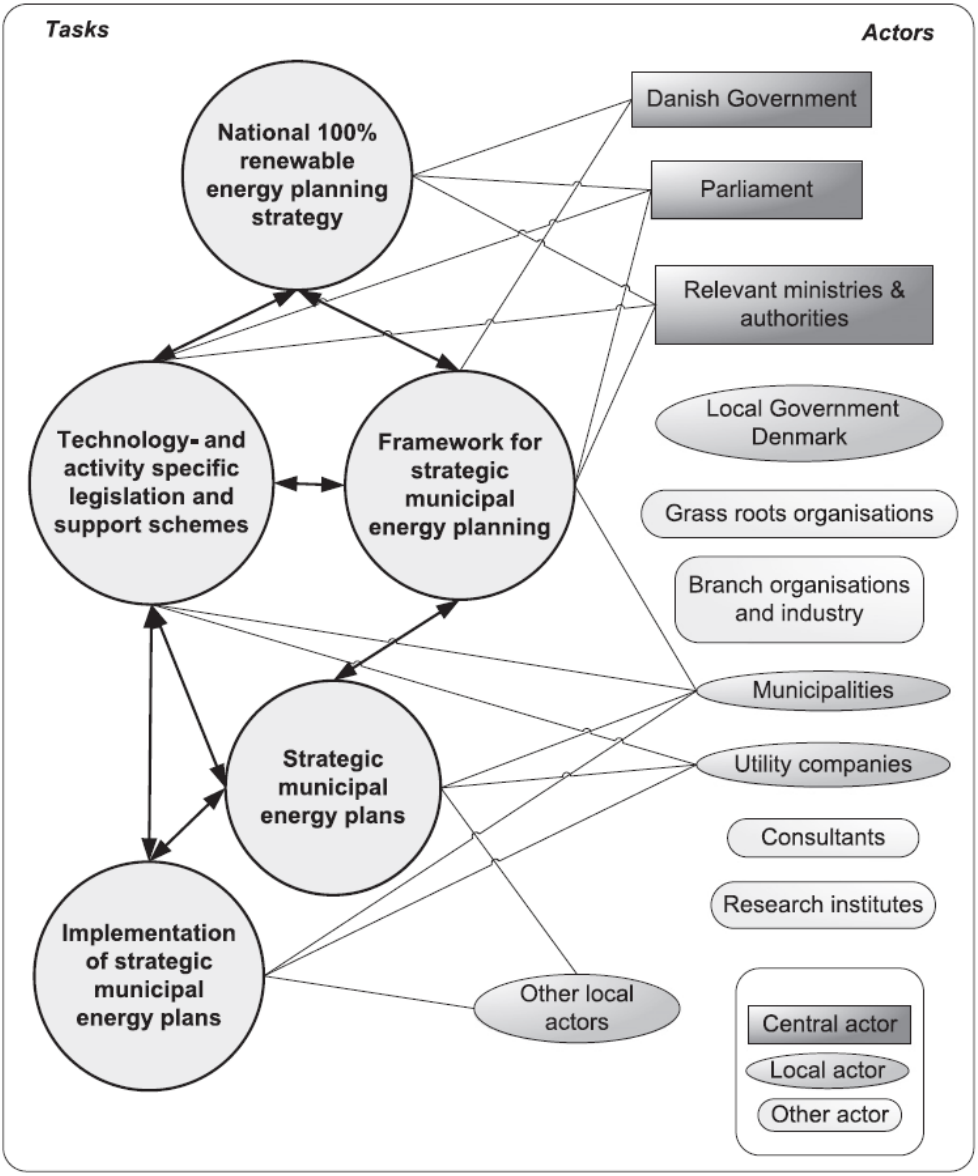

Figure 2.3: Dependencies of different strategic heat planning tasks [44, Fig. 6]

Hooimeijer et al. present a theoretical framework in the context of urban energy planning to develop working business models for DH in a liberalized energy market [45]. The framework includes four phases, namely “initiative,” “idea,” “development,” and “implementation & usage” [45], and is related to the different stages. Further, different concepts are introduced: “technical,” “organizational,” and “spatial development” [45]. Through this, the paper presents an overview from a time-related perspective (phases) and focuses on DH scope III with interfaces to other scopes. In addition, the authors introduce “tactics” [45] that can be helpful to realize the heat strategy. These tactics can be interpreted as interfaces of III to IV in cooperation with the different stakeholders in these activities. The classification by phases is an alternative to the classification by the hierarchy which is proposed in this thesis.

Hawkey et al. identify four key dimensions to evaluate the organization and governance of urban energy systems [46]. The first dimension is the priority on social capital versus financial capital, the second dimension is local or non-local ownership, the third dimension is the participation of customers in DH governance, and the fourth dimension is the level of internal expertise versus outsourced knowledge. These dimensions can be used to specify the DH scope IV and are defined by DH scope III.

Knutsson et al. present a systematic literature review on innovation in DHSs [28]. The results of the review support the DH scopes III and V and provide input on a meta-level to all scopes of DH. The authors conclude that a great deal of research is currently performed on the identification of the objectives of the transition. However, they also show that solutions are still lacking and the responsibility for the implementation is not sufficiently clarified by current research.

Lygnerud evaluates the changes in business models in the transition from 3rd generation district heating (3GDH) to 4GDH [47]. The article identifies the relevance of new business models (IV) in the context of the temperature reduction needed for new designs and operative planning (V and VI). The author describes the Stockholm marketplace as an example of advanced operative planning concepts (VI).

In another article, Lygnerud evaluated business models in Sweden based on a literature review and interviews with DH companies [23]. This article is related to the DH scope IV and emphasizes the relevance of customer integration for the development of a necessary change in business models.

Postnikov et al. postulate their own framework for DHSs [48]. In the planning of the DHSs, they synthesized their research on technical, economical, and organizational issues. The framework includes three sections: determination of the optimal sizing of a DHS, identification of the optimal organizational form and model of a liberalized heating market, and analyzing its reliability. The authors demonstrate the methodology by conducting a case study. Even though the interfaces of the three different sectors are not explicitly described, some dependencies between the determination of the DHS scale (with the meaning of system design), the market design, and the evaluation of reliability are presented. The article provides input for the DH scopes IV, V, and VII, but it does not describe the interdependencies between the different DH scopes in a general way.

Faria et al. present the application of different market designs of DHSs to support innovative business models for the integration of third-party access heat [22]. Their work demonstrates the dependencies of the organization (IV) (e.g., by introducing competition) on the operative planning mechanisms (VI).

Talebi et al. reviewed the modeling and optimization of DHSs and show that numerous tools exist for the modeling of the different parts of the DHS [49]. These are continuous or discrete variables (mixed integer linear programming (MILP)/mixed integer nonlinear programming (MINLP)), genetic algorithms, neural networks, or fuzzy logic systems.[1] The objective is to minimize operational costs, investments, and environmental impacts. The different findings of the review identify concepts and models which are used for the DH scopes V and VI. The intersection of operative planning and design is not discussed.

Another review of optimization and enhancement is performed by Li et al. with a focus on “renewables, TES and smart grid” [30]. They show that smart systems use TESs as well as the interaction with the demand side for the compensation of fluctuating renewable sources based on intelligent management technologies. Optimization and enhancement are important in these systems to reduce investments, operational costs, emissions, and payback time and to determine the optimal design of components and networks. The identified tools are used for the DH scopes V and VI, and recommendations for DH scope IV are also provided. A connection between the DH scopes is not discussed in the paper.

Sameti et al. review optimization tools in DH and show that several optimization techniques are applied [50]. The most common are mixed-integer optimization algorithms (e.g., MILP), genetic algorithms, and hybrid algorithms. The most important objectives are the minimization of emissions and of operative and capital costs. The paper presents some interactions between the DH scopes V and VI. The presented optimization algorithms were developed from a centralized perspective (e.g., by one vertical integrated utility).

Vandermeulen et al. review the control of flexibility in DHSs [19]. They highlight the fact that the resources of flexibility are storage units, buildings, and the network itself. They provide a definition of flexibility and also discuss the difficulties involved in quantifying flexibility itself. Flexibility is needed for different purposes related to the time interval which can be intra-day, long-term, or even seasonal. The review presents input for the DH scopes VI and VII with a

[1] For further information on the different types of algorithms see appendix A.3 (p. 327).

special focus on flexibility and grid operation. There are several application cases, each with a specific purpose.

Sayegh et al. identified the trends of European research in the DH sector [51]. The review presents the relevant research in the DH scopes VII and VIII.

2.4 Discussion of the state-of-the-art review

This chapter presents the requirements for the transition in DHSs in the first step. In the next step, eight *DH scopes* are proposed that aim to classify activities in the different fields of DH. The DH scopes are developed based on the knowledge and experience of the author and the literature. Systematic literature research is performed to identify available comprehensive methodologies that facilitate the transition toward 4GDH. These identified publications are evaluated by their coverage of the DH scopes. In this way, the new proposed DH scopes are tested, and the systemic perspective of the different publications is evaluated.

The new DH scopes are tested according to two hypotheses. Firstly, it should be tested if such a hierarchy does not exist. Secondly, it should be tested whether the proposed DH scopes can be applied to classify research topics in DH. The results of section 2.3 demonstrate that the proposed DH scopes are consistent with the findings in the literature. Even though some of the DH scopes are identified in different references, a comprehensive picture is not found in any single reference. This shows that the full list of the proposed DH scopes is novel and that it can be applied to classify the identified references. Therefore, the hypotheses are confirmed.

Through the coverage of the different scopes, it is shown that only some of the presented reports and articles provide a systemic development of these topics. The higher-level DH scopes, and particularly the *strategic heat planning* have been the focus of the research in recent years. Consequently, a great deal of knowledge is available and the interdependencies between *preconditions*, *policies*, and the *organization* are considered. In contrast, research in the DH scopes of *design*, *operative planning*, and *operation* is often not presented in a larger context to the higher-level DH scopes. Even though the transition to renewable heat sources and the related reduction of temperature is often considered in the presented studies, there is still potential for improvement by including it more explicitly in the existing methodologies. An existing comprehensive methodology that connects the DH scopes of design, operative planning, and operation and which includes a transparent point of view on the related activities thus cannot be identified. Therefore, a comprehensive methodology for the transition that combines the activities in design, operative planning, and operation, can be identified as a gap in the current research.

The literature review is carried out using the described method to identify existing comprehensive structures as far as possible. The search also identified much more literature that is focused on one of the DH scopes. Due to the focus on the interaction of the DH scopes, these publications are not presented in this chapter although some of them are used in the following chapters in relation to a specific DH scope.

2.5 Conclusion of the state-of-the-art review

The objective of this chapter is to identify and evaluate existing methodologies for the transition towards 4^{th} generation district heating (4GDH) that cover all the fields of district heating (DH).

In the first step of this chapter, the barriers that hinder the transition are evaluated. Derived from these barriers, the requirements for a transition facilitating methodology are identified. One central barrier is the lock-in effect to the established business logic of centralized fossil heating plants with high temperatures. Since a central requirement is a reduction of fossil fuels to zero and the integration of renewable, non-combustion-based heating sources, a reduction of the system temperatures and the provision of flexibility is needed. Due to the continuously evolving legal and technical conditions, an open and evolutionary environment is required, which is economically efficient and increases the transparency for the customers. Besides these general requirements, further specific requirements can be identified.

After these requirements are summarized, a new method is applied to evaluate the state of the art of transition methodologies. To do so, a set of DH scopes is proposed that aims to summarize the activities in the different fields of DH research and practice. These DH scopes are used to evaluate the coverage of the existing literature on the different fields of DH. It is shown that such a structure has not been developed previously and that the newly introduced DH scopes can be used to classify the literature of this systematic research. Thus, the DH scopes on their own are a contribution to DH research.

However, the main contribution of this chapter is that a research gap could be identified. Even though tools and methodologies to support the activities in the scopes *design*, *operative planning*, and *operation* exist in a broad spectrum, there is a lack of a clear and transparent methodology to relate all relevant activities of these scopes in a way that they can facilitate the transition. Since the activities and related processes of these different scopes must be resolved in existing district heating systems (DHSs), it is concluded that these processes have been implemented as parts of a continuing evolution based on established planning methodologies and pricing mechanisms that focus on fossil heating plants. As it is known that the established business logic for fossil heating plants hinders the transition towards 4GDH, it is proposed to systematically develop and implement a new *framework* that relates all relevant activities and processes in a transition-facilitating way. The application of the framework would serve as the currently lacking transition methodology.

Such a framework and the associated methodology for the design, operative planning, and operation scopes are identified as the main research gap and will be the subject of the remainder of this thesis whereby the framework must fit the identified requirements. Since conditions are continuously changing, the framework must be able to adapt to these changes. It must support the transition with a focus on lowering the temperature and supporting decentralized feed-in and should be applicable to both regulated environments and completely liberalized environments with competition in heat production. The framework should allow for a transparent and participatory development that facilitates the transition to the 4GDH while providing an economically efficient heat supply.

Chapter 3

Framework approach

The literature that is reviewed in chapter 2 shows the complexity of the transition and the number of aspects that should be considered. In the past, mainly incremental changes were made for the transition to 4^{th} generation district heating (4GDH) [28]. However, to perform the transition of district heating systems (DHSs), a radical change is required [3]. For this change to succeed, a systemic perspective is needed that combines the different activities of the different fields of DHSs in research and practice.

In chapter 2, eight *district heating (DH) scopes* are introduced to evaluate the coverage of the identified references of the different fields of DH. From this evaluation, three results are derived. Firstly, the proposed eight DH scopes form a new structure that has not been developed before. Secondly, due to the successful application of the scopes to the identified references, their applicability is validated. Thirdly, it is shown that a comprehensive methodology for the transition towards 4GDH is lacking for the DH scopes of *design*, *operative planning*, and *operation*.

This gap leads to the research aim of the thesis to develop such a *transition methodology* and thus relevant activities must be identified and combined in a comprehensive *framework* whereby the application of this framework constitutes the transition methodology. Since a similar framework has not been developed for the DH sector in a systematic way before, there is no blueprint that describes the procedure for such a development. This procedure (referred to as the *framework approach*) is introduced in this chapter and has a hierarchical structure. The top level of this hierarchical framework approach is presented together with global conditions for the subsequent chapters. The lower levels of the approach and the scope-specific conditions are introduced in the respective chapters.

The chapter is organized according to four sections. Based on the eight DH scopes (q.v. chapter 2), the relevant activities for each scope are summarized and based on this, a full *structure of DH scopes* is introduced in the first section. In contrast to existing structures, this new structure addresses the interrelations of the different scopes to give a comprehensive picture of all relevant activities for a successful transition. The second section introduces the highest level of the framework approach that is built upon the new structure of DH scopes. The third section presents global conditions that are considered in subsequent chapters. This includes global assumptions for the technical calculations and a description of the tools and libraries used for implementation. In the last section, a DHS case study is introduced that is used for the application and test of the developed implementations.

3.1 Introducing a new structure for DH scopes

The eight newly introduced DH scopes comprise the foundation of the framework approach of this thesis. Therefore, the DH scopes need to be further elaborated and related to each other to create a full *structure of DH scopes*. Three steps are performed to accomplish this. Firstly, the activities of each DH scope are further specified by using the identified literature from the state-of-the-art review in chapter 2. Secondly, the relation of the DH scopes to each other is further clarified, and thirdly, a resulting new structure is presented.

3.1.1 Specific activities in each DH scope

Based on the findings of the literature research in chapter 2, the introduced DH scopes can be further specified. Since these DH scopes are the basis for all further developments in this thesis, the following descriptions of the DH scopes aim to summarize the most relevant activities of each scope and clarify the DH scopes.

DH scope I: Preconditions

The first scope of the new structure represents the preconditions which include the social demands, available resources, and environmental conditions. For example, the environmental goals require a reduction of the use of fossil fuels through efficiency measures and the integration of renewable heat sources. It can be expected that the reductions will aim toward zero emissions by the end of the transition.

For the transition, renewable sources are required, and their integration is linked to different preconditions. Some of them have variations in local availability (e.g., industrial surplus) and some have fluctuations in production (e.g., solar thermal). The new sources will require thermal energy storage (TES) and the system will become more decentralized. Some sources require large investments (e.g., geothermal plants) or will even have high operative costs (e.g., heat pumps). The interaction with the electricity sector for the compensation of fluctuation in electricity generation will become another purpose of DHSs by flexible combined heat and power (CHP) plants, heat pumps, or electrical boilers. These numerous types increase the complexity of planning and operating DHSs. [29]

Further, social aspects are important, and DHSs should be operated in such a way as to be as economically efficient as possible to supply heat for the poor and thereby protect their health (e.g., by preventing the growth of mold due to damp conditions) [29]. The participation of customers and stakeholders in all activities and new business models is identified as essential for successful DH [23]. The homeowners are important, as the in-house efficiency is relevant for the whole grid and new interactions (as prosumers) are also necessary [47].

DH scope II: Policies

Since renewable technologies require new economic conditions, changes to policies are also required [34, p. 13]. Therefore, the second scope includes the policies, including all types of legislation and regulation. Since it is known that "in most cases the barriers faced are political and regulatory rather than technical" [39, p. 72], long-term goals and policies are needed that support the energy transition [39, p. 72]. As a part of these changes, legal and fiscal barriers should be removed [44]. The geographical layers of policies are described using three levels [34, p. 17, fig. 4]: the first level is the regional and local regulation, the second level is the national regulation, and the third level is the supernational (e.g., European Union (EU)) regulation. The national and EU authorities need to create a legal environment [34, p. 32] that should provide safeguards so that the local strategies fit into macro-level planning [34, p. 10]. To do so, the authorities on the different levels are addressed to remove administrative barriers and uncertainties, improve feasibility, and align local and superordinated policies with each other [39, p. 18]. This includes limiting the competitiveness of fossil fuels (e.g., through carbon taxation) [39, p. 73]. For example, Sweden has demonstrated that internalizing external costs through high prices on fossil fuels (carbon tax) is key to supporting DHSs in urban and heat pumps in less dense areas [43]. Further, the policies should support price signals that enable flexible interactions with the electricity grid [39, p. 41].

In the last few decades, the radical changes in DH (and cooling) systems affected the DH structure. Therefore, it is proposed that DH systems require an open and evolutionary architecture that includes both competition and cooperation. Part of this architecture could be the decision for more competition or more regulation in the DH market. In non-regulated markets, the natural monopoly must be handled and in regulated markets, different supply scenarios should be compared with each other. [40, pp. 134–138]

The references emphasize the relevance of a coherent interaction of policies and the local heat strategy. The assumptions and the method of the local planning should be defined by the central level including energy savings, efficiencies, renewable energies, and system regulation as well as system intelligence [44]. Additionally, the superordinate governments should set facilitating boundary conditions [41]. However, a central institution (on a national or international level) should not perform the local heat planning as the renewable heating technologies are dependent on local conditions and therefore cannot be applied generically. Instead, standardizing the legal conditions would support the replication of successful technologies and their business models.

DH scope III: Heat strategy

The third scope is the development of a heat strategy which can be understood as the transition from abstract political goals and policies to a specific plan for the implementation. The project *Hotmaps* defines “strategic heat planning [. . .] as action plans for realizing long term visions of radical change in key parameters of the heat supply” [34, p. 13] whereby the locally varying conditions make a local heat strategy necessary [34, p. 32]. As one part of integrated planning for the different energy sectors (electricity, heat, and transport), heat planning should be institutionalized in the municipalities [44].

Since heat strategies and DH are influenced by politics, they must be planned while facing the uncertainties of changing policies [33, p. 14]. In the case of major changes in policies, a “strategic restructuring” [33, p. 15] could be necessary to align with changing economic conditions [33, p. 15]. At the same time, a frequent evaluation of the heat strategy activities can support gathering feedback for policymakers [39, p. 94]. The engagement of stakeholders is described as important in many references (e.g., [23], [33], [39]–[42], [44]). Several tactics can facilitate the implementation of DH under existing policies [45].

One of the most relevant decisions in the heat strategy is whether a new area should be supplied by DH or by individual heating [28]. In such a case, competition between DH and alternatives should be considered [40, pp. 137–138]. A heat strategy can also include the extension of DHSs. For example, the city of London provides a policy environment for a local heat strategy and supports the connection of satellite networks that can subsequently be connected to larger networks [42, pp. 94–101]. Further, the heat strategy may also support the transition of existing DHSs. For example, Gonul et al. propose integrating a low-temperature supply into the development activities of the local heat strategy using several measures [41, pp. 78–86].

After the decision is made to build a new DHS, the local authorities should be responsible for stakeholder coordination and for the implementation of the infrastructure [41, p. 54]. The frame of "institutional, financial and organizational elements" [41, p. 49] should be defined, and supporting policies should be enabled [41, p. 49]. The heat strategy can form the later organization by defining the goal (financial, social), the ownership (local, non-local), the possibilities for customer participation, and the degree of internal expertise [46]. The treatment of a newly created natural monopoly is an important aspect of strategic heat planning. It must be handled in the "regulatory and/or organizational structure" [34, p. 21] (scope II and IV) which should also include concepts for ownership and price models [34, p. 21]. Further, the design and business structure should be actively managed [33, p. 19]. To support the development activities, municipalities should create energy plans to provide a framework for the specific project development [33, p. 77]. In this way, the heat strategy defines the boundary conditions for the next scopes. Most importantly, it defines the organization (scope IV) and an actively managed framework for design, operative planning, and operation (scopes V–VII).

DH scope IV: Organization

The organization can be understood as the implementation of the heat strategy through forming utilities and agents. This scope includes "financing," "risk mitigation," and "business models" in addition to the governance factors "ownership," "pricing," and "regulations" [41, p. 109]. There are several options for how to define business models and governance structures that depend on the ownership structure as well as the risk allocation [33, pp. 77–78]. The transition toward renewable heating sources requires new organizational structures and business models [34, p. 13].

The most important elements of the organizational structure are the structure of ownership and the level of competition. In relation to the local conditions, the best balance between cooperation and competition must be identified. In [40, pp. 137–138], four stages are described in which competition is relevant. Firstly, competition should be considered in the city planning context when the decision is made for or against a district heating and cooling (DHC) supply. Secondly, it should be considered in the organizational context depending on the market structure: in non-regulated markets, the natural monopoly must be handled and in regulated markets, different supply scenarios should be compared with each other. Thirdly, during operation, optimization of the existing plants and the access to new plants should be considered. Finally, customers should be allowed to leave the DH contract to secure the competitiveness of the DHS against other technologies. [40, pp. 137–138]

An option to increase the competitiveness of DH, support innovative business models, and introduce third-party access is the introduction of marketplaces [22].

In the electricity sector, such introduction of marketplaces has achieved low prices and transparency through increasing competition [22]. DHSs should be opened-up for third-party access to integrate surplus heat from industry or prosumers [31]. For example, in Stockholm, the increasing number of prosumers led to the introduction of a local marketplace [47]. Another option is the unbundling of network and supply [42, pp. 61–63].

In addition to a proper organizational structure, new business models are required that support the transition [43]. These new business models must solve the conflict of optimizing centralized plants and simultaneously providing a benefit for all actors resulting from lower temperatures and lower demand [23]. Examples of such new business models are supporting in-house energy efficiency measures and delivering data as well as new products (e.g., selling an indoor temperature instead of only heat) [23]. The role of prosumers is also seen as relevant [23]. Such customer-related business models could support by increasing the efficiency of the demand side by introducing better control systems, giving incentives to become prosumers, or providing low-temperature applications [47]. For example, the network can support the interaction of different temperature levels in different parts of the grid (e.g., by cascading the networks) [47]. To introduce such new business models, the customer tariffs must be made compatible, since a review [30] has shown that existing tariffs often do not facilitate the overall system optimization. As the demand in DHSs is considered inelastic, the price of heat only has a small impact on the demand [52]. This is particularly the case in buildings with rental apartments [52]. Novel pricing mechanisms include real-time pricing [52] which increases flexibility and incentivizes demand side measures [52]. Combined with higher transparency, this is seen as an incentive for efficiency and an improved interaction between the supply and the demand side [30].

Customer pricing is often realized in two parts, namely a fixed and a variable charge. The fixed charge is correlated to the capacity (investments) and the variable part is correlated to the heat consumption (cost per unit). The amount can be defined in different ways. Producers prefer a higher fixed part because this secures the return on investment whereas a higher variable part incentivizes energy efficiency on the customer side. A good pricing model balances these two dimensions. [52]

The form of an organization defines the conditions for the scopes of design, planning, and operation. It is important that the structure supports the transition to renewable heat sources as well as the improvement of efficiency while respecting the social demands of the customers by providing new business models and a low-cost heat supply.

DH scope V: Design

In the scope of the design, the technical concepts including constructions and controls are developed. The chosen concept defines the investments in plants and networks. At the same time, contracts are entered into e.g., for new customers or heat suppliers. As the design activities are complex topics on their own, the focus of this description is on how to design and less on what to design. The latter is the content of guidelines and textbooks for the DH design.

Since DHSs are infrastructure with a high share of investment and a low share of operational costs [39, p. 47], a high potential for cost savings is identified while planning the investments [28]. Related to the high investments in renewable heating technologies, asset management must be prioritized [28]. Further, the long lifetime of the DHS requires a continuous adjustment of the previous concept which can be through extension, renovation, or modernization [33, p. 43].

There are successful examples of economically efficient mechanisms to support the design, like the tendering process in Barcelona where a district cooling system was established with a concession for supply using detailed tendering documents that include the overall energy efficiency, environmental impact, and additional end-customer services. The tariffs are evaluated every year by a local regulator and thus the supplier is forced to stay competitive against other sources. Commercial customers make contracts directly with the supplier. The project in Barcelona is referred to as an example of a successful mix of competition and public regulation. [40, pp. 98–100, 137]

Since the goal of this scope is to find an optimal design that suits changing economic conditions, the design activities themselves should be actively managed [33, pp. 15, 19]. A continuous planning approach should engage stakeholders and therefore it requires a higher level of transparency [23]. Further, the design activities require standards to allow for comparability [32] and hence inputs and assumptions for the design activities should be standardized. For example, the *London Heat Network Manual* supports references to design standards and standard planning parameters such as components' lifetimes as well as temperature and pressure ranges [42, pp. 50–52].

The design must aim toward ensuring low temperatures [41, pp. 78–86] and high-efficiency measures [39, p. 105]. To do so, a balance is needed between investments in production capacities on the one hand, and in energy savings on the other hand [30]. Simply lowering the temperatures in existing systems can cause problems in existing grid layouts e.g., through bottlenecks [28].

The demand and resources need to be mapped to develop technical scenarios [41, p. 13]. Modern design procedures integrate the locations of sources and demand (geo-referenced) [30]. In the concept stage, stakeholders specify their development goals and planners develop an early concept [33, p. 43]. To evaluate different settings, variants of scenarios are calculated [39, p. 16] and different supply scenarios should be compared with each other [40, pp. 137-138]. The feasibility of the measures must be evaluated before the system can be designed and built [33, p. 43].

Numerous concepts and tools exist to support the design activities. Enhancements in design and control strategies are performed via scenario analyses based on simulations as well as optimization algorithms and experiments are used for the improvement of components [30]. For the system simulation, two types of models are relevant [49]: black box models (mostly using transfer functions) or physical models (requiring the design of every component). Optimization is used for enhancing the design of the system (e.g., network sizing and routing) [49].

For long-term optimizations, the whole-life costs are included whereby mixed integer linear programming (MILP) is the most frequently selected option. In the field of "distributed integration" [50], the optimal set of network, plant, and TES design and their interaction with the electricity grid is analyzed. "Superstructures" [50] are used to select the size, type, and number of heating plants from a catalog of options. While genetic algorithms are used for the optimum DH layout, the tools require further development as the evaluated studies only focus on small systems due to long computational durations. [50]

The design activities are important due to the long lifetime of plants in DHSs and thus the activities should be as transparent and efficient as possible while including many different aspects. Numerous tools and concepts exist that can support the activities. The design scope defines the technical and economic conditions for the operative planning and the operation. Examples are the minimum and maximum pressures, flow rates, and temperatures in the network. The implementation of the control system is also part of the design.

DH scope VI: Operative planning

The operative planning scope focuses on the short-term dispatch of the existing plants. This dispatch aims to optimize the variable costs while supplying the demanded heat. Since some heating plants are linked to the electricity and the heating sector, participation in the electricity markets is important.

The focus of short-term optimization is the supply side including TESs. Example applications are peak shaving and the optimization of the operational costs of the heating plants. For the implementation of such a system, more measurement data and a communication network for monitoring and controlling are required. Agent-based controllers can be used to reduce the amount of central data. In such a system, forecasts are becoming more important. [19]

In DHSs with only one vertically integrated utility, *centralized optimization* algorithms can be applied. If the production of heat is made by more than one company, the operative planning is completely different. In these DHSs, dispatch instances are used that are comparable to electrical *marketplaces*. Examples of such competitive environments are the DHSs of Stockholm and Copenhagen.

Several types of algorithms are used for the *centralized optimization* of heating plants including continuous or discrete variables (MILP/mixed integer nonlinear programming (MINLP)), genetic algorithms, neural networks, or fuzzy logic systems [49]. In most concepts, the whole DHS is simplified to an energy-based MILP model whereby TESs are aggregated to one buffer tank and the individual heat demand is aggregated as well. An example of such a model is presented in [53], which is used to optimize the operation of a CHP plant combined with thermal storage and electricity prices.

A more complex optimization concept is needed if hydraulic network restrictions should be considered. For example, bottlenecks may be introduced that can be described as maximum thermal power transmission capacities. The calculation of these bottlenecks depends on the network's temperatures whereby the temperatures are included as constraints and not as variables of the operation. The models of Varmelast (q.v. appendix B.4, p. 345) or [54] are examples of such models. The restrictions in the Varmelast model are estimated with the aid of simulations and the experience of the operators. In [54], different DHSs are optimized that are connected to each other.

The complexity increases if the optimal balance between pumping power (high flow rates) and thermal losses (high supply temperatures) should be found in the dispatch process. Since high computational times are still a strong barrier to the optimization of several variables for the operation of large DHSs, set-points for these variables (like for the supply temperature) are evaluated once, and afterward, these variables are not included in the dispatch processes [50]. Only a few studies are identified that consider the supply temperature in optimization: Bavière et al. use a model-predictive controller and demonstrate that variable supply temperatures may be advantageous with a decentralized heat supply [55]. Pirouti et al. balance the costs for pumping and heat losses by using different supply temperatures as input [56]. For a DHS with distributed heating plants, Vesterlund et al. optimize the pumps' electricity consumption and supply temperatures [57]. Fang et al. optimized the thermal production and supply temperature with genetic algorithms by considering pump electricity consumption, heat losses, and a linear fuel dependency on the thermal power of the heating plants [58].

The non-uniform temperature DH is a completely different concept that uses dynamic supply temperatures [59]. Here, the supply temperature is raised for several hours a day to charge the decentralized TESs so that the heat losses can be reduced [59]. If decentralized heat pumps are used, the temperatures can be lowered further [60].

In contrast to *centralized optimization*, competitive environments require *marketplaces* or similar concepts. In Stockholm, the increasing number of prosumers led to the introduction of a local marketplace [47] while in Copenhagen, a “heat dispatch unit” was introduced [40].

Copenhagen has a large DHS with areas assigned to 24 different distribution and three transmission companies [40, pp. 18–20]. The distribution companies are responsible for peak supply and for their local production and the heat from large-scale production units is transmitted through the transmission grids. The system has a high potential for optimization and therefore the heat dispatch unit *Varmelast* was introduced to compute daily “heat pool prices” [40, p. 19]. The day-ahead schedules are updated three times a day by an intraday procedure based on marginal costs. Additionally, competition is introduced in the design and investment process. [40]

Faria et al. argue that current developments towards the integration of surplus heat from third-party suppliers require liberalization of DHSs and present different concepts for this. The first of which is a pool market with a merit order and a market-clearing price that maximizes social welfare. The second concept is a peer-to-peer market that allows bilateral trading. Trading can take place under three different preferences, which all add a penalty to the price: distance, thermal losses, and emissions. The third concept is a community-based market where subordinate communities manage and trade their heat with other communities. The market designs are tested via the simulation of a case study. Under the assumed conditions, the peer-to-peer concept works best because the market includes one of the three given preferences and allows for trading in the whole network. Finally, the authors indicate that further development, including the full characteristics of the network, is required. [22]

To conclude, the focus of the operational planning is on the heating plants and TES, but the demand side is also considered to compensate for fluctuating renewable heat sources. Further, the operative planning scope is a bridge between the design and the operation scope. The operative planning can be different in systems that allow for competition and, for the introduction of competition, market mechanisms can be used.

DH scope VII: Operation

In the scope of operation, the system is operated and maintained, and its performance is optimized [33, p. 43]. An important aspect of the operation of modern systems is the control strategy that forms the connection to the operative planning scope.

Typically, a central instance controls the differential pressure of the network pumps and the supply temperature. The heat demand and the flow rate are controlled in a decentralized way by each substation and each building’s internal control. [19]

Variable flow and variable temperature controllers are most efficient. In most cases, the supply temperature is chosen by a correlation of a set-point and ambient temperature. The flow rate is controlled by the pumps which must hold the differential pressure. The set-point for the differential pressure is defined by the customer with the furthest distance to the production. The most common way to control the heating plants is a sequence control based on the individual prices. The control system must prevent a "hunting" [42, p. 20] mode which means that different control loops influence each other. The return temperature depends on the customer. [42, pp. 18–20, 26]

This control system design is considered robust. A disadvantage of the decentralized system is that the decentralized controllers can only include the local conditions and not the state of the whole DHS. Therefore, it does not work in a systemic way. For example, in times when the supply is too low, customers with a hydraulic advantage would have a better supply quality compared to customers who are located further away from the supply units. With an increasing share of fluctuation, renewable sources like this can become an issue in operation due to the lack of interaction between demand and supply. Therefore, there is a new requirement for load control which must control the flow (e.g., for charging TESs) or supply temperature (e.g., for charging the network). New control strategies can be performed in different ways, namely by centralized (e.g., operational optimization or model predictive control (MPC)), decentralized (cooperating and competing agents), or hybrid concepts (using both principles). [19]

The trend is that more automation combined with monitoring and metering is implemented at the heating plants, in the network, and at the customers. Relevant research is also conducted to improve the forecasts of heat consumption, and systems change from a simple correlation of supply temperature and ambient temperature to more complex control strategies using forecasts based on meteorological data combined with the building and DH models. The models used are "simple, complex, statistical, simulations, learning, adaptive and other" [51]. New control strategies are based on models, hierarchical, and implemented as multi-agents. [51]

The innovative control strategies can be based on forecasts, models, and simulations. Such control strategies require centralized coordination as presented in scope VI. Both scopes are closely interlinked.

DH scope VIII: Evaluation

The final scope is defined as evaluation and includes all activities that deal with historical data. Traditionally, billing is the main part of this scope combined with diagnostics based on the available data.

Modern DHSs implement an automatic meter reading which gathers the data of the heat meters in a centralized database for billing and diagnostics. Heat meters measure the temperatures and the flow rate. The next meter generation is the smart meter which supports real-time data and offers new applications such as the monitoring of the supply quality, fault detection, diagnostics, delivering data to customers, and new (dynamic) tariffs. [42, pp. 45, 111]

The introduction of these new meter types should be considered in the design scope. With increasing digitalization, demand side communication and management, as well as fault detection, becomes possible [43].

3.1.2 Relation of DH scopes

In this subsection, the relation of the scopes is discussed. Since the previous descriptions introduce the relations on a content-based level, the focus of this subsection is on a meta-level.

As the development and planning in DH must be able to adapt to changing conditions [33, pp. 14–15], a learning system is needed. The chapter *Agile Energy System: Integrated GIR Technologies Into Infrastructures* by Clark focuses on electrical systems and introduces the term “agile energy systems” [61]. It refers to what Lund et al. define as a “smart energy system” [3]. Clark emphasizes the relevance of both, namely regulation to secure the market and competition to incentivize business activities in a hybrid system [61]. Such market mechanisms at local levels enable a more “democratic” [61] energy supply. Further, the term *agile* indicates that the new scopes should be connected in an agile way.

The term *agile* is commonly used for a special form of project management that was first introduced in software development. Nowadays, it is introduced in the organizational structures of large and well-established companies. The (relevant) basic principles of agile management are the concept of self-organizing and autonomous entities with a continuous enhancement of products and processes in an evolutionary sense. In [62], Denning presents the results of a “learning consortium” [62], which was formed by several companies internally introducing agile principles. The evaluation of the introduction of agile project management shows that innovation can be implemented faster. Further, critical operational processes with high requirements for reliability and high complexity can also be handled successfully. From this, it can be concluded that agile is a mindset with a focus on the customer and on iterative development, both of which increase the transparency and the continuous enhancement of processes. [62]

Ciric et al. evaluate the introduction of agile project management versus traditional project management in both software and non-software developing forms of organization [63]. The advantage of agile techniques is the adaption of products and business models to complex and rapidly changing business conditions. The agile mindset accepts changes and continuous improvements. Therefore, work must be modularized to allow for iterative development and, in this way, it supports a higher level of competitiveness, flexibility, and speed in transitions. The authors conducted interviews which showed that 22.3 % of interviewed companies also use agile project management for non-software development.

Inspired by the term *agile*, which is commonly used for this type of project management, a synthesis of the agile (in the sense of agile project management) and an overall structure for the DHS is derived which is presented in the following subsection.

3.1.3 The new structure of DH scopes

Figure 3.1 presents the new hierarchical *structure of the DH scopes*. This new structure aims to clarify all relevant topics in the transition of DHSs and their interrelation. It summarizes the main activities of each scope and the relations to the subordinate scopes.

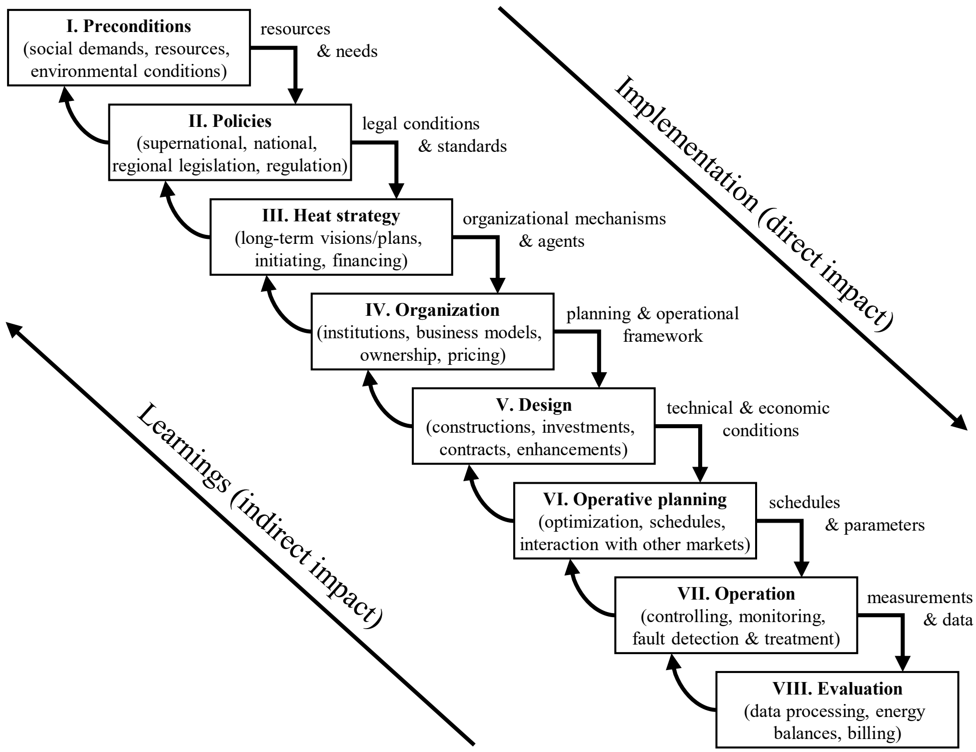

Figure 3.1: New structure of DH scopes for the classification of transition activities

The scopes are related in two directions. In the top-down direction, a higher-level scope defines the standards, mechanisms, and conditions for all scopes below. By implementing mechanisms, the higher-level scopes are directly impacting the lower levels.

In the bottom-up direction, the DH scopes are linked by a feedback loop. Inspired by the agile principles, an optimal system would benefit if the higher levels are open for improvement and iteratively learn from the specific implementations. Such feedback should be provided cyclically to create an open and evolutionary structure. All related activities should be evaluated regularly by engaging the relevant stakeholders of each level. Implementing self-organizing and self-optimizing mechanisms in each scope would allow for a fast adaption of products and business models to the changes of the transition.

3.2 Approach for the framework development

Since the state-of-the-art analysis (q.v. chapter 2) shows that a *transition methodology* for the DH scopes of *design*, *operative planning*, and *operation* is missing, a framework should be developed. If this framework is implemented in a DHS, the relevant activities of these DH scopes will be aligned for the transition. This serves as a transition methodology for the decisions of various stakeholders in the DHS. Through this, decisions in investments and operation and in policies and heat strategies may be made from a systemic point of view.

This *framework* is intended to summarize and relate all the necessary *activities* in the considered DH scopes. The activities are clustered in *framework processes* which should be implemented to coordinate the activities of different *agents*. These framework processes are linked to each other by *interfaces*. Since this framework should be designed in such a way that all internal activities support the transition to 4GDH, technical and economic *mechanisms* are introduced to link the different activities. These mechanisms are developed in such a way that individual activity is incentivized to act in a system-serving and transition-facilitating way.

To ensure a comprehensive and coherent result, a systematic *framework approach* for the development of the framework is applied that uses the newly introduced *structure of DH scopes*. Figure 3.2 presents the relationship between the framework and the DH scopes. It shows that the new framework covers the three DH scopes design (V), operative planning (VI), and operation (VII). The remaining DH scopes are used for the definition of the *outer conditions* of the framework. Especially the *organizational scope* (IV) and the *evaluation scope* (VIII) are most relevant since both have a direct connection to the framework.

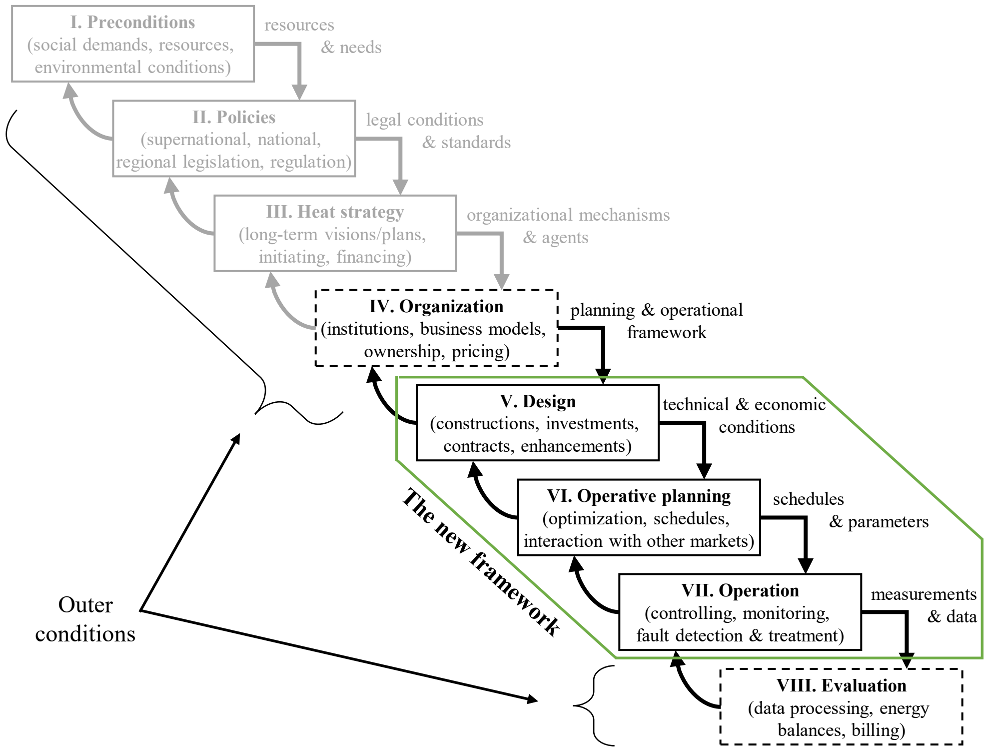

Figure 3.2: Overview of the relationship between the structure of DH scopes and the new framework

The framework approach is hierarchically organized and hence the development of the framework is performed in four main steps (presented here) and further detailed sub-steps (presented in the respective chapters). The four main steps of the framework approach, and the interrelation between the different steps, are shown in figure 3.3.

The application of the first two steps is presented in chapter 4, the third step in chapter 5, and the fourth step in chapter 6. Since each chapter has been developed as an independent but linked unit with its own problem statement, methods, analysis, development, results, and discussion sections, subordinate steps of the framework approach are presented at the beginning of each respective chapter. The top level of the framework approach combines these different units, and its four steps are presented in the following.

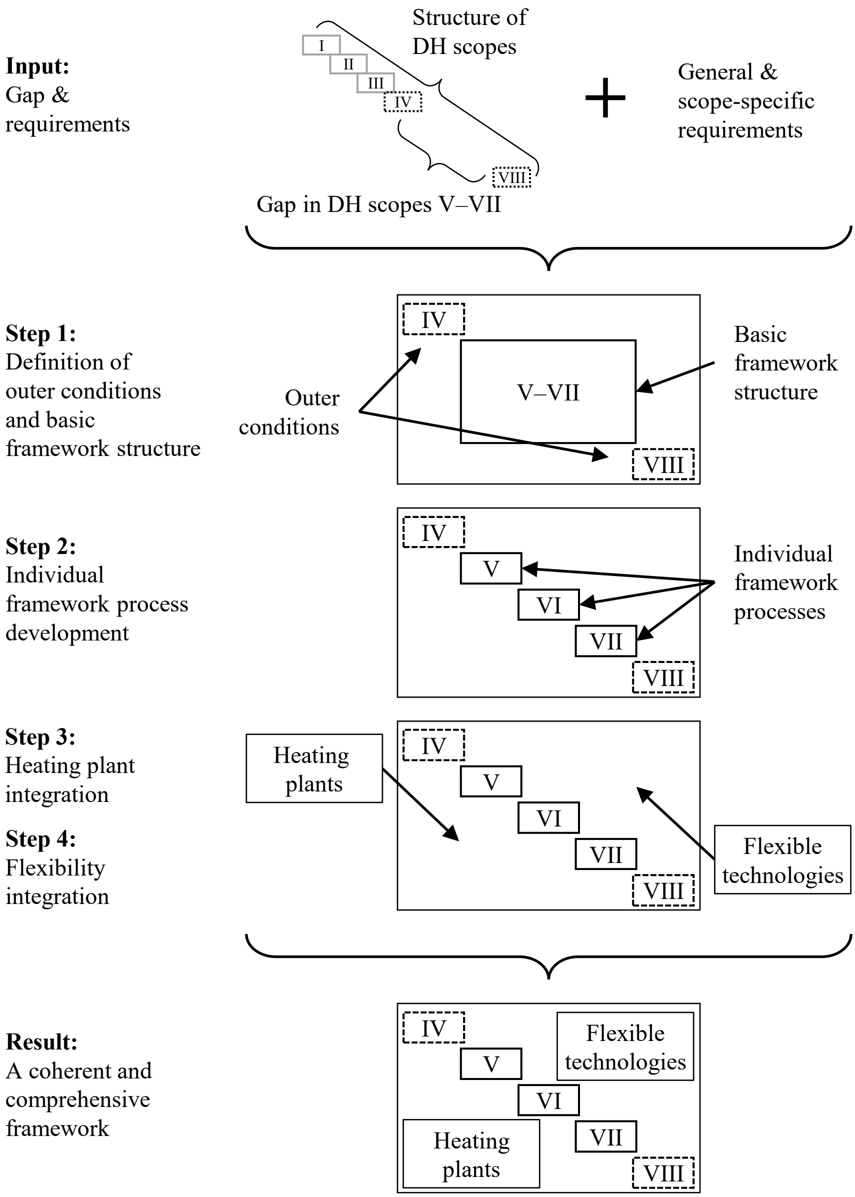

Figure 3.3: Top level of the framework approach

Inputs

The identified gap in combination with the requirements for a transition methodology serves as input for the framework development. The requirements can be divided into two groups: general requirements (for the framework) and specific requirements for each of the scopes. The framework must be embedded into the higher-level DH scope of the organization (IV), and it must be linked to the subsequent DH scope of evaluation (VIII).

Step 1: Definition of outer conditions and the basic structure

In this step, the basic framework structure is developed from a systemic perspective. To facilitate this *systemic* approach, the framework is considered like a technical system that consists of an inner system (here, the framework processes), outer conditions, and the system limit in between. The definition of outer conditions and the basic structure aims to clarify the system limit and the outer requirements as well as to identify the basic framework processes.

Thus, firstly, the limit of the framework is defined (shown by the green line in figure 3.2). This limit separates the DH scopes inside the framework (*design*, *operative planning*, and *operation*) from the other scopes I–IV and VIII. This limit is inspired by the gap identified in the state-of-the-art analysis.

Secondly, the outer conditions must be defined. For this definition, the general requirements that are derived from all higher-level DH scopes are relevant. Since the organizational scope is the superordinated level of the framework, it is most relevant for the definition of the outer conditions. As one of the general requirements is to resolve the *lock-in effect* to established business models, the introduction of new roles, agents, and business models should be evaluated that may help to overcome the lock-in effect. This includes the evaluation of introducing competition and of separating system operation and heat production. Finally, a *structure of organization* is proposed that is identified as the best compromise between facilitating the transition and securing a high economic efficiency. The chosen structure of the organization sets further constraints and requirements for the subsequent developments of the framework processes and their interrelation.

Thirdly, the new organizational structure requires the introduction of subordinated *framework processes*. These are defined in relation to the DH scopes. The framework processes aim to coordinate the activities of the concerned agents. The process development must be done in a top-down direction because a process that targets a higher-level scope sets the constraints for the lower-level scopes' processes. Finally, the framework processes are connected by *interfaces*.

A description including the sub-steps of the approach and the definition of the basic structure is presented at the beginning of chapter 4, followed by the individual framework process development (step 2).

Step 2: Individual framework process development

The individual framework process development is scope-specific and therefore the respective approach for each framework process is presented in detail in chapter 4. In general, each of the individual approaches includes a *requirement analysis*, a *state-of-the-art analysis*, a *concept development*, and a *result description*. Thus, activities and agents that are needed for the respective DH scope are identified by the analysis of the scope-specific and general requirements. To ensure that all activities of the framework facilitate the transition in a system-serving way, they are linked by technical and economic mechanisms. These mechanisms are either identified in the specific state-of-the-art review or are newly developed. The results are the framework processes that aim to coordinate all activities of the different agents in a system-serving and transition-facilitating way.

The individual framework process development is presented in the core part of chapter 4. At the end of the chapter, the new framework is formed by combining the basic framework and the outer conditions (from step 1) with the inner framework processes (from step 2). Further, the new framework is validated by a qualitative comparison with the given requirements. The results are discussed, and conclusions are drawn.

As a result of this discussion, it is shown that the framework cannot be fully implemented with state-of-the-art methods and tools. Therefore, further research and innovations are required for the implementation of this new proposed framework. Two aspects of this open research are the integration of the heating plants and the integration of flexibility into the framework. Since the supply temperature is key in the new framework, innovative methods are required that consider the supply temperature impact of heating plants and flexibility. Therefore, new methods are developed for these two aspects in the following steps 3 and 4 as a commencement of the open implementations.

Step 3: Integration of heating plants

After the core framework development, the third step of the framework approach considers heating plants in the framework as the first step of implementation. The investigations in steps 1 and 2 show that particularly the integration into the operative-planning process requires further research. Further, it is hypothesized that the supply temperature must be considered in all processes to ensure a system-serving integration of all subsystems. Therefore, the consideration focuses on the variable costs of heat production in correlation to the supply temperature and thermal power.

Since no appropriate concept can be found that sufficiently considers the supply temperature impact, a new method is developed and implemented as a model. This new model and the method are then applied to some exemplary heating plants of a case study DHS (q.v. section 3.3). The resulting data is used to evaluate if the supply temperature impact justifies a full consideration in the framework.

The heating plant integration is presented in chapter 5 which is built upon the previously defined constraints of the framework.

Step 4: Integration of flexibility

Some of the investigated and potentially new renewable heating plants depend on fluctuating heat sources. Therefore, the system must be able to adapt to volatile heat production. This adaptive capability of the system is referred to as *flexibility*. In the fourth step, the treatment of this flexibility is integrated into the framework processes to improve the DHS management.

The applied method for this integration can be split into three parts. Firstly, all types of flexible technology are assigned to the different framework processes and their mechanisms. Secondly, the integration into the operative planning process is conceptualized in more detail. In the last part, flexibility metrics are identified that are required to connect the operative planning process with the operation process.

These metrics are then implemented into models and applied to existing TESs in the case study DHS. In this application, the metrics are tested, and the concept is validated.

The improved DHS management, which integrates the different flexible technologies, is presented in chapter 6 and is built on the developments from the preceding chapters.

Result

The result of the framework approach is a coherent and comprehensive framework for the DH scopes of design, operative planning, and operation. After the specific developments in the four steps respectively in chapters 4 to 6, the thesis results are summarized and the level of achievement of the objectives is discussed in the last part. The limitations are discussed, and the need for future research is derived as part of the conclusion of this thesis in chapter 7.

3.3 Global conditions for implementation and application

Parts of the described framework are implemented and tested by their application to a case study DHS. Uniform assumptions and basics for the modeling should be used for all implementations. Therefore, this section presents the most important global assumptions and the tools and libraries used.

3.3.1 Global assumptions

The most relevant assumptions for the later implementations are related to the temperature limitations as illustrated in figure 3.4. It shows a simple principle for how temperatures in heating systems can be regulated without additional exergy demand which is important for the later analysis. Through this hydraulic design, the return temperature of the heating plant can be controlled between the return temperature of the network and the supply temperature of the heating plant. Further, the network's supply temperature can also be controlled between these two values. This demonstrates that return temperatures from the network that are too low or temperatures from the heating plants that are too high are not an issue in the supply.

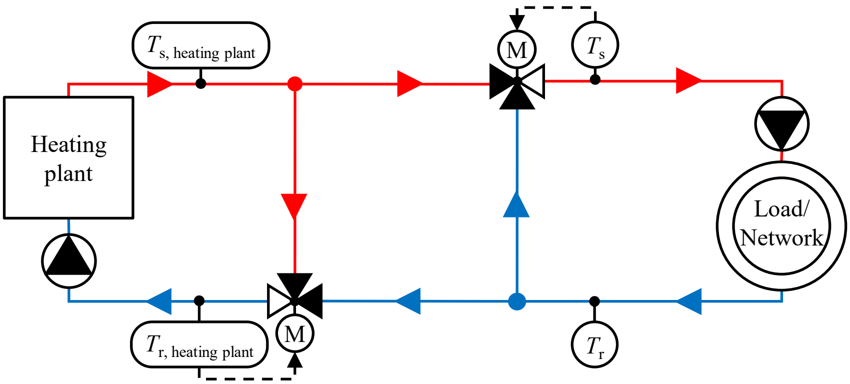

Figure 3.4: Boundary conditions for temperatures

The hottest system temperature is defined by the heating plant's supply temperature ($T_{\mathrm{s,\,heating\,plant}}$). The coldest system temperature is the network's return temperature (T_{r}). This results in the range of the network's supply temperature (T_{s}) in equation 3.1 and the range of the heating plant's return temperature ($T_{\mathrm{r,\,heating\,plant}}$) in equation 3.2.

$$T_{\mathrm{r}} \leq \quad T_{\mathrm{s}} \leq \quad T_{\mathrm{s,\,heating\,plant}} \tag{3.1}$$

$$T_{\mathrm{r}} \leq \quad T_{\mathrm{r,\,heating\,plant}} \leq \quad T_{\mathrm{s,\,heating\,plant}} \tag{3.2}$$

In this thesis, the maximum supply temperature (ϑ_s) is assumed to be 95 °C and is given by equation 3.3. Systems with a maximum temperature below 100 °C allow for less technical expenditure because the water is not able to boil in the system.

$$\vartheta_\mathrm{s} \overset{!}{\leq} 95\,^\circ\mathrm{C} \tag{3.3}$$

The minimal possible return temperature (ϑ_r) depends on the customer's internal heating system and the current demand. It can also depend on the network's supply temperature [64] and thus in real operation, the return temperature is volatile [2, p. 463]. In addition, the return temperature can be intentionally increased by the substation control. This may be done to use the storage potential of the return pipes [65], [66]. Since this would lead to lower efficiency of some heating plants such as heat only boilers (HOBs) [2, p. 139] and higher heat losses [2, p. 82], the aim is to keep the return temperature as low as possible. Because the impact of a volatile and intentionally increased return temperature would lead to a rather complex overall system behavior, it exceeds the scope of this thesis and hence the return temperature is assumed to have a constant mean value (q.v. equation 3.4).

$$\vartheta_\mathrm{r} \overset{!}{=} 50\,^\circ\mathrm{C} \tag{3.4}$$

Further global conditions such as global equations, constraints, and the related assumptions are integrated into appendix A (p. 309).

3.3.2 Modeling

In chapter 5 and chapter 6 of this thesis, thermo-hydraulic and economic models for the evaluation of heating plants and flexibility are presented. As the thermo-hydraulic models are based on steady-state processes, dynamics are not implemented in the models. Rather, the complexity of the models arises from the analysis of numerous operating points and therefore requires a large amount of data.

Due to its wide distribution and popularity in the scientific community for processing large amounts of data, as well as from own experience, the programming language *Python* (Version 3.7) [67] with the packages *Pandas* [68], [69] and *NumPy* [70] is used in this thesis.

Python is a high-level, interpreted programming language that supports the programming paradigm of object orientation. Therefore, it is well suited for prototyping and fast development. It is also free to use, and many different library packages exist which can be modularly combined. [71]

Python classes can be used to define identical instances with different parameter values. One example is the implementation of heating plants. Each heating plant type is implemented as its own class and different heating plants of the same type are expressed as objects (instances) of the same class. The classes include attributes (parameters) as well as functions.

Python functions can be used for the implementation of equations. The same functions can be used in different parts of the models and by this, both code redundancy and the possibility for errors are reduced.

As described above, the Pandas package is used for the handling and processing of data. Pandas provides a large set of functionalities. The core parts are the two datatypes *Dataframe* and *Series* [68]. The Dataframe can be described as a table and the Series can be seen as one column of a table combined with an index. Data can easily be parsed from Dataframes and Series to arrays of the package NumPy and vice versa. NumPy is made for vector operations. The data is stored in arrays that are somehow similar to the Series. The main difference is that this library supports more mathematical functionality for the vector operations. Through vector operations in both libraries, using Pandas and NumPy allows for fast computations in contrast to computations in loops. This makes both libraries efficient when working with a large amount of data.

Another package that is used is *SciPy* which provides mathematical algorithms and functions [72]. In the context of this thesis, it is used for interpolation and the solving of the pressure iteration. Finally, the package *Matplotlib* is used to create the visualizations of the results [73].

3.4 Case study DHS in Hamburg-Wilhelmsburg

This thesis contributes to the two research projects *Smart Heat Grid Hamburg* [25] and *Reallabor: Integrierte WärmeWende Wilhelmsburg – Integrierter Wärmemarkt* (*Living Lab: Integrated Heating Transition Wilhelmsburg—Integrated Heat Market*) [26]. The projects aim to facilitate the transition to 4GDH by developing innovations and their practical implementation in a DHS in the Wilhelmsburg district of the city of Hamburg in Germany. The DHS is operated by the company *Hamburger Energiewerke GmbH*.

For the later application of the developments (q.v. chapters 4 to 6), a case study DHS with exemplary plants is required. Due to the integration of this thesis into the research projects, the DHS in Hamburg-Wilhelmsburg is used as the case-study DHS. As the DHS is in a process of continuous development and construction, an interim planning version is used in this thesis. Figure 3.5 depicts this version, which is a mix of existing and planned components.

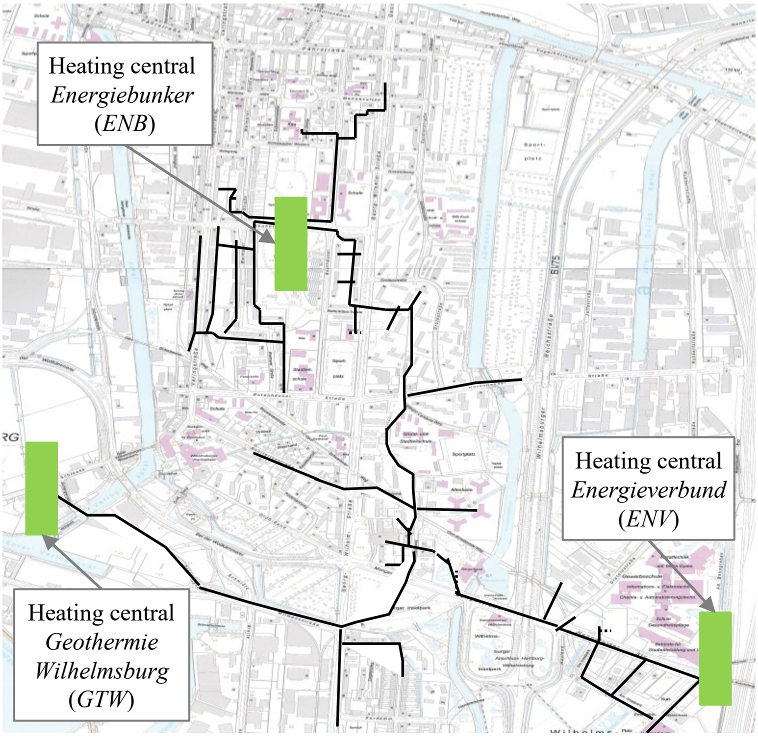

Figure 3.5: Case study DHS in Hamburg Wilhelmsburg with existing and planned parts (background map from [74])

In this DHS, two heating centrals exist: the *Energiebunker (ENB)* and the *Energieverbund (ENV)* (cf. [12], [75]). The Energieverbund (ENV) combines a CHP plant with a HOBs and two 20 m^3 storage tanks. In addition, decentralized plants are integrated into the network that feeds heat from small-scale solar thermal plants into the DHS. The Energiebunker (ENB) combines industrial surplus heat, a solar thermal heating plant, two CHP plants, and several HOBs. In this heating central, a 2,000 m^3 storage tank is used to buffer the heat from fluctuating production. As part of the Smart Heat Grid Hamburg project, a decentralized storage tank with a volume of 910 l is installed at a customer location in the ENB network.

A third heating central—the *Geothermie Wilhelmsburg (GTW)*—is currently being built at the time of writing [76]. For this heating central, a deep geothermal plant is planned with a depth of 3,500 m. Further, it is planned to create another heating central with a combination of an aquifer thermal energy storage (ATES) and a heat pump [77]. Specific data of the components are given in chapters 5 and 6 as well as in appendix C.

The whole network is exemplarily used for the discussion of a theoretical dispatch model in chapter 4. The heating plants are used in chapter 5, and the storage tanks are used in chapter 6. Since this DHS has been the subject of investigation in earlier research projects such as the *Smart Power Hamburg* [78], almost all of the data that was used is publicity available. For economic calculations, values from literature are used instead of real values, to protect confidential data.

3.5 Conclusion on the framework approach

This chapter presents the framework approach that describes how the new framework will be developed. The application of this new framework contributes to filling the gap of the lacking transition methodology.

Based on the results of the literature research in chapter 2, a structure of eight district heating (DH) scopes is proposed that can be applied to classify activities of DH research and practice. The new structure of DH scopes is a novel contribution to several applications. Since a large amount of literature is available and upcoming in the field of DH [1], the structure can guide and give orientation concerning these topics as it allows for setting specific research of one scope into a comprehensive context. This context can be used to discuss the interactions of different scopes and the identified issues in research can be assigned to specific scopes which ensure that appropriate solutions are developed for the issues.

Based on this new structure of DH scopes, a hierarchical framework approach is developed, and its top level is described in detail in this chapter. The additionally required subordinate steps of the approach are presented in the respective chapters.

The top level of the framework approach consists of four steps. In the first step, the outer conditions and the basic framework structure are defined. The most relevant aspect of the outer conditions is the organizational structure that defines the required agents. To coordinate the activities of these agents, subordinate framework processes and their interactions are proposed. In the second step, these inner framework processes are concretized, and their mechanisms are worked out in detail. In steps 3 and 4, the heating plants and flexibility are integrated into the framework as a first implementation of the proposed framework.

The last two steps include an implementation of the approach using models and their application to a case study district heating system (DHS). Therefore, global conditions are presented in this chapter, which includes a brief summary of technical limitations and a description of the modeling tools used. In addition, a case study DHS is introduced, which is used for the application and as a test of the developments.

Since no similar approach has been found in the state-of-the-art review in chapter 2, the framework approach can be regarded as a novel contribution to DH research.

Chapter 4

Development of a comprehensive framework

The review of existing solutions that facilitate the transition of the district heating (DH) sector identified a gap (q.v. chapter 2). A comprehensive transition methodology for the DH scopes of design, operative planning, and operation in district heating systems (DHSs), that has been developed in a systematic way, cannot be found in the literature. Activities and mechanisms that appear in these scopes must be changed from a comprehensive point of view to reduce and resolve barriers to the transition.

Therefore, building on the application of the framework approach developed in chapter 3, this chapter aims to devise a comprehensive framework for the design, operative planning, and operation to facilitate the transition toward 4^{th} generation district heating (4GDH). This framework will serve to fill the gap concerning the currently lacking transition methodology. It aims to integrate centralized and decentralized heating plants by interacting with the electricity sector as well as integrating short-term and seasonal flexibility. The solution should be independent of the chosen technology and must be scalable. Furthermore, currently lacking innovations need to be identifiable.

According to the framework approach (q.v. chapter 3), this chapter presents the development of the framework in two main steps.

Firstly, the basic framework structure and the outer conditions are defined. This basic structure is oriented by the previously introduced structure of DH scopes. This orientation secures development from a systemic perspective. For the definition of outer conditions, the organizational scope is most relevant. Here, roles and agents must be investigated that aim at high economic efficiency and that consider the physics of the DHS. The interim results of the first step are identified framework processes that require further specification.

Secondly, the individual framework processes are developed. In this step, the relevant activities of each framework process are linked by technical and economic mechanisms. These mechanisms are developed in such a way that the activities are incentivized to facilitate the transition. This step includes the synthesis of literature research, interviews with DH companies, and the practical experience of the author.

The chapter is organized into nine sections. In the first section, the methods for the development of the framework are further specified and in section 4.2, the basic framework structure is defined. Afterward, the individual framework processes are developed. Here, the processes and mechanisms are defined in the sequence of the DH scopes which starts with the development of the design process in section 4.3. Section 4.4 presents the development of the operative planning processes. In section 4.5, the process for operation is presented. After this individual framework process development, the interfaces of the framework with the evaluation scope are worked out (section 4.6). In section 4.7, the whole framework is summarized and related to a systemic perspective. Afterward, the concept is validated and discussed. Finally, relevant conclusions are presented and the requirements for further innovations are highlighted in section 4.9. Some of these required innovations are subsequently developed and presented in chapters 5 and 6.

A preliminary version of the proposed framework was previously published by the author in [79].

4.1 Methods to develop a comprehensive framework

The framework development is performed in two main steps and, for each of these two steps, a method that specifies the underlying sub-steps is presented. In the first subsection, the method for the definition of the *basic framework structure* and the *outer conditions* is introduced. This includes the definition of the organizational structure and the required framework processes. In the second subsection, the method of the *individual framework process development* is presented. In this second step, the framework processes are further specified. At the end of both steps, the framework is presented and validated against the given requirements.

4.1.1 Method for the first step: Definition of the basic framework structure and the outer conditions

The method for the definition of the basic framework and the outer conditions is depicted in figure 4.1. All sub-steps of this development are related to the general requirements that are identified in chapter 2. The development is made in a top-down direction since the higher-level scope defines the conditions for the lower levels.

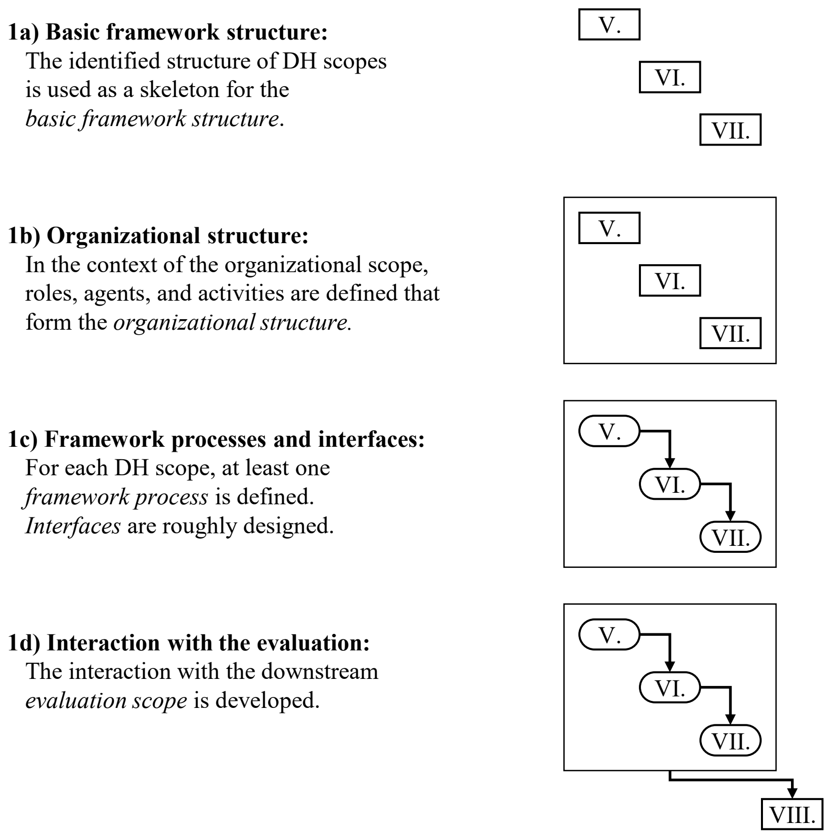

Figure 4.1: Method for the definition of the basic framework structure and the outer conditions

In the *first sub-step (1a)*, a *basic framework structure* is developed that is based on the new *structure of DH scopes* (introduced in chapter 3). It forms the skeleton of the framework and is based on the relevant DH scopes *design* (DH scope V), *operative planning* (DH scope VI), and *operation* (DH scope VII), whereby the focus on the scopes ensures the systemic perspective.

In the *second sub-step (1b)*, the most relevant aspects of the *organizational scope* (IV) such as roles, agents, and business models are evaluated. The evaluation aims to identify an *organizational structure* that fits the general and scope-specific requirements. This new organizational structure should especially help to overcome the lock-in effect of the established business logic. This includes the evaluation of introducing competition and of separating system operation and heat production. The resulting structure will be a compromise between facilitating the transition and securing a high level of economic efficiency and, since a perfect solution may not be found, the selected new organizational form will induce new issues. Resolving these issues is considered an additional requirement for the subsequent individual framework process development.

In the *third sub-step (1c)*, for each of the three DH scopes, at least one *framework process* is defined that connects the relevant activities by technical and economic mechanisms. In addition, the required interfaces are identified. A further specification of both will be done during the individual framework process development.

In the *final sub-step (1d)*, the interaction of the whole framework with the downstream *evaluation* scope is developed. To facilitate the improved readability of this chapter, this sub-step will be presented after the individual framework process development.

4.1.2 Method for the second step: Individual framework process development

The individual framework process development is the second step of the framework approach, and it concretizes the required framework processes that are identified in the previous step. This development mainly includes the development and combination of technical and economic mechanisms, both inside and in between the processes. These *mechanisms* are economic mechanisms such as pricing concepts or technical mechanisms such as control strategies. Since the DH scopes are different, the detailed method for each framework process development is different. However, the abstract method that is depicted in figure 4.2 is used for each individual DH scope. It includes requirement analysis, a state-of-the-art analysis, a concept development, and the result. These sub-steps are further specified in the following.

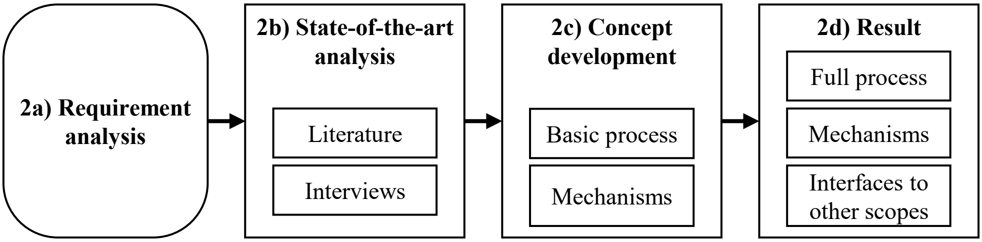

Figure 4.2: Method for the individual framework process development

In the *first sub-step (2a)*, the relevant requirements for the specific DH scope are summarized which result from the state-of-the-art evaluation in chapter 2 and the superordinate framework processes. The review identifies general and scope-specific requirements. The general requirements include the fact that the framework must be designed for a system during the progress of transition as well as for the time beyond. It should be open for new participants and transparent for the customers and it must also combine the requirements of the short-term and long-term. Further, it must consider the integrative character of the DHSs that requires the integration of all subsystems in a system serving way. Finally, the supply of heat must be always ensured.

If possible, the framework processes will be built on existing mechanisms. Therefore, existing solutions are identified by a scope-specific state-of-the-art analysis in the *second sub-step (2b)*. Possible mechanisms are either already identified by chapter 2 or found from additional scope-specific literature research. Since there is little research and literature on practical implementations, interviews with DH companies are conducted as part of the search for mechanisms. Since the DHSs in Copenhagen and their coordination unit Varmelast are identified as innovative in chapter 2, interviews with Danish DH companies were conducted in February 2019. The interviews included a presentation held by the interviewees and subsequent questions and discussions. The interviews were transcribed, and the protocols were reviewed by the interviewees. The protocols are provided in appendix B. In this chapter, the most relevant aspects are summarized and discussed.

After an overview of possible mechanisms is created in the previous step, the selection of the final mechanisms can be made from which the basic framework process and its interfaces can be formed in the *third sub-step (2c)*. Since the development of these complex framework processes requires several qualitative decisions, the following design principles are considered to secure the development of a coherent and systemic framework.

1. An identified issue or requirement should be solved in the best-fitting DH scope.
2. The decisions are argued from a macroeconomic perspective. The macroeconomic goals should be translated into microeconomic incentives and penalties.
3. The framework and its processes are designed in an agile way. They should learn from experience and allow for continuous changes.
4. The mechanisms should be designed in a system-serving way, which facilitates an integrative system. This means that a subsystem is embedded into the framework in such a way that its optimization leads to an overall optimum instead of a contrary, independent subsystem optimum (suboptimization). An example is to apply the cost-by-cause principle.
5. The two principles of opportunistic coordination—the principle of opportunism and the principle of least commitment—are applied. The principle of opportunism requires to consider all levels of freedom of a system for operative and strategic decisions. Conforming to the principle of least commitment, these decisions should be made as late as possible. [80]

In the *last sub-step (sub-step 2d)*, the resulting framework process with its mechanisms is finalized to include the interfaces to the other DH scopes. The result is the framework process which is combined with specific mechanisms. The process with its mechanisms is linked to the processes of the other scopes by defined interfaces. The novelty of the framework lies in the coherent composition of the individual processes from a systemic perspective, even though the process development builds on existing knowledge.

4.2 Basic framework structure and outer conditions

In the following subsections, the basic framework structure and the outer conditions are defined. The latter focuses on the organizational structure. In the beginning, the basic framework structure is developed and afterward, the organizational structure is worked out in three steps. Firstly, the requirements for the organizational structure are identified. Secondly, the state of the art of DH organizations is analyzed and possible solutions are discussed. Thirdly, a new organizational structure is developed and further requirements for the framework are described. Based on these requirements, the framework processes and their interfaces are defined.

4.2.1 Basic framework structure

The objective of the framework is to support the transition from 3rd generation district heating (3GDH) toward 4GDH. Therefore, the framework must fit a fully fossil-based supply and a completely decarbonized DHS. The framework development uses the structure of DH scopes as a skeleton and figure 4.3 depicts the DH scopes considered. The focus on the framework is the DH scopes of design, operative planning, and operation. In addition, the organizational scope is relevant, because it defines the outer conditions. Finally, the evaluation scope is directly linked to the framework as a subsequent process. The purpose of each DH scope is briefly introduced in the following paragraphs.

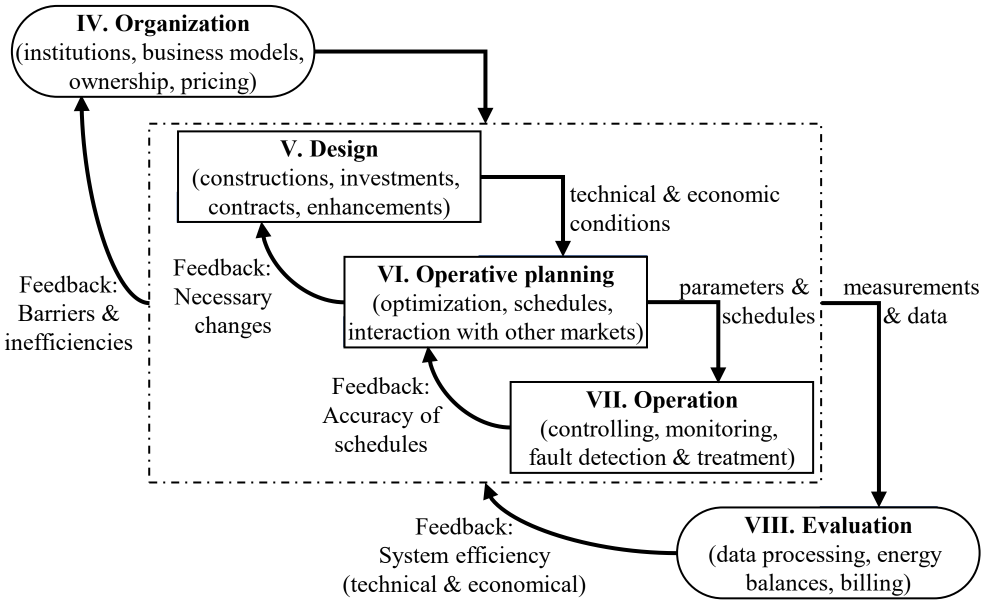

Figure 4.3: Basic structure of the framework

In the *organizational scope*, the institutions, business models, ownership structure, and the pricing that form the *organizational structure* are defined. The relation of this structure to the subordinate processes should be evaluated regularly to remove barriers and inefficiencies.

The *design scope* considers the capacity planning activities before implementation. Constructions are planned and their investments are calculated. This is relevant for new systems and for the enhancement of systems. One of these activities is entering contracts as, through this, the technical and economic conditions for the subordinate activities of operative planning and the operation are set. In return, these subordinate activities identify necessary changes in the DHS construction that should be considered in subsequent design decisions.

In the *operative planning scope*, the activities focus on the technical and economic optimization of existing plants. Schedules may be needed to interact inside the DHS and to interact with other markets (e.g., the electricity market). The schedules and other parameters are transferred to the operation. In return, feedback on the planning accuracy and other experience from the operation scope should be continuously considered in the operative planning activities.

In the *operation scope*, the activities focus on the control and monitoring of operations. Faults are detected and treated. Here, the whole framework produces data in the different activities.

As part of the *evaluation scope*, the data should be post-processed whereby energy balances and bills are one of the main tasks. In addition, the system efficiency (technical and economical) should be evaluated to improve the whole system.

4.2.2 Requirements for the organizational structure

As discussed in chapter 2, there is a lock-in effect of the established business logic in existing DHSs with fossil-based heat production (cf. [24], [23]). If the DHS requires high temperatures, these temperatures have a strong impact through higher costs for the renewable heating plants or it can even lead to a barrier for some types of heating plants. In contrast, the established combustion-based plants do not show such a significant impact of the supply temperatures on the costs. If the fossil-based heating plants still have a working business model, there is no incentive for a reduction of the temperature which results in a barrier for the new heating plant types. Therefore, it is an important requirement for the organizational structure to resolve the lock-in effect of the established business logic.

The organizational structure should incentivize a reduction of temperature and demand, as well as an increase of flexibility on the customer side through new business models. Further, it should support the integration of heat sources from prosumers, industry, and others. The structure should be made for both the transition process and for a full renewable supply. The organization should be able to adapt to different policies and regulations. Finally, all heating plants should be supported by fair treatment, independently of their size and location.

The requirements for the integration of renewable heat sources show that they need different economic conditions and a different organizational structure compared to fossil technologies. As discussed in chapter 2, the transition in the DH sector can lead to smaller and more distributed plants. The heat from surplus heat sources (like industry or supermarkets) may be used. In the case of such surplus heat sources, the heat source is owned by a third party. Therefore, the connection of these sources will require third-party access. The European Union (EU) directive "on [the] promotion of the use of energy from renewable sources" forces DH companies either to increase the share of renewable sources or to grant non-discriminatory access to third parties [81, article 24, § 4b]. Even if this requirement is softened by other paragraphs in the article (e.g., [81, article 24, § 5]), it indicates that competition is seen as a key to the transition. This indicates that *third-party access* to the DHS is required to achieve an economically efficient transition to renewable heat sources.

In the case of introducing competition, the economic efficiency may be increased due to several additional effects. Since some of the renewable technologies require specific knowledge or large investments with high risks (e.g., geothermal heating plants), small DH companies may not be able to implement them on their own. Further, if the DHSs are open for third parties, specialized companies could operate several plants of the same type in different DHSs. Through such a specification, the companies could increase their economic efficiency, focus on maintenance, and could get better prices for the plant or fuels. This effect is *economy of scale*. Another advantage of competition is that companies may benefit from their specific experience in another sector. An example of such an *economy of scope* is a petroleum company that implements and operates geothermal systems [cf. 82].

In addition to the third-party access and the increase in economic efficiency, the transition requires an evolutionary structure that adapts to changing conditions. It is well known that competition supports such technical transitions [83, p. 36].

4.2.3 State of the art of DHS organization

In this subsection, the state of the art of organizational structures for DHSs is analyzed. To do so, the different types of competition, which can be implemented in DHSs, are discussed. Furthermore, different types of ownership models, which guarantee fair access for independent producers, are also discussed. These theoretical basics are complemented with experiences from Copenhagen. Finally, the challenges and barriers to a competitive form of organization are identified.

Possibilities for competition in DHSs

In DHSs, the transmission and distribution (network operation) can be regarded as a *natural monopoly* because the implementation of two or more parallel piping networks for all customers is economically inefficient [84]. For all other parts (mainly the production and customer side), competition can be introduced. The advantages and disadvantages are discussed in the following section.

To understand different possibilities for introducing competition, a brief look is taken at the electricity sector. The different competition models and their advantages and disadvantages are described in appendix A.2.3 (p. 323). In the following, a brief summary of the different models is provided:

The established model is a *vertically integrated utility* that is responsible for generation, transmission, and distribution. The first step for introducing competition is the introduction of independent producers besides the vertically integrated utility. In this model, the vertically integrated utility acts as the only buying company (referred to as a *single buyer (SB)*). The second step is to separate production and distribution from the system operation as well as to install a wholesale market. The third step is to separate the retail from the distribution by introducing an additional retail market. [85, pp. 2–6]

In [86], the International Energy Agency presents a report related to improving DH policies in the year 2004. Even though the book does not include the latest developments in DH (transition to 4GDH) and focuses on transition economies, it provides a good overview of the discussion between competition and regulation in the DH sector.

If business and political interests are separated, it does not matter if the ownership is private or public. Instead, the business culture and other conditions (e.g., legal conditions) are important for an efficient DH operation. To achieve public goals with privately-owned DHSs, the heat supply and the public goals can be included in tendering procedures. [86, p. 27]

In general, there are two economic environments for DH: regulated and competitive (deregulated). The type is dependent on the local policies. In a competitive environment, the price for the customer is set by the market whereas, in a regulated environment, the price is set by the regulator. Both concepts have strengths and weaknesses. Regulated markets can include competition and competitive markets can include regulations. Denmark is an example of a regulated environment that does not allow the DH companies to make a profit. In contrast, other countries like Finland do not regulate the DH market. [86, pp. 77–79]

While there are some indications that unregulated prices under competition are lower than with regulation, the numerous influences on the price make an evaluation difficult. In non-regulated markets, more flexibility is available in the market. Independent of the market type (*regulated* or *competitive*), an independent regulator should be implemented. Further, both cases could include competition on the supply side. [86, pp. 21–26]

Competition in DH seems generally possible, but it is different in comparison to the electricity sector. In contrast to the electricity system, the relatively small size of DHSs and limited transportation distances makes it economically unfeasible for *retail competition* which would enable customers to choose their supplying company inside one DH network. Instead of choosing different suppliers inside one DH network, competition on the demand side exists between the DHS and alternative local heat sources. This is called *heat source competition* and acts as the retail competition. For this heat source competition between DH and local heat sources, the same conditions should be provided by the regulator for the different heat sources (level playing field). These conditions require a regular evaluation by the supervising authority. Further, competition can be achieved on the supply side inside of the DHS as *wholesale competition*. [86, pp. 81, 125–126, 134–136]

In DHSs, wholesale competition can be realized if the network company buys heat from a third-party producer. Wholesale competition inside the DHS can be used in a competitive or even in a regulated environment. Wholesale competition in DHSs can be achieved by an *informal access right* which uses bilateral contracts between the heat supplier and the vertically integrated utility. This is often used, although, in this type, a vertically integrated utility has a great deal of power and can limit the access to the DHS. Another possibility is a *formal access right,* which forces the vertically integrated utility to buy heat at standardized terms if the heat has lower costs than the other sources. This type is used in the DHS in Copenhagen (Denmark). Here, long-term contracts are used combined with a short-term dispatch. It is combined with an unbundling (q.v. section 4.2.3) of the DH network(s) and transparent transmission charges. [86, pp. 126, 135–145]

Wholesale competition is often used in DHSs and DHSs which have integrated a wholesale competition indicate that competition is working. Further, forcing wholesale competition can increase the transparency for the regulator or the competition supervisory authority by giving access to the transactions. [86, pp. 126, 135–145]

Ownership models for a fair third-party access

If the DHS is operated by a vertically integrated company, fair access for third parties could be hindered. Splitting off the network from the DHS to an independent network company without production is referred to as *ownership unbundling* and it is the most effective way to support fairness. In some cases, unbundling has already taken place. Examples are large-scale combined heat and power (CHP) plants or waste incineration plants. Unbundling offers the opportunity to increase economic efficiency. In general, the larger the DHS is, the more cost-effective is the unbundling. However, unbundling a market in equilibrium can also increase the system's costs. A disadvantage is that unbundled systems are harder to optimize for efficiency since the different owners aim to optimize their subsystems (referred to as suboptimization). Ultimately, there are no sufficient quantitative evaluations of the advantages and disadvantages of unbundling measures in DHSs that have been performed, and thus there is still insufficient experience concerning this. [86, pp. 135–144]

The report recommends an unbundling of large-scale DHSs combined with a short-term cost dispatch, as well as “fair and transparent network charges” [86, pp. 143–144].

In [87], a study about third-party access to DHSs is presented by the energy management consultant Pöyry. It was conducted for the Finnish Energy (branch organization). The authors define competition on the supply side as a “single buyer model” [87]. The introduction of third-party heat supply with access to customers (retail competition) is introduced as a “network-access model” [87]. The report includes the evaluation of three different models: a single buyer (SB) with open and transparent access, SB with regulated wholesale competition, and network access. The costs for these models are estimated by means of some assumptions. For example, it is assumed that unbundling a vertically integrated utility into one SB and one independent producer may double the administration costs for the existing system. In addition, it is assumed that the costs for operation and information and communication technology (ICT) infrastructure will increase as well. These assumptions are applied to case study DHSs of different sizes. For the best case—a large network (with an annual demand of 5 TWh/a)—the analysis shows that the costs increase by 1–3 % of production costs. The unbundling for small and medium-scaled DHSs is estimated to be much higher (by 10–50 %) and therefore, it is regarded as being too expensive. The evaluations based on the described assumptions lead to the conclusion that the unbundling of ownership could be expensive for these local markets. Besides this estimation of costs, the study provides some general conclusions and recommendations for introducing competition. For example, even though competition might be introduced, long-term contracts will be still needed. Further, the study showed that the existing companies could include new technologies themselves and hence there is an existing alternative to third-party access. The authors expect that there is no increased benefit from third-party access in DHSs. This is particularly the case in small-scale DHSs. However, they conclude that more transparency can be helpful for further technology development. Implementing marketplaces on hourly prices could improve the prosumer activities and new services and thus the authors recommend setting up a marketplace to increase the cost transparency. To do so, existing optimization systems should be updated for third-party access as marketplace software. They recommend implementing an SB structure but with the wholesale competition without an unbundling of supply. Producers should pay for the connection, which finances the costs for the connection. Further, it is concluded that innovations for new services and technologies are required e.g., to facilitate a more open DHS. An additional option would be a market for the capacity, which is not further evaluated in the study. Such a capacity market seems possible, but it will be complex to define in a general way that is valid for different DHSs. [87, pp. 4–5, 7, 16–18, 38, 62–63]

This study provides valuable information about the advantages and disadvantages of introducing competition as well as some requirements for its introduction. The evaluation of the costs of competition is made from a microeconomic perspective although positive effects from a macroeconomic perspective like those given in section 4.2.2 are not considered and especially the impact of competition on the facilitation of an economically efficient transition requires further research.

Magnusson et al. evaluate third-party access in Sweden. The authors describe how—after the customers have decided on a DH supply—they are locked in concerning this supply because the costs to change to an alternative heating source (heat source competition) are too high. Third-party access to DH can increase the competition and lower prices e.g., through the introduction of an SB structure. It is mentioned that auctions could be used for new plants to allow for competition between different producers. Another way of encouraging competition would be to connect different DHSs, thereby introducing retail competition for the customers. However, if the DHS is small, competition will not be an option and thus regulation is needed. The authors conclude that there are arguments for and against third-party access and propose a simple solution, namely that separating distribution and production inside the companies and providing transparent pricing could incentivize economic efficiency. [84]

Unbundling and third-party access in Copenhagen

An example of an unbundled DHS with wholesale competitive coordination is the DHS of greater Copenhagen in a regulated environment that does not allow making a profit. Since there is no sufficient literature available on the implementation in Copenhagen, an interview was conducted with the DH company VEKS. The full interview transcript is provided in appendix B.1 (p. 332) and the following extract from the interview demonstrates some of the challenges and advantages of their structure.

Copenhagen plans to become fully renewable in the year 2025. Therefore, fossil-driven CHP plants are converted to biomass while other technologies are also connected. Due to its size, the DHS of greater Copenhagen is separated into several transmission and subordinate distribution networks that supply 19 municipalities. The different networks and systems are owned and operated by unbundled companies. VEKS is one out of four transmission companies that are connected to the DHS. The other transmission networks are operated by the companies CTR, Vesterforbraending, and HOFOR. The large-scale heating plants and the peak supply plants are connected to these transition networks. VEKS is owned by 12 municipalities and supplies 170,000 end-users. Most of the 12 municipalities operate their own distribution system.

Even though the DHS is unbundled, VEKS has continuously decreased the return temperature. Over a period of 25 years, the temperature could be reduced from 55 to 48 °C by monetary incentives (and penalties) for the distribution system and the end customers as well as some softer measures. The long-term goal is to be able to reduce the supply temperature.

One of the renewable heating plant projects of VEKS is the connection of the industrial site of *CP Kelko* as a surplus heat supplier. In the beginning, the project was challenged by different barriers whereby the biggest challenge was the definition of the contract and the financial mechanisms. On the one hand, the industrial company requires short payback times (less than 3 years). On the other hand, DH companies are used to low costs and long payback durations. The solution to these barriers was transparent communication and a concept to realize short payback times for the industrial company. The partners agreed to define three periods: the first for the repayment of the industrial investment, the second for the repayment of the DH investment, and the third period during which the charge is divided by the partners. The charge is defined by the substitution price of the other heat sources.

These points demonstrate that an unbundled system is still able to become more efficient. Further, the innovative business model supports a fast return on investment for the industry and allows for third-party access. A disadvantage of the solution is that a substitution price only works if the full production is not organized by a third party. This is mainly related to the non-profit regulation in Denmark.

Challenges for a competitive environment in DHSs

As introducing competition and third-party access seems generally possible in large-scale DHSs, the question is how it could be introduced (or supported). Several barriers must be overcome. [84]

The challenges identified by the previous review can be summarized as follows:

One challenge is the costs for the introduction of the competition itself as the marketplace and the additional communication infrastructure for the transmission of schedules will cause additional costs [87, pp. 17–18]. A major issue is that administration costs could increase [84] and thus there is a risk that the costs for the competition are higher than the economic efficiencies while there is no proof that the costs will be reduced [84].

Another challenge is related to the planning of investments and capacity (DH scope V). Pricing can be made on marginal costs, but this is a barrier for new plants that is related to the insecurity of future prices [87, pp. 17–18]. This barrier makes large investments unattractive. The large and long-term investments are a barrier to entering the market [84]. Another important aspect is the question of who pays for network extensions [87, p. 20].

The more complex physics (in contrast to the electrical grid) requires special treatment in the DHS planning. The temperature of production and the location of feed-in is relevant [87, p. 6]. For example, the temperature levels that are provided by surplus heat sources could be too low [84]. Bottlenecks in the transmission network must thus be considered in the market mechanisms [87, p. 20].

Further general concerns can be identified. There is a risk of *suboptimization*, which means that subsystems are economically optimized instead of the overall system [84]. Another risk is related to the *market power*. There is a risk of the formation of an oligopoly [84] or the possibility of market concentration by the dominance of large-scale plants [87, p. 20]. Particularly at the beginning, the number of producers will be small [87, pp. 54–55]. In addition, there is a *risk for investments* due to changing policies or changing market conditions [87, pp. 54–55].

4.2.4 Organizational structure

Related to the requirements of the transition to 4GDH, an organizational structure must be chosen which supports the transition by securing fair access to new and renewable heat sources. As these sources and heating plants may belong to third parties, introducing wholesale competition can be key. A further effect of competition is that it supports price transparency and secures a cost-efficient transition. An unbundling of the usually vertically integrated DH utility to an SB and independent producers will secure a fair competition on the production side. Through such an unbundling, the lock-in effect of established, fossil-based business models may be overcome, because the SB can focus on temperature reduction and efficiency improvement. There is no conflict of interest to sell a larger amount of energy or hold on to higher temperatures so that lucrative fossil plants can continue to operate.

However, there are also several challenges if competition is introduced. A major challenge is an evaluation of whether the transition in a competitive organization is more cost-effective compared to the transition in a vertically integrated organization. For this evaluation, the administrative and transaction costs of the competitive structure must be compared with the economic inefficiencies of the vertically integrated utility. In both cases, it must be assumed that the transition will be successfully fulfilled. This will require an evaluation on a macroeconomic basis, which is not part of this thesis. Existing studies like [87] focus on the economic benefits as well as on challenges resulting from introducing competition. The effect of competition on the transition towards 4GDH has not been part of the reviewed evaluations. Further, the benefits through higher economic efficiency and the economies of scale and scope through the application in many DHSs are also not considered. These are further strong arguments for the introduction, or at least for the evaluation, of competition in DHSs.

Even though the final quantitative evaluation of introducing competition is not part of this thesis, a decision is required for the further development of the framework. There are two strong arguments to decide on the introduction of competition. Firstly, it allows for resolving the lock-in effect to established business models and therefore, it seems to be a catalyst for the transition. Secondly, a framework developed for a competitive and unbundled organizational structure may be applied to a vertically integrated utility as well. In turn, a framework, that is made for a vertically integrated utility may not be applied to a competitive environment. Therefore, the competitive environment is chosen as the more challenging boundary condition, and it will be assumed for further development. As a result, the following development must resolve the challenges that might come up with the introduction of competition. These challenges are to incite investments into the network and new heating plants under competitive conditions, to consider the physics of the network in design and operation, and to avoid suboptimization and the strong market power of a single company.

Figure 4.4 presents the resulting organizational structure that will be applied for the subsequent developments. The structure is based on the SB concept, which seems to be the most realistic first step of the implementation of competition resulting from the discussion above. It includes the customers, heat producers, and an SB. Further, a supervising authority should also be implemented.

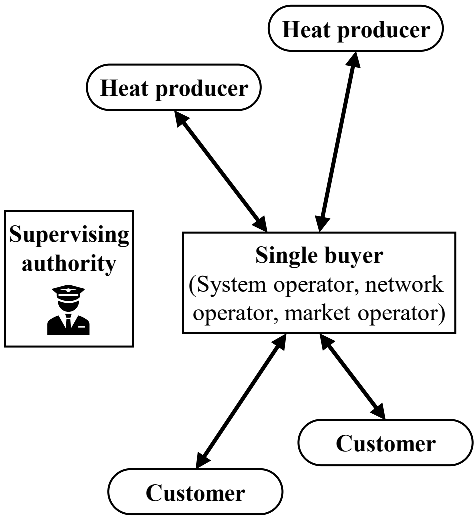

Figure 4.4: New organizational structure

The central role in this structure is the *single buyer (SB)*. It is responsible for the general system and network operation. The SB's goals are to secure the heat supply at the lowest cost while considering the ecological transition. To do so, it can focus on the relevant business model: the transformation of the network and the customers to higher efficiency and lower temperature. Hereby, it is important to install mechanisms that motivate the SB to reduce the demand and temperature as such a motivation would resolve the lock-in of established DHSs. This may be easier if the SB is unbundled and does not operate its own heating plants. Further, unbundling reduces the incentives to discriminate against independent producers. It can also support the evaluation of whether investments in the network are useful for reducing the costs of production (e.g., lowering supply temperature through increased transportation capacities). The main disadvantage of unbundling is the higher costs for administration which become more relevant the smaller the DHS is. For the further framework development, a full unbundling will be assumed since technical solutions that work in an unbundled organizational structure can also be applied to a non-unbundled structure.

Marketplaces for the coordination and economic optimization of production are required for the capacity (design scope) and the dispatch (operative planning scope). The marketplaces could be operated by the SB, or it would also be possible to have an external *market operator*. From a macroeconomic perspective, such an external service could be offered to several DHSs and would gain from the economy of scale. In this way, market transaction costs could be reduced, and the introduction of competition would benefit. For the later developments of this thesis, it is not relevant who operates the market.

The *customers* buy the heat from the SB. Due to the SB's new focus, it supports the customers to reduce demand and temperature. This may solve the lock-in effect of established high temperature and high demand promoting business models. To support these business models, the customers' pricing mechanism should consider temperatures for return and required supply temperature to incentivize the necessary changes to the inner-building heating systems. If customers want to become prosumers, they should participate in the marketplace. Related to the effort and the resulting barrier, it may be helpful that the independent producers act as aggregators who are responsible for the trading of several prosumers. In an unbundled system, the SB should not fulfill this role.

Producers are introduced to DHSs as a new role. Introducing independent heat producers requires the solution to several challenges. Peak and redundancy supply must be ensured at every point of time in operation. Some of the heating plants will require long-term contracts (e.g., renewable plants with high investments) which should be negotiated with the SB. This can lead to investment security for the producers and for the security of supply for the SB. In this case, contracts must be drafted which may include variable and fixed pricing although it should also be possible to allow for the connection without a long-term contract. For this case, a standardized connection charge should be defined. To integrate all producers in a system-serving way, their pricing should consider the physics of the DHS. This avoids suboptimization and ensures that the DHS remains an integrative system. Therefore, it is required that the temperature and distances are included in the pricing mechanism.

A *supervisory authority* could be installed to evaluate the performance of the market, the SB, and the producers and to identify antitrust violations. The marketplaces can help to increase the transparency of the authority.

The presented structure is independent of public or private ownership. To enable a strong stakeholder engagement, it may be an advantage to implement a municipally-owned or customer-owned SB but it is also possible to implement a private SB in combination with strong supervisory authority. The ownership of the producers should be open to public or private companies. This enables the possibility for specialized technology companies that can build heating plants of the same type in different DHSs. This offers the opportunity for the development of economies of scale and scope.

4.2.5 Framework processes and interfaces

The newly developed organizational structure sets further requirements for the processes of the framework to overcome the described challenges in the competitive environment.

Due to the introduction of independent producers combined with an unbundling of system operation and production, coordination is required for the planning of the production capacities and for the operative coordination of the production. In a competitive environment, marketplaces are a mature technique for centralized economic coordination which has been demonstrated in the electricity sector. For further information about centralized electricity trading q.v. appendix A.2.3 (p. 323).

Since long-term investments in the network and new heating plants are needed for the *design process* (DH scope V), they must be incentivized under competitive conditions while avoiding suboptimization and the strong market power of a single company. The discussion above shows that—due to the local scale—DHSs may still require long-term contracts.

For the short-term coordination of production, adaptability must be secured by a short-term dispatch. Therefore, the physics of the network must be considered in the *operative planning processes* (DH scope VI). Since the relevance of the interaction with the electricity marketplaces (day-ahead and intraday) will be increased in the transition, market processes for the DH sector must be compatible with these electricity markets.

Finally, the responsibility and control hierarchy must be clearly defined for the *operation process* in a competitive environment (DH scope VII).

Figure 4.5 depicts the result of the first step of the framework approach in which the required processes and the required interfaces are identified.

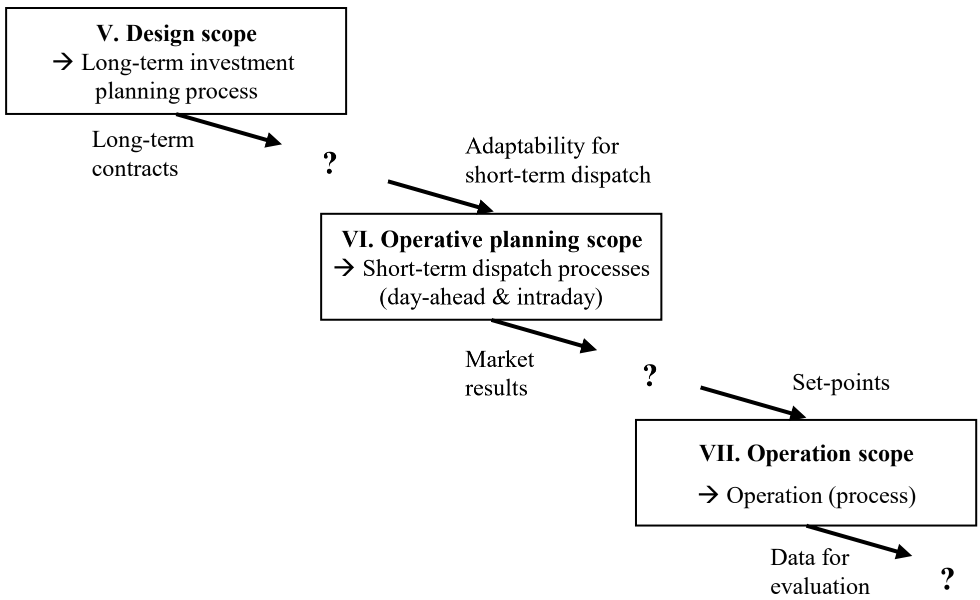

Figure 4.5: Framework processes and interfaces

At this point of the development, the general framework processes are defined, and their requirements are clarified. For a full concept of a comprehensive framework, these processes and their three interfaces need to be further developed. Firstly, the interface between the design process and the short-term dispatch processes requires further investigation since the connection of long-term contracts and the ability to adapt in the short term is challenging. Secondly, the short-term dispatch processes must also be linked to the operation, whereby set-points for the controls must be derived from the market results. Finally, a link to the subsequent process of the evaluation scope is required (DH scope VIII). Besides its other tasks such as billing for customers, this process must compare the delivered energy with previous market results.

This development is presented in the following individual framework process development. Even though the connection to the evaluation process is part of the outer conditions, its development will be presented after the individual framework process developments since it is downstream of the internal framework processes.

4.3 Framework process for the design scope

The goal of the design activities is to implement and enhance the heating infrastructure. This includes the heating plants, the network, and the demand side. Due to the new organizational structure and the (possible) unbundling of the ownership of the heating plants and the network, the design activities and particularly those considering the heating plants require special treatment. All design activities must be performed within the organizational structure and must consider the constraints of the higher-level DH scopes. Therefore, a new design process is developed in the following subsections. The process should satisfy the new constraints and requirements and it should be based on existing concepts and experiences.

In the next subsection, all requirements are summarized which have been identified in chapter 2 and during the development of the organizational structure in section 4.2. One experience is derived from an interview of the DHS in Odense, Fyn (Denmark), and is presented in section 4.3.2. Thereafter, a basic process for the design is worked out and complemented with concepts from literature. Finally, a coherent framework process for the planning of the design (DH scope V) is presented which is embedded in the organizational structure (DH scope IV) and provides mechanisms that link to the operative planning (DH scope VI). Further, it creates the basis for the operation (DH scope VII) and evaluation (DH scope VIII).

4.3.1 Requirements for the design process

There are numerous requirements for this process. The design process should include systemic planning [32] for the whole lifecycle [33, p. 43]. After the first implementation of a DHS, it must be continuously enhanced, extended, renovated, and modernized [33, p. 43]. The design process must aim at an optimal design that considers the risk of changing conditions (e.g., in policies and regulations) [33, p. 15]. The process should support the transition from 100 % fossil fuel and should be applicable for 100 % renewable production. The requirements for the design scope are presented in figure 4.6.

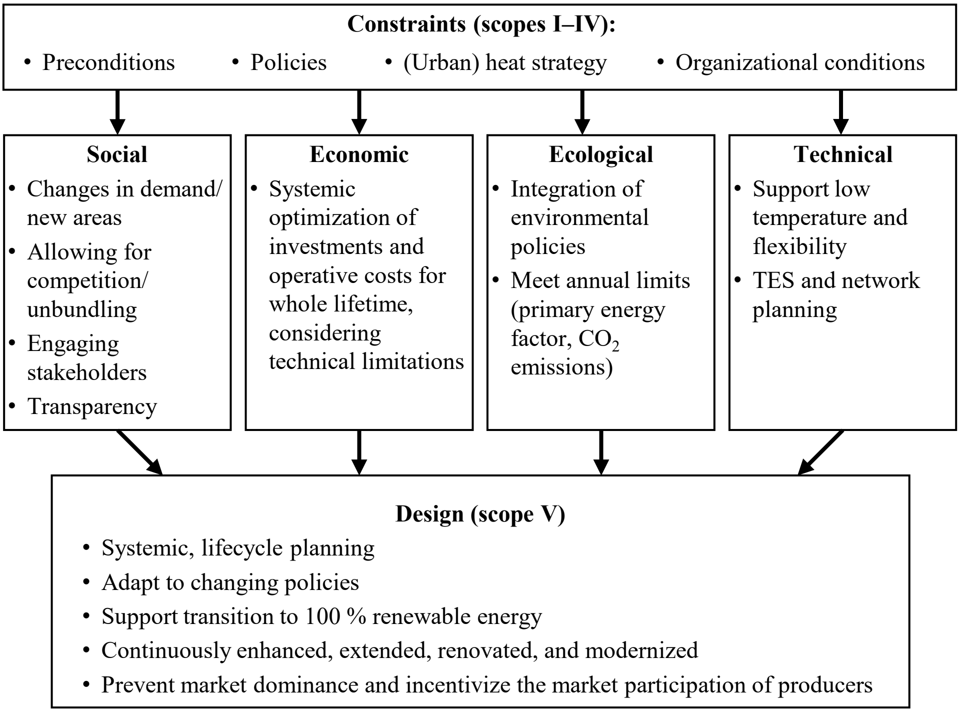

Figure 4.6: Requirements and framing of the design scope

Social requirements are needed to consider changes in heat demand [23] and to connect new customers if it is required [41, p. 13]. Determining the heat demand for new DHSs is a complex activity. It should be estimated in the strategic heat planning, and it must be detailed in the design process e.g., through interviews of the potential customers. Stakeholders should be continuously engaged by providing transparency of costs and decisions [23]. Customers should be supported to reduce temperature and demand and they should also be incentivized to increase flexibility [23]. The positive effects of unbundling (e.g., resolving the conflict of reducing customers' demand versus increasing profit by more heat production) go along with several new challenges as unbundling must be introduced together with wholesale competition on the production side [86, p. 126]. DHSs require large investments and therefore high financial risks are also involved [32]. On the one hand, the competition may create a barrier to large investments which are not attractive in relation to the long duration of return on investment, and this is a barrier to entering the market [35]. On the other hand, the smaller

DH market (compared to electrical systems) involves the risk of the formation of an oligopoly [84] or may create a market dominance of producers with large heating plants [87, p. 20]. Particularly in the introduction phase of competition [87, pp. 54–55], the market dominance should be carefully considered.

From the *economical context*, the market should include investments and a whole-lifetime optimization [33, p. 43] considering system effects (e.g., heat losses and pumping electricity [50]) as far as possible. Technical limitations must also be considered [28]. Further, the planning should consider the integration of new heat sources from prosumers, industry, and other third parties [31]. All heating plants should be fairly treated independent of their size and location [23] and peak and redundancy supply must be secured [87, p. 20]. The temperature, location of heating plants, and bottlenecks must be considered [87, pp. 20, 27]. This is particularly relevant in unbundled systems. To do so, the physics of the DHS must be considered to avoid suboptimization.

The process should take *environmental policies* into consideration. A challenge of ecological planning is that limits for emissions or primary energy are often given on a long-term (e.g., annual) basis wherefore these thresholds cannot be properly implemented in a short-term planning process as they require an annual perspective at least.

From a *technical perspective*, low temperatures and new control strategies are required [19]. Additionally, charging and discharging seasonal thermal energy storages (TESs) can be included in an annual perspective to provide optimal planning [88].

4.3.2 Existing design processes at a DH company

In the following part, excerpts from an interview conducted at Fjernvarme Fyn in Denmark are presented which demonstrate the design process in practice. The full interview transcript can be found in appendix B.2 (p. 338).

Fjernvarme Fyn belongs to Odense (Denmark) and is not part of the greater Copenhagen DHS. The DHS is owned by different companies which themselves are owned by the municipality. The DHS has different technical characteristics (pressure and temperature) for the transmission and distribution levels. The large-scale plants are connected to the transmission network while the smaller plants are connected to the distribution network.

The current main challenge is the replacement of a coal-fired CHP plant for which different solutions are evaluated. The design process uses standard expectations that are valid for all scenarios. They include standardized assumptions, price forecasts, heat demand forecasts, a technology catalog, future taxes and subsidies, and the existing plant setting. Investment planning is based on both scenario calculations and schedule optimization and several different phases of the designing process are performed. Firstly, in an Excel tool, which is based on an annual duration curve, investment and marginal costs are considered to calculate the levelized costs of energy. Secondly, an optimization is performed with investments, hourly marginal costs, storage capacities, ramps, solar generation, and different CHP modes to choose the technology and optimal capacity. In the last phase, the chosen plant setting is validated by a more complex scheduling model with fixed constraints, mixed integer linear programming (MILP), and an ideal heat accumulator. The last model is also used for operative planning. In all evaluations, hydraulics are not included yet although integration is planned for future developments.

In summary, it can be concluded that Fjernvarme Fyn also demonstrates a coherent planning process of different tools for the design and operative planning. Related to the previously discussed requirements, temperature, the physics of the network, and the integration of customers may be included in future developments of the design process. Related to their vertically integrated structure, they can easily combine the process of design with operative planning.

4.3.3 The basic principle for the design process in five phases

The design process in a DHS with unbundled production requires advanced economic mechanisms. A challenge of an unbundled DHS is the balance of sufficient supply and the profitability for the producers to enter the market. For the producers, the large investments under competition could be a barrier to entering the market. For the SB and the customers, the possible market dominance respectively the security for supply are key issues. Therefore, the smaller size of a DHS compared to the electrical markets requires a process to plan the investments and the system design. In [87], it is concluded that even in a competitive market, long-term contracts will be needed. The authors introduce the term “capacity market” [87] for a place where such contracts can be made. As the term *capacity market* fits best, it will be used for the process developed in the following.

Figure 4.7 shows the interaction of the different DH scopes with the capacity market. The previous DH scopes (I–IV) form the frame with specific constraints, and they have requirements for the capacity market. The economic outputs of the capacity market are contracts with customers and producers and the interfaces to the short-term dispatch which are developed in the following section. The technical outputs are the implementation of the design (i.e., building the network, TESs, substations, and heating plants). Further, the control system should be designed and measurements and meters must be implemented for operation (DH scope VII) and evaluation (DH scope VIII).

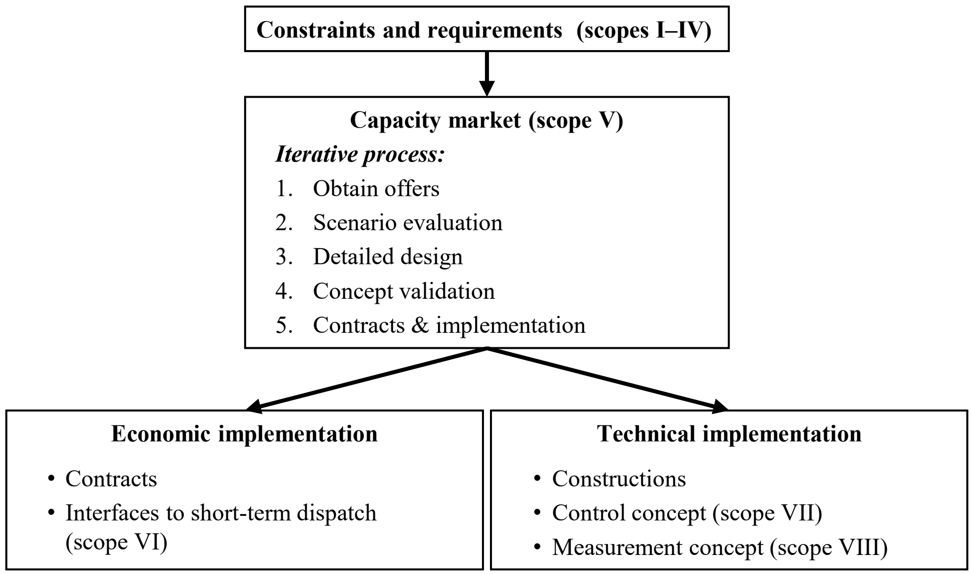

Figure 4.7: Basic concept for a capacity market

The capacity market will require manual evaluations due to the complexity of the different tasks. The responsibility for these evaluations lies with the SB because it is the only participant with full knowledge of demand, the network, and the operation. Five phases are proposed for the capacity market in an iterative process whereby phases 2–4 are inspired by the activities performed by Fjernvarme Fyn. The first phase is to obtain offers from the producers. Phase 2 is the evaluation of scenarios based on the offers, existing plants, and network in addition to simple economic optimizations. The third phase is a more detailed technical planning of the scenarios to consider technical boundary conditions and the fourth phase is the validation of the concepts. Finally, the contracts can be made, and the plants can be implemented. At any point in this process, it can be necessary to go back to a previous phase. It is proposed to perform these phases regularly to facilitate a continuous evaluation in an agile manner. A possible cycle for the market may either be yearly or every second year. The first and the last phases represent the main interaction with the independent producers. This will be defined in the next subsection. Thereafter, concepts and tools for phases 2, 3, and 4 are evaluated.

4.3.4 Development of economic mechanisms

Three main challenges are addressed in this subsection. The first challenge is to find an economic mechanism that supports long-term investments combined with competition between producers. The second challenge is to draft long-term contracts in such a flexible way that the producers are incentivized to continuously increase their efficiency, and to adapt to changing conditions such as short-term prices (e.g., electricity prices) and new policies. The third challenge is to identify mechanisms that avoid suboptimization even though the ownership of subsystems is separated according to different agents.

Phase 1: Obtain offers

Ensuring long-term investments in competitive but local markets is challenging. Therefore, the SB must be able to draw attention to new production capacities, and thus a first phase is introduced that aims to obtain offers for new production.

In [87], some advice is given for the planning of capacity in a competitive environment. A capacity market seems possible, but it will be complex to define in a general way that is valid for different DHSs. To connect new plants, tendering or auctions could be used. Besides the marketplace, contracts are required. Further, the peak supply must be secured. The back-up capacity can be provided by the network operator, or it can also be provided by an independent producer that is selected at a capacity market. If the amount of third-party production is low, redundant peak supply is required and if it is highly available, the redundant capacity can be reduced. [87, pp. 13–14, 17–18, 20]

An example of the application of a tendering mechanism is the implementation of a district cooling project in Barcelona [40, pp. 98–100, 137]. In contrast to the project, the required tendering here is related to the production side only and not to the complete supply including network operation. However, tendering is a frequently used procedure for competition before construction [40, p. 133].

In relation to the proposal in [87] and the positive experiences made with the district cooling project in Barcelona, tendering is evaluated as being the best option to introduce competition between the producers for long-term investments. Further, it must be combined with a short-term dispatch. Such a short-term dispatch may be realized by a spot-market and hence the long-term contracts must be combined with such a market.

In this phase, new demand or changes in existing demand may be announced by the customers as well. This can be the connection or disconnection of buildings or the adjustment of a contract to lower demand.

After this first phase, an internal decision for the different offers is made in three phases which are presented later. If the decision is made, contracts with the chosen tendering participants are entered in phase 5.

Phase 5: Contracts and implementation
Since the fifth phase forms the interface to the short-term planning, suitable mechanisms must be selected between the result of the capacity market and the following processes.

Kirschen et al. present several types of markets that are used in the electricity sector. *Spot markets* are used for short-term trading, but their unpredictability is a challenge to the stability of the system and its participants, and thus additional markets are used to reduce the risk of undersupply and changing prices. *Forward contracts and markets* can be introduced to secure the supply. In this case, future production is sold in a contract or—in a more standardized way—in a market with several participants (e.g., the other suppliers). In this market, the risk of changing prices is shared. In contrast to the forward markets, a transaction in the *future market* must not be secured by physical delivery. This introduces the new role of speculators who increase the market's liquidity. Another market principle is to use *contract for differencess (CFDs)* which is applied in the case when trading in the spot market is obligatory. With this type contracts, the buyer and seller agree on a fixed price, namely the *strike price*, outside the spot market. Both the trade in the spot market and the market difference are compensated outside the market. [85, pp. 34–41]

In DHSs, the market is small due to the locality of DHSs compared to the electrical system. Concepts such as forwards and futures seem to be too complex as they require further market participants, and they would introduce trading between the suppliers. To solve the issue of combining a spot market and a capacity market, it is proposed to implement the capacity market based on contract for differences (CFD) principles. Introducing CFD while forcing all producers to participate in the spot market would lead to high market activity and would support the security of the system operator and also for the suppliers.

In accordance with the customer pricing presented in [52], a *fixed part* and a *variable part* should also be offered by the producers so that the producers can place a pricing mechanism in the tendering that is related to their cost structure as far as possible.

The *fixed part* secures the investments for the producers and obligates the producers to deliver with a certain level of availability. The costs for the network connection should also be considered. The fixed price will be paid regularly for the whole duration of the contract (e.g., monthly for 15 years). Besides the contractually secured availability, the fixed price is not related to the amount of produced energy. To increase the competition, participation in the capacity market is not obligatory and producers that do not have a CFD will not be paid for the capacity. As proposed in [87, p. 19], they may pay a standardized and transparent connection fee to cover the costs of connection.

In the spot market, the heating plants are selected by their *variable price*[1]. To increase the competition, it is proposed that all producers should be forced to participate in the short-term dispatch. This is often obligatory in centralized markets [85, pp. 67–68]. The market should be cleared with a uniform marginal price [85, pp. 57–58]. The merit order of the spot market is depicted in figure 4.8. The bids of the producers are sorted by their monetary amount and all bids below the uniform marginal price will be chosen but the payment will be different for producers with CFD compared to those without CFD.

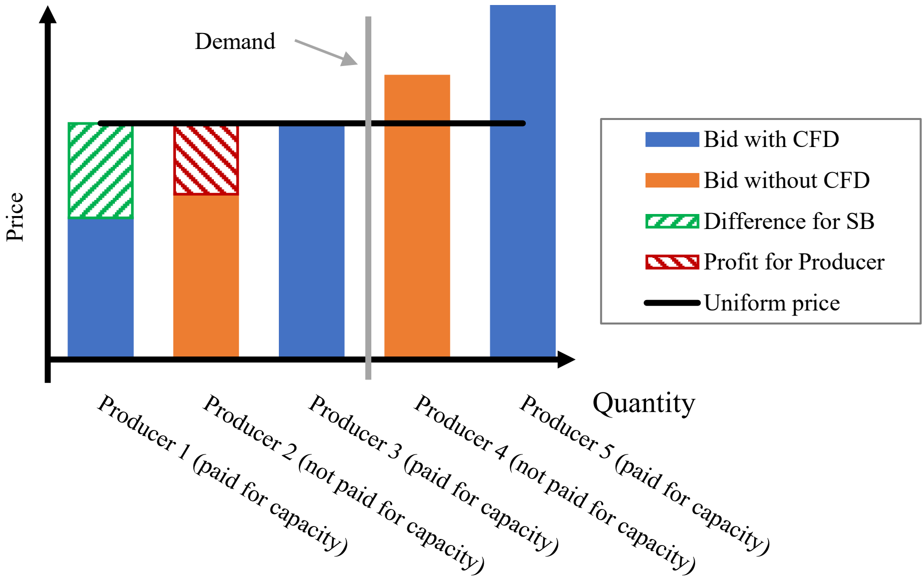

Figure 4.8: Contract for differences in the short-term market[2]

Producers with CFD can place bids at the agreed variable price (blue bars). If the clearing price of the market is higher than the bid, the difference must be paid to the system operator (green bar). If the clearing price is lower than the bid, the plant will not be chosen to produce and thus the variable price will not be paid for the respective producer.

Producers without CFD can choose their bid freely (orange bars) whereby the marginal price clearing will lead to bids at marginal costs [85, pp. 57–58]. The difference between the marginal price and the individual marginal costs (red bar)

[1]For further information on *centralized trading* q.v. appendix A.2.4 (p. 326).
[2]An adapted version of this figure was previously published in [79].

can be used to refinance possible investments by those producers who are not participating in the capacity market.

This mechanism forms the bridge between short-term and long-term marginal costs.

System-serving integration of all participants
One disadvantage of unbundling and competition in DH is that the integrative opportunities are lost and that splitting the organization between several agents can lead to the optimization of subsystems, which is not in line with the systemic optimization (described as *suboptimizing*) [84]. To counteract this, market mechanisms should be developed to incentivize systemic acting and penalize detrimental behavior. Therefore, the economic mechanisms should include a cost-by-cause principle which translates the physical mechanisms into economic mechanisms. For example, the bids of a heating plant should be correlated to the supply temperature. This is particularly relevant for renewable heating plants that are not based on combustion [cf. 24].

For long-term contracts, it is relevant to adapt to changing market conditions such as changing prices for fuels. Price revision clauses (PRCs) are proven mechanisms that are used for such adaption in DHSs. They are usually used in DHSs to adjust a customer charge that results from an initial tendering. The prices are represented by a formula that includes indexes for the related prices [42, p. 86]. Such indexes can be for the primary fuel or electricity. In Germany, some rules for these PRCs are defined by policies (e.g., in [89, § 24 (4)]) and the values for the indexes are published by the responsible authority.

To enable fair conditions for the independent producers and the SB, it is proposed to include such price adjusting mechanisms in the tendering offers. In addition to indexes for market prices, mechanisms to include the required supply temperature, part load ratio, and ecological key performance indicators (KPIs) (e.g., emissions) of the heating plants should be included to support an integrative operation as effectively as possible.

Mechanisms for the design process
Figure 4.9 summarizes the mechanisms of the first and fifth phases of the capacity market.

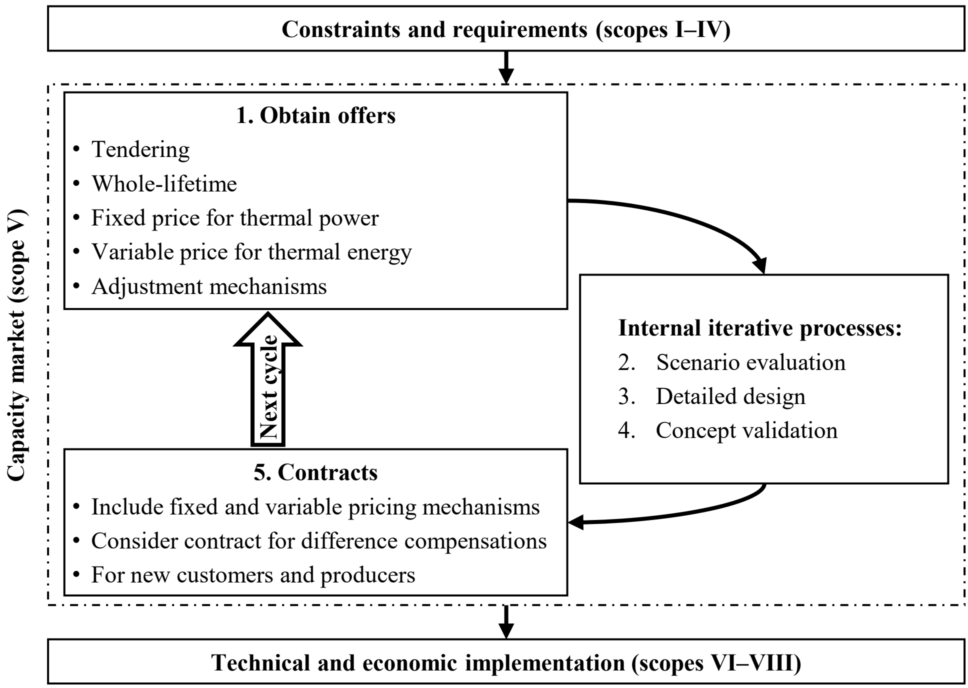

Figure 4.9: Phases 1 and 5 of the capacity market

In the *first phase*, offers must be obtained for which tendering is a typical mechanism. The tendering should include offers for the delivery of heat for the whole (minimum) lifecycle of the heating plants and the tendering offers should include a fixed and a variable price. The fixed price is related to the thermal power that could be used to finance the investments while the variable price is related to the cost per unit (thermal energy). PRCs should be implemented to allow for price adjustments by indexes during the operation to compensate prices on primary fuels or electricity, staff, rents, as well as for operational conditions like the supply temperature or part load ratio. Furthermore, standards are needed for these constraints. The *London Heat Network Manual* supports such standards as a reference for the design [42, pp. 50–52]. Following this, some parameters could be provided by the SB (e.g., pressure level and assumed temperatures). The indexes for the PRCs could be provided by more central instances.

In the *fifth and last phase*, the contracts are made with the producers and with new customers. The contracts should include fixed and variable parts. The long-term contracts with the producers should consider the CFD principle which are required for the later dispatch. The contracts should be standardized and include the variable and fixed pricing mechanism with PRCs as well as penalties for unavailability of the supply. After the contracts are made, new plants can be built.

Phases 2 to 4 are the internal evaluation of the plant setting. In the following, the phases of evaluation are determined.

4.3.5 Selection of tools to support the internal design process

The internal design phases aim to decide on investments and related technical implementations. Based on the offers of the first phase, different scenarios should be developed and evaluated in the second phase. In the third phase, the selected scenario should be further specified. In the fourth phase, the final developed concept should be validated.

The review in chapter 2 has shown that numerous concepts and tools exist that support these design activities. Examples are optimization algorithms, simulations, and experiments [30]. In the following paragraphs, they are ordered in relation to phases 2–5.

Phase 2: Scenario evaluation

The second phase aims at developing or enhancing the DHS's design to consider the ecological and social goals of the DH scopes I–III. The offers of the tendering (phase 1) form a catalog of options. The SB combines these options for the heat supply with changes to the network layout and substations for different scenarios. These scenarios are evaluated by the SB in relation to their long-term total costs and the achievement of ecological and social goals.

The development of various scenarios is a proven procedure for such a first phase of an evaluation [39, p. 16] and allows different solutions of supply to be compared with each other [40, pp. 137–138]. The system-wide optimization should include investments, operative costs, ecological goals, and the lifetime to identify the required types of plants and sizes of each plant and component. Maps of demand and supply can support the scenario development [41, p. 13]. Such a geo-referenced design integrates the locations of sources and demand [30]. The whole-life costs included in long-term MILP optimizations or *superstructures* can be used to select the size, type, and the number of heating plants [50]. Changes to the network, TESs, and customers should also be included to allow for systemic cost evaluation. Existing assets should be included, and the fixed costs of existing contracts and investments should be treated as sunk costs. The existing plants and other technical implementations in the DHS form the starting point for every new cycle of the design process.

Another relevant aspect is the temperature level of the DHS which directly impacts the design [41, pp. 78–86]. Besides the heating plants and network design, it is also important to evaluate measures for temperature reductions [39, p. 105]. The planning must balance investments in production and efficiency measures [30]. Both, lowering temperatures and adding new (more decentralized) heating plants at other locations can cause bottlenecks in the network [28], which must also be considered.

Besides the economic and ecological optimization goals, the progress of the transition to renewable sources of the DHS should also be considered in such an evaluation. Volkova et al. present KPIs which provide the evaluation of the transition (e.g., average supply and return temperature, and the share of non-fuel renewable energy) [90]. Heat losses and electricity consumption have significant impacts [91] and therefore they should also be included.

The results of the scenario analysis are the determination of the demand and the necessary changes to the existing DHS, which enable the achievement of the ecological targets in the most cost-effective way. These include, for example, the types, sizes, and locations of new heating plants, and changes to the network layout or customer-sided enhancements. In this phase, long-term total costs are considered.

Phase 3: Detailed design

In the third phase, the detailed design of the chosen scenario must be worked out. The technical design should be based on standards and a guideline e.g., as presented in [42, pp. 50–52].

Enhancements in design and control strategies are performed via scenario analyses that are either based on *simulation models* or *optimization algorithms* [30].

For the simulation of the systems, black box and physical models are most relevant. Block box models mostly use transfer functions and are more abstract while physical models require numerous parameters for the design of every component in detail. [49]

Optimization can be used for enhancing the design of the system (e.g., network sizing and routing) [49].

Genetic algorithms are the most frequently used optimization type for the optimum layout of the network. But the optimization tools which are used for layouts and design require further development due to their long computational durations. Therefore, they have only been applied to small systems to date. [50]

Besides the optimum layout of the network, there are two parameters that can be optimized in a complementary way: the supply temperature and the flow rate. The higher the temperature, the lower the flow rate is, but the higher the heat losses are. In contrast, high flow rates cause large pressure losses and therefore they require more electricity for the network's pumps. [57]

In addition to the technical parameters and hydraulic schemes, the variable control of low temperature and the ICT infrastructure should be integrated into the detailed design. This infrastructure is needed for the transmission of the schedules from the dispatch and for other innovations. Examples are monitoring of the supply quality, fault detection, diagnostics, delivering data to customers, and new (dynamic) tariffs [42, pp. 45, 111].

Besides smart technologies, there are other techniques that allow for the evaluation of enhancement potential. Related to the challenges of continuously lowering the temperature, exergy analyses can be used. Exergy is a thermodynamic quantity that combines energy and temperature [92]. Through the combination with an economic evaluation, it can be used to identify the potential for temperature reduction. The *specific exergy costing* technique balances exergy flows and correlates their costs [93]. It can be used to identify inefficient components (e.g., heat exchangers) or network layouts. It can also be combined with optimization algorithms [cf. 94].

Phase 4: Validation

In the fourth phase, the technical design and the economic conditions should be validated as presented in the interview with Fjernvarme Fyn. To do so, the operational planning tools for the dispatch should be applied with the new selection of plants and their prices. Further, such dispatch algorithms may be combined with a simulation model of the system. The schedule can thus be computed with the dispatch algorithm and tested with the simulation platform. In this phase, it should be evaluated whether all requirements are met or an adjustment to the setting is needed. In the latter case, the process should go back to phase 2 (or to phase 3 for simple modifications). If a sufficient solution has been found, the contracts between the system operator and the producers as well as new customers can be entered into.

4.3.6 Result: Capacity market

Figure 4.10 presents all five phases of the newly developed capacity market. The capacity market must fulfill numerous social, economic, ecological, and technical requirements. The requirements are described in section 4.3.1. The whole process should be fulfilled cyclically to allow for a continuous adaption to changing requirements. The long-term visions and plans of the local heat strategy can be embedded through this capacity market.

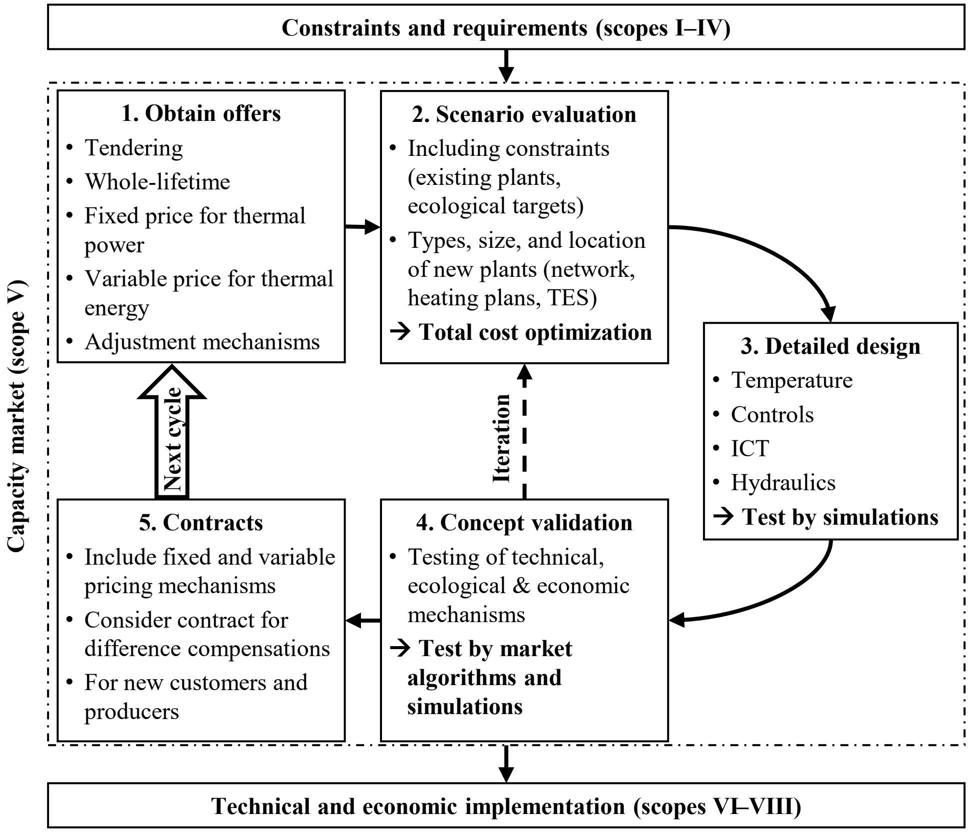

Figure 4.10: All phases of the capacity market

In the first phase, offers are obtained by tendering which should include a whole lifetime perspective. To increase the ability for continuous adjustments, prices should include variable and fixed parts as well as PRCs. The scenario evaluation (phase 2) should include constraints that are given by existing plants, ecological targets, and others. The results of the tendering represent a catalog of options for the supply side. The evaluation should consider investments in the network, TESs, and also the demand side measures. After the first selection of one or more scenarios, more technical details are required (phase 3). This includes the temperature level, ICTs, controls concepts, and hydraulics. The finally selected concept should be tested and validated with the dispatch algorithms and simulation models (phase 4). It is important to comply with annual thresholds e.g., for emissions or the primary energy factor. Further, a charging schedule can be created for seasonal TESs. If the validation is not successful, the concept(s) must be improved (phase 2). Only if the goals are achieved, can the contracts be entered into (phase 5). This market should be regularly repeated to ensure continuous improvement.

Figure 4.11 presents the outputs and interfaces of the capacity market to the lower-level DH scopes.

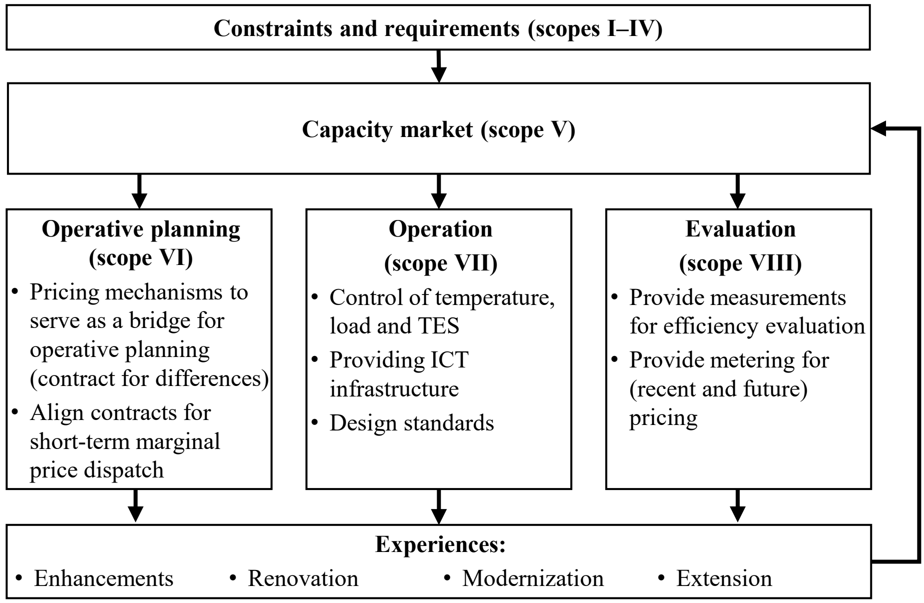

Figure 4.11: Outputs and interfaces of the capacity market

A coherent *operative planning* is required to perform a short-term dispatch of the plants. The proposed price mechanisms based on CFD and PRCs connect the long-term contracts between SB and independent producers to the short-term dispatch. The capacity market creates the conditions for a successful *operation* by implementing the required equipment for temperature, load, and TES control as well as by providing necessary ICT infrastructure. This infrastructure secures the measurements which are needed for efficiency *evaluation* and the metering which is needed for the pricing of recent and future tariffs. Finally, the experience of the operation should be feedbacked to identify measures for enhancement, renovation, modernization, and extension.

4.4 Framework processes for the operative planning scope

The goal of the operative planning is to identify the best operative combination of heating pants and the utilization of the system's flexibility to meet the demand with existing plants in operation. There are several new requirements induced by the transition to renewable energy sources. Therefore, a coherent concept must be developed which clarifies the required *mechanisms* of the process on the one hand and defines the concept of the *dispatch model* on the other hand.

To develop an optimal process, five steps are applied. Firstly, the requirements from chapter 2 and the previous sections of this chapter on this scope are summarized. Secondly, the state of the art is reviewed. Thirdly, a basic principle is developed which includes the relevant steps of the operative planning process. Thereafter, a detailed dispatch concept is developed and finally, a coherent framework process is derived from the individual mechanisms.

4.4.1 Requirements for the operative planning scope

Numerous challenges must be faced to secure an economically efficient transition.

On the production side, integrating renewable heating plants can lead to more decentralized production and these types of plants are more sensitive to temperature [29]. Third-party access may be required to integrate these sources and prosumers [31]. Further, the transition of the whole energy system requires more interaction with the electricity market [28]. The temperature has a significant impact on the costs of supply for renewable, non-combustion heating plants [24]. For example, heat pumps combined with low-temperature geothermal heat sources have an increasing electricity demand for increasing supply temperatures [95], which results in higher variable costs.

The changes on the production side have an impact on the network and its operation. The more complex the DHS is, the more variables can be considered. One example is the balance of flow rate and supply temperature [50]. Lowering the supply temperature at the same load would require a higher flow rate and vice versa. A higher flow rate causes higher pumping power which results in higher costs for electricity. A higher supply temperature causes higher heat losses and hinders the integration of renewable sources. The pressure can only be increased until the system's limit is reached. Such emerging bottlenecks must also be considered in the operative planning [28]. This is particularly relevant in systems with several points of feed-in.

TESs and flexible customers offer new opportunities for the reduction of the operational costs e.g., by reducing load peaks. Active load management can include storage units, the network, and flexible customers for intraday, long-term, and seasonal optimization. [19]

In such systems, new concepts for operative planning are required. Especially if competition is introduced, more market-based concepts are necessary [86, pp. 143–144]. The highest market efficiency can be provided by a marginal price clearing [85, pp. 57–58]. Related to the physics of DHSs, the temperature and location of the heating plants should also be considered [87, p. 6].

To meet the described challenges, a new operative planning concept must be developed that meets several requirements. The new organizational structure requires a market-based operative planning process that allows for third-party access and competition. This framework process must cope with a large number of decentralized plants. The heat producers must be empowered to interact with the different electricity marketplaces (e.g., day-ahead and intraday markets). The unbundling of network and operation requires an integrative operational planning concept, which means that the impact of physical effects such as heat losses, pressure losses, or higher temperatures must be transferred into economic considerations. An example is that the supply temperature may be included in a marginal price clearing of the supply. Further, the operative planning process must balance the pumping energy and heat losses by considering different network temperatures in operation. The different types of TESs and active load management in different time horizons must also be integrated and therefore it is proposed to include the whole physics of the DHS as far as possible into the planning and pricing mechanisms.

4.4.2 State of the art for a competitive operative planning

In this subsection, implemented systems for operative planning are reviewed. The first one is the dispatch of the DHS in greater Copenhagen. Here, two interviews were conducted. Furthermore, the spot market in Stockholm is also described.

Interview at Varmelast

The full transcript of the interview conducted at Varmelast can be found in appendix B.4 (p. 345). In the following, the relevant parts are presented.

Varmelast is the dispatch unit in the DHS of greater Copenhagen and coordinates the large-scale plants. Varmelast is responsible for the short-run marginal cost optimization and is not included in investment and network development. In Copenhagen, small-scale renewable heating plants are connected to the distribution level and are treated as load reduction. Two different companies operate the large-scale CHP plants and are competitors in the electricity market wherefore they are not allowed to know each other's prices.

The greater Copenhagen DHS forms a complex system with a complex ownership structure. The complexity increases due to the different business activities of the companies. Varmelast is a cooperation of the different transmission companies and aims for an independent overall marginal cost minimization. The transmission companies are the partners of the underlying business contracts. In 2006, a strategic analysis showed that implementing a dispatch unit in Copenhagen is the most cost-efficient solution for connecting different large-scale DHSs.

The scheduling is performed day-ahead and six times intraday. The day-ahead scheduling procedure is performed every 24 hours with a duration of 48 hours to improve the charging of the TESs. The cost optimization is performed using an iterative procedure. The first step is the load forecast. The second step is that the supply companies provide discrete supply curves for the energy costs depending on the start-up costs and the produced heat. In addition, the availability of the plants is considered. The third step is an optimization performed by Varmelast on a daily energy basis and the start-up costs. Step 4 is an hourly optimization on the supplier side including differential costs to allow Varmelast to evaluate alternatives. In step 5, Varmelast optimizes the hourly production including the technical limitations of the system. Finally, the supplying companies place their bids for electricity production in the energy spot market at the lowest possible price. In the case of very low electricity prices, heat only boilers (HOBs) are used instead of CHP production. The intraday scheduling is performed six times a day with the same model and procedure. The main difference to the day-ahead market is that differential costs are optimized instead of absolute costs. After production, Varmelast is responsible to compare the real and planned production.

The internal scheduling model is based on MILP and considers variable costs from fuels, emissions, operation, maintenance, energy taxes, and revenues. The optimization includes the most important network bottlenecks which are included as maximum capacities based on simulation data and the experience of the operative staff. Large-scale TESs are included in the optimization. The waste incineration has the highest priority due to political reasons. Their production is forecasted. The CHP plants have the second priority. Their scheduling procedure is complex due to the interaction with the electrical markets. The distribution networks are included as sinks. Their load is forecasted. Here, an upcoming challenge is the distributed renewable heating plants, which reduce the load of the system and are not measured or forecasted separately. Particularly in summer, when the load is low, this is an issue for the waste incineration plants.

To incentivize better cooperation, the price mechanism between the transmission companies and the underlying distribution companies has changed from a fixed charge to a new charging mechanism. Now, the charge has a fixed part and a variable part that changes seasonally. For future development, it is planned to implement more dynamic pricing. Besides the pricing, it is investigated how the plants could participate in the balancing power market.

Interview at HOFOR

An additional interview was conducted with HOFOR. The full interview transcript can be found in appendix B.3 (p. 341) and the relevant information is summarized here.

HOFOR is one of the transmission companies in the greater Copenhagen DHS and participates in the dispatch routines provided by Varmelast. The company is participating in a research project located in the district of *Nordhavn*. In this project, different flexibility concepts are developed and tested. These new concepts show future applications as well as the barriers to implementing them in the current routines.

For example, it is tested whether the DH network can be used for storing heat although this requires more advanced forecasts of the demand. Thus, in a first step, existing central storage tanks should be used in a smarter way e.g., to optimize production related to electricity and heat prices. Another possibility is to include the flexibility of the customers. It could be used for cutting peak loads or providing flexibility for the electricity grid with a duration of 3–5 hours. Smart thermal grid (STG) technology is seen as a possibility for optimization, monitoring, automatized maintenance, and billing. New products based on this technology are regarded as key to more transparency and customer interaction.

The interim results of the project show that these flexibility potentials cannot be sufficiently included in the current overall dispatch procedures and hence it is proposed to include them in future developments.

Open district heating in Stockholm

An example of an existing marketplace is the *open district heating* in Stockholm. Here, surplus heat can be sold to the Stockholm DH company at market price. The heat can come from a different source such as data centers which are cooled by heat pumps or supermarkets with surplus heat from their refrigerators. The current connected thermal power of such sources is about 1 MW. The prices for energy, supply temperatures, and the required amount is published day-ahead by 4:00 pm. There are two options for contracts *on demand* or *open spot* whereby *on demand* will be requested by the DH operator and *open spot* contracts are forced to participate in the market. The payment is made every month and a new connection takes 6–9 months. The DH operator pays for the connection, and the producer pays for the production technology. To date, 20 plants are already connected. [96]

4.4.3 The basic principle of the operative planning process

In this subsection, the basic steps of the new operative planning process are developed. The simplest approach for a dispatch is the combination of a fixed sequence control for the heating plants [42, p. 20] combined with a set-point for the network's supply temperature depending on the ambient temperature [51].

The examples from Copenhagen and Stockholm demonstrate that a more complex dispatch of heating plants, which belong to diverse third parties, is possible in wholesale market processes. However, some shortcomings can be identified which must be resolved if the operative planning concept should support the transition to renewable and non-combustion-based heating sources. Generally, the described implementations can satisfy their requirements. The companies which are related to the DHSs in greater Copenhagen (VEKS, HOFOR, and Varmelast) demonstrate that a DHS with several agents and unbundled network operators is possible and could be beneficial for large-scale DHS. The most important parts of the dispatch are the *day-ahead* and *intraday* procedures. A *heat demand forecast* is used to determine the demand. The planning procedures allow for an iterative planning process for the DHS and the electricity market (day-ahead and intraday).

Related to the references and interviews, the heating dispatch unit Varmelast has been identified as the most developed and practically validated concept and thus the basic concept of the dispatch will be related to the implementation in Copenhagen. A day-ahead and an intraday planning process are proposed. The intraday market may run several times a day and both will secure a sufficient interaction with the electricity sector. In the Danish heating sector, it is forbidden to make a profit [86, pp. 77–79]. Consequently, the dispatch is based on marginal costs. But, in contrast to the implemented procedures in Copenhagen, some further changes are proposed for a new operative planning process.

As proposed for the organizational structure, the market should work under competition and therefore it allows for profit. Thus, instead of a cost-based dispatch, marginal prices are used in the short-term markets. To promote investments and the security of supply, the principle of CFD is proposed as an interface between the capacity and short-term markets. This can support the transition of the system and builds a bridge between the long-term vision of the heat strategy and the short-term planning procedures.

Figure 4.12 depicts the new basic operative planning processes that are based on a day-ahead and an intraday market. The results of the capacity market form the constraints for the dispatch models (e.g., network capacities, storage units). The long-term contracts form the rules for the participating producers. This includes prices for thermal energy and power combined with PRCs. The proposed bids for the producers are different from those of Copenhagen as instead of marginal costs, the bids should be based on prices. Further, they should include alternative offers for different amounts of heat for each time interval. The customers' demand must be forecasted by the SB for both markets. The results of the markets are schedules that are applied in the operation. Data from the operation is feedbacked to the planning routines for the subsequent planning procedures.

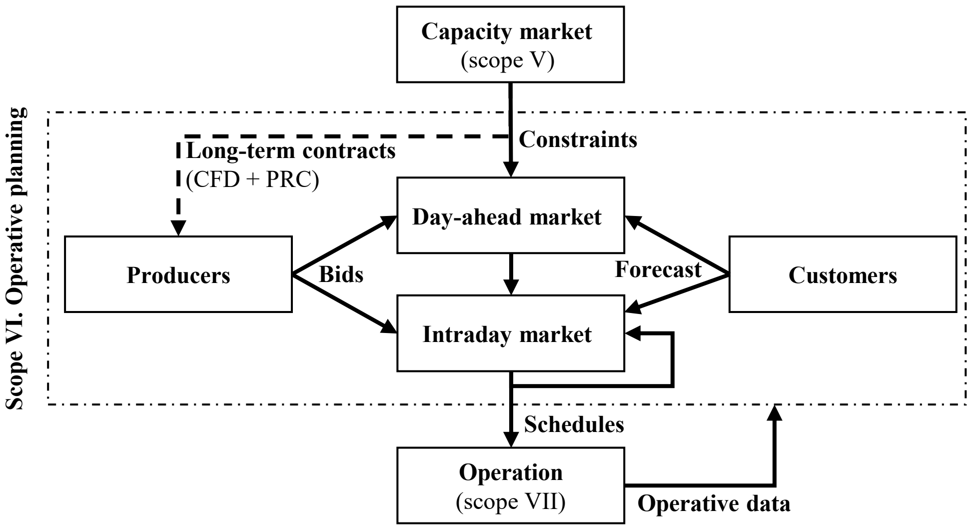

Figure 4.12: Market principle for short-term dispatch

Market clearing

The market clearing can be done in the same way as in electrical spot markets. Kirschen et al. describe the clearing as follows [85, pp. 57–58]: the demand for electricity is inelastic, and therefore, it is often forecasted and placed at a fixed value. The clearing price is called the *system marginal price*[3] and the payment for all customers and suppliers must be made at this price. In contrast to pay-as-bid, this allows the producers to place the bids at marginal costs, which is economically efficient. [85, pp. 57–58]

Placing bids at the system marginal price allows those market participants who do not participate in the capacity market to generate revenues to refinance their fixed costs. Due to the inertia of thermal systems, the balancing must not be as fast as the electrical system but deviations between market placements and real delivery must be evaluated and paid for. Producers who are not participating even though they need to participate (due to their long-term contracts), may be

[3]For further information on the *system marginal price* q.v. appendix A.2.4 (p. 326).

forced to pay the substitution price on the spot market or intraday market. If the availability of production is insufficient, peak supply or redundant supply can be used.

Physical impacts

In the case of Copenhagen, plants that are in the distribution network are not included in the scheduling procedure and they work as a heat load reduction. To fulfill the requirement of a long-term working framework, it is necessary to also include the decentralized plants because it is possible that through the transition, the share of small-scale plants will have a relevant size. Such inclusion of small-scale plants in a spot market is already performed in the Stockholm market.

The introduction of competition and the unbundling could lead to the suboptimization of the DHS. To prevent this, the market must adequately represent the DHS's physical efficiency mechanisms. The supply temperature is relevant for the costs of production, the heat losses in the system, and the flexibility of the piping network itself. In particular, the electricity demand of the network pumps and the supply temperature should be included in the dispatch model.

A market that includes the location of a product and its transportation costs in the clearing algorithm is called a *smart market* [97]. Smart markets have been developed for electricity systems [98], natural gas systems [99], communication systems [100], and water supplies [101]. However, a proposal for a smart heat market was not found in the literature.

The basis for such a smart heat market is the internal dispatch model. Different existing models, that partly include the physics in the price-finding algorithm are introduced in the description of the operational planning scope (q.v. chapter 3). A sufficient model that includes the temperature impact on the variable costs of supply and the network operation has not been identified. A concept for such is model is proposed in the next subsection.

4.4.4 Concept for a smart market dispatch model

For the implementation of the framework and the smart short-term markets, a new dispatch model is required that fits the requirements of the framework approach. Therefore, a concept for such a model is proposed in this thesis. This proposal is based on the identified requirements. Due to the limited scope of this thesis, the model is neither implemented nor tested. However, the resulting concept serves as a recommendation for future developments.

The production must be integrated with prices for temperature and energy and the customers must be incentivized by dynamic tariffs that also include their temperature whereby the SB must ensure that the minimum supply temperature is always delivered as is individually required by the customers. It must also use the flexibility of TESs, the network, and the customers to keep the costs as low as possible. To include the transportation costs, the transmission calculation must include the bottlenecks, the costs for pumping power, the costs for heat losses, the temperature losses, and the inertia of the network in the case of changing temperature. Further, the long-term damage to the pipes created by temperature changes must be included in the calculation. Temperature gradients and maximum cycle numbers may be used to reduce the thermo-mechanical stress.

In some of the reviewed dispatch concepts (q.v. DH scope VI in section 3.1.1, p. 32), the costs for pumping power and heat losses are already included. However, no reference could be identified which includes the supply temperature impact on production costs. In this level of detail, lower temperatures, which are required from the DHS would also reduce the heat production costs. Such a full cost concept based on the cost-by-cause principle is a requirement if the network and production are unbundled while keeping the DHS as an integrative system. In addition to the temperature variable production, the flexibility of the network should also be included.

An implementation that considers these effects would lead to a cost-optimal temperature profile that includes all variables and the inertia of the system. In contrast, concepts with a fixed schedule for temperature changes, and therefore fixed times for storing heat in the network, are not able to optimize production and the network's inertia at the same time.

Inputs for the dispatch model

The dispatch model has two inputs. The first input is the forecast of the local demand which includes the thermal energy, the required supply temperature, and a forecast of the return temperature. The return temperature can then be sent to the independent producers. Secondly, the producers compute and place their bids for different amounts of thermal energy and different values for the supply temperature.

The task for the SB is to optimize the DHS by including TESs, the network, and the customers. The main challenge is to identify an algorithm for the last step. After the different bids of the producers and the demand are set, the goal is to identify the amount and temperature of thermal energy feed-in to the network by using TESs and the network to satisfy the demand and the minimum temperature of each customer at the lowest overall costs.

To calculate the relevant physical impacts, a model of the DHS must be created. Figure 4.13 presents the abstraction. On the left side, the case study DHS in Hamburg Wilhelmsburg (q.v. chapter 3) is depicted. From the original DHS, a node edge model must be derived. Abstraction algorithms for such a reduced model are available in the literature [cf. 55] but must be adapted for this new application. The node edge model includes the energy centrals with the heating plants, the consumers, nodes (e.g., important t-pieces), and edges. The edges represent the main transmission pipes.

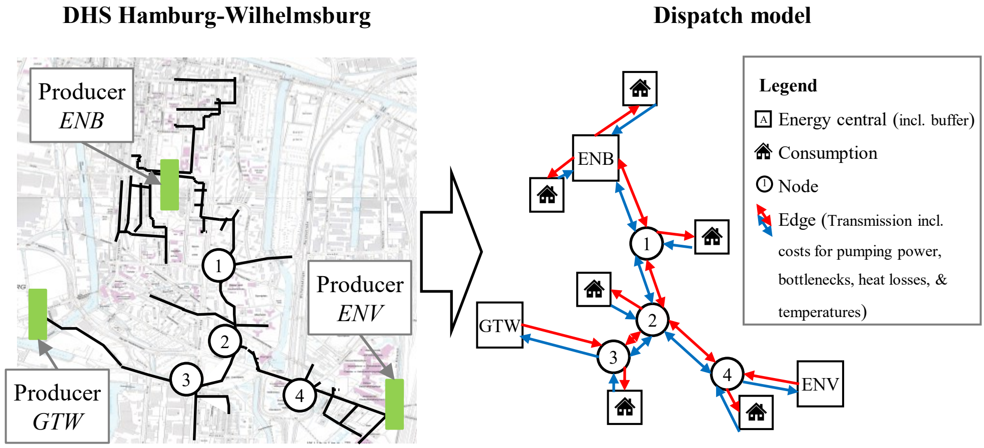

Figure 4.13: Energy dispatch with a node edge model including temperatures (background map from [74])

The internal dispatch computation

A new concept is proposed for the internal computation of the dispatch model, which is based on a distributed computing architecture. For the dispatch model, two types of computing processes are introduced: *(market) nodes* as local markets, and *(transmission) edges* representing market traders. These two types of computing processes have interfaces to each other and to producers and consumers. A simplified example is depicted in figure 4.14.

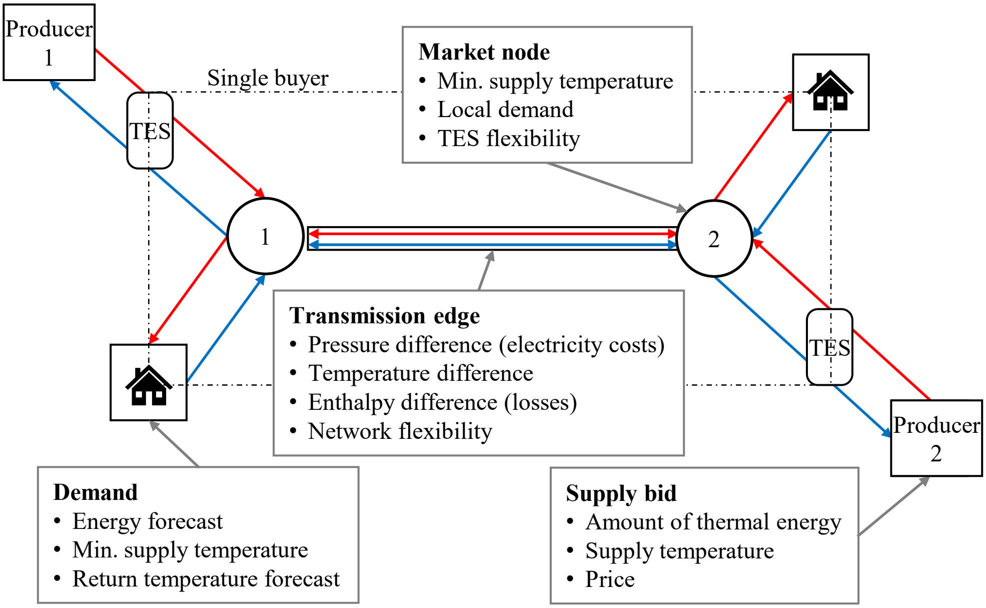

Figure 4.14: Concept for a dispatch model with market nodes and transmission edges

At a *market node*, the producers and consumers must place their bids before the model starts the computation processes. The producers place prices for different amounts of energy at different temperatures. The SB places the demand forecast for the customers and the minimum supply temperature at the market nodes. The balance of energy at one node is zero. If a TES is placed in a marketplace, it can be used to shift the demand in time to reduce costs. As all incoming enthalpy is mixed, it results in a single temperature at each node.

A *transmission edge* can buy thermal energy from one market node, and it can place the energy at another market node (figure 4.15).

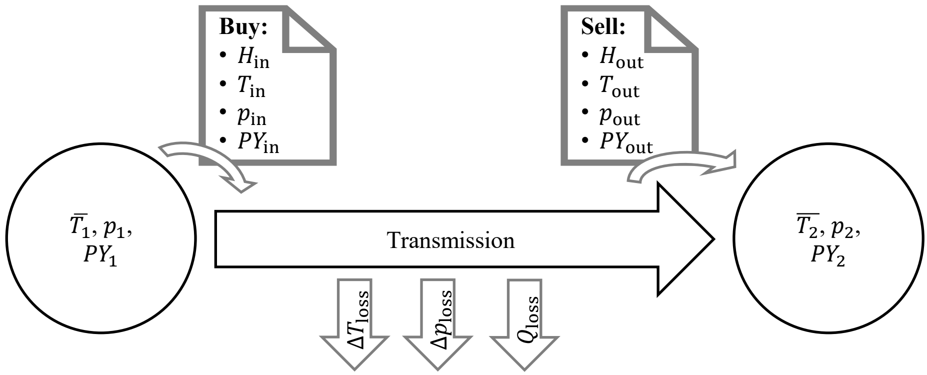

Figure 4.15: Transmission edge computation process

The transmission edges must consider the costs for pumping power and heat losses as well as the temperature and hydraulic bottlenecks. The heat losses (Q_{loss}) reduce the amount of energy that can be sold (H_{out}) in comparison to the bought amount of energy (H_{in}) (q.v. equation 4.1), and this increases the specific selling price. Further, the heat losses induce a temperature difference (ΔT_{loss}) between the input temperature (T_{in}) and the output temperature (T_{out}) (q.v. equation 4.2). If the output temperature (T_{out}) of the transmission edge is lower than the required temperature at the output-sided market node, the transmission edge must demand a higher temperature at the input-sided market node. Further, the transmission edge can benefit from the inertia of its internal temperature changes and use it for time shifts between the market nodes to benefit from lower prices on the input side and higher prices on the output side. The flow rate induces a pressure loss (Δp_{loss}) from the pressure of the input node (p_{in}) to the pressure of the output node (p_{out}) (q.v. equation 4.3). The pressure loss results in pumping costs ($C_{\text{el,pump}}$) which must be added to the buying price (PY_{buy}) to receive a cost-covering selling price (PY_{sell}) (q.v. equation 4.4). If the system's maximum pressure is achieved, the maximum transportation is reached (bottleneck).

$$H_{\text{out}} = H_{\text{in}} - Q_{\text{loss}} \tag{4.1}$$

$$T_{\text{out}} = T_{\text{in}} - \Delta T_{\text{loss}} \tag{4.2}$$

$$p_{\text{out}} = p_{\text{in}} - \Delta p_{\text{loss}} \tag{4.3}$$

$$PY_{\text{sell}} = PY_{\text{buy}} + C_{\text{el, pump}} \tag{4.4}$$

In systems that include meshes, the overall equilibria of the pressure must be considered which increases the complexity of the system.

Solving the new dispatch model

Since the implementation of the dispatch model is not part of this thesis, a final solving algorithm cannot be developed. However, the proposed concept clearly defines the requirements for the model, and based on these, a recommendation for the best-fitting optimization technique should be given from a preliminary theoretical consideration. This recommendation serves as a starting point for future implementation.

Different optimization techniques which are applied in the energy sector can be used to solve the model. The algorithms can be classified into "deterministic," "stochastic," "fuzzy," and "others" [102]. The deterministic algorithms include the exhaustive method, MILP, and mixed integer nonlinear programming (MINLP) and the exhaustive method requires the computation of all possible combinations of a discrete set of variables to identify the best solution. Genetic algorithms are the most relevant types of stochastic techniques while fuzzy algorithms are used when the quantification is challenging. [102]

In the following, the best-fitting algorithm will be identified by excluding the alternatives.

Fuzzy algorithms do not fit the described requirements as their main purpose is to describe uncertainties and to support the quantification of the problem. Since the problem can be well described in the presented case, fuzzy algorithms are thus not recommended.

Since the described problems are non-linear, MILP and MINLP have been described as being too slow for these complex problems if all possible variables are included (e.g., in [19], [103]).

The result of the dispatch model serves as an economic decision in a competitive environment (market clearing). This means that a solution near to the optimum may constitute a legal problem since independent heat producers can be discriminated against. Instead, the smart market should provide a transparent market clearing to build trust. Even though genetic algorithms may be a good solution from a technical perspective, they are not ideal, due to their specific characteristics to provide solutions near to the optimum and low transparency of the internal solving process.

In contrast to the genetic algorithm, the exhaustive method computes all possible combinations and, by this, provides higher transparency of the solution. Therefore, it is recommended to implement the dispatch algorithm of the smart market as an exhaustive algorithm. Even though the computation may be too ambitious with many decentralized heating plants, new techniques from big data treatment seem promising for this task. However, if a future implementation shows that using the exhaustive method is impossible, the application of a genetic algorithm is proposed as the best alternative.

4.4.5 Result: Smart short-term markets

Figure 4.16 presents the full new operative planning processes including the interfaces inside the operative planning scope and to the other processes.

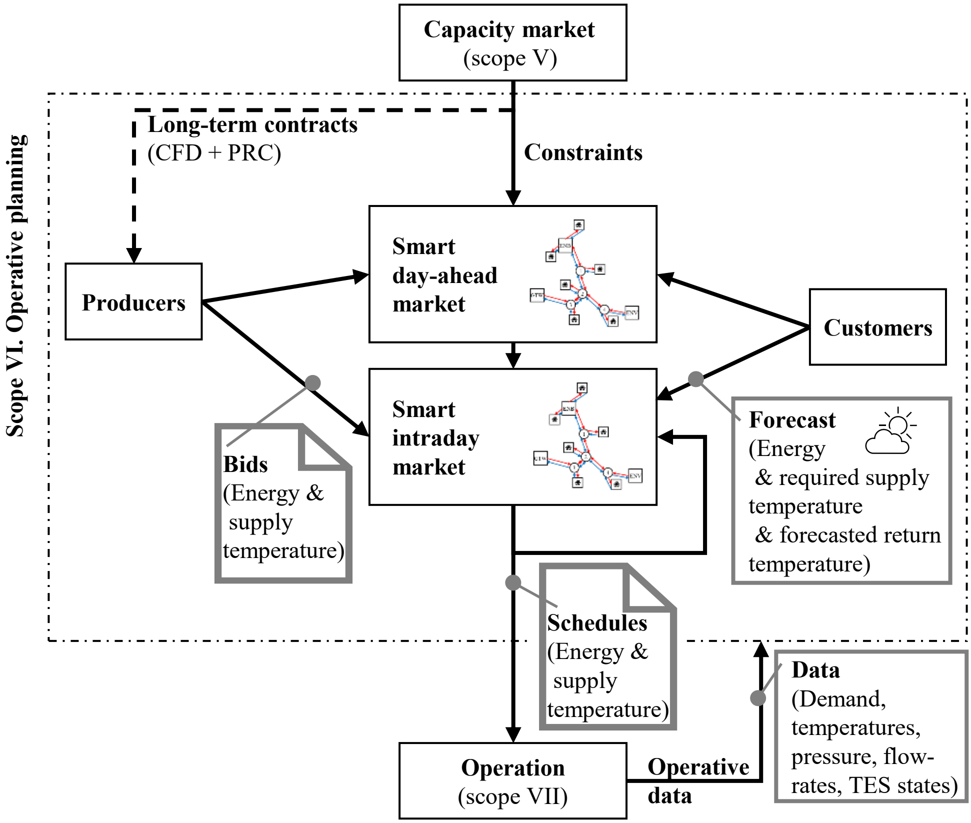

Figure 4.16: Short-term planning processes

The inputs for the operative planning are provided by the capacity market which sets the constraints for the smart market (e.g., network layout, TESs). Further, it defines the long-term contracts with the producers and the schedules for seasonal TESs. The day-ahead market creates the first schedule, and it is updated several times per day by the intraday market routine. The number of cycles for it must be evaluated individually in relation to the size of the DHS, and the process is designed for large-scale applications. In smaller DHSs, it must be evaluated whether introducing marketplaces is economically efficient or if the operative planning can be implemented in a leaner way (e.g., by implementing the day-ahead market only). The larger the DHS is, and the more producers are involved, the more often routines should be performed. In large-scale DHS, the intraday market resolution may be reduced to 15 minutes. The smaller the resolution, the less storage, and redundant supply are required. However, a higher resolution would require more market activities, and therefore it is proposed to start the implementation with a day-ahead market with an hourly resolution. After the first experience, the intraday market can be introduced with a low number of cycles, and the system can be continuously enhanced by increasing the number of cycles. At some point, the result will not increase with the increase in workload. In the case of Copenhagen, the number of cycles is chosen as six. Considering the physics of the network, both markets must be implemented as smart markets.

The heat demand must also be forecasted, and the forecast should include the required heat, the required supply temperature (e.g., by the tariff and ambient temperature), and the expected return temperature. Flexible customers and TESs should be used by the SB to reduce the price as much as possible.

The bids of the producers should include a price correlated to their thermal energy and the supply temperature. An example with some random prices is presented in table 4.1. The bid consists of a timestamp, the produced temperature, the amount of produced energy, and the price. For one timestamp, it is proposed to allow several bids (different temperatures and different energy). The SB can buy one bid for each heating plant and for each timestamp which allows for choosing the best fitting combination of energy and temperature at each location of production in the DHS.

The bids for the heating plants should correlate with the temperature impact on the specific plant's variable costs, and a new method to compute these bids is presented in chapter 5. Further, the flexibility must be described to be included in the framework, and hence it is analyzed in chapter 6. On the demand side, forecasts are required which include the demanded supply temperature and the resulting return temperature. The sketch of the smart market algorithm must be finally developed, implemented, and tested. Both will need further research.

Finally, the market results are transmitted to the control platforms of the SB and producers. These schedules may have at least an hourly resolution and are correlated to the energy and supply temperatures. The producers and SB translate the schedules into set-points for their plants. In turn, operational data must continuously be provided from the operation to the operative planning. This data includes the demand, temperatures, pressure, flow rates, and the states of the TESs. This is discussed in the next section.

Table 4.1: Structure of an exemplary supply bid including different temperatures, different amounts of thermal energy, and random prices

Timestamp	**Temperature** (in °C)	**Energy** (in MWh)	**Price** (in €/MWh)
01.01.2021 00:00	60.0	10.0	33.89
01.01.2021 00:00	60.0	10.5	39.16
01.01.2021 00:00	60.0	11.0	36.67
01.01.2021 00:00	60.0	11.5	40.61
01.01.2021 00:00	60.0	12.0	40.28
01.01.2021 00:00	60.0	12.5	34.31
01.01.2021 00:00	60.0	13.0	34.25
01.01.2021 00:00	60.0	13.5	39.78
01.01.2021 00:00	60.0	14.0	41.18
01.01.2021 00:00	60.0	14.5	40.09
01.01.2021 00:00	60.0	15.0	41.27
01.01.2021 00:00	62.5	10.0	36.17
01.01.2021 00:00	62.5	⋮	⋮
01.01.2021 00:00	62.5	15.0	36.80
01.01.2021 00:00	65.0	10.0	36.42
01.01.2021 00:00	⋮	⋮	⋮
01.01.2021 00:00	95.0	15.0	46.80
01.01.2021 01:00	60.0	10.0	33.89
⋮	⋮	⋮	⋮
01.01.2021 23:00	95.0	15.0	46.80

4.5 Framework process for operation scope

This section's goal is to clarify the operative activities in relation to the new organizational structure (DH scope IV) e.g., by defining the technical responsibility. Further, requirements for design standards must be identified (DH scope V). Finally, the concept must include a control strategy that supports the schedules described in operative planning (DH scope VI).

In the first step, the requirements for the operation are summarized. Subsequently, innovative control systems from the literature are presented. In the next subsection, a basic control principle for the whole system is worked out in relation to standardized hydraulic layouts. Finally, this new system control concept is applied to the new roles which are introduced in the organizational structure (DH scope IV).

4.5.1 Requirements for the operation

The controls must secure the supply with high reliability [51]. To provide this, issues must be detected fast and the allocation of responsibility for solving an issue must be clear. Related to required changes caused by the transition, the control of the system will have a greater focus on temperature control as well as decentralized control of feed-in and the control of loads. The control of the heating plants and supply temperature must react to the market processes as the market provides set-points in the form of schedules. The operational process must provide the communication of data for all DHS control levels from the markets to the plants and components and, vice versa, for the measurements and metering data.

4.5.2 State-of-the-art DHS control systems

The operational scope combines several different activities. In modern DHSs that consider the concept of *STGs*, some of these activities are automated and digitalized which leads to a high relevance of innovative control systems in this DH scope. Therefore, existing control concepts that focus on the challenges of the transition are presented in the following.

Vandermeulen et al. propose to introduce an additional load control. The reasons are additional degrees of freedom (flexibility) that can be used e.g., for peak reduction or the economic optimization of generators. The required data includes the valve positions, flow rates, temperatures, buildings' behavior, heating plants, and the state of charge (SOC) of the TESs. The authors distinguish between central, decentral, and hybrid concepts for such load control. The central concept is the optimization or model predictive control (MPC) which also uses optimization techniques. Decentral concepts are described as cooperating multi-agents that react to price signals. A hybrid concept would combine both: central optimization and decentralized control. The hybrid concept is regarded as promising. [19]

STGs implement supervisory control and data acquisition (SCADA) systems which can be combined with (thermal and hydraulic) models and other tools. Control systems in literature often apply a model-based concept that can be implemented in hierarchical or multi-agent architectures. [51]

Zotica et al. present a hierarchy of control for a plant that has three groups: optimization, control layers, and the plant. The optimization can be divided into three different timescales: weeks, days, and hours. The optimization should set the priority of each heating plant. The control layers have been divided into supervisory control (reacting in minutes) and regulatory control (reacting in seconds). The authors evaluate three variants for the supervisory control: split range control, proportional-integral control with different set-points, and MPC. The authors indicate that all three variants can be used for supervisory control. Further, they mention that MPC is complicated to implement. [104]

Moustakidis et al. present a control architecture for an automatic and efficient operation of DHSs. Their architecture consists of three levels. The high level uses a mixed logical dynamic optimization system to identify the optimal energy strategy. In the middle level, an MPC is responsible for slow load management. Therefore, it optimizes continuous variables (temperature and mass flow) in the central units to set constraints for the lower level. In the lower level, proportional-integral-derivative controllers execute the control (supply temperature, flow rate, and pressure) with fast response times at the building level for time-critical control. The results of their tool can be used as recommendations for the parameters by the network operator. [105]

4.5.3 The basic principle of DH operation

In this subsection, a coherent control strategy is proposed based on the state of the art and the requirements from the developments of the previous DH scopes. Figure 4.17 depicts the different parts of the technical DHS by using the notations for heating systems from [106]. The overall system can be distinguished in different control levels[4]. In the first subordinated level of the overall system, the heating centrals, buildings, network, and others are summarized as *subsystems* whereby each subsystem can be designed in different ways. However, it is proposed to use standard layouts on the subsystem level to allow for replications of technical systems and their business models.

Two heating centrals are presented in a parallel layout including a storage tank and an energy transfer station. The parallel layout was published and discussed in a previous publication by the author (q.v. [12]).

[4]For further information on *DHS control levels* q.v. appendix A.1.3 (p. 313).

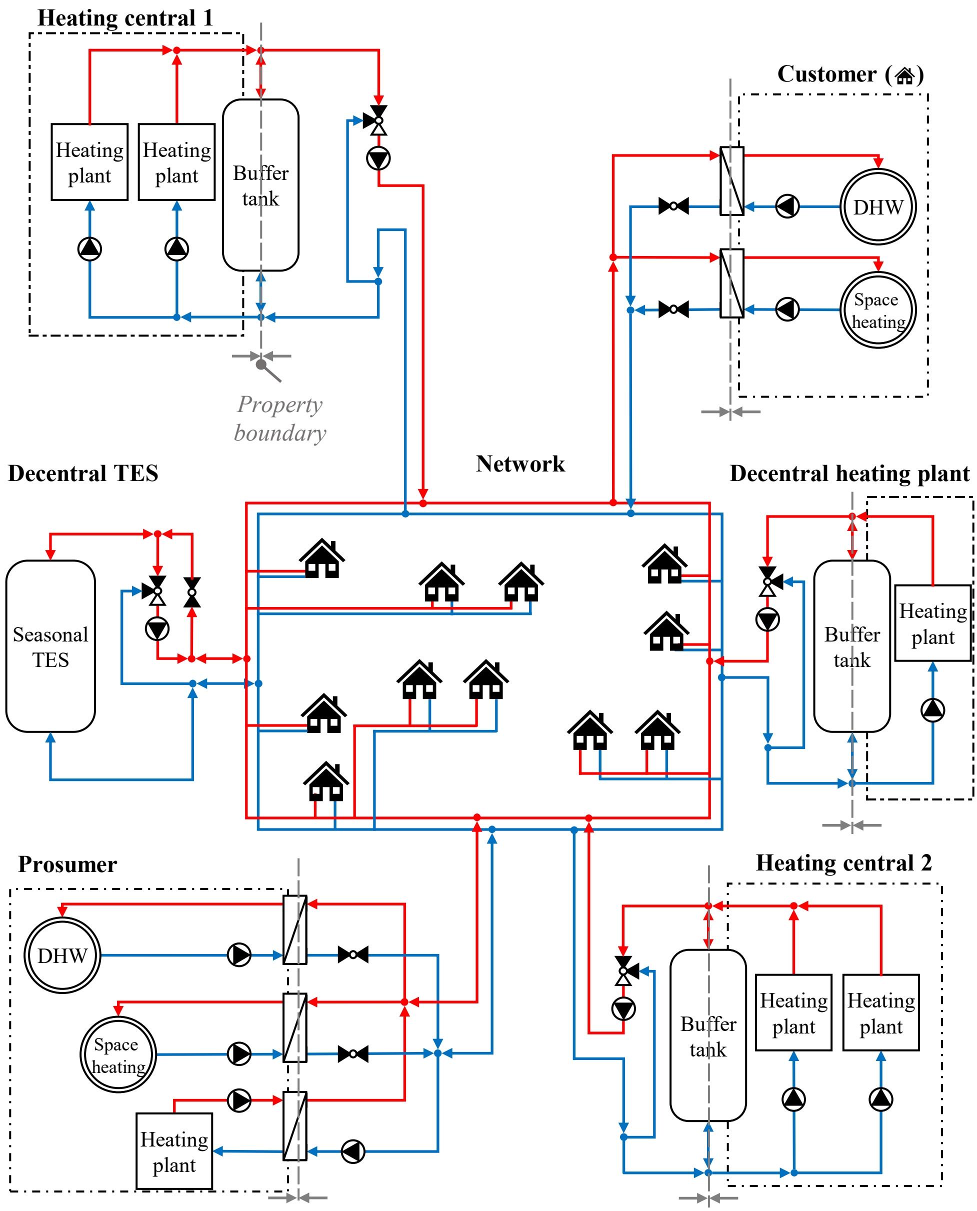

Figure 4.17: DH scheme for the full system level

The customers are connected via an indirect connection (with heat exchangers). The consumers' internal distribution systems can be designed in numerous ways [2, pp. 360–429]. Most systems have one or more heating circuits for space heating and another circuit for the domestic hot water (DHW) supply. The figure depicts the simplest solution without a decentralized buffer tank (according to [29]) in which the substation is the connection to the network.

The presented network topography is a random example. DH networks can be built in different ways [cf. 107]. Further, a simple concept for a prosumer, decentral TESs, and a decentralized heating plant are proposed.

In the new framework, the set-points for the *heating plants* will be determined by the short-term markets. Heating plants that are located decentralized or at prosumers should receive the same set-points as centralized heating plants. They will receive set-points for on/off, thermal power, and for the supply temperature. The buffer tanks can be used for the compensation of short-term deviations (<1 hour). If the deviations are too large for the system's storage capacities, a supervisory control should be used. To do so, a sequence of heating plants should be prepared (e.g., based on intraday prices) which can be used to compensate for the deviations until the intraday market performs the next cycle (e.g., every 4 hours). Such a supervisory control can be made manually in a control center. Alternatively, it can be managed automatically based on MPC or split range control [104]. The SOC of the buffer is used as the main indicator.

The feed-in temperature to the *network* can be controlled by three-way mixing valves whereby the valves' controls will also receive their set-point from the markets. By this, the network's storage potential can be used in operation. The differential pressure for the network is controlled in the usual way by the pump of the primary heating central which must be defined. The set-point for the differential pressure is defined by one or more measurements at customers with long distances in the network. The other points of feed-in will receive a set-point for feed-in related to the centralized schedules.

The control of the *demand side* is typically performed by two-way valves which deliver the demanded heat related to the set-points of the customers. The demand can arise from space heating, DHW heating, or charging TESs.

Some *storages* will not require additional control. For example, the buffer tanks in a heating central are managed by the difference between feed-in and production. Seasonal TESs which can be placed in a decentralized way will require active management for charging (control of the demand side) or discharging (control of the supply side). Their load management is related to the market results. Particularly for seasonal TESs, the capacity market is relevant to identifying the daily amounts of heat (q.v. chapter 6). The short-term markets will dispatch these daily amounts of energy to hourly values.

4.5.4 Result: Operational process

An important part of the new operational process is the ownership and the responsibility. Through the introduction of competition, independent producers are new roles in addition to the SB and the customers. In the operative context, the SB fulfills the role of the system operator.

In the following, the responsibility (and simultaneously the ownership) will be separated at the subsystem level. The responsibility for the systems can be defined as follows: the customer is responsible for the building, the producer is responsible for the heating central or decentralized heating plants, and the system operator is responsible for the network and decentralized TESs. The overall responsibility for the system level is carried by the system operator.

The complicated part is the detailed position of the *property/responsibility boundary* between the subsystems. The boundaries for the responsibility are depicted in figure 4.17 with dash-dotted lines. All parts that are not inside such a rectangle belong to the subsystem network. Related to overall responsibility, it is proposed to include the energy transfer stations and the substations in the responsibility of the system operator. The system operator should be able to control the pumps at the points of feed-in and the valves of the points of feed-out. This responsibility allows the system operator to control the pressure of the network and optimize the overall system. To simplify the separation of responsibility, it is further proposed to use heat exchangers or storage tanks at the property boundary, as these components allow for a hydraulic separation. Buffer tanks between the network and the production units allow the system operator to optimize the load flow and buffer short-term deviations. These suggestions for the property boundaries should be included in the contracts and standards of the DHS design (DH scope V).

These operational conditions and interfaces are combined in a new systemic concept. The final hierarchy of the operation and the interfaces of the operative scope to the markets are shown in figure 4.18. In the following, they are introduced in a top-down fashion. For the detailed implementation in the individual control levels, proven solutions can be used.

Market: The smart-market concept requires operational data from the network and the demand. Further, the independent producers must place their bids. Based on these inputs, the market provides optimized schedules for all variables of the system. This includes the thermal power of production and load management as well as the supply temperatures.

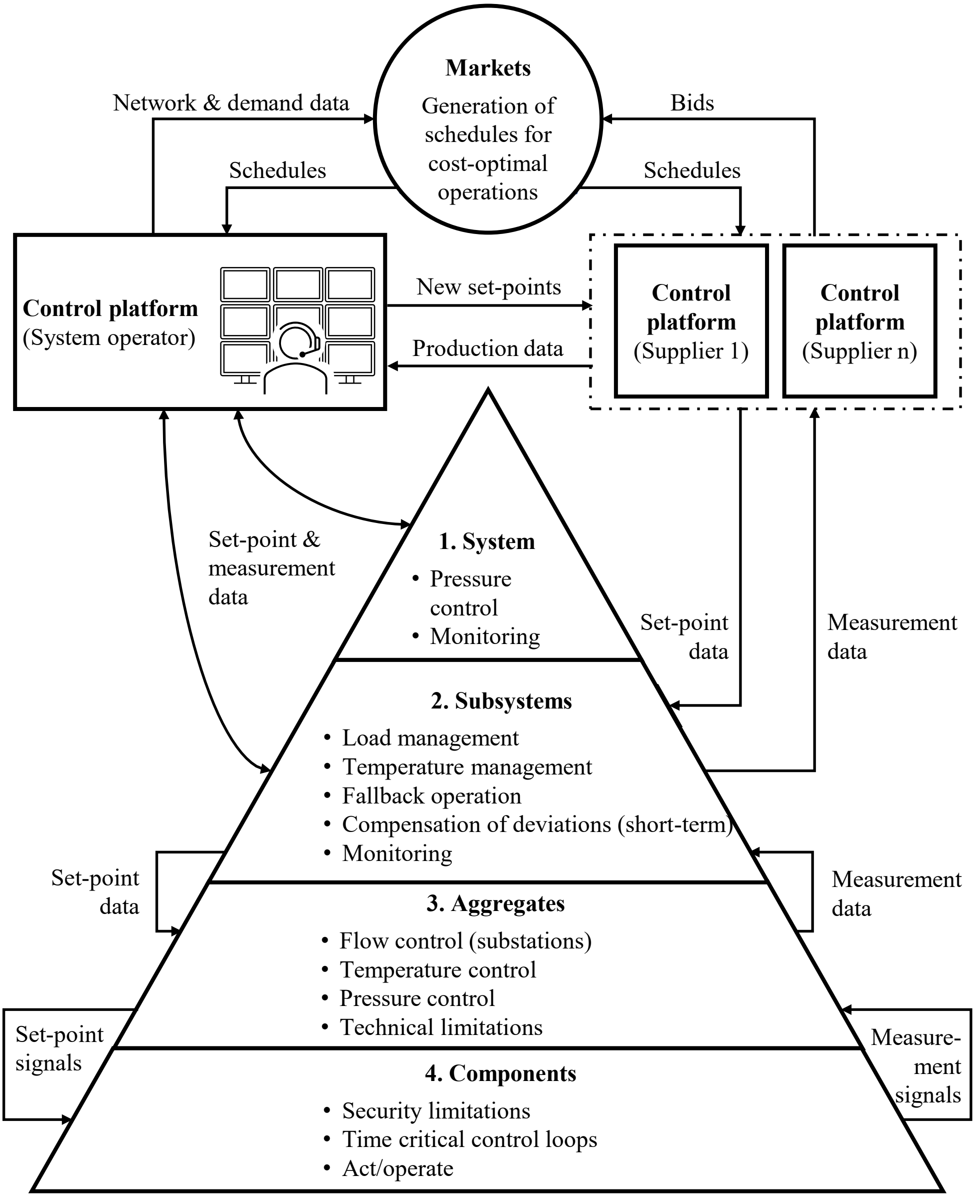

Figure 4.18: DH operational hierarchy

Control platforms: The different subsystems and the system are monitored and controlled by control platforms. In the case of energy centrals with heating plants belonging to independent suppliers, they are connected to the control platform of the individual supplier. In the case of all other parts (e.g., substations or network), they are connected to the system operator's (SB) control platform. Short-term data (e.g., heating plant faults) must be rapidly communicated between the system operator and the producers which may require short-term updates of their set-points. SCADA systems are a typically-used technology for such control platforms.

System level (1): This level summarizes all subsystems (heating centrals, buildings, network, and others) and connects the technical DHS to the markets of the operative planning scope. On the system level, the pressure difference of the primary point of feed-in and the flow rates of the secondary points of feed-in are defined, and the interaction of all plants is monitored.

The interface between the first and second levels can vary. The controllers may be directly connected via protocols or may communicate via the control platforms. This may also depend on the size of the DHS.

Subsystem level (2): Examples of subsystems in DHSs are heating centrals, buildings and their internal distribution system, the network(s) as well as other decentralized subsystems (e.g., large-scale TESs or single heating plants). On this level, the load and the different temperatures of the individual aggregates must be managed. Further tasks are the fallback operation if no schedule is transmitted and the compensation of deviations in short terms. For these cases, supervisory controls should be implemented that can use internal sequence controls for the heating plants. Finally, the subsystems must be monitored locally and by the control platforms.

The interface between the second and the third level is the set-points for the plants and measurements in return.

Aggregate level (3): Typical aggregates are the individual heating plants (e.g., a HOB or heat pump), the consumers' substations, energy transfer stations, TESs (buffer tanks or seasonal TESs) as well as heating circuits (e.g., the different heating circuits in a building). The customers' substations perform the flow control and the central energy transfer stations perform the pressure, load, and supply temperature control. The controls include time-critical control loops. On this level, proportional-integral-derivative controllers are a proven solution [cf. 105].

The interface between the third and fourth levels is mostly comprised of signals. For example, the voltage of 0 to 10 V or the current of 4 to 20 mA controls the set-point for the opening angle of a valve between 0 and 100 % [cf. 108].

Component level (4): In DHSs, many different components are required. For the focus of this thesis, the most relevant components are the controllable components (mainly pumps and valves) in addition to sensors and meters (mainly for temperatures, volume flow rates, heat flow rates, pressure, and pressure differences). On this level, the main security limitations such as maximum temperature control must be implemented.

To conclude, it can be said that this concept includes all the required interfaces to operate the DHS. It explains the transfer of a monetary market signal (price for temperature) into a technical signal like a current for setting the valve position to control the temperature. Therefore, it is an important part of the framework. For the postprocessing of the operation, the data is recorded in the meters and at the control platforms. Its analysis is part of the next scope—the evaluation process.

4.6 Connection to the evaluation scope

Data and its evaluation are key for a technically and economically efficient DHS and form the basis for further learnings and improvements of the system. The data can be provided by the SCADA systems. [2, pp. 486–487]

The evaluation of data from the operation has many different purposes. It is required for the billing of customers and suppliers and can become more important in the case of dynamic pricing mechanisms. Further, it can be used to identify faults and the potential for enhancements. Finally, it can be used to evaluate the state of transition of the DHS e.g., by using the KPIs from [90]. Since this thesis does not focus on the evaluation scope, the objective is to identify the interfaces and boundary conditions for the other DH scopes.

Related to the presented framework, the DHS should be transferred to an STG. Using smart meters, consumption and production can be automatically registered [42, pp. 45, 111]. Meters are required at every point of feed-in and feed-out of heat. Besides the thermal energy and power, the supply and return temperatures should be recorded. Further, the electricity demand of the network pumps and the electricity demand of the heating plants should be recorded separately for each unit. Heating plants that require fuels such as gas should also include a smart meter as this allows for the evaluation of individual energy balances and costs of each plant related to its supply temperature. The data can further be used to calibrate models that are required for the framework. Through these measures, production, consumption, storing, and transportation can be evaluated separately. Forecast algorithms can be trained and the planned and realized production can be balanced.

The energy balances are needed to evaluate the income from markets and operations and to identify penalties and profits from deviations of the market and operations (cf. section 4.4.3). Further, it is necessary to identify the compensation payment between the capacity market and short-term markets.

4.7 A coherent and comprehensive framework proposal

In this section, the new framework is presented. It is developed for DHSs that allow for competition, and which have an unbundled network operator (SB). The framework is presented in figure 4.19.

In this figure, all DH scopes are represented. The DH scopes I to III (preconditions, policies, and heat strategies) form the requirements and conditions. The organizational structure (DH scope IV) is the frame for the planning and operation where consumers, independent producers, and an SB are defined.

Competition has a special role in this context. Firstly, some of the heating sources, such as surplus heat from industry, belong to industrial companies, and therefore, they do not belong to the DHS operator. That is why third-party access is necessary here in any case. Secondly, some of the new heating sources (e.g., geothermal heat) require very specific knowledge and they may have high investments and risks which cannot be provided by small DH companies but by external companies instead. Thirdly, it can help to reduce costs. If companies can use their experience from other sectors, the DH sector can benefit from an economy of scope. For example, companies from the oil industry have knowledge that can be applied to geothermal energy. Another aspect is that if companies can operate numerous similar heating plants in different DHSs, they will benefit from economies of scale. This requires a high standardization at the interface to the local DHS operator. If third-party heat production is introduced, the most transparent and less-discriminating organization would be an unbundling of the system operation and production. Therefore, it is proposed to introduce independent heat producers and a SB. Due to the local and small scale, it does not seem preferable to introduce further retail competition and, even if it would be preferable, the introduction of a SB would be the first step of implementation.

One challenge of the competitive environment is that the DHS may lose its integrative characteristic. By separating the ownership of heating plants from the rest of the system, the heat producers are incentivized to optimize their heating plant subsystem instead of contributing to the optimization of the overall system. This effect is referred to as suboptimization. Another challenge is the local scale of DHSs. On the one hand, this can give the producers strong market power since an alternative heating plant cannot be constructed in the short term. On the other hand, there is a high risk for investments in new plants for the producers, because an overcapacity may decrease prices below the rentability. To confront these challenges, the framework is proposed with four framework processes.

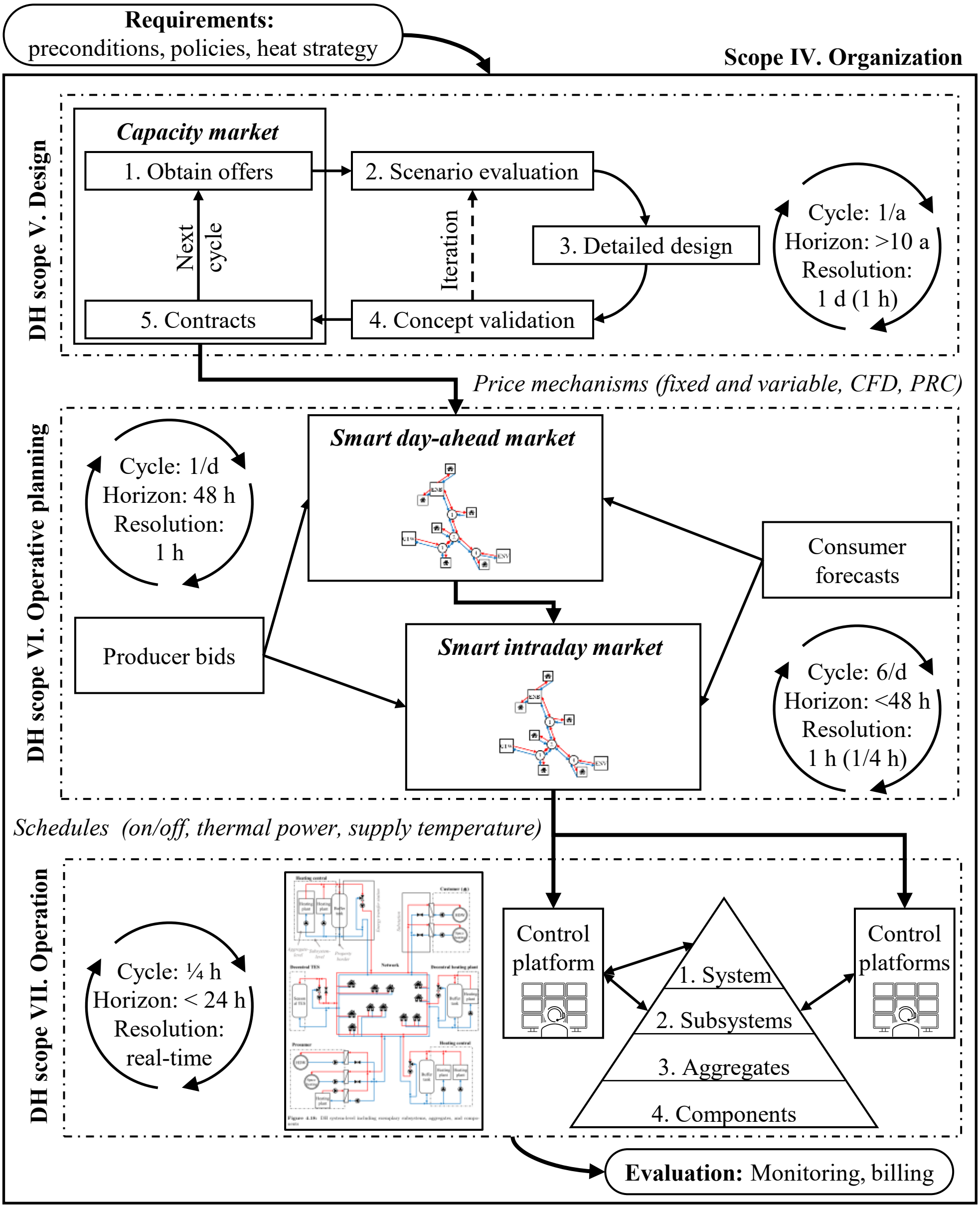

Figure 4.19: A coherent and comprehensive framework

The first framework process is the design process. This process should be implemented (for larger DHSs) as a capacity market with five phases. In the first phase, offers from independent producers are obtained by tendering. The offers should include a variable and a fixed price which may be correlated to the variable and fixed costs of the heating plants. In the second phase, scenarios are developed and evaluated by the SB which should include the offers for supply as a catalog of supply options, changes to the network, as well as other investments into the DHS infrastructure and customers. The goal of this phase is the minimization of the total costs in a long-term perspective for the whole system while meeting the goals for the reduction of emissions. In the third phase, a detailed design can be made which includes more technical details. In the fourth phase, the concept should be validated. This can be performed by conducting tests with the operative planning tools. If the concept is not valid, another iteration must be made. If the concept is valid, contracts can be entered into. These contracts should consider that a short-term dispatch is necessary, and they should force producers to participate in short-term markets. Further, they must consider the physics of the DHS and by this, its integrative character. The interface to the short-term markets can be provided by the principle of CFD. The contracts may be combined with PRCs to implement the cost-by-cause principle. For example, the supply temperature impact on the variable cost of heat production can be considered. The market should be repeated regularly. A proposed cycle is annual. The horizon of the market should include the plants' lifetime (> 10 years), and the resolution of the production should be at least daily. For the technical design, hourly values will be needed. In this market, a first rough schedule for seasonal TESs can be made. Current contracts, in which a fixed payment is agreed on, are treated as sunk costs. This solves the issue of the investment risk because if a producer receives a fixed payment (thermal power price), the investment has a lower risk. For example, if the SB decides to accept a new producer with a new bid—because the total costs of the heat from the new plant are still lower than the variable costs of the old one—the old producer will still receive the fixed payment. This is economically efficient because the heat consumer will pay less in this case compared to the previous supply. Further, the long-term perspective allows for complying with annual ecological limits as the SB can now control the amount of renewable heat production on an annual basis. For example, renewable heating plants can receive a high fixed price for thermal power, and therefore, the variable price for energy may be low. In this way, the renewable plants are privileged in the short-term planning. Due to this mechanism, the ecology is translated into an economic mechanism and, as a result, no extra ecological constraint is necessary for the short-term planning.

The second and third framework processes consider the short-term operative planning (dispatch). The existing plants and the results of the capacity market form the boundary conditions for these processes. The short-term dispatch is realized by a day-ahead (second process) and an intraday market (third process). Both markets are defined as smart markets which consider prices for temperatures and include the physical characteristics of the DHS. The SB forecasts the demand of the consumers. The producers place their bids with prices related to the amount of energy and the supply temperature. The market should support the iteration with electricity markets as far as possible. In the clearing algorithm, the costs for transport and heat losses should be included. Those bids that allow for a supply and result in an overall cost minimum are chosen. The day-ahead market has a daily cycle with a rolling horizon of 48 hours whereby the resolution is 1 hour. The number of cycles for the intraday market depends on the size of the DHS and the number of suppliers. It may have six cycles a day and (depending on the time of the procedure) a rolling horizon between 24 and 48 hours. The resolution is 1 hour or even 15 minutes. Some agents may only be interested to participate in the intraday market. Examples are flexible customers, who are not able to estimate their potential over a long horizon. Through the intraday market, the SB can adjust production to spontaneous deviations.

The fourth framework process is the operation. The responsibility of the system operator (SB) is the overall system operation, the network, and all energy transfer stations and substations including TESs. The independent producers are responsible for the heating plants. The customers are responsible for the inner-building distribution system. The market results are sent to the control platforms of the system operator and the independent producers. They will transform the results into schedules and set-points for the individual plants. The schedules should include an on/off signal, a power signal between minimum and maximum, and the supply temperature set-point. The control platforms will send these schedules and set-points to the plants in the DHS. On a system level, the pressure is controlled, and the load deviation is monitored. On the subsystem level, the load and the production are managed. Further, overall temperature management must be implemented. On this level, controls to compensate for deviations must be implemented as well. On the aggregate and component levels, typical control systems (e.g., proportional-integral-derivative controllers) can be used.

The evaluation scope includes the necessary postprocessing, and the data for this evaluation must be collected while operating. Based on this data and the meters, energy balances can be calculated which include the planned production, the carried-out production, and the contracts from the capacity market (CFD). Deviations must be paid. Further, long-term evaluations of the state of the transition of the DHS and the efficiency of the implemented framework processes should be made regularly.

4.8 Validation and discussion of the framework

In this chapter, a new framework for planning and operation in DHSs is systematically developed. The framework consists of four framework processes: a capacity market, a smart day-ahead market, a smart intraday market, and the operation. A framing is given by the organizational structure. The requirements for the subsequent evaluation are defined. The development includes the principles which are given in the method: a scope-related issue solving, a coherent and systematic development, the facilitation of an integrative system, a macroeconomic evaluation, an agile reaction to changes, and the principles of opportunistic coordination (considering all degrees of freedom and least commitment). In this section, the framework will be validated based on the requirements of chapter 2 in the first step. Subsequently, the results will be discussed.

4.8.1 Proof of achievement of the requirements

The developed mechanisms are conclusive under the assumed conditions. On the one hand, they are developed in a coherent manner. On the other hand, fundamental changes in the conditions may negatively impact the coherence of the solutions. Therefore, the validity of the whole framework with all components should be proven.

In this section, a qualitative test of the requirements is presented. To conduct the test, the requirements of the transition that were identified in chapter 2 will first be listed. For each requirement, it is discussed if and how this requirement is fulfilled. The validation will be organized by the different DH scopes. Before starting with the scope-specific requirements, general requirements are discussed.

Validation of general requirements

Table 4.2 summarizes the general requirements that are identified in chapter 2. These occur due to the transition in DH.

G.1: In the introduced organizational structure, more market activities are implemented (q.v. section 4.3) and through the integrative approach of the whole framework, suboptimization is prevented.

By the proposed unbundling, the SB's focus is set to the network operation, services for the customers, and for buying heat from the producers. By introducing proper tariffs and contracts between the customers and the SB, the SB is incentivized to increase both the system and the customers' efficiency. Through this new structure, the SB is incentivized so that the most economical heat sources will be connected. The competition and the proposed mechanisms will force suppliers to innovate and continuously increase efficiency. This forms an economically efficient system.

Table 4.2: General requirements for the framework

No.	Requirement
G.1	Low cost/economically efficient heat supply (social requirement to support heat for poor)
G.2	Increasing transparency in the overall process
G.3	Supporting the transition to zero fossil fuel
G.4	Supporting the integration of renewable sources
G.5	Supporting the interaction with the electricity sector (as part of a smart energy system)
G.6	Supporting the process of temperature reduction
G.7	Facilitating TESs and flexibility to compensate fluctuations
G.8	Providing an open, evolutionary structure

To identify the most efficient organization, a vertically integrated and an unbundled organization must be compared on a macroeconomic basis. This comparison is very complex and therefore, it is not part of this thesis. Hence, while the developed framework cannot be validated as the most efficient, it can be evaluated as an economically efficient system due to broad experience in competitive environments.

G.2: The unbundling of the network and the production combined with the market procedures allow for complete cost transparency of production and transmission. Implementing a supervising authority can further ensure that no producer will misuse its market power.

G.3: The transition to zero fossil fuel is related to the constraints that are given by the higher-level scopes (scope-related issue solving). Further, the framework includes different types of rules in the market procedures. Most important is the capacity market, which allows for the annual limitation of emissions or other mechanisms (q.v. section 4.3). It is also compatible with carbon taxes/prices which seem to be the best option for the transition of the full energy system (as a smart energy system).

G.4: The framework was developed to work for the transition as well as for a fully renewable system. An example is that all heat producers are forced to participate in the short-term market. If small plants would be excepted from the dispatch (like in Copenhagen), there will be an issue in the future when the share of small sources increases. The integration of the temperature in the pricing mechanisms of the producers will ensure that the most cost-effective solutions will be integrated first. By this, the transition to lower-temperature heating plants is supported.

G.5: The interaction with the electricity sector is also secured by the short-term market. The market is designed in relation to the already implemented dispatch in Copenhagen. This dispatch allows for a good interaction with the electricity market, and it can be evaluated as a proven concept.

G.6: The temperature is a central KPI in the framework (q.v. section 4.4) and it is controllable at all relevant points in the system. Further, the proposed markets include the temperature for an economic evaluation. Local consideration of temperatures in the smart market ensures that all network sections are operated at the minimum temperature in accordance with customer requirements. In addition, it is proposed to include the temperature in long-term strategies (DH scope III). The target values for reduction can then form a constraint for the capacity market.

G.7: The framework includes flexibility and TESs in all framework processes. Seasonal storages must be included in the capacity market, to enable a benefit from them. The short-term markets facilitate the use of short-term flexibility e.g., for central buffer tanks in the day-ahead market or for flexible demand in the intra-day market. Through the implementation of the proposed smart market concept, the flexibility of the network will also be considered. Further developments for the integration of flexibility will be presented in chapter 6.

G.8: The agile approach of a learning framework with regular feedback to upper levels secures a coherent DH sector with an evolutionary structure. Further, the open market facilitates the engagement of stakeholders.

Validation of organizational requirements

Table 4.3 presents those requirements that are relevant to the organizational structure (DH scope IV).

Table 4.3: Specific requirements for the organizational structure (DH scope IV)

No.	Requirement
IV.1	Incentivizing low temperature, low demand, and flexible customers (resolving the lock-in effect to the traditional business logic)
IV.2	Supporting integration of prosumers and access heat (e.g., from industry, supermarkets)
IV.3	Facilitating a long-standing framework (working beyond fossil-sources)
IV.4	Adapting to different policies and regulations
IV.5	Supporting a fair treatment of centralized, large-scale and decentralized, small-scale production

IV.1: A vertically integrated utility would benefit from higher demand. This established business model can be resolved by the unbundling of the network and production. Here, the SB owns the network and is responsible for its operation, services for the customers, and for buying heat from the producers. There is no interest in increasing the amount of sold heat from existing centralized plants. Instead, the SB can now focus on the improvement of the distribution and demand side. Tariffs and contracts between the customers and the SB can be designed differently in such an organizational structure. For example, the SB should be paid for achieving the goals concerning lower temperature, higher efficiency, lower emissions, and flexibility. The costs for the SB and the production should be placed separately on the bill for the customers. By this, the SB is not incentivized to sell more energy.

IV.2: The unbundling removes the barrier of discrimination, and the capacity market standardizes the third-party access. Further, security can be promoted by long-term contracts. The open-access, transparent connection conditions, and participation in the short-term markets promote the integration of third-party heat sources like prosumers or access heat providers.

IV.3: The framework is planned to work during the transition and beyond with 100 % renewable and decentralized plants. The capacity market ensures that unfair competition between fossil and renewable sources is minimized.

IV.4: The framework can be used with carbon taxes/prices or annual goals for the reduction of emissions. These are the most relevant policies, which are expected.

IV.5: Heat production will be selected by the fixed and variable prices for production and costs for transport, the provided temperature, and ecological conditions. The size and ownership of plants are not a criterion for the selection. Because of the unbundling, the SB will not own any heating plants. This ensures that existing centralized fossil plants are not advantaged in the markets but must operate under the same conditions as new plants.

Validation of design requirements

Table 4.4 presents the requirements for the design scope.

Table 4.4: Specific requirements for the design process (DH scope V)

No.	Requirement
V.1	Supporting a systemic planning for the whole lifecycle (investments and operative costs)
V.2	Handling of high investments and high risks
V.3	Bridging short-term and long-term marginal costs
V.4	Regularly facilitating enhancements, extension, renovation, and modernization
V.5	Considering bottlenecks
V.6	Facilitating a low temperature design
V.7	Engaging stakeholders

V.1: The design process supports systemic planning by the capacity market for the whole lifecycle. The investment evaluations include total costs and also evaluate investments in the infrastructure. Fixed costs for existing contracts are treated as sunk costs.

V.2: The proposed fixed charge of the capacity market can reduce the risk of investments for the producers. Allowing third parties to access the local DH market and allowing profit incentivizes companies and actors to invest. The risk of changing prices (e.g., for primary energy) can be buffered by the PRCs.

V.3: The bridge between the short-term and long-term planning is secured by using CFD with PRCs. Long-term issues are solved in the capacity market and short-term issues are addressed in the operative planning markets (dispatch). Participants of the capacity market accept the price-fixing due to the long-term contracts.

V.4: The capacity market has a regular cycle. For larger DHSs, this cycle is proposed to be annual. By such a regular evaluation with a long-term perspective, continuous improvement can be ensured.

V.5: The capacity market considers the hydraulics of the network and bottlenecks.

V.6: A low-temperature design is secured by the combination of an unbundled SB and the capacity market. The unbundled SB has no incentive to hinder the transition towards low temperature without interest in its own high-temperature production. The capacity market considers a full cost concept, which includes an evaluation of investments for different measures e.g., for lowering demand and temperature or new heating plants.

V.7: Due to the open market with more transparency, different stakeholders can be engaged. Customers can be involved in a supervisory board while third-party producers are engaged via market opportunities.

Validation of operative planning requirements

Table 4.5 shows the specific requirements for the operative planning process (DH scope VI).

Table 4.5: Specific requirements for the operative planning process (DH scope VI)

No.	Requirement
VI.1	Dispatching heating plants depending on short-term costs
VI.2	Iterative re-adjusting to changing conditions (electricity market prices, heating plant faults, etc.)
VI.3	Evaluating bottlenecks
VI.4	Balancing pumping power and heat losses (evaluate set-points for supply temperature)
VI.5	Providing realistic computational times

VI.1: The dispatch of the heating plants is included by the day-ahead and intraday market based on short-term variable costs.

VI.2: For long-term changes, the interaction with the capacity market secures an adjustment. For short-term deviations, the intraday market allows for reactions in less than 4 hours. For shorter-term deviations, additional sequence controls are proposed and for deviations of less than 1 hour, the buffer tanks are used.

VI.3: The evaluation of bottlenecks in the operative planning is included in the proposed smart market concept which integrates bottlenecks and the costs for pumping into the model.

VI.4: The balancing of pumping power and heat losses is included by a full cost consideration in the smart market concept.

VI.5: While it cannot currently be evaluated if the smart market algorithm performs in realistic computation times, this can be identified as a requirement for future developments.

Validation of operation requirements

Table 4.6 presents the specific requirements for DH scope VII.

Table 4.6: Specific requirements for the operation (DH scope VII)

No.	Requirement
VII.1	Controlling the heating plants (central and decentral)
VII.2	Controlling the feed-in supply temperature and differential pressure
VII.3	Detecting the set-point for pressure difference control
VII.4	Controlling heat demand (and resulting flow rate)
VII.5	Avoiding interference of controls
VII.6	Managing TES and flexibility
VII.7	Securing supply and operation

VII.1: The proposed control hierarchy includes a hybrid concept. A centralized optimization of all variables is performed by the short-term markets. Further, a faster control on the supervisory level is implemented to react to short-term deviations. The heating plants should be able to control both supply temperature and thermal power.

VII.2: The control of the feed-in temperature and of the differential pressure is included in the control concept. All heating plants will receive a control signal for supply temperature from the market. Differential pressure is controlled in the usual way by a primary point of feed-in, and all secondary points of feed-in will receive a set-point for their flow rate. To handle the control of the pressure, the responsibility for the energy transfer stations and the substations should be at the SB.

VII.3: The detection of the set-point for the differential pressure is promoted in the usual way by measurements located at selected points/customers in the DHS.

VII.4: The control of heat demand is implemented in the usual way at the substation while additional load management is performed by the SB to utilize the full storage potential.

VII.5: The interference of controls is secured by different reaction times. The fastest control is the differential pressure control. Interferences are avoided here by the pressure regulation at the system level. A primary point of feed-in controls the differential pressure and the other (secondary) points of feed-in deliver a fixed flow rate. The supply temperature set-points will be identified by the market, and it will not be changed within the market resolution (e.g., 15 minutes). A special focus is on the development of the supervisory control for the compensation of deviations.

VII.6: TESs, the storage potential, and flexible customers are included in the proposed smart market by the SB to reduce the costs for the customers. Further, some parts of the buffer tanks may also be reserved for short-term deviations.

VII.7: The different mechanisms and processes of the operative planning and of the control will secure the supply. Short-term deviations can be buffered by TESs, while larger deviations may be buffered by a change of production via sequence control and via the intraday market. At the capacity market, sufficient capacity will be selected. The contracts must secure the independent producers to supply the required heat. Depending on the availability of independent producers, peak and redundancy supply could be installed and operated by the SB or by independent producers. The obligatory participation in the short-term market secures the operation.

Validation of evaluation requirements

The requirements for the evaluation are presented in table 4.7. There are two requirements related to the framework for this DH scope. The comprehensive framework must support the data for billing and for the enhancement of the system.

Table 4.7: Specific requirements for the evaluation (DH scope VIII)

No.	Requirement
VIII.1	Providing data for billing of consumption and supply
VIII.2	Providing data for the detection of inefficiencies and faults

VIII.1: The data for billing is collected by the control platforms and the SCADA systems as well as by the heat meters. The locations of the meters are defined by the boundaries of ownership. Besides thermal energy, the supply temperature is relevant.

VIII.2: The metering data is one part of the data collection for the system evaluation. Additionally, further measurements for pressure, flow rates, and temperatures are needed. The data is stored by the control platforms and the SCADA systems.

4.8.2 Discussion of the new framework

The presented validations indicate that the developed framework is theoretically valid to fulfill the requirements of the transition. The framework can include large-scale and decentralized heating plants and supports the interaction with the electricity grid. It utilizes the flexibility of different types (e.g., buffer tanks, seasonal TESs, and the network). Further, by improving the conditions for competition and introducing new roles, the solution aims for high economic efficiency. At the same time, the integrative character of the DHS is retained by considering the physics of the system and the translation to economic mechanisms. The framework facilitates the transition towards 4GDH, and the scalable solution does not depend on a specific technology. Such a systematically developed framework has not been presented before.

The validation has proven that the requirements are fulfilled. Since the development has focused on full development, not all possible alternatives for each mechanism could be evaluated, and hence the validation has not shown whether alternative solutions would fit the requirements even better. A central point of discussion is that the introduction of the proposed framework could lead to higher costs for market transactions and administration through the unbundling of DH companies and the introduction of the markets. It must thus be evaluated if other solutions are able to meet the requirements at lower total costs on a macroeconomic level. The main difference would be if the DHS is not unbundled. In a DHS with a vertically integrated utility, the framework processes must be adjusted. In the tendering phase of the design process (DH scope V), it would not be asked for an external heat supply. Instead, the vertically integrated utility would evaluate the potential heat sources and would obtain offers to build the heating plants on its own. In the operative planning processes (DH scope VI), the proposed short-term planning algorithms can also be applied but instead of a clearing at marginal prices in a competitive environment, the internal known marginal costs (e.g., for the production) can be used. However, in this case, the SB may discriminate against third-party production at the capacity market. To provide this, more supervision or even non-profit suppliers are required. The main issue, in this case, is that the lock-in effect of established high-temperature business models is not resolved.

In contrast to vertically integrated systems, the proposed organizational structure would benefit from a large-scale implementation (country-wide or even EU-wide). If conditions in different DHSs are similar (e.g., through policies for unbundling), business models can be replicated through which economies of scale and scope allow for a more competitive DH sector in general. Software, models, and solutions need to be developed that are targeted towards a larger market and more customers. The more these tools are used, the lower the individual costs for their implementation. Moreover, the success of the framework depends on external conditions (DH scopes I–III) such as the DH market policies (e.g., regulated or deregulated markets). Even though the concept is developed for competitive environments, many parts of the concept can be applied in regulated markets as well. For example, the planning processes can be implemented in the same way.

Concluding, the macroeconomic effects of the competition and unbundling can only be discussed but not be proven here. For a realistic evaluation, implementations with unbundled SBs are required. Further, it must be evaluated at which DHS size what effort of market operation may be economically efficient as the larger the DHS is, the more different options seem to be available for market participation. The final validation will only be possible if the framework is implemented in total. But, before the full framework can be implemented, some innovations are still required. For the capacity market, it is necessary to combine standards, existing tools, and other concepts in a toolbox for the evaluation of the design. The proposed smart market algorithm needs to be implemented and tested for large-scale DHS. Further, the control concept together with the ICT infrastructure needs to be detailed, implemented and tested. Moreover, the impact of supply temperature on the variable costs of production needs to be evaluated to implement the novel bid mechanism which includes temperature in the price. This evaluation is presented in chapter 5 and comprises the first step of the smart market development. In addition, the temperature impact on TESs and other units with flexibility require a further evaluation to implement them in the smart market with temperature correlated prices. The flexibility of DHSs is presented in chapter 6.

4.9 Conclusion of the framework development

In chapter 2, it is shown that a comprehensive framework for district heating systems (DHSs) is lacking that combines the district heating (DH) scopes of design, operative planning, and operation in a coherent way. The framework development is performed in two steps according to the framework approach (q.v. chapter 3): the definition of the basic framework structure and the outer conditions and the development of the individual framework processes.

In the first step, the basic structure is proposed in relation to the identified DH scopes. Further, an organizational structure is proposed that unbundles production from the DHS and introduces the role of the single buyer (SB) as well as the independent heat producers. For each scope, at least one framework process is introduced, and the required interfaces are identified. The framework consists of four framework processes: a capacity market, two smart short-term markets (day-ahead and intraday), and the operation.

In the individual framework process development (step 2), technical and economic mechanisms for each of the processes are identified and combined. Interfaces between the different processes are developed and ensure that the DHS stays an integrative system, even though an increase in competition and unbundling is introduced.

The capacity market's purpose is to secure long-term planning. This includes investments in the infrastructure, long-term contracts with the independent heat suppliers, pursuing the heating strategy, and facilitating the energy transition. In the capacity market, structural changes to the DHS are decided and the conditions for the lower-level processes are defined. This includes a long-term schedule for seasonal storage. Further, the long-term ecological goals must be secured and translated into short-term mechanisms on an economic basis. One of these mechanisms is the pricing for the heat producers which defines the share of fixed and variable parts of the charge for the producers. Ecologically preferrable plants may require higher fixed charges and low variable charges. This secures a high production level of renewable heat in the smart short-term markets.

The smart short-term markets' purpose is to secure the supply. Here, the plants' availabilities, forecasts of production, and short-term prices (e.g., impacted through electricity prices) are considered. The day-ahead market ensures the first schedule while the intraday market allows for faster changes to deviations and changing external conditions. Both markets facilitate efficient interaction with the electricity sector. The proposed *smart market* algorithm includes all costs for temperature, heat losses, and transmission. Participation in the smart short-term markets is obligatory for all producers. The SB uses the system's flexibility to achieve the lowest costs for the consumers. The producers can place their bids at marginal prices and those producers who have long-term contracts will make differential payments with the SB outside the market.

Finally, the control concept and the responsibilities are designed for all parts of the DHS. Their interface to the smart short-term markets is defined by the market results including thermal power and temperature schedules. The boundary of ownership is defined in a way that allows the system operator (SB) to control all relevant parts of the network. In this way, the system operator can actively manage the load of the whole system to secure the demand in the most economically efficient way.

The combination of the individual processes forms a comprehensive framework which is the main contribution of this chapter and through which the identified gap is filled. It can be used as a starting point for further developments and improvements. Further, it should initiate more scientific discourse on a system level instead of discourse over technical solutions or economic issues of single DH scopes.

In the coming years, many changes in policies and economic conditions but also innovations are to be expected. Therefore, an agile and evolutionary character is needed in all DH scopes. The developed framework contributes as one part of a coherent transition in the heating sector. Together with a suitable heating strategy as well as transition-supporting policies, an innovative and evolutionary structure can be formed that facilitates the transition.

Before the framework can be used on a wider scale, some further innovations are required. On the macroeconomic level, the implementation and, by this, the final proof-of-concept are still open. On the technical level, further solutions are needed. For the capacity market, existing tools for evaluation must be combined in a toolbox (layout optimization, system simulation, scenario evaluation, etc.). The control concepts will require further detailed developments (e.g., controls on the system level for sequence control in case of deviations). This may be accompanied by standards for these controls and the information and communication technology (ICT) infrastructure. Finally, the proposed smart market concept goes beyond the state-of-the-art models by using bids for the generation including the temperature impact on prices. Therefore, a new and performant algorithm is required.

As a first step of the smart market development, the variable costs of the heating plants are required that include the discussed temperature impact. This development is presented in chapter 5. Further, the integration of flexibility is also required for the smart market. This is presented in chapter 6.

Chapter 5

Heating plant integration into the new framework

A coherent framework is proposed in chapter 4 which supports the transition to 4^{th} generation district heating (4GDH), mainly by introducing competition to district heating systems (DHSs). Besides the presented advantages of introducing competition to district heating (DH), the separation of ownership and a possible unbundling between production and system operation could lead to some issues. By introducing independent suppliers, they will own production sites which are subsystems of the DHS. One important challenge of the unbundling is to avoid the suboptimization of these different subsystems and to maintain the DHS as an integrated system whose overall efficiency can be optimized. Therefore, innovation is needed to create a system that enables competition while incentivizing all participants to behave in a way that serves the system. This can be accomplished through the introduction of price mechanisms that motivate the different agents to optimize their subsystems and thus their profits in the interest of an overall optimum.

For this to succeed, such price mechanisms must be designed according to the cost-by-cause principle. Applying this principle to the production side involves two relevant aspects. Firstly, fixed costs should be transformed into base prices and variable costs should be transformed into unit prices. As proposed in chapter 4, fixed costs should be a result of the tendering phase in the capacity market. In contrast, the variable costs for thermal energy are relevant for the previously introduced smart short-term market concept. Since it is concluded that the development of the smart market concept is the most urgent step of implementation, only the variable costs are considered in this investigation. Secondly, the temperature is an important quantity in DH in general and particularly for the transition of DHSs. Therefore, this chapter analyzes the correlation between temperature and the variable costs of production. Through this, the heating plants can be integrated into the framework and particularly into the smart short-term market.

As the first step of implementation, a concept for the integration of heating plants into the new framework is developed and presented in this chapter. This implementation must fulfill several goals. The first goal is to find or develop a method that can provide an evaluation of the impact of supply temperature and thermal power on the average variable costs of heating plants. The second goal is to demonstrate the applicability of the method by using case studies. The third goal is to evaluate whether the impact of supply temperature is big enough to justify the effort to include the temperature in the bids and the smart market.

The chapter is organized into six sections. In section 5.1, existing methods that evaluate the impact of supply temperature or thermal power on the variable costs of single heating plants are reviewed. Further, the data availability of variable production costs is analyzed. As a suitable method and the data of variable costs including a temperature correlation cannot be identified, a novel method is developed and presented in section 5.2. In the following section 5.3, this method is applied to case studies of existent or planned heating plants in the DHS in Hamburg-Wilhelmsburg. The results are presented with a three-dimensional plot in section 5.4. Afterward, the results are compared and discussed, and their plausibility is evaluated. Finally, it is concluded if the new method fulfills the requirements. Further, the relevance of the temperature impact on variable costs is evaluated. By applying the method to the case studies, it is demonstrated how the bids for the unbundled smart market can be created.

Parts of this chapter were already published by the author in [75] and direct citations of this paper will be used throughout the chapter.[1]

[1] This chapter is structurally based on the paper. To ensure a good readability, the literally duplicated parts are only indicated with footnotes. In some cases, there are small additions, omissions, and changes to the text to improve the accessibility of the chapter. If complete sections or subsections are duplicated, this will be indicated by footnotes to the headings whereas in the case of full paragraphs, this will be highlighted by using a footnote at the end of the paragraph.

5.1 State-of-the-art evaluations

The goal of this section is to identify a method that adequately shows the impact of supply temperature and thermal power control on the average variable costs in heat production. This requires a transparent approach without aggregation in the sense of mean annual values or mean values for operation. The following paragraphs highlight methods that are applied in other studies while the references for the variable costs of operation are evaluated in later parts of this section.

5.1.1 Existing methods for the evaluation of the impact of supply temperature and thermal power on the average variable costs of production

The transformation from older generations to 4GDH involves a broad field of current research activities with a focus on “lower and more flexible temperature distributions” [109]. Transformation studies like [90] highlight the challenges that require a whole system transition including temperatures, hydraulics, and operative procedures. The study developed key performance indicators (KPIs) to evaluate the whole transition progress including those for temperature. A common approach to evaluating the impact of temperatures on the transition is the comparison of different scenarios with temperatures as fixed input parameters. As one example, by varying the supply temperature between 80 and 55 °C Nord et al. showed that low supply temperatures are important to utilize renewable sources and that they are necessary for DHSs in low heat density regions to increase the competitiveness for individual heating. Further, they describe the trade-off between the heat losses of the pipes at high supply temperatures and higher electricity consumption at lower supply temperatures with higher flow rates [91].[2]

Temperatures have an impact on variable heat production costs. An example of this is a geothermal heat source with low reservoir temperatures which requires a heat pump to achieve a certain supply temperature level [95]. The lower the DHS supply temperature, the lower the electricity demand of the heat pump and thus the variable costs. Another impact of a high required supply temperature is that it can limit the maximum thermal power, e.g., in solar thermal collectors. Their efficiency decreases with increasing supply temperature, thereby resulting in a lower thermal power [110]. These effects can be included in scenario evaluations which vary the temperature levels and thereby can give specific recommendations for the overall DHS design. However, as scenario evaluations do not provide detailed information correlated to the whole range of each controllable variable, they do not satisfy the requirements for the daily operation.[2]

[2]This paragraph is also published in [75]. In some cases, there are small additions, omissions, and changes to the original text.

To determine the optimal supply temperature, Lund et al. present a long-term analysis of temperatures from a societal point of view to provide general recommendations [95]. The analysis is based on scenarios that consider different temperature regimes and calculate the socioeconomic costs (including costs of emissions). The interim result of this evaluation shows that a temperature reduction down to 55 °C is beneficial. Further temperature reductions (5th generation district heating (5GDH)) currently require large investments in the substations because heat pumps must be integrated.[2]

These studies consider the impact of temperature by including it as a constraint for evaluations of different scenarios. The results of these scenarios, such as the overall costs of the whole operation, are aggregated quantities. The correlation between the supply temperature and thermal power of each plant is not given individually. Therefore, scenario evaluations on a system level as well as aggregated KPIs do not provide the required information.

Averfalk and Werner present an individual evaluation of different renewable heating technologies for two scenarios [24]. The first scenario uses the temperature levels of the 3rd generation district heating (3GDH) and the second one uses the lower 4GDH temperature levels. These include the internal temperature behavior of the plants, the heat losses in the system, and the peak-load production with biofuels to evaluate the impact from a system point of view. To simplify the evaluation, the electricity demand of pumps is neglected and the central KPI is the cost reduction gradient given in (€/TJ/°C) which was first introduced in [2]. This KPI provides an aggregated evaluation of the impact of different temperature levels on costs (at a system level) to provide design recommendations. The results of Averfalk and Werner show that while heat losses do indeed play an important role, lower production costs through better utilization of non-combustion sources and the subsequent avoidance of peak production are the most important factors for cost reduction in the transition from 3GDH to 4GDH. The overall result of their investigation is that (non-combustion) technologies based on renewable sources are much more sensitive to lower supply temperatures than combustion-based technologies. Existing DHSs with a large share of these conventional technologies do not present high direct economic incentives and therefore they constitute a barrier to the transition to lower temperatures which, in turn, presents a barrier to the integration of renewable sources.[2]

The cost reduction gradient presented by Werner and Averfalk is a helpful quantity to evaluate the impact of temperature reduction on the overall system costs. Again, this KPI does not provide each plant's individual information correlated to the full range of supply temperature and thermal power that a plant can produce.

Another possible KPI for the evaluation could be exergy. Exergy is a mature concept for combining energy and temperature in thermodynamics [92]. Economic studies have been developed based on this aggregated quantity, namely the so-called exergo-economic analyses. One example is the *specific exergy costing* method [93] which analyzes all streams of exergy and their costs. It is suitable to identify technical enhancement potential (e.g., replacing ineffective heat exchangers) or operational optimization. The *specific exergy costing* method has been applied to different types of DHSs e.g., with geothermal heat sources [111]. The exergy method can also be combined with multi-objective optimization algorithms to facilitate an evaluation of costs and exergy efficiency [94]. The advantage of this exergo-economic analysis is that aggregating temperature and energy to exergy simplifies the evaluation while a disadvantage is that, through the aggregation, important information about the temperature is lost.[2]

Related to this loss of information, exergy is not the KPI that allows for a transparent correlation of costs to supply temperature and thermal power.

5.1.2 Availability of average variable costs of heat production

While searching for available methods, another problem was identified, namely that many references do not clearly present their variable costs. To demonstrate this issue, the following examples are provided.

- The textbook compiled by Kaltschmitt et al. presents exemplary and detailed energy cost calculations for different technologies [112]. Although the evaluation of the operational costs for exemplary solar thermal plants includes the electricity demand of the whole heating system (combination of solar thermal and heat only boiler (HOB)) and an assumed price for electricity, the variable costs of the solar thermal plants are not presented [112, pp. 238–244].
- The German association for district heating ($AGFW$) published a comparison of different heating systems [113] but this report also presents the costs of combined systems and not individual heating plants.
- Another example is the appendix of a study about the German energy transition [114] which includes some economic data related to heating technologies that are applied in DHSs. Many parameters and assumptions are listed, but the costs for the operation are given on an average basis as a share of investments and are not separated according to the variable and fixed costs of operation.
- The study [115] presents tables and technology information with different elements of costs. For some of the later evaluated technologies, the variable costs of operation are not provided.
- Tereshchenko et al. evaluated the economic issues related to the selection of the heating plants [116]. The authors present the inputs for their evaluation separated into variable and fixed parts. However, since the evaluation focuses on biomass (combined heat and power (CHP) plants and HOBs), heat pumps, and electric boilers, the input data is limited to these technologies. As this

study focuses on levelized costs of heat, the output data shows aggregated quantities only. The only exception to this is the share of fuel costs related to each technology because it presents a part of the variable costs.

- The most complete set of data that has been identified is provided by the Danish Energy Agency [117]. The agency provides the data as a basis for comparative energy studies, and it is also used by several papers like [116] and [118]. This catalog will be used for validation later.

Finally, no method has been found that presents the average variable costs (or a comparable KPI) related to the impact of different supply temperatures and different points of operation for thermal power. Further, the availability of data for average variable costs can be evaluated as low in general. The development of a systematic method for the evaluation of average variable costs and its application to selected case studies will be presented in the following sections.

5.2 A novel method to evaluate the temperature impact on the average variable costs of heating plants[3]

In this section, a new general method for the production side in DHSs is presented that fits into the framework approach and can be applied to all types of plants with a two-pipe connection. The method is innovative by correlating the *average variable costs* for heat production with the *thermal power* and *supply temperature*. The thermal power and supply temperature are given in the form of a discrete pattern (the specific patterns are introduced in section 5.2). To achieve comparable results, the following preconditions are considered:

The objective is the evaluation of variable costs in the scope of operative planning. Therefore, fixed costs that occur e.g., from investments or staff salaries, are not considered. For heat sources that are owned by third parties (e.g., in the case of industrial surplus heat), additional variable costs can arise from the tariffs which are arranged in the contracts between the DH and the heat supply companies. The supplying companies need these revenues to finance their investments (e.g., for assets for the heat extraction from industrial processes) or to be incentivized for the production in general. Such costs are neglected because, firstly, the origins are fixed costs and secondly, there are no standard tariffs that can be applied for this type of contract. Further, the economic benefit of substituting other heating technologies (opportunity costs) will not be included in the evaluation of an individual heating plant. Instead, the presented method should be applied to all existing heating plants in the evaluated system—including fossil or peak-load production—to create a comparable data basis for subsequent optimization.

[3]This section is also published in [75]. In some cases, there are small additions, omissions, and changes to the original text. The subsection *presentation of results* includes several changes related to the different plotting approach.

The basic concept of the method is presented in figure 5.1, which shows the thermodynamic system limits (dash-dotted line). All internal costs and conditions that emerge inside the system and the external costs and conditions that act on the system must be identified. Therefore, the method requires knowledge of the physical principle of each technology and the different impacts of the thermal and hydraulic characteristics on variable costs. Figure 5.1 presents the boundary conditions of any abstract heating technology (highlighted blue). Further, it presents the measurements of the two considered variables (supply temperature and thermal power) on the secondary side (highlighted green). In the presented case, a heat exchanger is included to separate the different hydraulic circuits and to control the secondary side supply temperature. While not all heating plants require this separation by a heat exchanger, control over the supply temperature can be achieved with other components such as mixing valves. These different variants of heating plant integrations and the specific hydraulic circuit designs (e.g., valves and thermal energy storage (TES)) on the secondary side require an additional evaluation of the electricity demand of the secondary pump on an energy central level. However, heating plants with the same size and secondary side integration will have the same electricity demand behavior on the secondary side correlated to different secondary supply temperatures and thus the electricity demand of the secondary side is not included in this evaluation. In contrast to the secondary supply temperature, the secondary return temperature is an external condition that cannot be controlled from the production side.

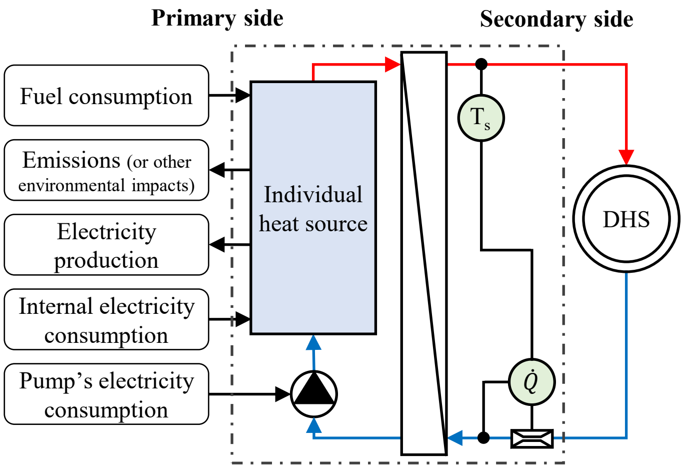

Figure 5.1: Boundary conditions for each individual heating plant[4]

[4]This figure was previously published in [75].

The variable costs mainly occur as a result of the balance of energy production and consumption as well as from other minor factors such as wear. As shown in figure 5.1, energy costs can arise from fuel consumption (e.g., in HOBs), electricity production (e.g., in CHP plants), internal electricity consumption (e.g., in heat pumps), and electricity consumption of one or more primary pumps. In some cases, additional costs can occur from penalties for the environmental impact such as emissions (e.g., CO_2 taxes). If these costs must be considered, they are mostly internalized in the fuel or electricity costs and hence they will not be mentioned separately in the method.

The method is based on a discrete numerical concept for steady-state points of operation and requires discrete patterns of supply temperature and part load ratio (PLR) which additionally allow for good comparability of different types of heat generation technologies. The numerical concept has several advantages. Firstly, it allows for the use of non-linear equations and thus does not require simplification in terms of linearization in the numerical heating plant model. Further, it allows for the use of data-driven models based on measurement data as an alternative to models based on theoretical calculations. The steady-state concept simplifies the evaluation by excluding the time dimension (which could be considered by further developments of the method). Consequently, the analyzed operational period (Δt) can be chosen freely (e.g., 15 minutes or 1 hour).

The calculations are implemented in the Python programming language together with the packages NumPy [70] and Pandas [68]. Pandas is used to organize the data into a results table called *data frame* provided by the package [69]. Figure 5.2 shows the different steps of the evaluation. The two main variables (1) are used as inputs for the thermodynamic calculations (2). Based on the results, the hydraulic calculations can be performed (3) after which the technical results from thermodynamics and hydraulics are used to calculate the average variable costs (4). All details are explained in the following subsections.

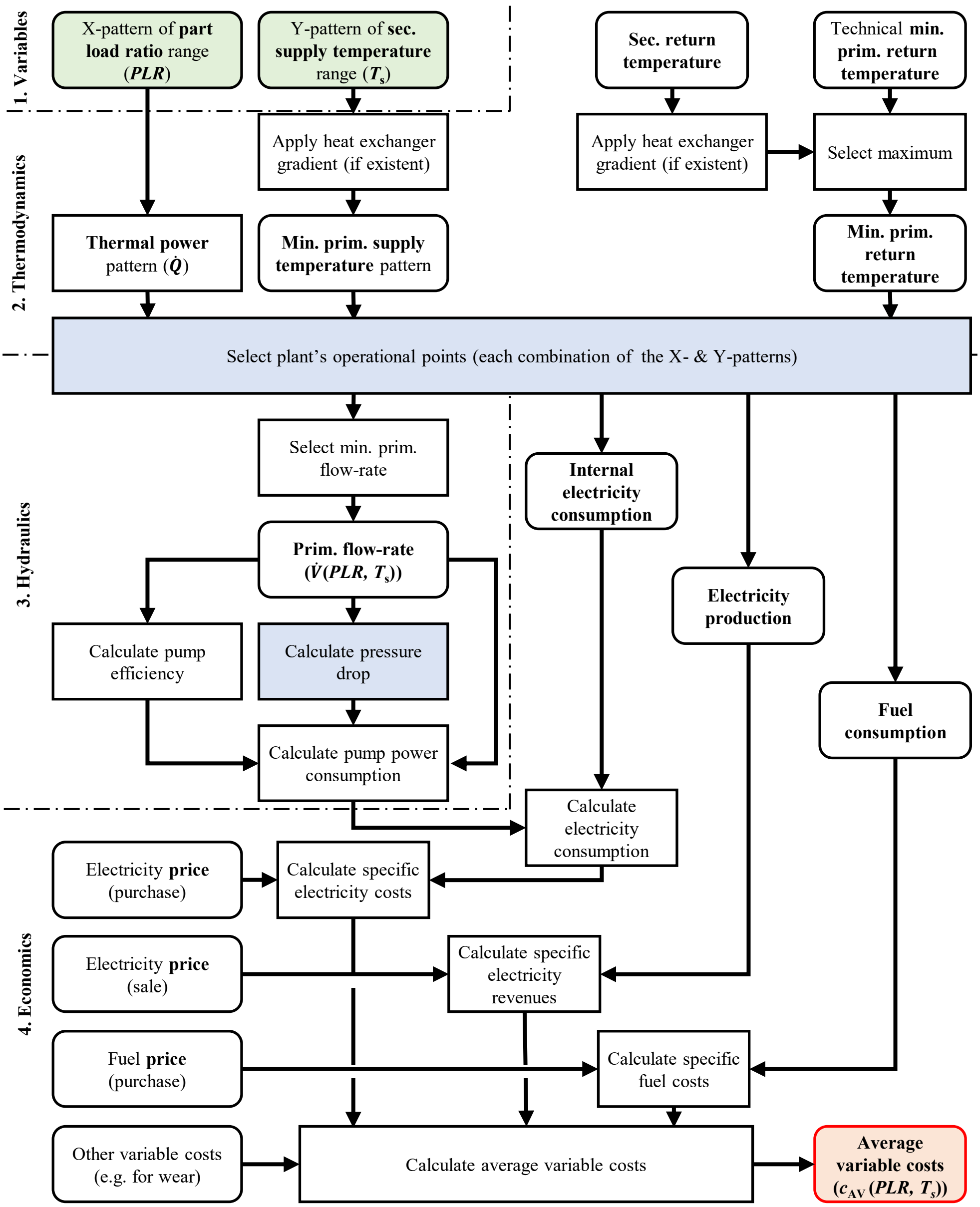

Figure 5.2: Method for the average variable cost calculation correlated to supply temperature and thermal power*

*An adapted version of this figure was previously published in [75].

Variables of the evaluation

The use of the PLR, a relative quantity that expresses a current thermal power output (highlighted green), allows for the comparability of plants with different maximum thermal power. The PLR is the quotient of current thermal power ($\dot{Q}$) and maximum power ($\dot{Q}_{\max}$) (equation 5.1).

$$PLR = \frac{\dot{Q}}{\dot{Q}_{\max}} \tag{5.1}$$

The discrete PLR pattern is defined by equation 5.2, and it depends on the resolution of the chosen step width ($\Delta\dot{Q}$) and the minimum thermal power ($\dot{Q}_{\min}$). The minimum thermal power is defined as the smallest thermal power that is allowed during operation.

$$\begin{aligned} PLR =& \frac{y \cdot (\dot{Q}_{\min} + x \cdot \Delta\dot{Q})}{\dot{Q}_{\max}}, \\ & \text{for } y \in \{0,1\},\ x \in \mathbb{N} \wedge 0 \leq x \leq \frac{(\dot{Q}_{\max} - \dot{Q}_{\min})}{\Delta\dot{Q}} \end{aligned} \tag{5.2}$$

The secondary supply temperature pattern (T_s, highlighted green) is defined by equation 5.3 and lies between the minimum ($T_{\mathrm{s,\,min}}$) and maximum supply temperature ($T_{\mathrm{s,\,max}}$). Its step size—the temperature difference (ΔT_s)—is chosen as 2.5 K. Although a higher resolution would be more precise, in practice, due to temperature controllers' inaccuracies, set-values beyond such precision could never be achieved in real operation.

$$\begin{aligned} T_\mathrm{s} =& T_{\mathrm{s,\,min}} + x \cdot \Delta T_\mathrm{s}, \\ & \text{for } x \in \mathbb{N} \wedge 0 \leq x \leq \frac{T_{\mathrm{s,\,max}} - T_{\mathrm{s,\,min}}}{\Delta T_\mathrm{s}} \end{aligned} \tag{5.3}$$

Thermodynamic calculation

Lowering the return temperature would have a strong impact on the variable costs [119] and is the objective of many studies. However, for the sake of simplicity and because of the focus on the supply temperature, a constant secondary return temperature is assumed for this evaluation. However, it would be possible to relax this restriction and include it as an additional variable. The minimum values of the primary supply and return temperatures can be calculated by applying the temperature gradient of the heat exchanger to the secondary temperatures. In most cases, the primary return temperature should be controlled to be as low as possible. But, in some cases, it can be increased to control the thermal power or must be increased due to specific technical constraints.

The next step—selecting the plant's operational points—is the key part of the calculations (large blue box in figure 5.2) and it must be implemented individually for each technology. Examples of this are presented in the following case studies. The internal set-points for each combination of PLR and supply temperature are chosen if the combination is possible within the technical constraints, whereby each possible set-point combination represents a row in the internal results table. The first columns include the combinations of PLRs (X-dimension) and supply temperatures (Y-dimension). The following columns include the internal electricity consumption (e.g., for heat pumps), fuel consumption (e.g., for HOBs), and electricity production (e.g., for CHP plants). Another column includes the primary flow rate ($\dot{V}$) on the primary side that is used for the subsequent hydraulic calculations.

Hydraulic calculation

The primary flow rate causes a pressure drop (Δp_{pump}) that must be calculated individually for each plant (small blue box in figure 5.2). The pressure drop and the flow rate ($\dot{V}_{\mathrm{pump}}$) combined with the pump's efficiency (η_{pump}) facilitate the calculation of the pump's electrical energy consumption ($P_{\mathrm{el,pump}}$) (q.v. equation 5.4), which is also included in a separate column in the internal results table.

$$P_{\mathrm{el,\,pump}} = \dot{V}_{\mathrm{pump}} \cdot \Delta p_{\mathrm{pump}} \cdot \frac{1}{\eta_{\mathrm{pump}}} \tag{5.4}$$

Economic calculation

The primary side pump's electricity demand and the internal electricity demand can be summarized to calculate the specific costs for electricity consumption ($c_{\mathrm{electricity}}$). The same can be done for the fuel consumption (c_{fuel}). Electricity production (e.g., via CHP plants) results in specific revenues ($r_{\mathrm{electricity}}$) that reduce the variable costs. Together with other specific costs (c_{others}) that are related to the duration of operation (e.g., costs for wear), these lead to the variable costs (c_{AV}) (red box in figure 5.2) as shown by equation 5.5. All costs are included as separated columns in the internal results table.

$$\begin{aligned} c_{\mathrm{AV}}\left(PLR, T_{\mathrm{s}}\right) =& c_{\mathrm{electricity}}\left(PLR, T_{\mathrm{s}}\right) - r_{\mathrm{electricity}}\left(PLR, T_{\mathrm{s}}\right) \\ &+ c_{\mathrm{fuel}}\left(PLR, T_{\mathrm{s}}\right) + c_{\mathrm{others}} \end{aligned} \tag{5.5}$$

Presentation of results

The results of the evaluation are three-dimensional and therefore an intuitive presentation is challenging. For the figures presented in the following, the package Matplotlib [120] is used.

As part of the presented development, different types of plots were evaluated. Two types of plots were identified to facilitate a sufficient presentation: three-dimensional scatter plots and colored mesh plots. In contrast to [75], three-dimensional scatter plots will be used alongside the colored mesh plots to combine each plot type's advantages and to allow for a qualitative and quantitative evaluation. In particular, the minimum and maximum limits of the z-axis help to interpret the magnitude of the costs in the three-dimensional plots. The average variable costs in both plots are colored in the two stacked colormaps *spectral* and *nipy spectral* in logarithmic and uniform scales.[5]

The plot axes represent the PLR and supply temperature ranges and are uniformly limited to achieve comparability of the plots. Costs that are below 0.01 €/MWh are rounded up and costs over 200 €/MWh are rounded down. The uniformity and the logarithmic scale allow for a comparison of the different plants even though their cost results ranges may differ considerably. The visualization according to the described rules is an essential part of the new method and can be reproduced for future applications of the method.

5.3 Case studies and specific implementation

The developed method is demonstrated by its application to selected plants. As this development is part of the research project Smart Heat Grid Hamburg, the case studies are defined according to plants of the DHS in Hamburg-Wilhelmsburg [12], which can be classified as 3GDH in the transition towards 4GDH.[2]

To allow for a differentiated discussion, some future plants (of hypothetic sizes) and variants of existing plants are included in the case studies. The plants and their specific implementations will be described in the following sections. Table 5.1 presents an overview of all the evaluated cases.

[5]This paragraph is not part of [75].

Table 5.1: Overview of heating plant case studies

Abbreviation	Type	Location	Max. thermal power in kW
ST-ETC	Solar thermal (evacuated tube collector)	Wilhelmsburg (Energiebunker (ENB))	740
ST-FPC	Solar thermal (flat plate collector)	Variant of ST-ETC	760
GT-130/60	Geothermal (130 °C reservoir, 60 °C injection)	Planned in Wilhelmsburg (variant)	17,900
GT-96/60	Geothermal (96 °C reservoir, 60 °C injection)	Planned in Wilhelmsburg (variant)	9,250
GT-96/50	Geothermal (96 °C reservoir, 50 °C injection)	Planned in Wilhelmsburg (variant)	11,200
ISH	Industrial surplus heat plant	Wilhelmsburg (ENB)	300
HP-40	Heat pump (40 °C source return)	Planned in Wilhelmsburg (variant)	2,000
HP-14	Heat pump (14 °C source return)	Planned in Wilhelmsburg (variant)	2,000
CHP-mean/mean	CHP plant (mean day-ahead price and mean biomethane price)	Wilhelmsburg (ENB)	650
CHP-high/mean	CHP plant (high day-ahead price and mean biomethane price)	Wilhelmsburg (ENB)	650
CHP-mean/low	CHP plant (mean day-ahead price and gas medium biomethane price)	Wilhelmsburg (ENB)	650
HOB (natural gas)	Heat only boiler (natural gas)	Like existing ones in Wilhelmsburg	1,280
HOB (biomethane)	Heat only boiler (biomethane)	Like existing ones in Wilhelmsburg, but with biomethane fuel	1,280

The most important hydraulic (e.g., pressure drop for pump energy consumption) and thermal conditions (temperatures and enthalpy flows) are implemented in a simplified way to demonstrate the method. These simplifications are described in the following.[2]

The hydraulic calculation considers the pressure losses of pipes using the methods from [121] and equations from [122] as well as the pressure losses caused by heat exchangers simplified by quadratic regression. The coefficients for the regression are given in the individual parameter tables while other pressure losses are analyzed individually for each technology. The efficiency of the pumps (η_{pump}) is simplified by equation 5.6 [cf. 123] which depends on the volumetric flow rate ($\dot{V}_{\text{pump}}$) and on the nominal values for volume flow rate ($\dot{V}_{\text{pump, nom}}$) and efficiency ($\eta_{\text{pump, nom}}$).[2]

$$\eta_{\text{pump}} \approx 1 - (1 - \eta_{\text{pump, nom}}) \cdot \left(\dot{V}_{\text{pump, nom}} / \dot{V}_{\text{pump}}\right)^{0.1} \tag{5.6}$$

Thermodynamic equations are needed to consider the supply temperature and to calculate the required flow rates. These equations must be implemented individually for each heat source, and they are presented in the respective subsection. Heat exchangers are included in a simplified way by assuming a fixed temperature gradient. The required plant parameters are either taken from publicly available references or estimated.[2]

All parameters and assumptions for the case studies are presented in appendix C (p. 353). For weather and economic data, the year 2019 is chosen and the secondary side return temperature is assumed to be 50 °C while the maximum network temperature is defined as being 95 °C.

5.3.1 Solar thermal heating plants

Solar thermal (ST) collectors capture solar radiation and convert it into heat. There are different types of solar thermal collectors which can be categorized into concentrated and non-concentrated solar thermal collectors [110, pp. 97, 147]. Non-concentrated solar thermal collectors are more relevant for DHSs. The most important collector types are flat plate collectors (FPCs) and evacuated tube collectors (ETCs) [124, fact sheet 7.1, p. 7]. ETCs have lower heat losses due to a vacuum inside [125, pp. 9–10]. Even though ETCs have a better performance, FPCs are often used due to their better price/performance ratio [124, fact sheet 7.1, p. 12].

The costs of operation are evaluated by considering the electricity consumption of the pumps to overcome the pressure losses inside collectors, pipes, and the heat exchanger[2]. It is assumed that the flow geometry inside the collector is a pipe. Further, it is assumed that the flow regime inside the collector is turbulent, which is mostly the case in DHSs [2, p. 444]. For these conditions, the pressure drop can be simplified by a quadratic function [126, p. 248]. The coefficients of the quadratic function are determined by quadratic regression using the nominal pressure loss at a nominal flow rate from the datasheet of the collector [127]. All component dimensions are determined by own design calculations in the course of this thesis and are based on local weather and critical hydraulic conditions[2]. Pipe diameters are designed according to the data in [124, table 7.3.2].

The collectors can be arranged in serial, parallel, or combined connections [125, pp. 11–12]. A series increases the temperature, and a parallel connection allows a higher flow rate. In serial connections, pressure drops are added and in parallel connections, the pressure drop is equal [122, pp. 146–150].

The evaluation is performed for two variants (ETC and FPC) and table C.7 (p. 359) shows all parameters that are used for both variants while the individual parameters for each variant are shown in tables C.8 and C.9 (pp. 360–361).

The first case (*ST-ETC*) is the existing solar thermal plant on top of the *ENB* in Hamburg-Wilhelmsburg [128], where ETCs are used in two sizes: *Ritter XL 34 P* and *Ritter XL 50 P*. Each of the 63 parallel collector rows installed consists of two *XL 34 P* and three *XL 50 P* [129] modules. The plant has a maximum thermal power of approximately 740 kW.[2]

The second variant (*ST-FPC*) is a hypothetical variant of the first one. Instead of ETCs, FPCs are used. A typical product for this application is the collector *HT-SolarBoost 35/10* that has been implemented by various large-scale plants (e.g., [130]–[132]). The plant is designed with the same collector area resulting in nine parallel rows of 10 serial modules. The maximum thermal power is approximately 760 kW.

The collector's heat production ($\dot{Q}_{\mathrm{coll}}$) can be calculated using equation 5.7 with the collector surface (A_{coll}), collector efficiency (η_{coll}), and total solar irradiance (G_{t}) [110, p. 122]. The expression for solar thermal collector efficiency is standardized by [133] in equation 5.8. The efficiency correlates with the mean collector temperature ($\overline{T}_{\mathrm{coll}}$), ambient temperature ($T_{\mathrm{a}}$), and the total solar irradiance. The zero-loss efficiency (η_0) and the first and second order loss coefficients (a_1, a_2) are parameters given by manufacturers [125]. The mean collector temperature in equation 5.9 is the average of the collector's input (T_{in}) and output temperatures (T_{out}) [110, p. 124].[2]

$$\dot{Q}_{\mathrm{coll}} = \eta_{\mathrm{coll}} \cdot A_{\mathrm{coll}} \cdot G_{\mathrm{t}} \tag{5.7}$$

$$\eta_{\mathrm{coll}} = \eta_0 - a_1 \cdot \frac{\overline{T}_{\mathrm{coll}} - T_{\mathrm{a}}}{G_{\mathrm{t}}} - a_2 \cdot \frac{(\overline{T}_{\mathrm{coll}} - T_{\mathrm{a}})^2}{G_{\mathrm{t}}} \tag{5.8}$$

$$\overline{T}_{\mathrm{coll}} = \frac{T_{\mathrm{in}} + T_{\mathrm{out}}}{2} \tag{5.9}$$

Equations 5.7 and 5.8 show the large impact of ambient temperature and solar irradiance on thermal production. Consequently, different weather conditions must be evaluated separately which can be done by using weather forecast data.[2]

Weighted by the frequency of hours with an irradiance of more than 150 W/m^2, 18 °C is the mean ambient temperature for the considered plant site while 300 and 700 W/m^2 are selected for the evaluation as typical values for Hamburg (q.v. figure C.1, p. 354).

5.3.2 Geothermal heating plants

The geothermal (GT) heating case study analyzes a deep hydrothermal doublet that is planned for the DHS in Hamburg-Wilhelmsburg with a depth of approximately 3,500 m [76]. As this plant is currently in the planning phase, no public data is available and hence a hypothetical example and some variations of it are created that are based on parameters and assumptions from literature. The relevant components of each plant are an extraction well with a down-hole pump, the closed heating system at the surface including a heat exchanger and other periphery components, and an injection well. In the underground, the system is hydraulically open and the geothermal medium flows between the outlet of the injection well and the inlet of the extraction well. Detailed parameters for the components and the geological composition are listed in tables C.10 to C.15 (pp. 362–365).[2]

Three different variants are evaluated (q.v. table 5.2). The parameters are taken from the case studies *power plant 1* and *heat plant 1* [134, pp. 383–389] and complemented by other references as presented in the appendix (tables C.10 to C.15, pp. 362–365). The variants (*GT-96/60* and *GT-96/50*) are based on assumptions concerning the maximum production temperature and the injection temperature.

Table 5.2: Overview of the geothermal case studies

Name	**Th. power**	**Depth**	**Reservoir temperature**	**Injection temperature**	**Reference**
GT-130/60	17.9 MW	4,000 m	130 °C	60 °C	*Power plant 1* [134, pp. 384, 386]
GT-96/60	9.3 MW	3,000 m	96 °C	60 °C	*Heat plant 1* [134, pp. 387, 388]
GT-96/50	11.2 MW	3,000 m	96 °C	50 °C	*Heat plant 1* [134, pp. 387, 388]

The maximum primary supply temperature equals the geothermal extraction temperature whereby the extraction temperature itself depends on the geological characteristics and the wells. Particularly relevant for the presented evaluation is the temperature at the considered depth (reservoir temperature) and the heat losses in the well.[2]

The reservoir temperature of different wells can differ on a large scale as a result of the different local geological conditions [134, p. 31]. Hamburg lies in a geological region called the *North German Basin (NGB)* and the local geological conditions affect the extraction temperature which can vary in a broad range and can only be verified after a well has been drilled. For the projected plant, it is estimated at 130 °C by the executing company [76].[2]

Because of this uncertainty, different values for the reservoir temperature are considered in this analysis. The first variant is related to the current estimation of 130 °C. For the second and third variants, a lower temperature is assumed. These variants are assumed to have a relatively low reservoir temperature of 96.4 °C. However, although the chosen temperature is low, the variants are of a realistic magnitude since an existing plant in Neustadt-Glewe has an extraction temperature of 97 °C at a depth of 2,450 m and it is also located in the North German Basin (NGB) [135].[2]

The temperature reduction in the well is computed in correlation to the flow rate. To do so, it is assumed that the underground temperature increases linearly from 8 °C [136, p. 35] near the surface to the reservoir temperature at the bottom. The well is divided into 1 m long cylindrical elements and each element's temperature results from the heat transfer from the inner medium to the underground and is calculated using parameters and equations from [137]. The calculation has been verified by the data provided in [136, p. 150].[2]

The minimum injection temperature of the first two variants is assumed to be 60 °C to prevent precipitation in case of a high salinity [134, p. 320][2]. Since the chemical composition of the reservoir is unknown, the third variant is assumed to have a low salinity, which leads to an estimated minimum injection temperature of 50 °C. The maximum thermal power of all plants is given by these temperatures and the maximum assumed flow rate.

The relevant parts for the hydraulic calculation of this plant are the wells including the down-hole pump as well as the heat exchanger on the surface. The pressure difference (Δp_{pump}) of the hydraulic open system is calculated using equation 5.10 from [134, p. 311] to determine the electricity demand of the down-hole pump.[2]

$$\Delta p_{\text{pump}} = p_{\text{WH}} + \Delta p_{\text{loss}} - \rho \cdot g \cdot Z_{\text{DFL}} \tag{5.10}$$

The term consists of three parts: the static wellhead pressure (p_{WH}) to prevent degassing in the geothermal medium, the friction of the well pipes (Δp_{loss}), which can be calculated from the pipe's characteristics, and the pressure resulting from the dynamic fluid level height (Z_{DFL}). The dynamic fluid level can be calculated with equation 5.11 [134, p. 311] and is responsible for the main pressure loss. It describes the fluid level in the ground that is reduced by the pump from the static fluid level (Z_{SFL}) to the dynamic fluid level. The geothermal productivity index (PI) represents the characteristics of the geological formation.[2]

$$Z_{\text{DFL}} = Z_{\text{SFL}} + \frac{\dot{V}}{PI \cdot \rho \cdot g} \tag{5.11}$$

Because of the complex chemistry of the geothermal fluid, the density of normal water (q.v. figure A.5, p. 316) is not valid for this medium. Detailed calculations would require more assumptions regarding the fluid chemistry which cannot be included in this analysis and therefore the density is assumed as constant in this case (q.v. table C.12, p. 363). Because no information is given in the case study, the static fluid level is assumed to be 100 m. The value is verified by the calculation of the overall pressure drop and the pump's electricity consumption. The pipe roughness is another parameter that is estimated. Based on pressure losses given by Stober et al., it is estimated as being 0.013 mm. This value is validated by the comparison with the results in [136, p. 220]. The magnitude of the roughness is also plausible if it is compared to the values given in [121, p. 35].

Applying the equations to the parameters that are provided in tables C.12 to C.15 (pp. 363–365) results in a maximum electrical consumption of the geothermal pump of 1,150 kW for the 3,000 m well and 1,200 kW for the 4,000 m well. To verify the magnitude of the electricity consumption, the pumping power is compared to different reference cases in table 5.3. Due to the different productivity indices and other different parameters that are related to the individual geological regions, the case studies shown are hardly comparable. Although the relatively low productivity index results in high demand for electrical power, the magnitude of the electrical pumping power is plausible. The table also shows that studies investigating the same geological region (NGB) indicate a plausible magnitude for the assumed productivity index. Due to the lack of availability of other data, the chosen geothermal productivity index of 30 m^3/h/MPa is acceptable. The impact of the uncertainty on the quantitative validity of these assumptions will be discussed in section 5.5.[2]

Table 5.3: Reference studies of other geothermal reservoirs*

Site	Max. flow rate	Productivity index	Electrical power	Reference
Case study, Hamburg, Germany (NGB)	70 l/s	30 m^3/h/MPa	1,150 kW/ 1,200 kW *	
Textbook example	77 l/s	30 m^3/h/MPa	1,270 kW	[134, p. 365]
Bavaria, Germany	145 l/s	290 m^3/h/MPa	1,050 kW	[138]
Alasehir, Turkey	69 l/s	745 m^3/h/MPa	157 kW	[137]
Kizildere, Turkey	63 l/s	-	250 kW	[139]
Groß Schönebeck, Germany (NGB)	-	0.6–15 m^3/h/MPa	-	[140]
West Mecklenburg-Vorpommern, Germany (NGB)	-	22–40 m^3/h/MPa	-	[141]

*This table was previously published in [75]. The electrical power of 1,200 kW is added for the 4,000 m deep well.

The main costs arise from the electricity consumption of the down-hole pump. In addition to the electricity consumption, costs arise from worn parts and components due to the high mechanical stress of the down-hole pump.[2] These are estimated at approximately 40 € (3,000 m well) and 60 € (4,000 m well) per hour of operation. This estimation is based on two factors that indicate the maintenance costs as a share of the surface and subsurface investments. The plant-specific subsurface investment is provided in table C.10 (p. 362) while the surface investment is given in table C.11 (p. 362). The factors are provided in table C.12 (p. 363).

5.3.3 Industrial surplus heating plants

Industrial surplus heat (ISH) can be expressed using different terms such as industrial *waste heat*, *excess heat*, or *heat recovery*. It means that surplus heat is recovered which would otherwise be emitted into the environment. Related to Brueckner et al., surplus heat is defined as "all forms of heat [...] that escape a system [and] are not the purpose of the system. Heat from CHP plants is therefore not considered" [142]. Besides heating applications, the heat could also be used in organic-Rankine-cycle processes to generate electricity [143] but especially low-temperature surplus heat often cannot be utilized in a profitable way inside an industrial site [144]. Of course, the best option for heat recovery depends on each site's specifications. But, as demonstrated in the case study by Battisti et al., DHS's heat utilization can be more profitable than electricity generation via organic-Rankine-cycle technologies [143]. Also, Moser et al. conclude that space heating can be a good utilization of low-temperature surplus heat [144]. These evaluations give a strong indicator for a preferred utilization in DHSs.

Besides the advantages of using surplus heat, Brueckner et al. indicated that its utilization is hindered by different economical and technical barriers [142]. The reasons are that producing heat is not the core business of the industrial companies as they do not have the knowledge or the personnel to produce heat. Technically, the heat production and the demand are not always synchronized, which leads to the requirement of more flexibility on the DHS's side. Economically, the required investment fund is often not sufficiently available, or too high rates of return are expected. From the DHS perspective, there is uncertainty concerning the economic future of the industrial site. Further, it is complicated to define the price of heat in monopoly systems at each point in time. [142]

The potential and efficiency of industrial surplus heat are strongly related to the temperature level of the surplus heat source and the demand side temperatures [145]. The characteristics of these types of heating plants strongly depend on the local heat sources and their hydraulic integration.[2]

For this case study, an existing industrial surplus heating plant in the DHSs in Hamburg-Wilhelmsburg is evaluated [146, p. 16] and its piping and instrumentation (P&I) diagram is presented in figure 5.3. The plant extracts the heat from several industrial processes and the exemplary evaluation of this plant demonstrates the application of the method. Further, it can be shown how different temperature levels of different heat sources can be combined and aggregated to a single heating plant.

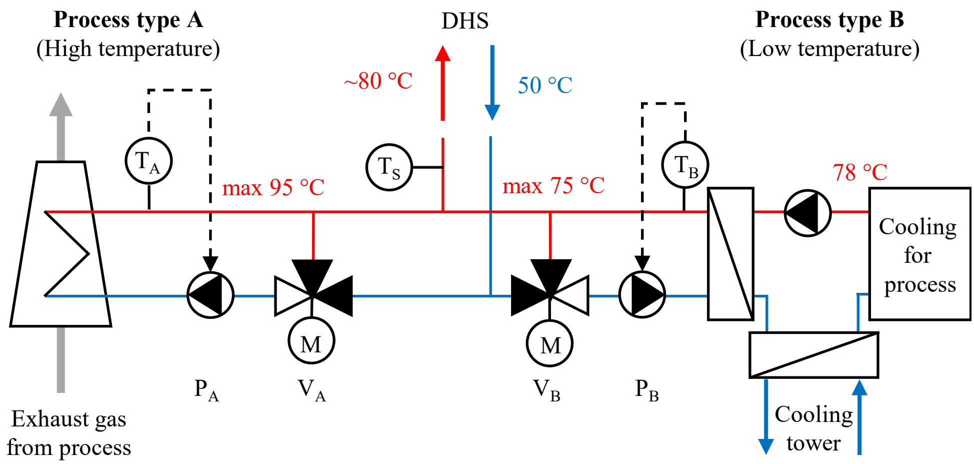

Figure 5.3: P&I diagram of the industrial surplus heat plant (simplified from [147])

The plant can be simplified into two types of processes. The first process (A) uses exhaust gas heat, can produce 100 kW at a maximum temperature of 95 °C and, if enabled, it can only run at full thermal power. The second one (B) is a cooling process with 200 kW and a maximum temperature of 75 °C. Using a downstream cooling tower, the amount of heat led off can be adjusted. The plant's supply temperature is the mixing temperature of both streams. The electrical energy consumption depends on the pressure losses of the process heat exchangers and the pipes to overcome the distance on the industrial site (300 m). More parameters are listed in table C.16 (p. 366).[2]

5.3.4 Heat pump plants

In Sweden, large-scale heat pumps (HPs) are connected to DHSs since 1980. There are different types of heat pumps. The most common types that are used for DHSs are compressor heat pumps and absorption heat pumps. An absorption heat pump is driven by a thermal energy source while compressor heat pumps are often driven by electrical motors. The heat pump can raise a lower temperature level of a heat source to a higher one for the heat sink. The coefficient of performance (COP) is the most important KPI that represents the needed driving power in relation to the produced heat. Particularly for bigger heat pumps, the COP can be improved if several heat pumps are combined to fulfill the temperature increase. [2, pp. 218–235]

The COP can be calculated using equation 5.12 and expresses the relation of electrical power to heating power [2, pp. 219–224]. The internal temperatures

$T_{\text{HP, sink}}$ and $T_{\text{HP, source}}$ of the heat pump represent the isotherm conditions during evaporation and condensation. In technical applications, heat exchangers (HEXs) must be used to transfer the heat from the source to the heat pump and from the heat pump to the DHS. These heat exchangers induce temperature gradients between the primary and secondary sides. For the further calculation, the gradient $\Delta T_{\text{HEX, s}}$ and $\Delta T_{\text{HEX, r}}$ are simplified to be constant. This allows one to calculate the COP_{Carnot} using the DHS supply temperature and the heat source return temperature ($T_{\text{r, source}}$) (q.v. equations 5.13 and 5.14).

$$COP_{\text{Carnot}} = \frac{\dot{Q}}{P_{\text{el}}} = \frac{T_{\text{HP, sink}}}{T_{\text{HP, sink}} - T_{\text{HP, source}}} \tag{5.12}$$

$$T_{\text{HP, sink}} = T_{\text{s}} + \Delta T_{\text{HEX, s}} \tag{5.13}$$

$$T_{\text{HP, source}} = T_{\text{r, source}} - \Delta T_{\text{HEX, r}} \tag{5.14}$$

The technical implementation of an ideal Carnot cycle leads to efficiency reductions, resulting in a lower COP. Losses that are induced by a fraction, or electrical consumptions like internal pumps, reduce the theoretical Carnot COP to a $COP_{\text{technical}}$. The resulting factor f_{Lorenz} (equation 5.15) is related to specific technical characteristics [118].

$$f_{\text{Lorenz}} = \frac{COP_{\text{technical}}}{COP_{\text{Carnot}}} \tag{5.15}$$

The authors Arpagaus et al. prepared a review of high-temperature heat pumps and found that many large-scale heat pumps can produce more than 90 °C. Only a few of the manufacturers can build aggregates for 120 °C or even higher. Although some of these high-temperature heat pumps are available, it is currently a field of ongoing research. The review further showed that the relation of COP to Carnot COP (q.v. below) lies between 40 and 60 %. [148]

Here, the factor is assumed to be 50 %.

If the heat pump is driven in part load mode, the COP is further reduced. Lee et al. analyzed the optimal behavior related to the PLR of heat pumps. As one of their results, it can be said that the modulation of several parallel heat pumps and the combination with TESs can improve the heat pump operation and its efficiency. [149]

Related to the data from Lee et al., figure 5.4 presents the data for interpolation.

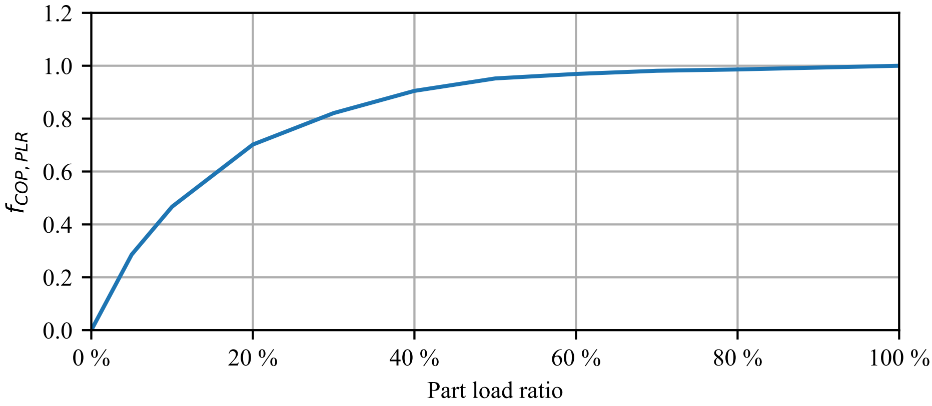

Figure 5.4: Factor for the COP to PLR relation of a heat pump (data from [149])

The data is normalized to the factor $f_{\text{COP, PLR}}$ in relation to the maximum value at $(PLR = 1)$. This is expressed by equation 5.16.

$$f_{\text{COP, PLR}}(PLR) = \frac{COP(PLR)}{COP(PLR = 1)} \tag{5.16}$$

Combining these factors, the COP_{heating} can be expressed by equation 5.17.

$$COP_{\text{heating}} = COP_{\text{Carnot}}(T_{\text{s}}, T_{\text{r, source}}) \cdot f_{\text{Lorenz}} \cdot f_{\text{COP, PLR}}(PLR) \tag{5.17}$$

The PLR impact was further analyzed by Edwards et al. who found that for a single mode, the minimum PLR is 10 % [150].

Besides the influences due to thermal power and supply temperature variation, Waddicor et al. worked out that high losses through start-up also occur. These losses can be compensated by using the heat pump in part load instead of start-stop operation. An important result of their evaluation is that startup losses are not negligible and that even small-scale heat pumps should be operated for a minimum duration of 20 minutes. [151]

These evaluations show important operational conditions for heat pumps. Nevertheless, no studies were found that combine the PLR and supply temperature impact variable costs. Therefore, it will be analyzed by using two compression heat pump variants *HP-40* and *HP-14*. The compression heat pumps are selected due to their relevance to the electrical grid and possible interaction with electrical markets. The parameters of both variants are presented in table C.17 (p. 367) and their maximum thermal power is assumed to be 2,000 kW. The difference between the variants is the return temperature of the heat source. Variant *HP-40* cools its heat source down to 40 °C (e.g., a return temperature) while variant *HP-14* reduces the source temperature down to 14 °C (e.g., to the groundwater temperature).

5.3.5 Combined heat and power plants

The combined heat and power (CHP) technology allows for the recovery of heat while producing electricity. There are several types of CHP technologies: steam processes (back pressure, extraction-condensing, and combined cycles), gas turbines, and small-scale CHP plants such as gas engines or also fuel-cells. Each technology has its own characteristics. For example, the extraction-condensing cycle has the advantage that the amount of heat is not fixed in relation to the amount of electricity. Some technologies are also independent of the fuel used. This is especially relevant when it comes to solid fuels such as waste or biomass [2, pp. 146–189].

Furthermore, some processes can be driven by low-temperature heat sources such as organic-Rankine-cycle, Kalina, or Flash processes [110, p. 354].

In the considered case studies, Otto-engines firing biomethane will be analyzed which are used in the DHS in Hamburg-Wilhelmsburg.

Compared to the other CHP technologies, the gas engines allow quick start-ups and a good electric load following and they can produce hot water or low-pressure steam. The part load operation is possible under high efficiency, which is valid for part loads between 50 and 100 %. [152, pp. 27–38]

In the market overview [153, p. 9], it is shown that larger plants have higher efficiency. Depending on the size and model, the electrical efficiency (η_{el}) is between 25 and 49 % while the mean value is 38 %. The thermal efficiency (η_{th}) is between 22 and 65 % and the mean value is 49 %.

Investigations that include the part load production of Otto-engines are mostly related to smaller-scale plants. The authors Bianchi et al. use a normalized factor for the electrical and thermal efficiency to express the part load behavior [154] which is presented in figure 5.5. The data was given for micro-CHP (below $100\,\mathrm{kW_{el}}$). In the case that is presented later, it will be applied on a slightly larger scale (approximately $500\,\mathrm{kW_{el}}$).

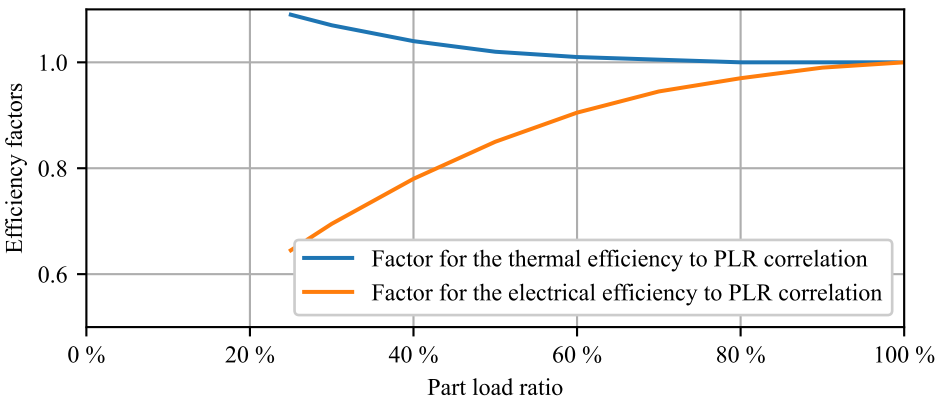

Figure 5.5: Factor for the efficiency to PLR correlation of a CHP plant (data from [154, Fig. 9a])

In [155], Thomas conducted tests with different kinds of micro-CHP to analyze the relation of supply temperature to efficiency. For gas-Otto CHP plants, the result is that the electrical efficiency is not affected by lower supply temperatures. This is related to the internal construction of the engine. To prevent condensation in the cylinder, the minimum internal temperatures must be approximately 80 °C. Nevertheless, it is shown that the thermal efficiency is slightly lower at high supply temperatures. The results show that the efficiency is reduced by about 2 % in relation to 20 °C higher supply temperatures. [155]

Even though the values are recorded for a smaller scale, the engine principle should be identical to the larger-scale CHP plants. Related to the results from [155], the factor $f_{\eta_{\mathrm{th}},\mathrm{T_s}}$ is developed which includes a linear regression using the plant's nominal ($T_{\mathrm{s,nom}}$) and maximum supply temperature ($T_{\mathrm{s,max}}$) (q.v. equation 5.18).

$$f_{\eta_{\mathrm{th}},\mathrm{T_s}}(T_{\mathrm{s}}) = 1 + \frac{\eta_{\mathrm{th}}(T_{\mathrm{s,nom}}) - \eta_{\mathrm{th}}(T_{\mathrm{s,max}})}{(T_{\mathrm{s,nom}} - T_{\mathrm{s,max}})} \cdot (T_{\mathrm{s,nom}} - T_{\mathrm{s}}) \tag{5.18}$$

Combining these results, the thermal efficiency (η_{th}) can be expressed by equation 5.19 using the nominal thermal efficiency ($\eta_{\mathrm{th,nom}}$) and the thermal factor ($f_{\eta_{\mathrm{th}},\mathrm{PLR}}$) from figure 5.5. The electrical efficiency (η_{el}) can be expressed by equation 5.20 using the nominal electrical efficiency ($\eta_{\mathrm{el,nom}}$) and the electrical factor ($f_{\eta_{\mathrm{el}},\mathrm{PLR}}$) from figure 5.5.

$$\eta_{\mathrm{th}}\,(PLR, T_{\mathrm{s}}) = \eta_{\mathrm{th,nom}} \cdot f_{\eta_{\mathrm{th}},\mathrm{PLR}}(PLR) \cdot f_{\eta_{\mathrm{th}},\mathrm{T_s}}(T_{\mathrm{s}}) \tag{5.19}$$

$$\eta_{\mathrm{el}}\,(PLR) = \eta_{\mathrm{el,nom}} \cdot f_{\eta_{\mathrm{el}},\mathrm{PLR}}(PLR) \tag{5.20}$$

For the evaluation, the gas-Otto CHP plant *Sokratherm GG 530* is selected, which is installed in the *ENB* [156]. All parameters are listed in table C.18 (p. 368). In addition to the freely available technical data, some assumptions are made. As explained above, it is assumed that the thermal efficiency degenerates by 2 % related to a 20 °C higher supply temperature. The costs for the electricity-grid-connection are listed in appendix C.1.2 (p. 355) while the costs for the gas-grid-connection are listed in appendix C.1.3 (p. 358). In Germany, the average variable cost calculation for CHP plants is complex due to different subsidy systems.

In this evaluation, the CHP will be assumed as a biomethane plant in the German renewable energy regime (*EEG 2012*). The subsidy takes flexible operation into account. It can be calculated with equation 5.21 including the fixed subsidy ($subsidy_{\text{fixed}}$), a management bonus ($bonus_{\text{management}}$), the price ($py_{\text{sale}}$) at the spot market (lowered by sales costs), and a monthly mean price reference ($\overline{py}_{\text{reference}}$) [157, pp. 93–94]. In addition, the energy tax, which must be paid for the gas consumption, can be refunded for CHP plants [158] and is therefore not considered in the gas cost calculation.

$$r_{\text{el,sale}} = py_{\text{sale}} + subsidy_{\text{fixed}} + bonus_{\text{management}} - \overline{py}_{\text{reference}} \tag{5.21}$$

The revenues and costs are sensitive to the electricity and fuel prices and therefore a basic variant and two sensitivity variants will be evaluated. Table 5.4 presents the three CHP case studies.

Table 5.4: Overview of CHP plant case studies (data from [159] and [160, p. 9])

Abbreviation	**Electricity price**	**Fuel price**
CHP-mean/mean	mean day-ahead price (36.64 €/MWh)	mean biomethane price (70.60 €/MWh$_{\text{GCV}}$)
CHP-high/mean	high day-ahead price (46.34 €/MWh)	mean biomethane price (70.60 €/MWh$_{\text{GCV}}$)
CHP-mean/low	mean day-ahead price (36.64 €/MWh)	low biomethane price (56.00 €/MWh$_{\text{GCV}}$)

The price of the electricity itself fluctuates all time and thus two variations were defined related to figure C.2 (p. 357). Variant *CHP-mean* uses the volume-weighted mean annual day-ahead price for Germany in 2019 (36.64 €/MWh) while variant *CHP-high* uses the mean daily day-ahead price at the 10 % highest position (48.34 €/MWh). Another important impact on costs results from the price of the fuel. The case studies use biomethane which has its origin in bio-gas plants. The gas is cleaned up and fed into the natural gas grid. Biomethane is transferred through the natural gas grid and balanced based on certificates. There are several types and different prices of biomethane [160] and, for the evaluation, gas from cultivated biomass is used. The first and second variants use the mean price for biomethane from cultivated biomass (70.60 €/MWh_{GCV}), and the third variant uses the lowest price (56.00 €/MWh_{GCV}) [160, p. 9].

5.3.6 Heat only boiler plants

Heat only boilers (HOBs) based on combustion previously were the most important source of heat in heating systems. Besides fossil fuels, many types of HOBs can burn biofuels [cf. 2, p. 122] or synthetic fuels to produce heat.

At present, natural gas-fired HOBs are used for the current heat supply and, in many cases, new heating plants must be competitive in regard to this technology. Therefore, a natural gas HOB is used in this case study for benchmarking purposes and the gas-fired HOB analysis is comparable to the CHP analysis. For highly efficient gas-fired HOBs, the efficiency dependency on PLR ($\eta_{\mathrm{th,\,PLR}}$) can be interpolated by the data given in [161]. The efficiency is normally given in relation to the net calorific value (NCV). For correct analysis, it is transformed to the gross calorific value (GCV) as shown in figure 5.6.

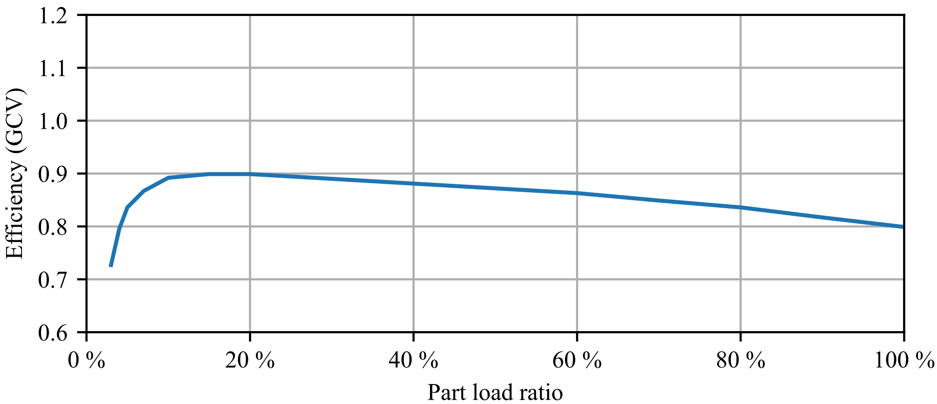

Figure 5.6: HOB efficiency (GCV) related to PLR (NCV data from [161, fig. 2.8])

Even though gas-fired HOBs are very common for the heating of residential buildings, data that combines supply temperature and PLR for efficiency is rarely available for them. One reason could be that the real operation of HOBs is mostly very dynamic and mean values could be more useful in practice than specific operational points. Another reason is that the losses incurred by varying the supply temperature can be relatively small compared to start-stop losses or other impacts.

Nevertheless, the influence of the system temperature on radiation losses is described in [162, p. 43]. The efficiency is shown related to an increasing pair of the supply and return temperatures with a gradient of 20 K. Through the high impact of the return temperature on HOBs, this data cannot directly be used, but demonstrates the negative influence of increasing system temperatures based on efficiency.

The authors Terhan et al. showed that the highest share of losses is related to the flue gas (16.8 %) and only 1 % to radiation [163].

Both evaluations do not explicitly calculate the efficiency over PLR and supply temperature in combination with a fixed return temperature. Therefore, the efficiency interpolation is combined with an efficiency correction offset ($\Delta\eta_{\mathrm{th}}$) in equation 5.22. This equation is used in [164, p. 63] for annual HOB evaluation up to 70 °C. Here, it will also be applied to higher temperatures. As shown later, the effect is relatively minor, and thus small errors from this simplification approach will not have a significant impact on the general results.

Resulting from these steps, the HOB efficiency (η_{th}) can be calculated using equation 5.23.

$$\Delta\eta_{\mathrm{th}}\,(T_{\mathrm{s}}) = 0{,}0024/\,^{\circ}\mathrm{C}\cdot(70\,^{\circ}\mathrm{C} - \vartheta_{\mathrm{s}}) \tag{5.22}$$

$$\eta_{\mathrm{th}}\,(PLR, T_{\mathrm{s}}) = \eta_{\mathrm{th,\,PLR}}(PLR) + \Delta\eta_{\mathrm{th}}(T_{\mathrm{s}}) \tag{5.23}$$

All input parameters for the evaluation are listed in the appendix in table C.19 (p. 369). The gas grid costs are explained in appendix C.1.3 (p. 358). The evaluation is focused on one HOB with a maximum thermal power of 1,280 kW which can be found in the DHS in Hamburg-Wilhelmsburg. In the first variant, the HOB is fed by natural gas as a benchmark of the existing fossil heat supply. The price for the fuel is taken for the year 2019 [165, p. 23]. In the second variant, the HOB is fed with biomethane to allow for a comparison of this technology with the other renewable sources. The price is identical to the one presented in section 5.3.5. Table 5.5 shows the two variants.

Table 5.5: Overview of HOB case studies

Abbreviation	**Fuel price**
HOB (natural gas)	mean natural gas price (25.55 €/$\mathrm{MWh_{GCV}}$)
HOB (biomethane)	mean biomethane price (70.60 €/$\mathrm{MWh_{GCV}}$)

5.4 Results of the heating plant evaluation

In this section, the individual results of each case study are presented. For a graphical depiction, the previously introduced plot is used. Additionally, the data is described and interpreted.

5.4.1 Results for solar thermal heating

Figure 5.7 depicts the average variable costs of the solar thermal variant *ST-ETC* at 300 (a) and 700 W/m^2 (b) as well as the variant *ST-FPC* at 700 W/m^2 (c). The highest level of production can be achieved at the lowest temperatures and the costs are not affected by the chosen temperature. In contrast, the costs are impacted by the PLR.

Because of the low pressure loss inside the system and resulting low power consumption for the pump, the average variable costs are low. Parts (a) and (b) show that the high efficiency of the ETCs leads to a high possible supply temperature and a small control range of the PLR. The supply temperature is almost independent of the chosen PLR and only for the maximum PLR does the full supply temperature decrease. In principle, the PLR can be reduced by increasing the primary flow rate and, as a result, an increased internal collector temperature would result in lower efficiency. The maximum production (PLR) is limited by the weather conditions, which is demonstrated by the lower PLR of (a) compared to (b) correlated to the different irradiances in (a) and (b). A PLR of 100 % can only be achieved at the maximum radiation for this site and optimal temperature conditions. The minimum production is a result of the technical maximum internal collector temperature.[2]

Both points of operation have the lowest costs in the medium range, while the edge areas are more expensive.

In contrast to the ETC cases, case (c) has a lower maximum PLR at 700 W/m^2. The PLR can be controlled to low values near zero. This is related to the higher losses of the FPC at high internal temperatures. At high PLRs, the temperature has a significant impact (approximately 10 % less PLR at 95 °C compared to 60 °C). Lower PLRs do not have an impact on the average variable costs. In this case, high PLRs also lead to a small (absolute) increase in costs.

As shown, the performance of solar thermal plants is significantly impacted by the weather conditions. The annual irradiance is presented in figure C.1 (p. 354). This weather-dependent behavior leads to two different feed-in strategies for DHSs. The first possibility is that these plants have a small dimension compared to the demand in the grid. In this case, the production (which mainly takes place in summer) can be continuously consumed. The other option is to include seasonal TESs. Both options should be considered in the annual evaluations of the capacity market.

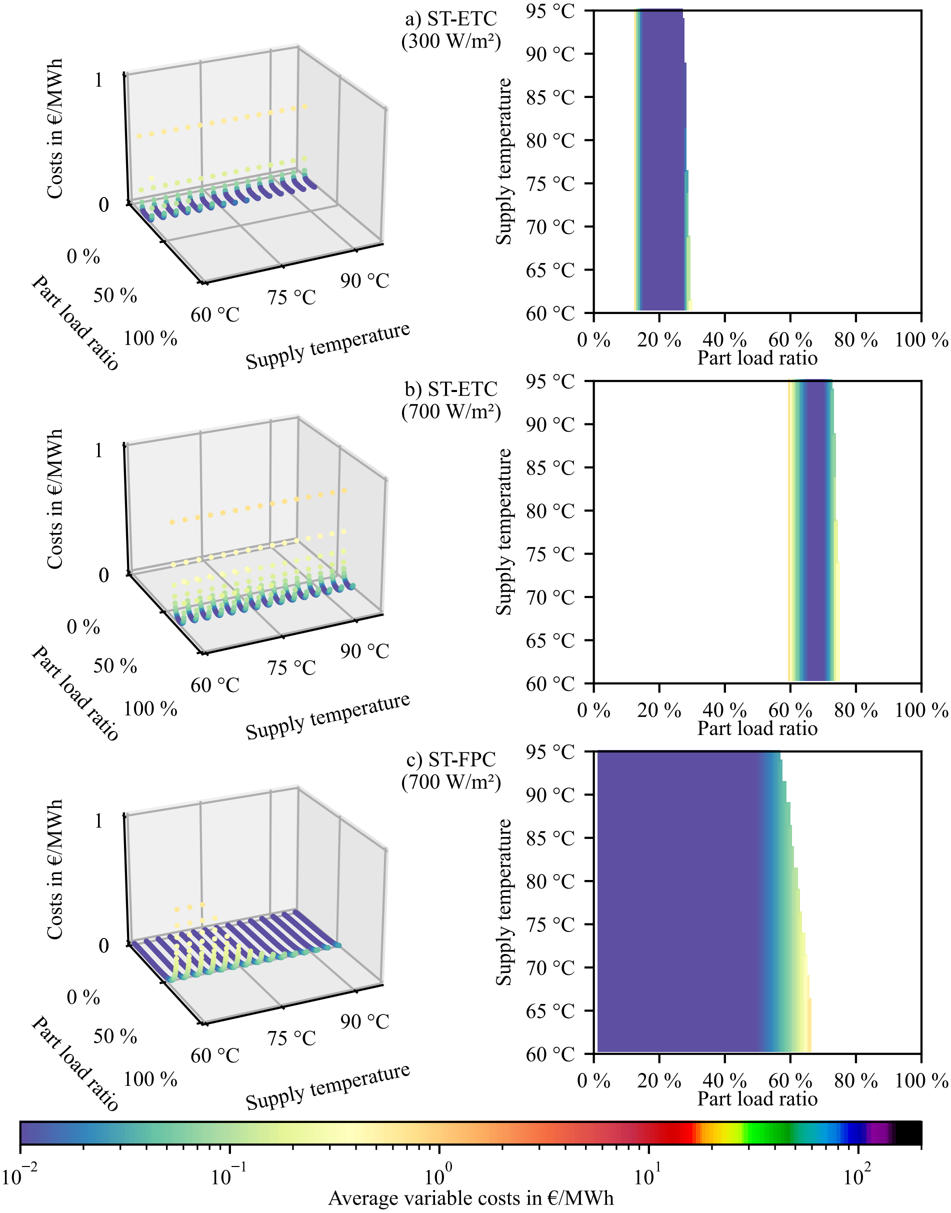

Figure 5.7: Average variable costs of the solar thermal plants*

*The plot of case (b) on the right was previously published in [75] with a different colormap.

5.4.2 Results for geothermal heating

Figure 5.8 presents the correlation between the geothermal flow rate and the extraction temperature of the variants' geothermal wells. The reservoir with 130 °C has a depth of 4,000 m and the reservoir with 96 °C has a depth of 3,000 m.

The figure shows that low flow rates result in lower supply temperatures through the increasing influence of the heat losses in the well on the geothermal medium due to the longer dwell time.[2]

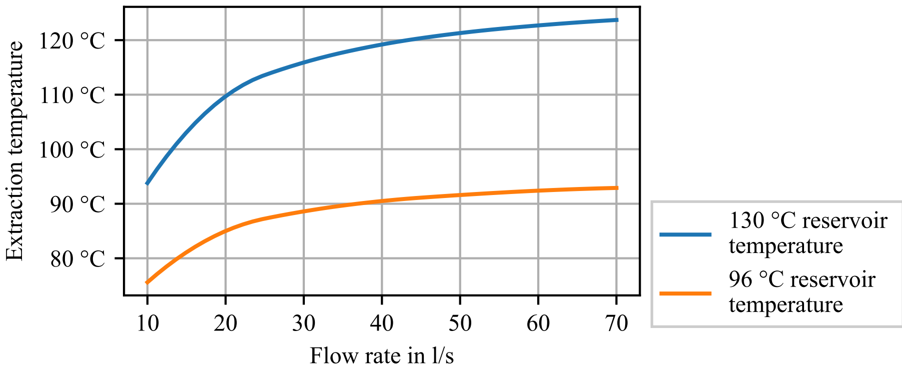

Figure 5.8: Extraction temperature dependence on flow rate for the geothermal plants

The results for the average variable costs of the geothermal heating plants are depicted in figure 5.9. In general, the costs are higher than for the solar thermal plant. This is particularly induced by the high electricity demand and the high electricity price for the down-hole pump and also due to the wear of parts and components.[2]

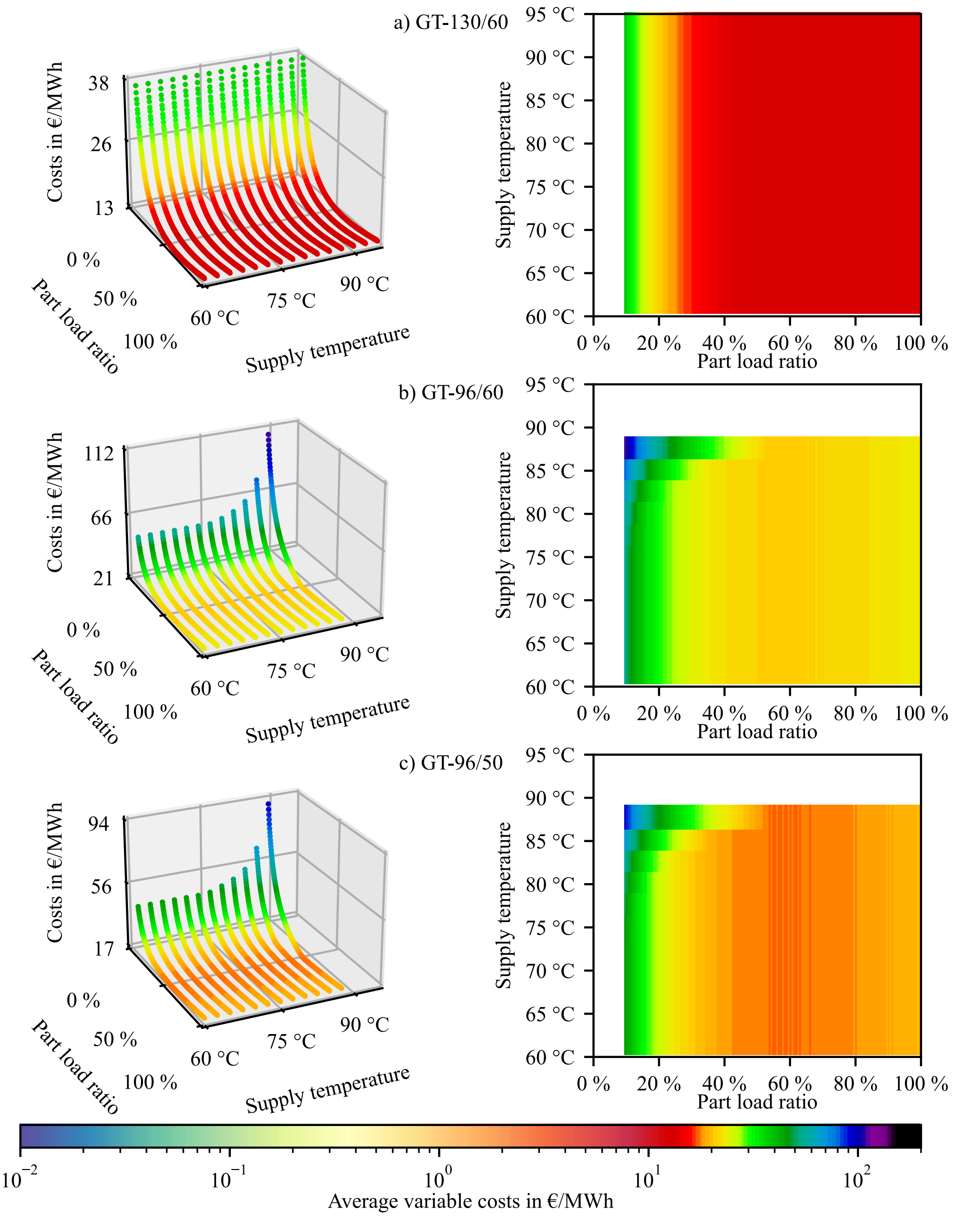

Figure 5.9: Average variable costs of the geothermal plants*

*The plot of case (b) on the right was previously published in [75] with a different colormap.

The variant *GT-130/60* is presented in part a). What is striking is that the costs are lowest between 38 % and 100 % PLR with a minimum of 13 €/MWh. Lower thermal power is more expensive and can result in costs of more than 20 €/MWh (up to 38 €/MWh). This sharp rise (in the direction of a lower PLR) results from the higher share of operational costs due to the lower energy production and an hourly basis for the costs of wear. All in all, the average variable costs are relatively low for this variant with a high reservoir temperature and the average variable costs do not show a significant impact on the supply temperature.

Figure 5.9 b) shows the average variable costs for the *GT-96/60* case. The average variable costs are much higher compared to the previous case (indicated by the limits of the z-axes). The lowest average variable costs are at medium PLRs with a minimum of 21 €/MWh. Again, lower production leads to higher average variable costs which are rather high (30 to 50 €/MWh) and which, at high temperatures, would further increase to more than 100 €/MWh. The lower reservoir temperature results in a maximum secondary supply temperature of almost 90 °C. The temperature impact is high at low production and high temperature.

Part c) shows the average variable costs for the *GT-96/50* case. Through the lower injection temperature, this case is more cost-efficient than the *GT-96/60* case. The lowest average variable costs are around 17 €/MWh at medium PLR while the average variable costs at full production are slightly higher. The general characteristic is identical to the *GT-96/60* case.

At full load, the requested temperature only has a small impact because of the high extraction temperature at high flow rates. However, with decreasing PLR, the costs increase. This is particularly the case at a high temperature and low PLR and this effect is caused by the temperature to flow rate correlation. If the PLR is low and high temperatures are required, the flow rate must be high to generate the temperature. But, due to the requested operational point, not all the energy is transferred inside the heat exchanger, and thus the injection temperature increases. The unused exergy is subsequently reinjected into the ground.[2]

The average variable costs are mostly dependent on the electricity consumption of the down-hole pump and costs for wear. As a result, it is shown that supply temperature plays an important role in operation when it comes to medium-high reservoir temperatures.

5.4.3 Results for industrial surplus heating

The given conditions of the industrial processes result in the average variable costs shown in figure 5.10. As it can be seen, the costs are very low in general although an increase in the costs occurs at low temperatures and full loads. The high load requires a high flow rate if the resulting temperature difference between the supply and return line is small and the high flow rate induces a higher electricity consumption. Another interesting result is the maximum temperature related to the PLR. For a PLR below 33 % (100 kW), heat extraction is only possible from process B because the heat output of process A is not adjustable. At exactly 100 kW, process A can deliver its full thermal power and the maximum temperature of 95 °C. With an increasing PLR, an increasing amount of energy from process B is added. This results in a decrease in the maximum possible temperature for a higher PLR.[2]

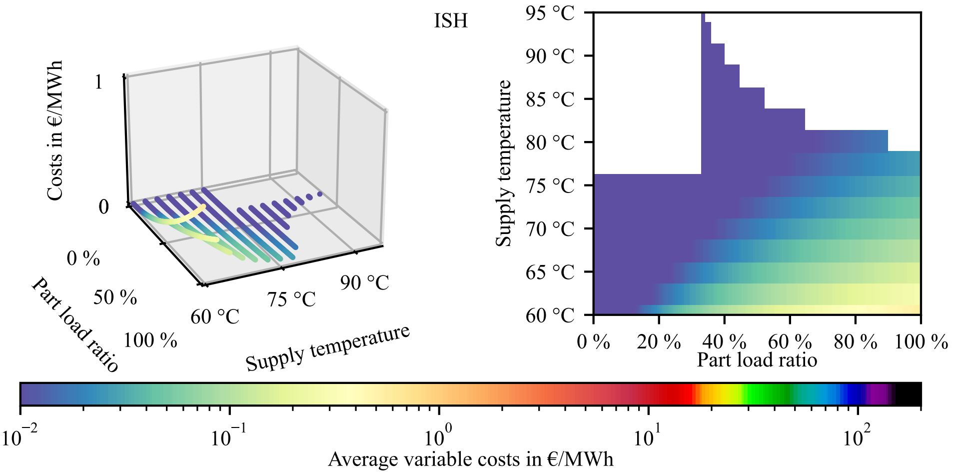

Figure 5.10: Average variable costs of the industrial surplus heating plant[6]

In alignment with [144], it can be shown that the lower the DHS's required temperature, the higher the possibility and benefit of industrial surplus feed-in. Low supply temperatures should go hand in hand with lower return temperatures to avoid excessively high flow rates.

[6]The plot on the right was previously published in [75] with a different colormap.

5.4.4 Results for heat pump heating

The results of the heat pump evaluation are presented in figure 5.11.

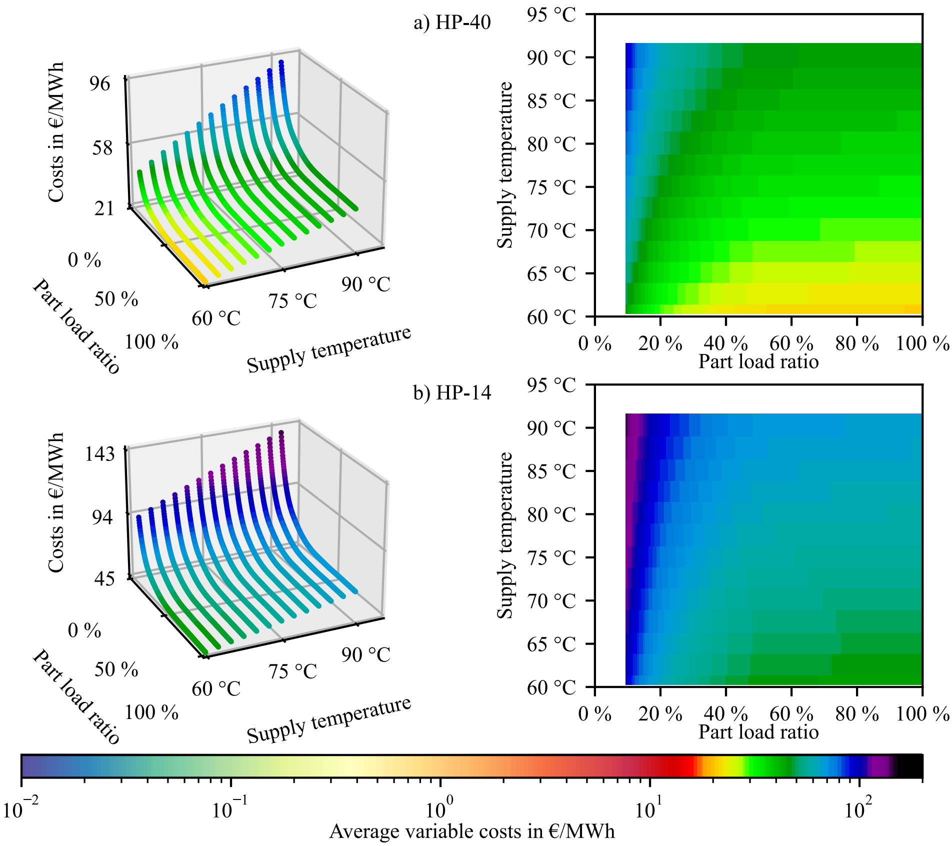

Figure 5.11: Average variable costs of the heat pump plants

Like in the previous evaluations, the German electricity mix is used to drive the heat pumps. The heat produced by the heat pump with the high-temperature source (a) has lower average variable costs compared to the low-temperature source (b). Both variants are influenced by the PLR and the required supply temperature. The impact on costs of the PLR is very strong, especially below 50 %. This seems plausible compared to the input regression used in figure 5.4 (p. 153). Furthermore, increasing the supply temperature decreases the COP which leads to higher variable costs.

These operational points lead to two important conditions or requirements for the feed-in of heat pumps. Firstly, the heat pump should always be driven with a PLR of more than 50 % (or better, 100 %) and the supply temperature should be chosen as low as possible. Secondly, heat sources should allow for high (return) temperatures.

5.4.5 Results for CHP heating

The results of the three CHP variants are presented in figure 5.12 (a–c).

Even though the CHP plants receive subsidies, the variable costs are all at least medium or rather high. The reasons for this include the high bio-methane costs and high costs for operation and maintenance related to an hour of operation. The supply temperature only has a minor impact on the variable costs. This seems plausible in relation to the low impact on the efficiency as described in section 5.3.5 although at least the lower supply temperature can reduce the average variable costs. In contrast, the PLR has a much stronger impact. The most economical point of operation is the full production. Reducing the PLR to 50 % leads to an increase of more than 20 €/MWh. The impact of the electricity price can be evaluated by comparing (b) to (a). The impact of the electricity price results in a difference of approximately 7 to 10 €/MWh. The impact of the fuel costs is demonstrated in case (c) compared to (a). The much lower costs for fuel drastically reduce the average variable costs. As a result, it can be concluded that the CHP plants are impacted by the fuel market and should be operated in a flexible and electricity price-driven way. Further, it can be said that the CHP plants have variable costs in a competitive range because of the high subsidy of 180 €/MWh_{el} (q.v. table C.18, p. 368) that is paid for existing plants in Germany.

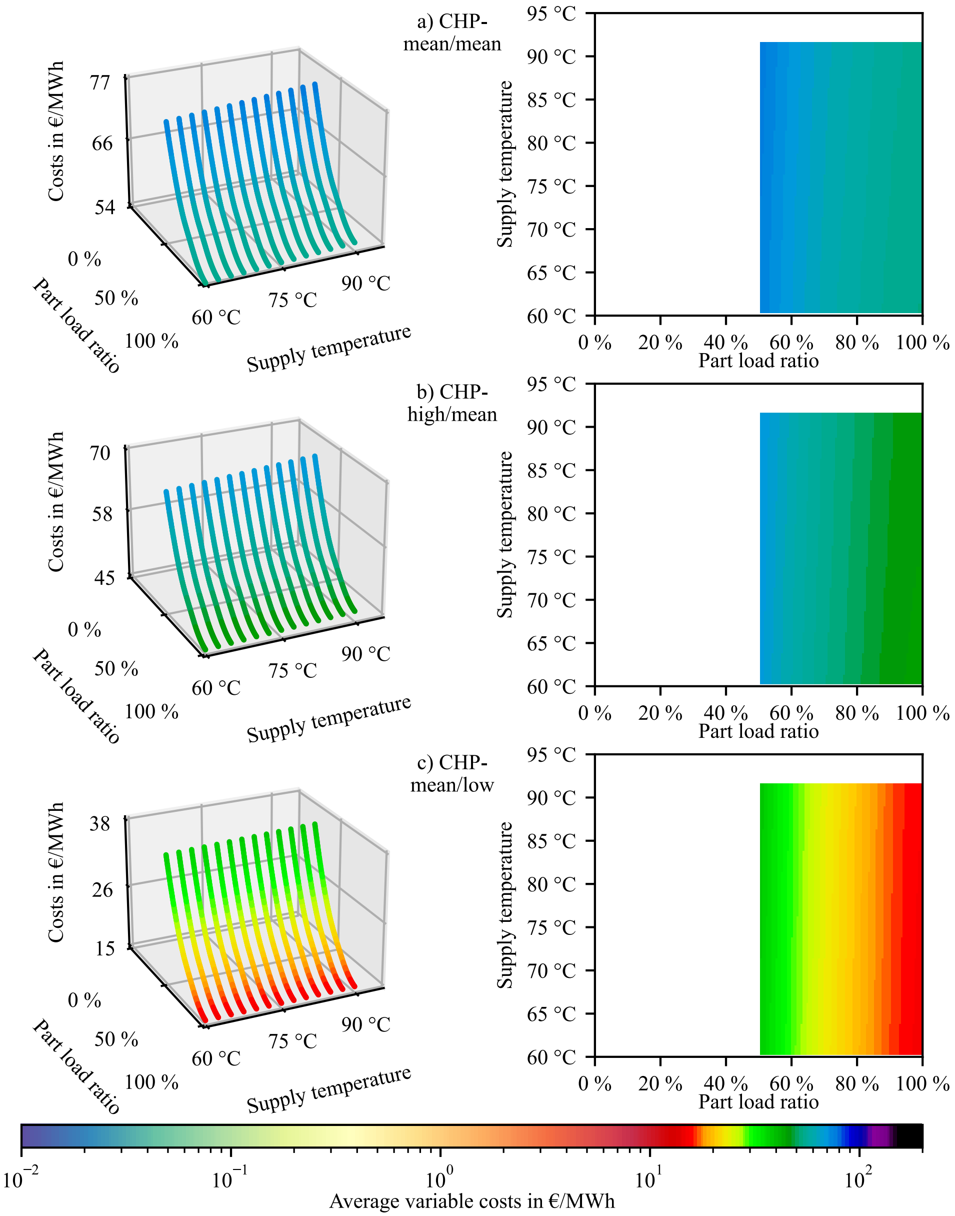

Figure 5.12: Average variable costs of CHP plants

5.4.6 Results for heat only boiler heating

The results of the evaluation are depicted in figure 5.13.

The costs for the HOB using natural gas are medium-high and show a small impact of the supply temperature. The PLR starts at 10 % which is the minimum power the HOB should be driven with as a lower power would result in very high specific heat costs due to the poor efficiency. For more than 15 % it can be said that the higher the PLR is, the higher the costs. The HOB should therefore be operated in low to medium-high PLR and with low supply temperatures, if possible. But, as shown, the HOB is able to produce high temperatures without too many additional costs.

The variable costs for the HOB using biomethane are much higher compared to the natural gas variant. Even though the magnitude is different, the temperature and PLR impact on the characteristics of the cost is identical.

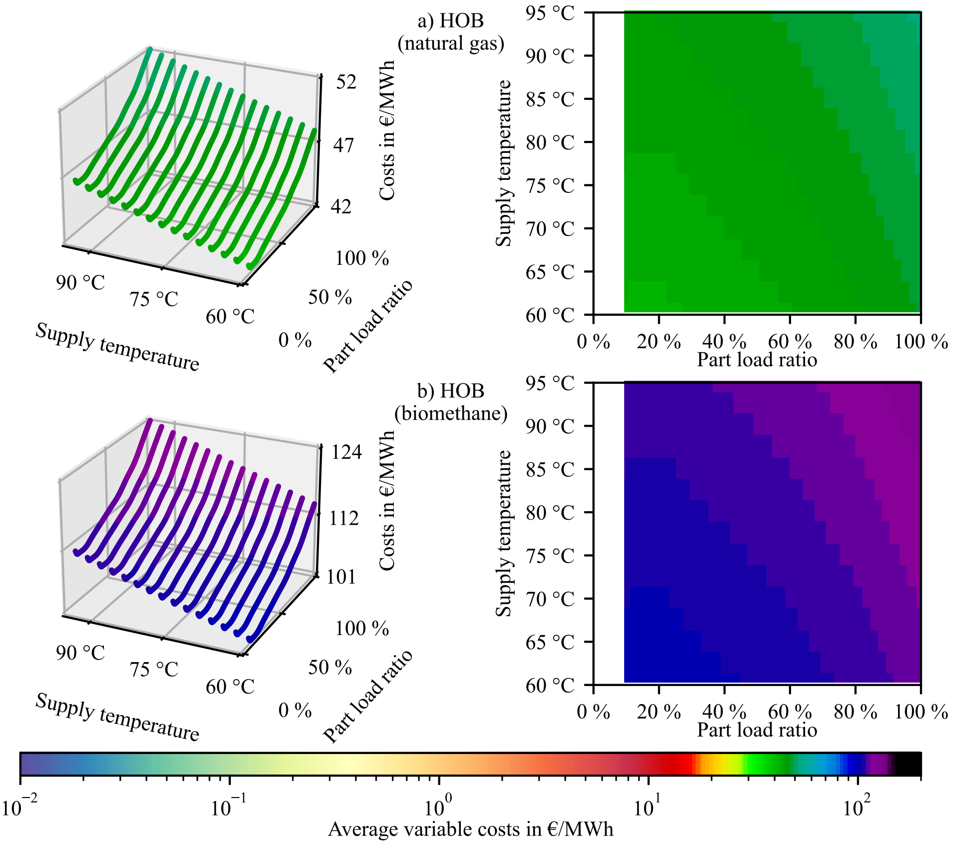

Figure 5.13: Average variable costs of the HOB plants

5.5 Comparison of heating plants

The previous sections show that the different heating plants have rather different characteristics. Some heating plants show a strong impact of their supply temperature on costs while others do not. For some heating plants, the costs increase with increasing PLR while others behave oppositely. In the following section, the plants are firstly compared in a qualitative and secondly in a quantitative way. Based on the qualitative results and external data, the magnitude of the results is validated. Finally, the most cost-effective supply temperature is discussed.

5.5.1 Qualitative comparison

The maximum production of the solar thermal plants is dependent on the weather conditions and thus it is time-dependent. The two types of collectors show different characteristics. In the case of the ETC plant, the chosen supply temperature has a small impact on the maximum production and no impact on the average variable costs. The control range for the PLR is small. In the case of the FPC plant, the temperature has a bigger impact on the maximum power of production but again, the supply temperature has no impact on the average variable costs. In contrast, the FPC plant shows a broader control range for the PLR.

In general, the geothermal plants show high average variable costs at low PLR. While a medium PLR is optimal, a full PLR still allows for low-cost production. The variable costs are related to the reservoir characteristics and particularly to the reservoir temperature as reservoirs with low temperatures show a significant impact of temperature on costs at low PLRs while the high-temperature reservoir does not show a relevant impact on costs at higher PLRs.

The evaluation of the industrial surplus heating plant is site-specific and the PLR can be controlled in the full range. But, if high temperatures are required, the PLR may be reduced. Production at full PLR should be done with the highest possible temperature to reduce the effort of pumping and unnecessary electricity costs.

The evaluation of the heat pumps shows that higher source temperatures reduce the average variable costs. Further, the PLR should be used at as high a value as possible as values that are lower than 50 % lead to high average variable costs. In general, a lower secondary side temperature is beneficial. The lower the required temperature is, the lower the costs.

The CHP plants have a low impact on the secondary supply temperature compared to the other technologies. Instead, the PLR has a high impact. Operation at 50 % is the minimum of the presented plant and the higher the PLR is, the lower the average variable costs. Another important impact on the average variable costs is the electricity prices and the fuel costs. The CHP plant should be operated at high electricity prices.

The HOB has a small temperature impact. In contrast to most of the other technologies, the HOB has the lowest average variable costs at low to medium PLR.

5.5.2 Quantitative comparison and proof of plausibility

In this subsection, the quantitative results are evaluated by a comparison of the case studies with each other. Further, the characteristics of the cost correlation to PLR and supply temperature are evaluated concerning their plausibility. As almost no external data is available for the full range of PLR and supply temperatures, only the maximum PLR will be compared to literature values for validation.

For further graphical comparison, the data must be aggregated, which reduces the information but is helpful for the interpretation of the results. Figure 5.14 is created to demonstrate the utilization of the computed data and shows the minimum average variable cost correlated to the PLR.[2]

In this figure, the solar thermal and industrial surplus heat case studies are depicted with a logarithmic y-axis. The presented curves will be used to evaluate if the qualitative characteristic is plausible. Further, the magnitude will be validated by values from the literature.

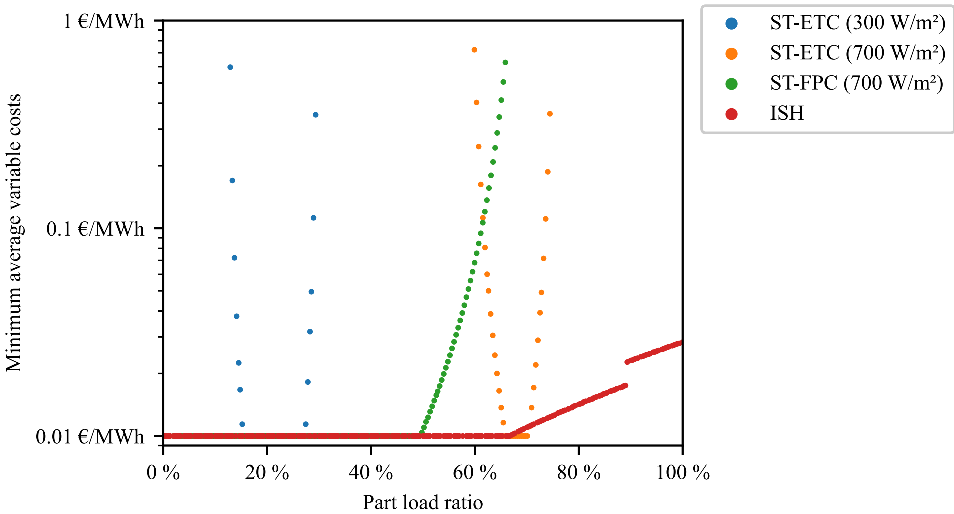

Figure 5.14: Minimum average variable costs over PLR of solar thermal and industrial surplus heat plants[7]

[7] The results of the *ST-ETC (700 W/m^2)* and *ISH* case studies were previously published in [75].

The variable costs for the industrial surplus and the solar thermal heat are quite low and appear to be acceptable over the full PLR range. As described above, the costs are rounded up to a minimum of 0.01 €/MWh and can therefore be even lower. For the given weather conditions, the solar thermal plant *ST-ETC (700 W/m²)* has a small range of PLR compared to the other plants. In the upper part of its PLR, a trade-off between lower costs and slightly more production can be made.[2]

At lower irradiance (300 W/m^2), the plant's costs have almost the same shape, but the PLR is lower. The higher costs of the ETC plant at the edge points of operation are related to the higher flow rate and the higher electricity demand. The FPC plant has low overall costs until the end of the PLR is reached and the costs increase due to the higher electricity demand. The industrial surplus plant has minimum costs at the lowest flow rates which can be achieved with a bigger temperature difference. At higher PLR, the maximum possible supply temperature decreases, which requires higher flow rates. The step at 90 % PLR results from the discrete temperature resolution. While the step seems large, due to the logarithmic scale it is just a small uncertainty. The costs of the plants can be explained and hence the implementation seems plausible.

Figure 5.15 presents the other heating technologies. In contrast to figure 5.14, even though it is also logarithmic, the y-axis has another magnitude.

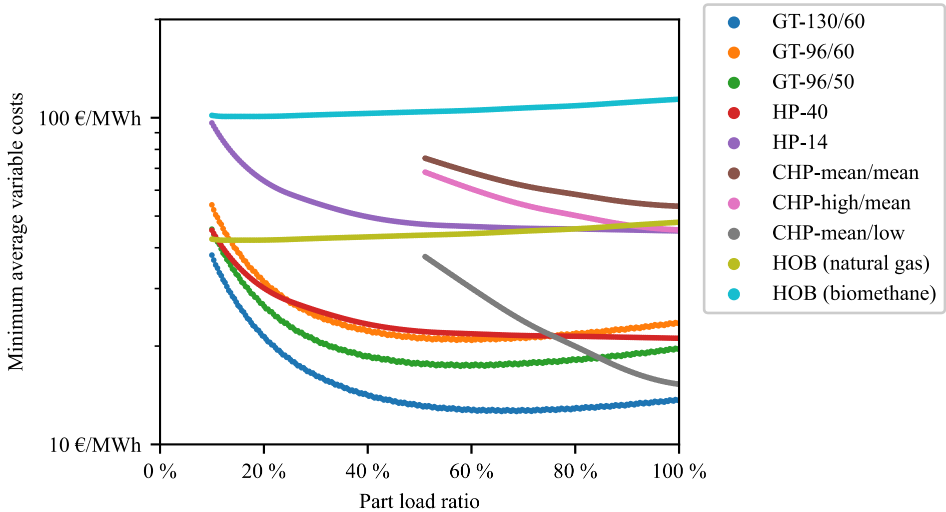

Figure 5.15: Minimum average variable costs over PLR of geothermal, heat pump, CHP, and HOB plants[8]

[8]The results of the *GT-96/60* case study were previously published in [75].

The geothermal plant *GT-96/60* has rather high costs in general and with lower PLR the costs increase. The overall high costs of this plant can be explained by the high electricity prices in Germany and the non-optimal geological conditions that are assumed for this variant. In this case, lower electricity costs would linearly reduce the costs for production.[2]

The other geothermal case studies show a similar shape at lower values. The increasing costs at low PLR result from the increasing share of the hourly costs for wear on the average variable cost of production. The smaller increase at high PLR results from an increasing electricity demand at high flow rates. The shape is considered plausible, and the heat pumps show a similar shape of costs correlated to the PLR. The variant *HP-40* and the *GT-96/60* case are of the same magnitude. However, reducing the primary source temperature to 14 °C leads to much higher variable costs for the heat pump. The decreasing slope of the heat pumps' costs correlates with figure 5.4 (p. 153) and therefore, they are plausible. The CHP plant, which has a mean biomethane price and a mean electricity price, has the highest costs of all CHP plants. This is related to the high fuel prices and the medium-high revenues. All CHP plants' costs strongly decrease with higher PLR. This is consistent with the slope of the electrical efficiency shown in figure 5.5 (p. 155) and can be considered plausible. The CHP plant with a lower price for the biomethane has much lower costs and a higher electricity price also reduces the costs although the effect is not as significant as that of the lower biomethane price. The costs of the HOB with natural gas are high and its shape is the only one with an increasing slope (from low to high PLR), which is plausible referring to figure 5.6 (p. 157). The costs of the HOB with biomethane are much higher than the one with natural gas and it has the highest costs of all plants. The shape of both HOBs is identical. All plants in this figure show a relatively constant shape for the costs in the range of 50 to 100 % PLR.

5.5.3 Maximum supply temperature at the lowest costs

Figures 5.16 and 5.17 show the maximum supply temperature correlated to the PLR at the points of operation where the costs are lowest (as shown in figure 5.14, p. 170). In other words, it shows the highest and most cost-effective temperature for each PLR.[2]

As presented in section 5.2, the evaluation is based on discrete values using a step size for a supply temperature of 2.5 K. Consequently, the results are related to these steps (shown by the dots). To demonstrate the range between the discrete data, lines are used as envelope curves.

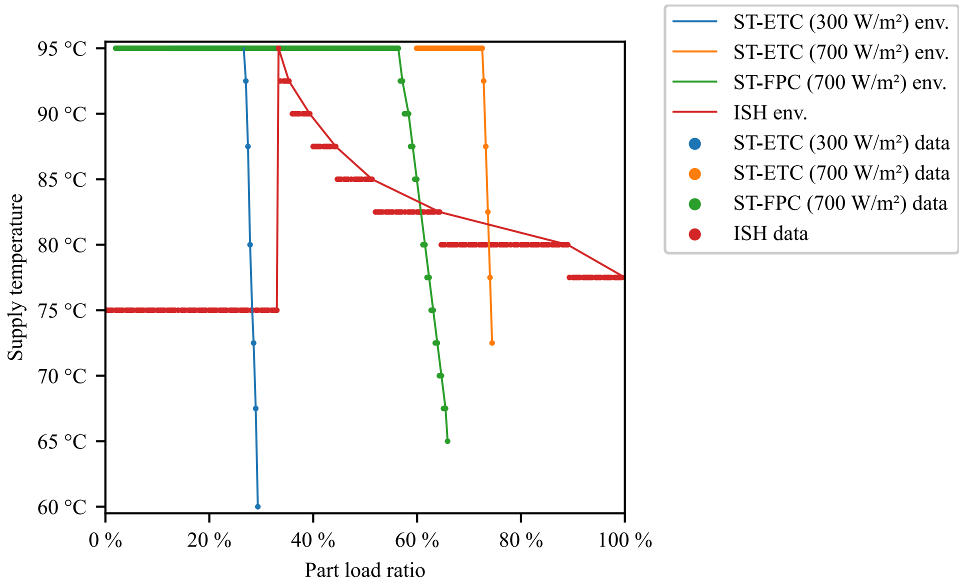

Figure 5.16: Maximum temperature at minimum average variable costs over PLR for each of the solar thermal and industrial surplus heat plants (data points (*data*) from evaluation and envelope curves (*env.*))[9]

The solar thermal and the industrial surplus plants can supply their heat at their maximum temperature even though the lowest costs are aimed for. The limitations to the supply temperature are provided by the technical restriction of these plants.[2]

[9]The results of the *ST-ETC (700 W/m²)* and *ISH* case studies were previously published in [75].

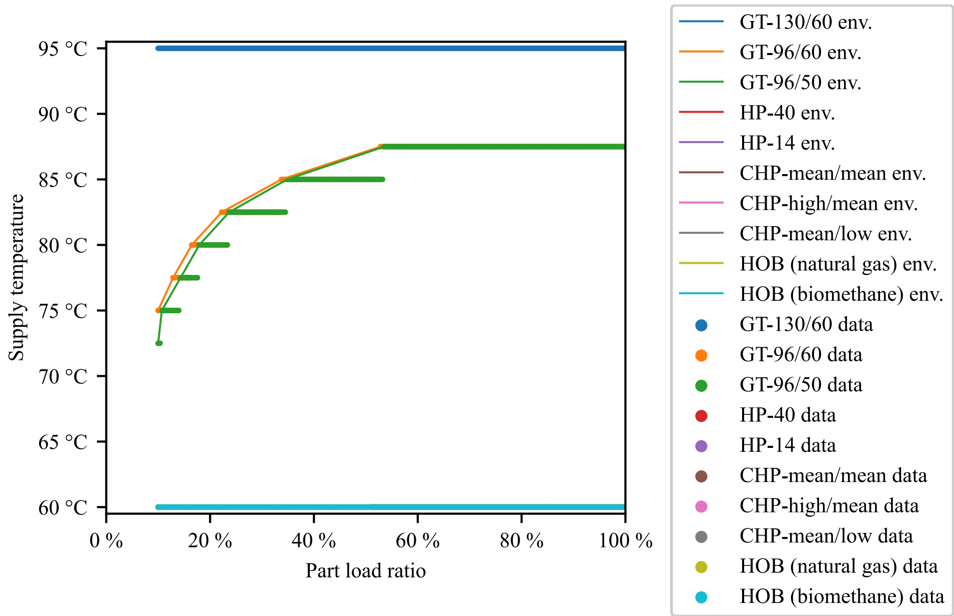

Figure 5.17: Maximum temperature at minimum average variable costs over PLR for each of the geothermal, heat pump, CHP and HOB plants (data points (*data*) from evaluation and envelope curves (*env.*))[10]

Figure 5.17 shows the other plants. Except for the geothermal plants, all other plants' costs benefit (at least marginally) from a lower supply temperature, and thus their costs form a constant line at the lowest evaluated temperature (60 °C). The geothermal plants provide higher temperatures at the lowest costs. The first case study with the high reservoir temperature *GT-130/60* provides the maximum temperature at all values of PLR. The other two plants have almost identical temperatures which are related to the identical reservoir temperature. All values for the PLR above 50 % result in a maximum temperature of almost 90 °C. Below 50 %, the cost-effective temperature increases with increasing PLR. This is related to the lower demand for electricity that is related to lower flow rates and the correlating lower extraction temperature (q.v. figure 5.8, p. 161).

[10]The results of the *GT-96/60* case study were previously published in [75].

5.5.4 Validation of the costs at maximum PLR

Table 5.6 shows the maximum PLR and the lowest average variable costs of the case studies from figures 5.14 and 5.15. Further, the table presents the full electricity and fuel costs (including variable grid fees and levies) and the full revenues for the CHP plants related to the previously introduced subsidy mechanism. As described previously, external data for the complete range of supply temperature and PLR is not available, and thus to allow for a rough quantitative validation, the results are compared to the literature values.

Table 5.6: Lowest average variable costs at maximum PLR

Case study	Max. PLR (%)	Average variable costs (€/MWh_{th})	Electricity costs (€/MWh_{el})	Fuel costs (€/MWh_{GCV})	Electricity revenues (€/MWh_{el})
ST-ETC (300 W/m^2)	29 %	0.35	198	-	-
ST-ETC (700 W/m^2)	74 %	0.36	198	-	-
ST-FPC (700 W/m^2)	66 %	0.63	198	-	-
GT-130/60	100 %	14	154	-	-
GT-96/60	100 %	23	154	-	-
GT-96/50	100 %	20	154	-	-
ISH	100 %	0.028	198	-	-
HP-40	100 %	21	154	-	-
HP-14	100 %	45	154	-	-
CHP-mean/mean	100 %	54	177	86.8	177
CHP-high/mean	100 %	45	191	86.8	188
CHP-mean/low	100 %	16	177	69.3	177
HOB (natural gas)	100 %	48	210	38.8	-
HOB (bio methane)	100 %	114	210	92.8	-

The Danish Energy Agency has published and regularly updates a catalog of technology data for DH [117]. In contrast to almost all other references, information on the different elements of costs is given, and not only aggregated quantities such as levelized costs of energy are published. Therefore, it is used as the reference for validation.

Variable operational costs of solar thermal plants are given at 0.19 €/MWh and are completely related to the electricity consumption [117, p. 371]. Even though the Danish electricity price may vary compared to the German one, the maximum costs (0.35–0.63 €/MWh) for the presented operation points of the results from the solar thermal computations are of the same magnitude. Figure 5.9 (p. 162) shows that there is potential for much lower average variable costs through a trade-off between reducing the maximum production and lowering the costs.

The geothermal plant is much harder to compare due to its strong dependency on the reservoir characteristics and the catalog does not include a similar geothermal plant. Instead, a geothermal well with a 2,000 m depth and a temperature difference of 35 K is given [117, pp. 341–342]. The electricity demand for the pumps is estimated at 8 % of the geothermal heating power. Additionally, 3 €/MWh are given for the variable operation and maintenance costs (for a plant that also uses an absorption heat pump). Applying the electricity price of table 5.6 (154 €/MWh), the reference variable costs for geothermal heat can be calculated at 15.3 €/MWh. Compared to the 14–23 €/MWh of the case studies, the magnitude of costs can be considered plausible.

Industrial surplus heat is only considered as a heat source for heat pumps and industrial processes with a sufficient temperature level are not included in [117]. Due to the site-specificity of this heat source, validation is not possible, and therefore, the low value of 0.03 €/MWh should be regarded as highly uncertain. Nevertheless, it is plausible that the value is low if costs from contracts are neglected as described in section 5.2.

For the validation of the heat pumps' results, a reference case with a 1 MW heat pump is used which supplies 70/30 °C on the DHS side and uses 25/15 °C on the source side [117, pp. 303–304]. The COP is given at 4.1 while other variable costs are given at 2.7 €/MWh. Applying the electricity price from table 5.6 (154 €/MWh), the referenced variable costs for heat pumps can be calculated at 40.3 €/MWh. This shows that the magnitude of the case studies (21 and 45 €/MWh) is plausible. The lower costs of 21 €/MWh for the *HP-40* arise from the high source temperature.

For CHP gas engines, the electrical efficiency is given at 40 % and the thermal efficiency at 44 % [117, p. 79] whereby both values are converted to GCV. Further, other variable costs are given at 5.4 €/MWh. Applying the revenues and fuel costs from table 5.6 results in the following variable costs in the order of the cases above: 42 €/MWh, 32 €/MWh, and 2 €/MWh. The difference in the results (54 €/MWh, 45 €/MWh, and 16 €/MWh) which are shown in table 5.6 are due to the lower electrical efficiency (given by the datasheet of the CHP plant).

Gas-fired HOBs are listed with an efficiency of 93 % (converted to GCV) and 1.1 €/MWh additional variable costs [117, p. 326]. Applying the fuel costs from table 5.6 for the natural gas variant results in variable costs of 43 €/MWh for heat. The costs of the case study are 48 €/MWh. This is the correct magnitude but has slightly higher costs. Applying the same calculation to the biomethane variant results in variable costs of 101 €/MWh. While the deviation from the result of the evaluation of 114 €/MWh is larger in absolute values, it is identical in relative values. The values are computed for the full PLR, which is not the optimal point of operation. In real operation, the full range for the PLR will be used which leads to lower variable costs, and therefore, the results are considered plausible.

The results shown in the previous evaluation are based on literature values and assumptions. Due to the lack of data mentioned for some technologies in the previous sections, some assumptions are quite rough. Additionally, the combination of different data and dependencies for the PLR dependencies on the one hand, and supply temperature dependency, on the other hand, could cause uncertainties. Even though the overall relations and their quantity were checked for plausibility, a detailed validation should be the next step. To facilitate a detailed validation, real plants should be equipped with measurements of each energy balance as well as the supply and return temperatures. This data could be directly used for the new method to allow for a more precise evaluation. In this case, the return temperature should be included as another important fluctuating dimension.

Further, these results just describe the operative costs and do not show the total variable costs that can behave quite differently. However, these results allow for setting the plants' order in operation and emphasize the must-run condition for solar thermal and industrial surplus heating plants.[2]

5.5.5 Discussion

This comparison shows that temperature has a significant impact on the average variable costs and that the correlation varies for different plant types. In addition, their operation is not completely flexible (e.g., due to weather conditions). Such plants, which have low average variable costs like the presented solar thermal and industrial surplus heating plants, would waste their energy if a requested PLR was too low. In other cases, if a demanded supply temperature is too high, the energy production is also reduced. Therefore, it would be avoided to reduce the PLR in practice, even if it is possible to control the plant's thermal power beyond an optimal point of operation. Instead, from a systemic point of view, it is desirable to be able to combine different plants' operational points to create an overall optimum while considering their technical and conditional limitations.[2]

The results are used for qualitative discussions and to demonstrate the method. The case studies include the simplifications and parameters shown in section 5.3 and therefore the quantitative results are site-specific. Particularly those for the geothermal plant are sensitive to some specific inputs such as the reservoir conditions and the electricity prices, which are high in Germany. The complexity of this technology and the low public availability of data shows that there is further demand for an investigation. Nevertheless, the qualitative results are valid. For example, the geothermal plant will always have a non-optimal point of operation at low PLR and high temperature, even though the quantity of the impact can be much smaller or even higher.[2]

Another requirement for research is the combined evaluation of temperature and PLR impact. The method for the heat pump, CHP plant, and HOB evaluation presented above combines two different factors—one for temperature and one for the PLR. Further research should investigate if there are interferences between controlling the two variables in operation. Particularly heat pumps should be further evaluated due to their higher sensitivity to temperatures.

Sensitivity analyses for the used parameters could improve the accuracy of the quantitative results to allow for more general statements concerning the magnitude of the costs. For further improvements, the method could be extended with physical calculations that could consider the plant's dynamics (e.g., ramps between different points of operation) or non-constant return temperatures.[2]

The presented case studies consider only a fraction of the available heat generation technologies suitable for sustainable DHSs that can be evaluated with the proposed method. However, the resulting characteristics allow for some general conclusions. The suitability of the method is successfully demonstrated and an application to other heating sources and technologies (e.g., those with combustion processes) appears possible and desirable. The results obtained show the impact of supply temperature and PLR on the average variable costs and that the characteristics of the different types of heat production plants vary significantly. The results can also be used directly for the operational optimization of the given plants in Hamburg-Wilhelmsburg.[2]

5.6 Conclusion of the heating plant integration

As a result of the framework development (chapter 4), it is proposed to integrate the heating plants of the independent producers via bids into the smart market procedure. It is further proposed to include the temperature and thermal power impact into these bids. To support the unbundling and to create the bids in a competitive environment, this chapter presents a new method for the calculation of the variable costs of heat production including the impact of supply temperature and part load ratio (PLR). Through this, it contributes a relevant part to the implementation of the new framework.

After analyzing existing methods for the evaluation of the impact of supply temperature and PLR on average variable costs of heat production, a lack of a systematic method is identified and thus a new method is developed and presented to fulfill the first goal of the chapter.

The new method is applied to existing and planned heating plants of the case study district heating system (DHS) in Hamburg-Wilhelmsburg. By this, six different heating plant types are evaluated: solar thermal, geothermal, industrial surplus heat, heat-pump, combined heat and power (CHP) as well as gas-fired heat only boiler (HOB) plants.

The application to the case studies demonstrates how the bids for the smart short-term market can be calculated. This method can be applied by the producers. Those producers with a long-term contract may add a margin to their variable costs before the contract negotiation of the capacity market. Producers that participate in the short-term market only, may use the method for the calculation of their marginal costs. The second goal is fulfilled by this demonstration.

The specific results show that the supply temperature and the PLR have a relevant impact on maximum thermal power and on average variable costs of some types of plants such as the heat pumps. Through this, it is proven that the available temperature dynamics in operation should be used to optimize the variable costs. This shows that including the supply temperature into the bids for the smart short-term market is necessary to fulfill the cost-by-cause principle and to integrate the production in a system-serving way. By doing this, the third goal is fulfilled.

The method can be applied to all types of heat sources and technologies and is thus suitable to establish comparable databases. These data sets can be complemented by measurements of existing plants, particularly as measurement data will increasingly be available through the ongoing digitalization process in DHSs.[2]

This chapter presents the general method and its validation by an application in the case studies whereby the temperature impact is regarded as being relevant. Through this, the objective of the chapter is fulfilled.

Investment and design decisions are taken at the capacity market. Here, the presented method must be extended by an evaluation of the costs for capital and the fixed costs of operation, which are treated as sunk costs here.

Besides the supply temperature and the PLR, the evaluation shows further parameters that impact the costs of the heating plants. For example, some heating plants, like solar thermal and industrial surplus heating plants, are dependent on the availability of their primary source. External influences such as the weather, electricity prices, and production from industry are not under the control of the operator. If the share of production by these fluctuating sources exceeds a critical value, it must be compensated by the DHS. This is investigated in the next chapter by evaluating the available and demanded flexibility and integrating it into the new framework with the goal to improve the DHS management.

Chapter 6

Improving DHS management by integrating flexibility

The previous chapters show that renewable heating technologies need an adaptive reacting system to integrate fluctuating production and to combine different types of heating plants economically. This adaptive characteristic is mostly referred to as flexibility. The state-of-the-art analysis (chapter 2) points out that flexibility is an important research topic in the district heating (DH) sector and that it is required for the transition to 4^{th} generation district heating (4GDH). Flexibility is necessary to reduce peak supply and to compensate for fluctuating renewable heat sources [3]. It can be used to optimize the costs of heating plants e.g., by using electricity prices for combined heat and power (CHP) plants' operation and through this, it is a key characteristic of a smart energy system [3]. Seasonal storages can be used to shift heat production (e.g., solar thermal) from summer to winter [3] and therefore contribute to flexibility. Compared to other sectors, thermal energy storages (TESs) are cheap and by providing their flexibility to different sectors (e.g., electricity), all sectors can benefit from this type of flexibility [109].

Due to its relevance to the DH sector, flexibility must be considered systematically by the new framework. Therefore, the objective of this chapter is to identify or develop a generic concept for the integration of flexibility into the framework in such a way that the district heating system (DHS) can be managed in an economic efficient and system-serving way. This concept should enable the system operator to take advantage of the flexibility of all technologies used in the DHS to minimize the purchase price for heat. To do so, it must be compatible with the concepts of competition and unbundling, and it must consider the physics of the DHS.

A literature review shows that such integration for flexibility cannot be found and hence a new concept is developed which combines the relevant technologies with the new framework in a comprehensive way. As it considers all relevant types of storage technologies as well as the temperature impact on them, it can be considered a generic in the application. In this way, the presented concept facilitates the requirements of the transition (chapter 2) and is coherent with the proposed framework (chapter 4).

The chapter is organized according to nine sections. Firstly, the method for the evaluation of the flexibility and the integration of the flexibility technologies into the framework is presented (section 6.1). Secondly, the term flexibility is defined for its application to DHSs (section 6.2). After this, the requirements for the flexibility integration are analyzed, including the demand of the DHS for flexibility and the flexibility potential of available technologies (section 6.3). Based on these requirements, existing integration solutions in the literature are reviewed and a gap in the existing concepts is identified (section 6.4). To fill the gap, the different technologies are evaluated individually (section 6.5) in the first step. Based on this individual evaluation and the existing reviewed solutions, a novel generic concept is proposed for the integration of flexibility in DHSs (section 6.6). This concept includes a general part that defines the optimal integration into the framework. Further, it includes a specific part for the integration of flexibility into the smart market. In the third part, it includes metrics for the quantification of flexibility which are identified. These metrics are subsequently applied to existing storage tanks in the DHS in Hamburg-Wilhelmsburg, as the first step of implementation (section 6.7). Finally, the results are discussed (section 6.8), and conclusions are drawn (section 6.9).

6.1 Method for the integration of flexibility into the framework

The objective of the chapter is to integrate flexibility into the new framework in an optimal way. For the development of the integration, the following method will be applied (figure 6.1). The method is a systematic approach to ensure the most coherent integration into the framework. The method is organized in six steps, which are arranged as sections in this chapter (step 1 in section 6.2, step 2 in section 6.3, etc.).

In the *first step*, a new definition for the term flexibility is proposed. This is done by reviewing existing definitions. As the identified definitions are regarded as not being suitable for the application to DHSs, an own definition is proposed for the specific application to DHSs considering flexibility demand and potential as well as the relevance of temperature.

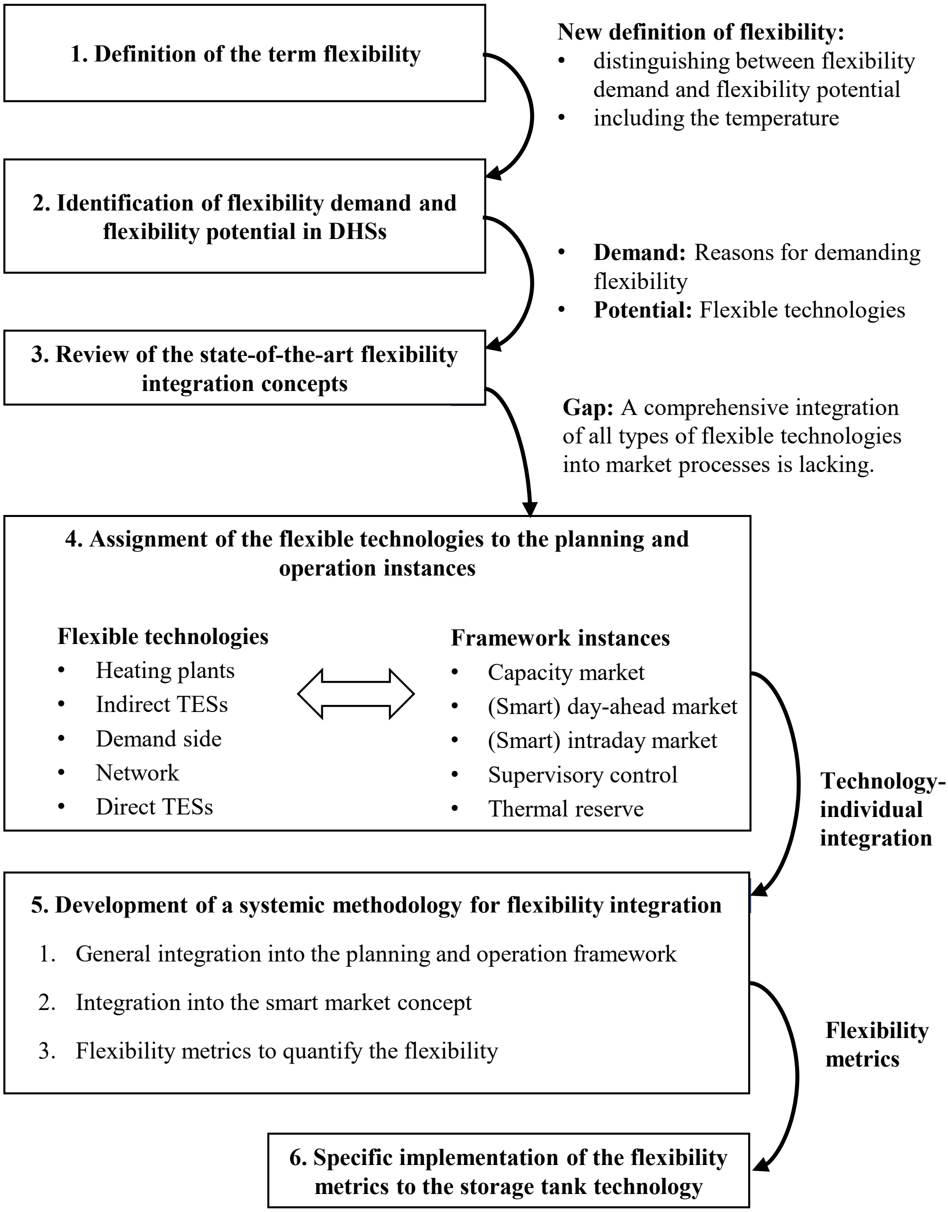

Figure 6.1: Method for the evaluation and integration of flexibility

In the *second step*, these two aspects of flexibility (demand and potential) are further investigated. Firstly, reasons for the demand for flexibility are identified. An example is a fluctuation in heat production. Secondly, the potential of the flexibility in DHSs is identified. This is focused on the different technologies which offer flexibility for the DHS. These technologies are the heating plants, demand side, network, and TESs. In relation to [166], TESs are divided into direct and indirect types. Indirect TESs can only be discharged at low temperatures and require additional heating (e.g., a heat pump). In contrast, direct TESs can be discharged at high temperatures and the stored heat can be used directly without additional heating.

In the *third step*, existing flexibility treatments and integration concepts are reviewed with a focus on a systemic perspective. The findings are divided into the flexibility solutions that focus on the design process and those that focus on the operation. Finally, the research gap is identified: a lack of a technology-open and coherent integration, which can be combined with the framework proposed in chapter 4.

In *step 4*, each technology that can offer flexibility in DHSs is individually evaluated. The evaluation combines findings from literature and own case studies. The goal of the evaluation is an assignment of each type of flexible technology to the framework processes by the optimal duration for storing heat and by the way to access the flexibility.

In *step 5*, the results from step 4 are combined into a new generic integration of flexibility. It can be divided into three parts:

1. A general integration is developed which allows for the integration of each technology into the proposed framework. The goal is to identify the best framework process (capacity market, day-ahead, intraday, or operational control) in which the technology can be integrated. Further, the integration approach is specified.
2. The smart market, which is proposed for the intraday and day-ahead market in chapter 4, requires further specifications to integrate the different flexible technologies. To do so, different ways to integrate the technologies into the planning model are discussed and a solution is recommended.
3. Flexibility metrics are identified which allow for quantifying the potential and state of flexibility in the system and which are a requirement for the further development of the smart market. Like in chapter 5, the variable costs are important and therefore, a method that combines a description of the flexibility, the temperature, and their impact on costs is developed.

In *step 6*, these general metrics are applied and implemented. The implementation must be done individually for each technology. To demonstrate the implementation of the metrics in this thesis, the most relevant technology is chosen, namely storage tanks. To do so, a storage model is developed and validated. Afterward, this model and the metrics are combined. Finally, the new metrics are applied to three storage tanks of the case study DHS and the results are discussed.

Finally, the results of the whole chapter are discussed, and the main contributions are concluded.

For the whole chapter, literature is used that is identified using a literature review. The literature review is performed using Google Scholar [36]. For the review, the term *district heating* is combined with *flexibility* and *storage*. In both search procedures, the first 100 titles are read, thereby resulting in 138 reviewed abstracts and 37 reviewed articles. Finally, 20 articles are used in combination with the previously identified references.

6.2 Flexibility definition for DHSs

When dealing with the topic of flexibility and searching for a suitable definition, it becomes clear that it is difficult to grasp this concept. For this reason, this section will take a closer look at the definition of the term flexibility. This is done in two steps. In the first step, existing definitions are reviewed with the result that there is no suitable definition of the term flexibility for the application in DHSs. In the second step, a new definition is formulated.

6.2.1 Existing definitions of flexibility

Numerous definitions of flexibility exist. Many definitions which are used for thermal applications have their origin in the electricity sector. Table D.1 in appendix D (p. 375) presents the most relevant definitions from thermal and electrical systems as well as production engineering. To make the definitions comparable, the full-text definitions are combined into an abstract definition as this makes it possible to compare these definitions in a meaningful way. The most relevant abstract definitions are shown in table 6.1.

Table 6.1: Abstracted definitions of flexibility in the literature (for full table q.v. table D.1, p. 375)

No.	Meaning
1–4	Flexibility is the ability to respond to changes in production and consumption (cf. [167]–[170]).
5–6	Flexibility is the ability to delay or force feed-in and feed-out (cf. [19], [171]).
7–8	Flexibility is the ability to adapt to changing conditions (cf. [172], [173]).
9–12	Flexibility is the ability to modify production and consumption (cf. [174]–[177]).
13	Temperature-flexible operation is the ability to switch off and serve from decentralized storages (cf. [178]).
21	Flexibility is a need to balance production and consumption (cf. [179]).

These definitions highlight several aspects:

1. Many definitions describe flexibility as an ability to do something. In most cases, it is the response to or the compensation of a deviation between production and consumption. Other definitions (e.g., number 21) show that flexibility can also be defined by the need for this compensation. This demonstrates that the definition of flexibility can depend on the perspective: *what does the system need?* or *what does the system (or parts of it) provide?* It can therefore be concluded that there is a demand and a potential for flexibility.
2. Most of these definitions are derived in the context of the electrical system and only some of the identified definitions are made for thermal systems. Most of the latter are derived to describe the flexibility of thermal systems in combination with the electrical system (e.g., through heat pumps or CHP plants). For this reason, temperature is not included in these definitions. An exception is number 13, which describes a "temperature-flexible operation" [178]. The described concept and the related definition focus on a full shut down of the DHS. A flexibility definition including an adjustable temperature is lacking.
3. Some of the definitions that are identified focus only on a single technology (e.g., numbers 18 and 19). For example, flexibility can be "understood as a building property" [174]. This contrasts with the objective of this chapter to develop a technology-independent integration.

These aspects show that all identified definitions are not suitable for the systemic application in DHSs and, therefore, new definitions are proposed with a focus on thermal flexibility and its application to DHSs.

6.2.2 Proposal for a new flexibility definition

The previous sections give an overview of some flexibility definitions that are used in the electrical, thermal, and production context. Due to the possibility of the definition of flexibility from a demand and a potential perspective, two new definitions for thermal flexibility in DHSs are proposed. The adaptivity of DHSs to modulate temperatures is one of the most important characteristics that distinguish the flexibility in the DHS from others e.g., electrical systems. Based on the listed definitions, the following definition is proposed, which includes the relevant temperature aspect, the demand, and potential perspective, and a systemic point of view for all technologies in the DHS.

> The *thermal flexibility (potential)* in DHSs is the ability to adapt the energy and/or the temperature level of the system (or parts of it) in response to changing conditions.

A new definition of flexibility (potential)

Through this, the thermal flexibility potential can be understood as the synergy of the energy flexibility potential (changing the energy level) and temperature flexibility potential (changing the temperature level).

> The *thermal flexibility demand* arises from the deviation of inflexible production and consumption. It is a need to balance a *thermal energy difference* and/or a *temperature difference* of production and consumption.

A new definition of flexibility demand

These new definitions are used in this thesis. In the next section, the demand and potential are further investigated.

6.3 Identification of flexibility demand and potential in DHSs

Based on the new definition, flexibility is divided into demand and potential. In this section, both parts are investigated in detail. In the first subsection, it is determined which types of flexibility demand exist as the different demands set the requirements for the flexibility integration. For example, different types of demand require a fast or a slow reaction of the system. Afterward, the potential is analyzed by identifying the technologies in DHSs that can offer flexibility.

6.3.1 Flexibility demand

Flexibility can be demanded from inside the DHS or even from the outer conditions. For example, the electricity sector requires flexibility for the compensation for fluctuating renewable generation.

Vandermeulen et al. identified the following demands for flexibility [19]: reducing peak supply, reducing the number of heating plant starts, increasing the utilization rate of base load plants, reducing the transmission capacity (in new networks), optimizing the heating plants, offering ancillary services (e.g., for the electricity grid), and supporting the transition towards renewable heating sources and lower supply temperatures. [19]

On the electricity side, flexibility is needed in the *day-ahead*, *intraday*, and *balancing power markets* [180]. In the heating sector, many heat sources are sufficiently available in summer, but the highest demand is in winter, which requires seasonal flexibility [181].

Lund et al. review flexibility measures in the electricity system [172]. The demand for flexibility in the electricity system is classified by different timespans: *very short (milliseconds to 5 minutes), short (5 minutes to 1 hour), intermediate (1 hour to 3 days), and long (seasonal, several months).* CHP plants are highlighted as a flexibility option. If they are combined with other plants (heat pumps, TESs, heat only boiler (HOB), and electrical boilers) their flexibility can be increased. [172]

Another need for flexibility comes from the uncertainty of the demand based on weather fluctuations and the consumption behavior [182]. Further, there is a challenge related to the resolution of the proposed market. For example, if an hourly forecast would be totally accurate, the load would still vary in this hour of operation [cf. 78, pp. 217–221]. In case of failure, flexibility can be used to increase the system's reliability [166].

Table 6.2 summarizes the technical reasons for thermal flexibility demand. These technical reasons may lead to changing prices and therefore they also form the economic conditions.

Table 6.2: Thermal flexibility demand in DHSs

Type	**Example**
Heat production fluctuation	High solar thermal production in summer and high heat demand in winter or low available supply temperature (q.v. chapter 5)
Electricity sector	Fluctuating renewable electricity generation requires flexibility in different electricity markets (day-ahead, intraday, balancing power)
Uncertainty of forecast	Weather changes or different customer behaviour leads to errors in forecasts
Inner interval fluctuation	Fluctuations of heat demand inside the resolution of the forecast
Failure	Heating plant failure

6.3.2 Flexibility potential

Different technologies offer flexibility to the DHS. For example, the utilization of TESs can increase flexibility [171]. However, besides the TESs, which are made to provide flexibility, there are several other flexible technologies in the DHS. These are identified in the following subsection.

Guelpa and Verda present an overview and classification of TESs which can be found in DHSs [166]. On the highest level, the authors differentiate between sensible, latent, and chemical TESs. The most frequently used type is the sensible type. The latent TESs mostly use phase-changing material (PCM). Further, it is differentiated between *short-term* (hours to a day) and *long-term* (weeks to months, seasonal). TES usages that have a lower extraction temperature than required for the utilization are called *indirect*. *Direct* usage is possible if the storage temperature is equal to or higher than the demanded supply temperature. The most commonly used type of short-term storages is hot water storage tanks. Further flexibility potential can be found in the capacity of the piping network itself and the capacity of the supplied buildings by changing the buildings' demand whereby the latter approach is called *demand side management (DSM)*. If several buildings are aggregated, a "virtual storage" [166] can be formed. Another way of storing energy is the shift between the different energy sectors which is called "multi energy system" [166] by the authors and is equal to the "smart energy system" [17] defined by Lund et al. Depending on the economics, energy can be converted between fuels (e.g., gas), heating, and electricity systems. Typical technologies are: "power to gas, heat pumps, power to heat, [CHP plants], heat only boilers and power plant[s]" [166]. [166]

Dahash et al. summarized the available knowledge on large-scale thermal accumulators. The most relevant types were indicated as being *tank thermal energy storage (TTES)*, *pit thermal energy storage (PTES)*, *borehole thermal energy storage (BTES)*, and *aquifer thermal energy storage (ATES). Tank thermal energy storages (TTESs)* are tanks that can be made of steel or concrete and can be placed on or in the ground. They use the principle of stratification, which allows high capacities and short-term charging cycles. The main disadvantages are a limited size of construction and high construction costs. *Pit thermal energy storages (PTESs)* also use the stratification storage principle. They are made using a big hole in the ground (often in the form of a pyramid) whereby the ground is enclosed by watertight liners. The costs for such construction are cheaper related to the *TTES*, there are almost no limits to the dimensions, and they have a high capacity in relation to the volume. The disadvantages are the limited slope angle of the bottom and the fact that it is hard to repair if the liners break. *Borehole thermal energy storages (BTESs)* consist of vertical boreholes that are filled with water to transfer the heat into the ground. The system is a closed system and therefore has no contamination risks. In contrast to the previous technologies, *BTESs* have low construction costs and can easily be extended. Some of the disadvantages are the low thermal capacity, the lack of insulation, and the low-temperature level. The latter causes the requirement of a heat pump if a high supply temperature is needed, and this does not support a short-term charging cycle. *Aquifer thermal energy storages (ATESs)* use underground water reservoirs (aquifers) to store the heat. The system consists of two wells (warm and cold) to access the permeable underground filled with water. The system has very low construction costs and a medium thermal capacity (related to volume). The thermal energy is stored without insulation, which causes relatively high heat losses. Heat losses are reduced by larger scales through a better surface-to-volume ratio. A disadvantage is that the storage has a lower temperature compared to *PTESs* and *TTESs*. Consequently, heat pumps are often needed, and thus for short-term storage, the system should be combined with additional storage tanks. [181]

Sneum and Sandberg evaluate different economic impacts on flexibility in DHSs for the Nordic countries [175]. The authors focus on the impact of fuel and electricity prices as well as subsidies, tariffs, and fees on investment and flexible operation of TESs and heating plants in DHSs. They show that the use of electric boilers and heat pumps is sensitive to the structure of the tariffs and grid fees of the electrical grid. Especially the high fixed fees resulting from short and high power peaks hinder the implementation of these technologies. CHP plants are also influenced by the tariff structure and the taxes and subsidies have an especially significant impact on their implementation and operation. The authors conclude that the legal and economic conditions (e.g., the share of fixed and variable parts of the tariff) decide whether and how these heating plants may be used for a flexible operation. Further, it is shown that—independently from the chosen production technology—DHSs benefit from implementing TESs in all considered cases. [175]

In summary, the following technologies and parts of the DHS are identified to be able to provide thermal flexibility (q.v. table 6.3).

Table 6.3: Technologies with thermal flexibility potential in DHSs

Type	Example
Heating plants	Flexibility through fuel (e.g., gas-fired HOB), through smart energy system (e.g., CHP plant, heat pump) or through supply temperature control (q.v. chapter 5)
Direct TES	Central buffer tank, domestic hot water (DHW) tank (customer side)
Indirect TES	ATES with heat pump, PCM TES
Network	Energy transfer station or substations (changing the temperature) combined with transmission pipes (delay in transmission)
Demand side	Flexible room temperatures

Heating plants can offer flexibility by shifting production. This is based on the storage capacity of the primary fuel (e.g., gas) or the flexibility of another energy sector (e.g., electricity). Examples are gas-fired HOBs, CHP plants, or heat pumps. In chapter 5, it is shown that the supply temperature also has a relevant impact. Numerous types of TESs exist which all have different characteristics whereby a relevant characteristic is if the TES requires an additional temperature increase. Therefore, it will be distinguished between direct and indirect TESs. Examples of direct TESs are centralized storage tanks or DHW tanks on the customer side. Examples of indirect types are TESs which use PCM technology or ATESs with too low temperature. Another part of the DHS offering flexibility is the inertia of the piping network. To use this flexibility, the temperature at the energy transfer stations or the substations must be changed. Thermal energy can be stored through the delay in temperature transmission. Finally, the inertia of the buildings' mass can be used to manage the demand side. For example, the temperature inside the rooms may be changed slightly.

6.4 Review of the state-of-the-art of flexibility integration

As presented in the previous sections, flexibility is required to secure an efficient operation and facilitate the transition toward 4GDH. Several technologies which are part of the DHS offer potential to meet the demand. To bring the flexibility potential and demand into line, integration of the flexibility is required. This flexibility integration must be coherent with the framework that is presented in chapter 4. To do so, existing integrations are reviewed in this section as a first step.

In the literature, many evaluations of flexibility and TESs in DHSs exist. The focus of this review is on concepts for the integration which enable a systemic perspective. This means that publications are presented that fulfill one of the following requirements: either they include more than one type of flexibility potential shown in table 6.3, or they include a generic concept for the integration.

The publications that are not used are those that focus on utilizing thermal inertia for electricity coupled heating plants (e.g., CHP plants or heat pumps) for dispatch on the electrical side and that do not consider further requirements on the thermal side. Evaluations that focus on a specific type of technology, for example only the inertia of the network or only the stratification of storage tanks, are also not considered. However, such technology-specific publications will be used for individual evaluation later.

The results are presented in subsections related to the design and the operation of DHSs. Finally, the gap in existing integrations is identified and described.

6.4.1 Flexibility in design

In the design process of a DHS, different aspects of flexibility are important compared to the aspects of the operation. For example, the size and location of TESs can be chosen. For the design decisions, two relevant references are identified. Jebamalai et al. evaluate the location of storage tanks [183] and Zhang et al. compare different types of technology [184].

Jebamalai et al. analyze TESs at different locations in the DHS: at the heating plant, in the distribution network, or in the buildings. The objective is to identify the most cost-effective placement of TESs in the design scope of DHSs. The authors use an automatic designing tool based on a geographic information system combined with Excel for dimensioning and cost calculation of different scenarios. By placing TESs in the distribution network and in the buildings, the pipes' diameters can be reduced. It is shown that centralized TESs can reduce network costs. For the assumed plant setting, the costs decrease with the introduction of centralized storage by avoiding peak supply. With increasing storage sizes, the costs decrease until a minimum is achieved at a storage time of several hours. For longer storage durations, the total costs increase (even in the case of seasonal

TESs). Placing distributed TESs (at the substation level) leads to a decrease in costs in the case of short-term storage. The building level TESs is the cheapest integration for small size tanks. Optimum sizes and locations are identified for all TESs. While comparing TESs at different locations in the DHS, the best combination is identified as centralized large-scale TESs for long-term flexibility combined with small-scale TESs at the building level for short-term flexibility. [183]

Zhang et al. compare four different types of short-term storages related to different scenarios for low-temperature DH. The types are a central storage tank, the piping network, DHW tanks, and the building mass. The authors implement four (iterative) steps for the evaluation: the determination of the demand, the design of the system, dynamic modeling, and optimization of the operation. Afterward, the central optimization sends a signal to the local controllers. The evaluation shows that all types offer some degree of flexibility. In the case of the DHW tank, it is important to mention that a good hydraulic connection combined with a good control system has further benefits for lowering the system's temperature. Based on the presented design of the DHW tank integration, the authors indicated that it has the highest cost savings due to the benefits related to lower return temperatures. The flexibility of the piping network is considered critical because the supply temperature must be increased for charging which is against the low-temperature regime of the evaluation and would lead to higher costs in heat supply. The authors recommend including future (low temperature) requirements in the design of TESs. A central storage tank can store the heat for the longest duration. Although the building mass can store heat, it has some shortcomings related to the lower heat demand for space heating with renovated buildings and, due to the fact that heat demand in summer is not needed, the flexibility is therefore not available. [184]

The evaluations show that there are many different parameters and individual advantages and disadvantages that should be balanced in the design concept. In general, it can be concluded that the different storage technologies, as well as their sizes and locations, can be applied to different timescales of flexibility. This application is evaluated in the next subsection.

6.4.2 Flexibility in operation

In this subsection, the different concepts to integrate flexibility into the framework processes are presented that have been identified in the review. The concepts are organized by the applied durations in the publications. Firstly, short-term concepts are presented. Secondly, concepts that combine seasonal and short-term flexibility are presented. Finally, concepts are presented which include the location of the flexibility by combining network and storage flexibility.

Short-term concepts

In the following paragraphs, different evaluations of short-term flexibility are presented.

Romanchenko et al. compare the flexibility of storage tanks with that of buildings (demand side management (DSM)). The authors use a *unit commitment model* based on mixed integer linear programming (MILP) including a model for storage tanks with a uniform temperature and a two-node building model. They show that the DHS could benefit from using both types of TES for short-term storage. In contrast to DSM, the storage tank can also be used for medium terms of up to 2 weeks. The building flexibility has the additional disadvantage that the capacity is dependent on the weather, and it is not constant. [185]

A concept presented by Vanhoudt et al. uses a model predictive control (MPC) for evaluating the control of a CHP plant combined with three storage variants: central TESs, TESs located at the building combined with DSM, and DSM only. In the case of DSM, the room temperatures are actively managed. For the determination of the flexibility, a multi agent system is used, which performs three steps. In the first step, bids are estimated and aggregated. The bids are based on "virtual prices" [186]. For the storage tanks, the bid is based on the state of charge (SOC). In the following step, the bids are optimized. In step 3, a proportional-integral controller secures the overall aggregated demand. The control signal is translated into individual set-points based on the bids. The application of this concept to a case study shows that it is possible to shift the operation of the CHP plant. Further, decentralized TESs show the best performance. This is related to the higher efficiency in transmission due to lower heat losses at higher mean flow rates. [186]

Cai et al. investigate the integration of DSM in a distribution system in Copenhagen which is part of the greater Copenhagen DHS. The authors use a steady-state simulation model. In the DSM, flexibility for space heating and DHW are included and the delay in the network is not considered. Three cases are evaluated: a benchmark, a price-based, and a central concept, and the marginal costs from the day-ahead planning from Varmelast are used as prices. The price-based concept shows advantages in costs compared to the benchmark case while the comfort requirement can be met. However, it leads to the suboptimization of the demand side and thus it may lead to challenges for the system operator due to higher pumping power in the network. Therefore, a central control is simulated which allows for controlling the demand side flexibility in a systemic way. Such control could be used for peak reduction combined with a temperature reduction for times of peak demand. A disadvantage of this concept is that a schedule is required for each building. As an alternative, the authors propose integrating the network costs into the price of the price-based control. [187]

Li et al. investigated the utilization of network and building flexibility to improve the electrical production of a CHP plant. The DH network is reduced to a resistor-capacitor model which is combined in an iterative algorithm with a quadratic programming problem. The investigation of Li et al. demonstrates that the flexibility can be increased by storing heat in the network. In the considered time range of 24 hours, storing heat in the buildings offers more flexibility than the network. The largest flexibility can be obtained if both types are combined. [168]

Leśko et al. combined the flexibility of storage tanks, the network, and buildings (DSM) in a simplified MILP problem. The network is included with a focus on transmission delay, temperature levels, and heat losses. It is simplified as two storage tanks (supply and return). Further, homogenous temperatures at the substations are assumed. The DSM is also implemented in a simplified way and the non-linear problem is solved iteratively. Firstly, a temperature profile is assumed to calculate the system's states, and afterward, the decision variables are optimized. Subsequently, the states are calculated for all timesteps again. This procedure is iterated until only minor changes occur. A show case was successfully demonstrated using the iterative procedure and the simplified model shown. All scenarios show that using the flexibility has economic benefits (for the operation of a CHP plant) compared to the no-storage scenario whereby the storage tank shows the best result. If all types are combined, the algorithm uses the central TES first, followed by the DSM, and finally the network flexibility. The authors conclude that an overall optimization is needed and that the model must be improved (e.g., by reducing the simplification). However, full models seem to be too complex for MILP. [103]

The evaluations show that DSM and the piping network offer short-term flexibility and central storage tanks can be identified as the simplest solution. Besides the different time ranges of the technologies, different technical solutions are used and partly combined. The tools used are MPC, multi agent systems, MILP, as well as iterative solutions for non-linear problems. In summary, all the concepts combine technical control problems with economic optimization.

Short-term and seasonal concepts

In this paragraph, evaluations are presented that combine seasonal and short-term flexibility. An important aspect is the uncertainty of future demand, which must be solved for seasonal dispatch.

Saloux and Candanedo developed a rule-based control for the combination of a short-term TES and a seasonal TES charged by a solar thermal plant. The two main conditions are the flow rates between the two TESs as well as the temperature difference for the solar thermal plant. The authors proposed a reactive control strategy based on the inner energy (or also on the relative SOC) of the short-term

TES. The strategy is based on described rules which include ramps for control of the pumps. The limits for the parameters of the strategy (flow rates, temperature differences, and inner energies) are optimized using a genetic algorithm. [188]

Dominkovic et al. evaluated DSM and seasonal storage in DHSs. The evaluation is mainly based on two steps. Firstly, a detailed simulation model of the buildings and control strategy is built and evaluated. The resulting key performance indicators (KPIs) are the cut-off duration, load shifting capacity, and hourly demand. Secondly, these KPIs are used in an optimization model on a system level. An evaluation of the demand side flexibility shows that in the case of preheated buildings (an increase from 21 to 24 °C), the DSM supports intraday flexibility. In the case of heat supply cut-off, the buildings require up to 6 hours until a temperature of 18 °C is reached (on cold winter days). Further, the authors showed that seasonal storage is complementary to DSM. [189]

Egging-Bratseth et al. investigated the combination of DSM, seasonal TES, and uncertain demand. By using a linear stochastic optimization model, the impact of uncertainty was evaluated. The uncertainty results in a higher charge of the TESs. The authors show that the seasonal TES is useful for shifting supply from summer to winter and the DSM can be used to shift the load within one day. The combination of the flexibility reduces the peak supply which results in a 10 % cost reduction for the presented scenario. [182]

The presented studies combine short-term and seasonal flexibility. It is shown that DSM and storage tanks can be well combined with a seasonal TES. Further, the presented studies include only these specific types of flexibility technologies. The concepts are technology-specific and hence they are not considered as being generic.

Network and TESs concepts

In the following paragraphs, concepts are presented that combines local TESs with the operation mode of the piping network. A synchronized charging of the local TESs allows for reducing the central supply temperature or even shutting down the full supply.

Moallemi et al. present a novel concept based on non-uniform temperatures. The authors propose to operate the system at a very low temperature (40 °C) which should be sufficient for modern space heating. Twice daily, the DHS is heated up to 75 °C for 2 hours to charge the DHW storage tanks in each building. Using this concept, the temperature is sufficiently high for hygienic DHW and, for the rest of the day, space heating is provided. By simulations with numerical models, it is shown that heat losses can be drastically reduced. [59]

This concept is extended by Arabkoohsar. Here, the transmission network runs always at a low temperature and heat pumps are implemented on the distribution level. These heat pumps increase the temperature for short durations of the day. During this time, TESs in the buildings are charged. Using simulations, this concept is evaluated as being highly competitive compared to other low-temperature solutions. Furthermore, the heat pumps would allow for interaction with the electricity sector. [60]

The authors Hammer et al. evaluated a so-called "temperature-flexible" [178] DHS operation with TESs on the customer's side. This concept is also defined under the term "pulsating" [178] DHS. In the summer operation, decentralized TESs are charged simultaneously. Subsequently, for some periods the whole DHS is shut down. The concept is evaluated with simulations and the result is that transmission losses are reduced by 6 % related to the produced heat. The authors indicate that such an operation would lead to a reduction in the lifetime of the pipes due to thermomechanical stress. [178]

The presented concepts show that it would be possible to have a strong interaction of local TESs and the network variables. As these concepts may all have a strong negative impact on the lifetime of the network, such temperature amplitudes do not seem desirable. Instead, the impact of heat losses and transmission should be included in an overall mechanism, like the presented smart market concept.

6.4.3 The gap in existing flexibility integrations

The presented references show that flexibility is already evaluated in many ways in the DH sector. The studies show that some types of flexibility may be preferably used for short-term flexibility, including network, DSM, and decentralized storage tanks while central and seasonal TESs may be used for longer timespans. In the studies of the references presented, the advantage of using flexibility is evaluated in an economical way (e.g., reduction of costs).

In addition—as described previously—there are numerous evaluations of specific individual technologies that are not presented here. A typical example is the combination of a storage tank with a CHP plant and HOB. Because of the number of existing publications, the gap between individual technologies and specific implementation can be considered small.

In contrast, a generic and systematic flexibility integration for all technologies could not be found. Almost all identified references consider only some types of flexibility or propose specific solutions. Further, most of the identified concepts do not adequately consider the supply temperature, as they include temperatures as constraints instead of as variables even though it is known that using energy in sensible TESs as a quantity without considering the quality (temperature) leads to faulty findings [190]. However, the combined effect of storage tanks and their capacity depending on variable temperatures has been used by the special concepts in [59], [60], [178] which present slightly extreme temperature concepts (like on/off operation). Further, their temperature and durations are based on fixed time schedules and not on economic optimization. Solutions that support competition are also identified in some concepts for the DSM.

All in all, the identified concepts are very different and specific. Some concepts are based on simulations, some on optimization techniques, and others on control strategies. Further concepts combine these different tools, which seems to be the most promising approach due to the complexity of the problem. A full generic concept is not found. Further, the identified concepts do not directly fit into the previously developed framework. It can be identified as a gap where a coherent concept is lacking that allows for the integration of the flexibility into the framework. Particularly for the flexibility integration into the smart markets, the impact of temperature on costs should be systematically evaluated as it is done for the heating plants in chapter 5.

6.5 Assignment of flexible technologies to the framework processes

The review shows that a comprehensive integration of flexibility is lacking and therefore, a new method for the integration is developed. In the first step of this development, each type of technology is individually evaluated. The five different types of technologies that offer flexibility are summarized in table 6.3 (q.v. section 6.3.2) as including *heating plants*, *direct TESs*, *indirect TESs*, *pipes*, and the *demand side*.

These flexible technologies must be integrated into the proposed framework of chapter 4. The framework has different processes: the *capacity market*, the *day-ahead market*, the *intraday market*, and the *operation* (in the form of the *supervisory control*). In addition, the thermal inertia of the DHS provides (passive) *thermal reserves* that compensate for fast deviations in operation. Table 6.4 presents the framework processes and the thermal reserve.

Table 6.4: Framework processes relevant for flexibility integration

Type	Cycle	Resolution
Capacity market	annual	1 hour to 1 day
(Smart) day-ahead market	daily	1 hour
(Smart) intraday market	4 hours	15 minutes to 1 hour
Supervisory control (operation)	15 minutes	minutes
Thermal reserve (operation)	real-time	-

The objective of this section is to assign the flexible technologies to the framework processes. To do so, the integration of each type of technology is discussed in a qualitative way. To validate the arguments, references from literature are used or simple examples are calculated. The assignment is systemically and coherently based on the flexibility demand and the time window. This assignment to the framework itself is a novel contribution to this thesis.

6.5.1 Heating plant flexibility

For electricity markets, it is discussed that the trading of flexibility could be improved by shorter trading cycles (e.g., to compensate for errors in forecasts) [172]. But, at the same time, excessively short cycles could lead to a reduction of the market liquidity [172]. This is particularly relevant for DH markets due to their local and small dimension.

Heating plants are evaluated in chapter 5 in detail. Here, the most relevant conclusions are presented. Depending on the type of heating plant, they can offer flexibility in different magnitudes. Some heating plants are dependent on the weather conditions and their maximum production fluctuates. Furthermore, some plants are not able to produce at high supply temperatures.

Integration of the production side flexibility into the framework

To optimize the available temperature, the heating plants must be included in the smart short-term markets considering their supply temperature. The solution for this integration is already presented in chapter 4: heating plants participate by placing bids on the smart market(s). Since the different market routines are performed with different cycles (several times a day for the intraday market), the heating plant schedules are readjusted regularly. In addition to these market routines, it is proposed to include flexible heating plants into the supervisory control as well. Here, the marginal prices of the intraday market may be used to define a sequence for compensatory heating plants (positive and negative). These prices are further relevant as they are the basis for opportunity costs for storage technologies.

6.5.2 Direct TES flexibility

Storage tanks are the most frequently used type of TES in DHSs [191].

Storage tanks are typically made of a steel core tank with insulation. In these tanks, the water volume is constant all the time. The tanks use thermal stratification with a hot top part, a cold bottom part, and a movable thermocline in between (figure 6.2). It is important that no jet occurs during charging and discharging which could disturb the transition layer. During the charging process (hot-water feed-in at the top and cold-water feed-out at the bottom) the layer moves down. During the discharging process, the layer moves up. There are different types of these tanks. Steel tanks that allow only temperatures below 100 °C or better 95 °C are most frequently used. [2, pp. 250–256, 374]

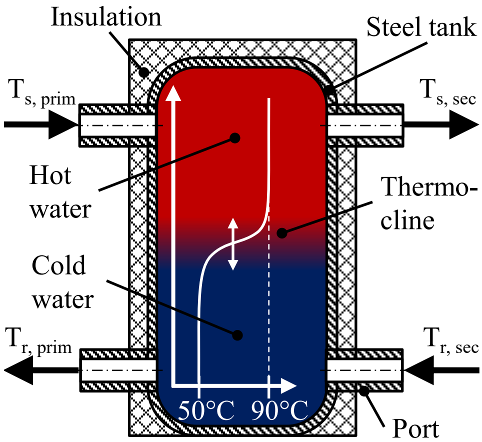

Figure 6.2: Cross-section of a storage tank (own figure inspired by [181, Fig. 4], [192, p. 30])

The tanks are insulated to reduce heat losses and have connection ports. The position of the ports is important as they should be located as far to the top and bottom as possible to increase the usable volume. The thickness of the thermocline should be kept as small as possible. [181]

As described in section 6.4, storage tanks are used for different timescales and different places in the DHS related to their size. A typical integration approach is to include them in heating plant dispatches in a simplified way assuming a fixed capacity, e.g., as shown in [193]. Supply and return temperatures are assumed as the maximum and minimum storage temperatures but the stratification requires careful treatment [cf. 194].

Integration of direct TESs into the framework

Due to their high relevance, storage tanks are evaluated in more detail later. Related to the applications in literature (q.v. section 6.4), large centralized tanks should be used, at least in day-ahead planning, and smaller tanks (e.g., for DHW) may be used for shorter durations. An important aspect of the tank is its location in the DHS as it must be correctly included in the smart market.

In most hydraulic concepts, the tanks do not have any actuators to control the charging and discharging. In these concepts, the tanks will naturally act as a buffer of mass flow differences (q.v. section 4.5.3, p. 107). If the production is higher than the demand, the production mass flow is also higher. In this case, there is a mass flow in the tank from top to bottom. For such a hydraulic concept, no extra control is needed.

6.5.3 Indirect TES flexibility

Many types of indirect TESs exist. In DHSs, these types are mostly used in the context of long-term storage or even seasonal storage. These types can differ in a broad spectrum and thus it is not possible to consider all variants in detail in this thesis. Instead, an exemplary plant that is planned for the DHS in Hamburg-Wilhelmsburg will be evaluated [77].

Evaluation of a case study

In the DHS in Hamburg-Wilhelmsburg, an ATES is planned combined with a heat pump, which is required for the discharging process. An exemplary and simplified piping and instrumentation (P&I) diagram is depicted in figure 6.3 which shows the discharging case.

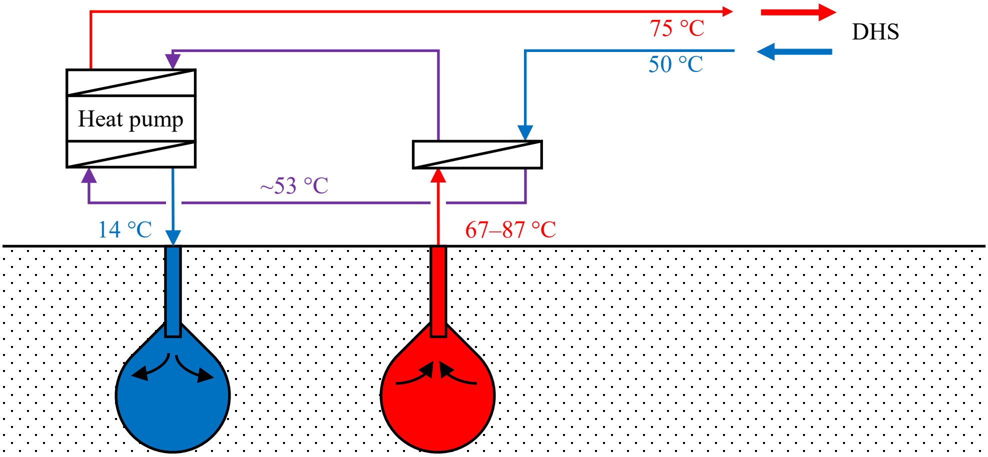

Figure 6.3: Simplified P&I diagram of the ATES while discharging

The seasonal storage system (i.e., ATES and heat pump) consists of two wells: a hot and a cold one [195]. The medium of the aquifer is separated in its own hydraulic cycle [195]. For the discharging process, a heat pump is required to reduce the temperature in the cold well and, by this, to increase the share of extracted energy [cf. 196]. More parameters based on publicly available data and estimations are given in table C.20 (p. 370).

In the charging process (figure 6.4), the cold water is taken from the cold well, led through the heat exchanger, and heated up by the supply temperature of the DHS [195]. Finally, the hot water is pumped into the underground where it forms a hot bubble [195].

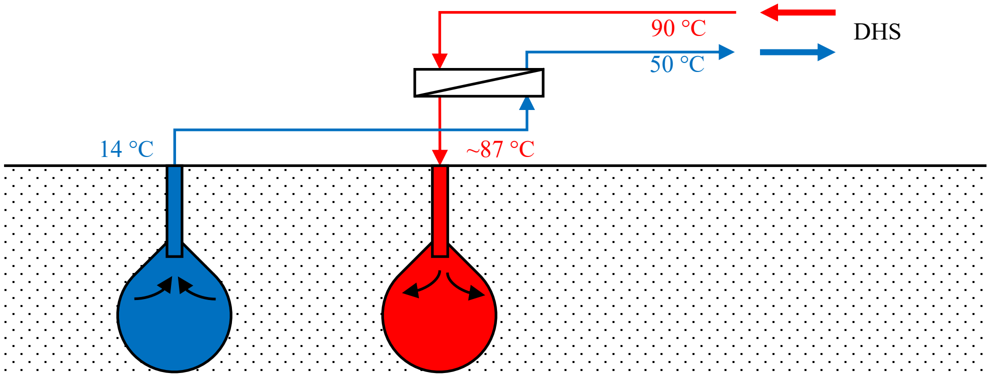

Figure 6.4: Simplified P&I diagram of the ATES while charging

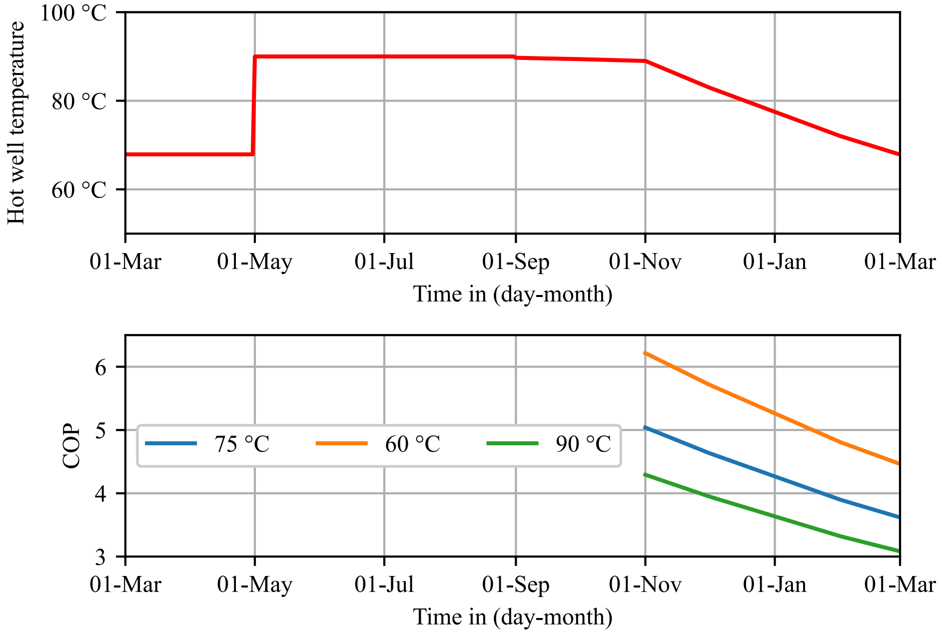

Figure 6.5: Extraction temperature (top) and resulting technical COP of the overall system depending on the required supply temperature (bottom) (temperature data from [197])

Figure 6.5 shows the hot well temperature of one year of operation in the upper graph, based on the data provided in [197]. In this example, the ATES is charged from the beginning of May until the end of August with a temperature of 90 °C. In September and October, the ATES is in standby mode. From November until the end of February, the ATES is discharged, which reduces the hot well temperature from 87 to 67 °C.

In contrast to the charging process, the discharging process requires a heat pump to increase the hot water side's temperature and particularly to reduce the cold-water side to groundwater temperature. A cooling down to this temperature would not be possible without a heat pump. The lower graph depicts the coefficient of performance (COP) of the overall system including the benefits of the direct heat transfer through the first heat exchanger. This COP is related to the overall heat extraction of the system in relation to the electricity demand. For the equations pertaining to the heat pump, q.v. section 5.3.4 (p. 151). The parameters for this calculation can be found in table C.20 (p. 370). Three curves depict the relation between the ATES hot well temperature and the required secondary temperature. Both temperatures have a large impact on the COP and, through this, on the variable costs. The lower the required supply temperature for the DHS, the higher the COP is. With the decreasing hot well temperature, the COP decreases. In the medium case of 75 °C supply temperature, the COP starts at 5 and goes down to approximately 3.6.

Integration of indirect TESs into the framework

TESs that have a discharge supply temperature below the required supply temperature are called indirect TESs. Seasonal TESs are often indirect TESs. Even though the presented example is only one possible application, it can be seen as being representative of this type of technology. The charging and the discharging processes are technically different. The charging process is simple because the supply temperature of the heat source is higher than the temperature in the TES. Therefore, the TES can be charged by a heat exchanger. In the discharging process, the temperature of the TES is too low for direct use and thus the temperature must be increased. In the presented example, this temperature increase is facilitated by a heat pump. Due to the different characteristics of the two processes, their planning and operation will be integrated separately into the framework. One constraint for this abstract separation is that charging and discharging are never done simultaneously.

The discharging process is always related to the use of the heat pump. In this case, the heat pump is the more complex part of the operation. Therefore, it is proposed to integrate the discharging process of the indirect TES with a heat pump as a heating plant. As presented in chapter 5, the required supply temperature on the heat sink side has a significant impact on the variable costs wherefore it is proposed to integrate the discharging process of such indirect storage as a heating plant with bids including prices for energy and temperature. In general, the same requirements are valid as for a normal heating plant. However, in contrast to a heat pump with a low-temperature underground heat source, too many starts must be avoided as numerous starts would lead to higher losses in the wells which require a heat up at every new start [198]. Therefore, the discharging process should be operated in a continuous form.

The charging process is more flexible than the discharging process because the heat is only transferred with a heat exchanger. This increases the possibility of more flexible charging strategies. The integration of the charging process is proposed using three steps. Firstly, charging should not be done simultaneously with the discharging. Secondly, a long-term charging plan is needed in the case of a seasonal TES. This long-term plan can be created in the capacity market whereby the heat demand for the charging must be added to the demand forecast. Thirdly, as the charging is easy to control, its flexibility may be used in the short term. The short-term flexibility of the seasonal charging process can be represented by an abstract direct TES (as a substitution model).

6.5.4 Network flexibility

Thermal energy can also be stored through the inertia of the piping network [2, p. 250]. The heat can be stored by preheating the network (force) or by cooling down the network below the recent supply temperature (delay) [64]. In comparison to the delayed concept, the preheated concept allows for more energy shift until the thermal comfort is impacted [66]. Further heat can be stored in the supply pipe or in the return pipe [66]. As changing the temperature leads to a distribution of different temperatures due to the delay of transport [199], storing heat in the network is a complex process due to the movement of the storage medium [66].

The evaluation of this complex flexibility technology is done in three steps. Firstly, the principle of the charging and discharging process is explained. Secondly, the effect of a simple pipe is analyzed by using a case study. Thirdly, studies from the literature are evaluated. All these inputs are used to propose an integration method for the flexibility of the network.

Principle and constraints of network flexibility

Storing heat in the supply pipe requires no changes to the design and just another set-point for the supply temperature. Due to the increase in the temperature, more heat can be stored in the network and the momentary thermal power of feed-in is increased. The higher temperature is spread over the network to the substations. At the moment the higher temperature arrives a substation, the substation control will reduce the flow rate. If all substations are reached, the network is fully charged. While the supply temperature is held, the heat is stored on standby. To discharge the system, the supply temperature is reduced, and the lower temperature moves through the network to the substations. The lower supply temperature at the substations leads to higher flow rates and if the lower temperature has reached all substations, the network is discharged. [cf. 64]

In contrast, storing heat in the return pipe requires bypasses between the supply and return pipes and leads to higher return temperatures [66]. Further, it is possible to combine the flexibility of supply and return pipe, which would provide the highest amount of flexibility, but would also lead to a very strong increase in the return temperature [65]. The higher return temperatures lead to lower efficiency of the heating plants [2, p. 497]. Due to this lower efficiency, increasing the return temperature will not be considered in the integration of flexibility (q.v. chapter 3, p. 51).

The fatigue of the pipes due to thermomechanical stress is another problem when regularly changing the temperature [19] whereby large amplitudes and frequent changes are the most harmful [200].

A constraint for temperature changes in the network is that the required temperature must be delivered [55]. A primary supply temperature that is too low may lead to unstable hydraulic conditions due to the control of the substations. If the temperature is not sufficient at a substation, the control of the substations will try to increase the temperature to reach the set-point (which cannot be achieved). Therefore, the valves will be completely open. This may increase the demanded flow rate above the limits of the system.

Evaluation of a case study

To evaluate the impact of some conditions, a small case study is presented. It includes a pipe with a length of 3,000 m and a norm diameter (DN) of DN200 to visualize the impact of supply temperature and the required temperature. The parameters are provided in table C.21 (p. 371) and the heat losses are calculated using equations A.10 and A.11 (pp. 317, 319). In this evaluation, two principles are included. The first required quantity is the transportation time which is calculated from thermal power and cross-section geometrics. The second effect is the heat losses that occur during the transportation at the minimum temperature, and the additional heat losses, which occur from the storage process. A boundary condition for the evaluation is that, in every case, the supply temperature which is required by the customers (here 75 °C) must be achieved. Figure 6.6 depicts the temperature distribution over the relative length of the pipe for the DN200 pipe at three different values for thermal power (200, 500, and 2,000 kW).

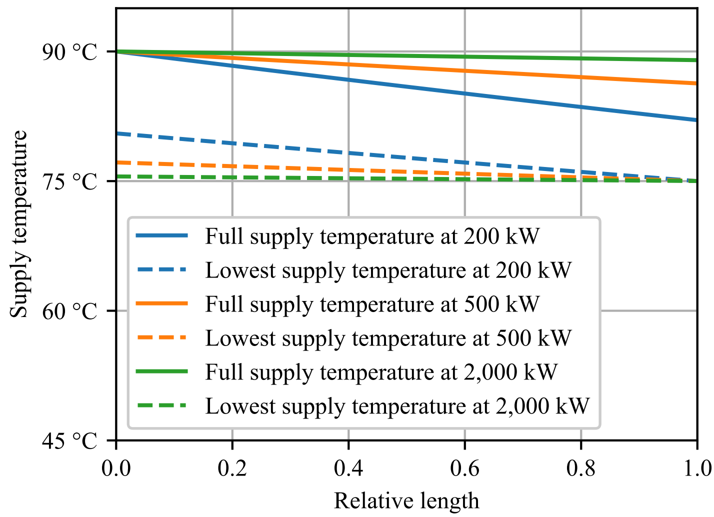

Figure 6.6: Temperature distribution of the DN200 pipe at 90 °C primary and 75 °C required secondary supply temperature for different thermal power values

The dashed lines represent the minimal primary supply temperature to reach the required secondary supply temperature. At low power (and low flow rates) the temperature decreases more than at high thermal power. A primary temperature for charging is given (here 90 °C). At the same time, a required secondary temperature for a complete discharged pipe must be given (here 75 °C). The mean internal additional temperature for charging is represented by the area between a full and a dotted line of the same color. This figure demonstrates that the temperature difference (and with it the capacity) of a pipe is higher at higher thermal power transmission.

This case is an example of the complexity of using the storage effects of the network.

Evaluation of literature case studies and concepts

The computation of the storage dynamics is rather complex due to the non-linearity [66]. In general, hydraulics can be computed in relation to the laws of Kirchhoff [201] whereby meshes increase the complexity [121]. The thermodynamics must consider the delay, the heat losses, and the mixing effects at T-pieces (nodes) [201]. Many studies aim to use the flexibility for the optimization of generation (mostly CHP plant optimization for flexibility on the electrical side).

There are mainly two approaches, which are applied to do so, namely simulation and optimization.

The first approach is to perform simulations for a better understanding of the behavior of the flexibility. Vandermeulen et al. studied the flexibility of the network in an abstract way to identify the required modeling depth with a focus on the substation and secondary side [64]. Leśko and Bujalski evaluated different network models [202]. Hinker et al. made parameter variations with simulation models to evaluate the detailed limits of this flexibility [199]. Balić et al. evaluated the flexibility by using step functions [201]. Vivian et al. identified more abstract KPIs such as capacity and the difference in heat feed-in, which are evaluated by simulations [66]. In [203], Lorenzen analyzed the impact of different variables on the storage effects in a steady-state simulation. The model is used by Lorenzen et al. for a detailed evaluation of the storage potential and the results are included in a simplified MILP optimization [65].

Several studies were performed to optimize CHP plant operation using the network's flexibility for cost optimization.

Zheng et al. combine a DHSs simulation and an optimization of the CHP generation. The network flexibility is included in a linear optimization in an aggregated way and the exact temperatures are computed afterward. Heat losses are included in the optimization by fixed (relative) values. [204]

Li et al. included the flexibility of buildings and the network in a quadratic optimization model [168]. Xu et al. evaluated the flexibility of the network combined with a single CHP unit [205] while Yu et al. developed an optimization model including stochastic demand and abstracting the network flexibility to simple storage [206]. Xue et al. developed a model based on a two-stage robust optimization problem [207]. All these models use the assumption of a fixed mass flow. Such a strategy is often used for example in China [204], but it is not the state of the art in modern (low temperature) DHSs (q.v. DH scope VII in section 3.1.1, p. 32). The constant flow rate significantly simplifies the optimization problem.

Merkert et al. developed a simplified concept for the abstraction of network flexibility. Their concept aimed to derive a SOC formulation of the network flexibility for the utilization in MILP optimization. However, their findings show different problems with the accuracy of the concept (e.g., by assuming fixed mass flows). [208]

Leśko et al. developed an optimization model for the operational planning of different flexible technologies (tanks, networks, and DSM). The integration of the flexibility of these technologies forms a non-linear problem, which is solved by the authors through an iterative solving of linear optimization problems. The pipes of the network are simplified and considered storage tank models. [103]

Besides simulation and optimization, some concepts based on MPC are identified.

Bavière and Vallée present a temperature control based on an MPC for short-term production scheduling. The concept includes a load forecast and an iteration of a dynamic network simulation combined with an MILP optimization. It is implemented with a rolling horizon of 24 hours and a resolution of 15 minutes. [55]

Vandermeulen et al. evaluated the impact of demand forecast uncertainties for the utilization of network flexibility in combination with an MPC. In general, the impact is evaluated as limited, and the schedules are affected less than the peak supply. [209]

However, increasing the supply temperature may have a positive (reducing) effect on return temperatures at substations with an indirect connection due to the better heat transmission of the heat exchangers [64].

Vandermeulen et al. evaluate the modeling accuracy for storing heat in the DH network. By comparing different modeling depths, they show that the impact on the primary return temperature is important and should not be neglected. To do so, good temperature forecasts are needed. [19]

Another integration approach is the use of pulsating temperatures or even a full switch of on/off operation. Examples are [59], [60], and [178] (for details q.v. section 6.4.2). Both strategies aim to reduce the variable cost but do not consider the storage effect of the DHS as their focus.

As presented in chapter 4, it is possible to optimize the heat losses of the network and the electricity for pumping. Increasing the temperature results in higher heat losses but higher temperatures in the supply pipes and equal temperatures in the return pipes increase the temperature difference and therefore the flow rate is reduced at equal thermal power demand. Lower flow rates lead to lower demand for electricity for the pumps of the network. Examples are provided in [56], [57], and [58]. Laakkonen et al. apply neural networks for the prediction of the network behavior and use a brute-force optimizer for the optimization of heat losses and pumping power [210].

It can be concluded that using the flexibility of the network's pipes is considered in several references and concepts. The consideration of the network's flexibility is complex due to the strong interrelation of the different physical conditions which form a non-linear problem. Since the storage medium is moving in the pipes, storing heat in the network is a dynamic process. Furthermore, each intervention of the operational variables (such as changes to the supply temperature) leads to several effects on the whole network. Therefore, the flexibility of the network should be accessed carefully and in compliance with the overall system operation.

Integration of the network into the framework

There are different ways in which the network operation can be integrated into the framework. In all cases, the integration faces several challenges:

Firstly, if an ideal set-point for the supply temperature was identified by a full-cost optimization (including heat losses and electricity for pumping), a retrospective change of the temperature to make use of the network's flexibility will increase the costs. Therefore, storing heat in the network pipes could conflict with the previously proposed optimization of heat losses and pumping electricity in the context of implementing a smart market.

Secondly, changing the network's temperature leads to mechanical stress. To reduce mechanical stress on the pipes, the network flexibility may be used moderately. This can be supported by additional hard restrictions like limiting the number of cycles or to restrict the ramp of temperature change. Another concept would be to add the costs of fatigue for changes in temperatures.

Thirdly, the integration should be coherent with the previous developments and comprehensive for all types of flexibility. For example, in contrast to studies of DHSs in China that use a constant flow rate (e.g., [168], [205], [206], and [207]), variable flow rates must be considered.

All solutions presented above may have some weaknesses for a comprehensive integration into the framework which considers the requirements of the DHS. The MILP solutions require linearization and simplification. In contrast, the simulations do not present the optimal solution on their own and can only test pre-defined operational concepts. The MPC concept which combines the dynamic simulation with the MILP optimization seems promising but a continuous change of operation may conflict with day-ahead commitments.

Therefore, a two-step concept is proposed. The day-ahead and intraday processes should include the network's electricity consumption and the heat loss in the smart market algorithm. If possible, the delay of temperature changes may be included in the market mechanism. This would probably require resolutions of the market below 15 minutes to consider the effects. For example, the internal resolution may be reduced to 5 minutes, which is a value proposed by Vandermeulen et al. [cf. 211]. Setting limits for temperature gradients may simplify this issue and increase the resolution.

In addition, the costs for deviating from the market-optimal solution should be computed after the market clearing. These costs should be provided for the supervisory control of the network operator. In the case of deviations, the network flexibility may be used in the short term for compensations if it is more cost-effective than other forms of flexibility, while including the costs for fatigue.

6.5.5 Demand side flexibility

Two types of heat demand mainly exist in residential buildings: space heating and DHW. DSM has been evaluated in numerous ways. Some concepts include the DHW tanks, while others include the space heating only. In general, the flexibility of the demand side can be implemented as “forced” by preheating or “delayed” due to an accepted cool down [179]. Further, the demand side flexibility can be facilitated indirectly by economic incentives or directly by controlling the demand [212]. Due to the complexity of the demand side flexibility, it cannot be evaluated using its own case study. Instead, existing studies from literature are evaluated, and the requirements and concepts are derived from these. Finally, solutions are selected that best fit the proposed framework.

Evaluation of literature case studies and concepts

The studies which are presented in the state-of-the-art review (section 6.4) have shown that demand side flexibility can be used on a timescale of some hours up to an intraday timeframe. Some of the previously presented concepts, which combine different types of flexibility, access the demand side flexibility in a centralized way. This is particularly the case for those evaluations which include the demand side flexibility in centralized optimization algorithms like [103], [189], or [168]. For such concepts, control systems are required which allow for changing the individual room temperature [185].

An alternative is an implementation described by De Coninck and Helsen. The authors describe a case study in which it is not possible to change the individual room temperatures. Instead, the supply temperature of the in-house distribution system is controlled. The authors propose the introduction of cost curves that provide the quantification of flexibility, and which can be used to aggregate the flexibility of different buildings. Thereby, the minimum costs are computed for the normal operation by first applying optimization to the costs for heat demand. Secondly, a fixed offset to the heat demand is assumed and the costs for this new demand are also optimized. The resulting difference between the minimum and the offset costs are the costs for flexibility. These calculations are performed by an MPC using a gray-box model at 15-minute intervals. It is shown that flexibility has costs that can vary broadly, and the authors propose considering these costs in DSM measures. [213]

Even though the main purpose is to provide flexible heat pump operation, the presented concept can also be applied to DHSs.

Le Dréau and Heiselberg evaluated the DSM potential of residential buildings by simulation with different indoor temperature set-points. They use one strategy with a forced and another one with delayed heat demand. Further, the authors use different KPIs for the evaluation of the buildings (namely capacity, efficiency, thermal comfort, and power shifting). They show that houses with low insulation provide only short durations for load shifting (up to 5 hours) but larger amounts of thermal energy. In contrast, houses with better insulation have longer durations (up to 24 hours) but with lower amounts of energy. The authors did not implement a specific control concept in the simulations. Instead, it is shown that the control of DSM has high requirements, and the acceptance of the occupants must be investigated. Thus, they propose that further research is needed. [214] Vanhoudt et al. present a mixed concept. In a first step, the individual controllers of the buildings place bids in a central model predictive controller which optimizes the flexibility in the time horizon. Afterward, the results are split in relation to the bids and are sent as set-values for each building's active control. This is repeated in every timestep with a rolling horizon. [186]

Aoun et al. develop a concept that allows for impacting the room temperatures without a measurement of the room temperatures. The only required measurements and controls are located at the substations. Here, the building's internal supply temperature is controlled. Therefore, this concept is evaluated as being "non-intrusive" [215]. The smart control strategy is based on a MPC (with MILP). The controller uses a rolling horizon of 24 hours, and it is repeated every 15 minutes. The control can react to prices and offers short-term flexibility. The non-intrusive concept is chosen to handle issues concerning the data privacy of room temperatures which should not be known by external people like the DH operator. While the concept works, it is sensitive to forecast inaccuracies which may be solved if feedback from the rooms is provided. [215]

The references [187], [216], and [217] investigated DSM measures in the DHS of greater Copenhagen. These concepts seem relevant as the Copenhagen dispatch mechanism is partly similar to the proposed framework.

Cai et al. compare different DSM mechanisms based on the day-ahead hourly prices in the greater Copenhagen DHS. The authors assume that their DSM measures do not interfere with these prices. The first concept is price-based, day-ahead, and includes a horizon of 24 hours. The mechanism shows that the costs for the individual building could be decreased, but the resulting peaks in the distribution system create new challenges due to high flow rates during low-cost times. Therefore, the authors implement another mechanism with a centralized control considering the flow rates in the network. In this concept, the pumping costs are included, and bottlenecks are avoided. Further, this concept may also be used to reduce the system's temperature by optimizing flow rates. The disadvantage of this central concept is that a schedule must be made for each building. Therefore, the authors propose including the network's costs in individual pricing for each building. Further, they propose implementing the control with a rolling horizon to compensate for forecast errors. This could be related to the existing intraday scheduling procedure in Copenhagen. [187]

Foteinaki, Li and Péan also investigated the DSM potential of an apartment block in the greater Copenhagen DHS. The authors compared two different strategies based on the existing communication. The first (static) strategy can be implemented without communication by fixed tariffs for different times of the day. For example, network peak times are the most expensive. The other concept is based on a dynamic pricing signal. The building's control takes its decision to charge, discharge, or standby based on thresholds. The thresholds are static and differ for each month. The comparison shows that the static concept can shift more energy while in contrast, the dynamic concept can better decrease the costs. [216]

Luc et al. use the same concept as [216] but upscaled it to a small district. The results show that DSM is beneficial. The largest impact is the preheating shift from the morning into the night. The authors propose that further investigations must be performed to identify the best strategy. [217]

Kontu et al. compare four concepts of DSM in DHSs. The first concept considers a peak load reduction by the customers. In the second concept, the DH operator reduces the production costs. The third concept extends the second one by an individual timing for each building. In the fourth variant, an individual DSM strategy is performed for each customer section. The most relevant cost savings for the customers are achieved with the first scenario. This is based on the recent tariff structure in which the customers pay for energy and peak. This scenario does not show a benefit for the DHS operator. The other scenarios indicate different profitability for each customer segment. In all scenarios, the annual peak of supply was not significantly reduced. This is explained by the low DSM potential on cold days. The authors conclude that there is no perfect solution (related to their conditions) for all kinds of DHSs and, therefore, individual solutions are needed. DSM measures are considered complex. Finally, the authors propose to change the customer pricing to incentivize DSM. This new pricing should be beneficial for both customer and operator. [218]

It can be concluded that many different concepts exist. Generally, DSM should be implemented carefully with different strategies and in line with the requirements of the DHS operator to avoid new peaks or other undesirable effects [219]. Dynamic pricing seems promising combined with MPC and an MPC with a rolling horizon can be regarded as a robust solution against inaccuracies [220].

Integration of the demand side flexibility into the framework

Based on the findings of the review, the following proposal for the integration of the demand side is made. DSM should be based on a dynamic price signal which includes the network costs. The costs are known from the intraday market and are known for several hours (up to a full day) in advance. Such an implementation would allow for local solutions that fit into the given situation of the individual building. The DHW storage tank could also be part of it. In future developments, the demand side flexibility may also be included in the intraday scheduling procedure as a pre-planned and centralized controlled load shift. However, this could require a much faster intraday cycle to ensure high accuracy levels and would result in greater complexity. Instead, a DSM implementation with a dynamic pricing signal seems more realistic as a first step. Further, the required supply temperature may be included dynamically in such systems to indicate the minimum demand for the DHS operator.

6.6 A new, systematic flexibility integration

In the previous section, the flexibility potential of the individual flexible technology types is evaluated, and the technologies are assigned to the framework processes. In this section, a general and systematic method is developed based on individual evaluations and assignments. Therefore, the different requirements and characteristics of the technologies must now be systematically arranged. This is done in three parts:

1. A general integration into the framework processes (with a focus on time),
2. a specific integration into the smart market (with a focus on location),
3. and the identification of flexibility metrics as an interface between planning and operation.

The result is a novel and comprehensive concept to combine the framework with all relevant types of flexibility technologies in a generic way. Each of the three parts is presented as its own subsection.

6.6.1 General integration into framework processes

For a coherent integration of flexibility into the new framework, three aspects must be combined: the flexibility demand, flexibility potentials (for each flexible technology), and framework processes.

The flexibility demand has a broad range. It starts with seasonal flexibility e.g., solar thermal integration, over medium-term flexibility such as day-ahead flexibility for the compensation of fluctuations in the electricity system, down to short-term flexibility for the smoothing of load variations.

To create a comprehensive result, the flexibility of all relevant technology types must be considered. To ensure a systemic integration, each technology must be integrated regarding its specific technical and economic characteristics. Moreover, the newly introduced ownership must be considered as well. This means that the single buyer (SB) is responsible for the network, TESs, and customer services. In this way, the SB can use the flexibility of the whole system and is empowered to buy thermal energy at low costs. In contrast, the independent producers are responsible for the heating plants. Since the ownership of these plants is unbundled, the interface to the heating plants requires special treatment of flexibility to ensure a system-serving integration. The first concept for this treatment is already introduced by the innovative bids in chapter 5.

The framework has four different processes for different time windows: a capacity market, a smart day-ahead market, a smart intraday market, and operation. The operation can be split into active management by the supervisory control, and the passive system reaction which is referred to as thermal reserve. In the following, each of these instances is discussed separately for each type of flexible technology.

Flexibility in the capacity market

In the capacity market, new installations of required plants are considered, and preliminary annual operational planning is made. For this long-term perspective, two aspects are most relevant. Firstly, storage is required to compensate for a seasonal mismatch of production and consumption. Secondly, it influences the dimensioning of new plants. For example, by using TESs, the peak production capacity can be reduced. Figure 6.7 shows the integration of the different technologies into the capacity market.

According to the process of the capacity market (q.v. chapter 4, p. 76), the producers place offers in the tendering which include the main *heating plant* parameters. Besides the decision to enter a contract with the producers, a rough annual schedule will be created. Due to the uncertainty of forecasts (e.g., thermal demand or electricity prices), it is not possible to create valid hourly production plans. In addition, the planning of the *seasonal TESs* is an important part of the capacity market. Here, daily amounts of energy should be scheduled, which leaves flexibility for the hourly short-term planning.

Storage tanks, the *demand side*, and the *network's flexibility* cannot be exactly pre-planned seasonally but their flexibility potential should also be included in the design and dimensioning of the plants. For example, the capacity of direct TESs may be considered to reduce the required peak production in operation. DSM and the network's flexibility might be used for reduction of peaks in supply and transmission e.g., by including them in the dimensioning of pipes if their potential is validated.

Temperature is used for the dimensioning of the heating plants and pipes. Hydraulics to control the temperature in a flexible way must be considered in the design and control strategies.

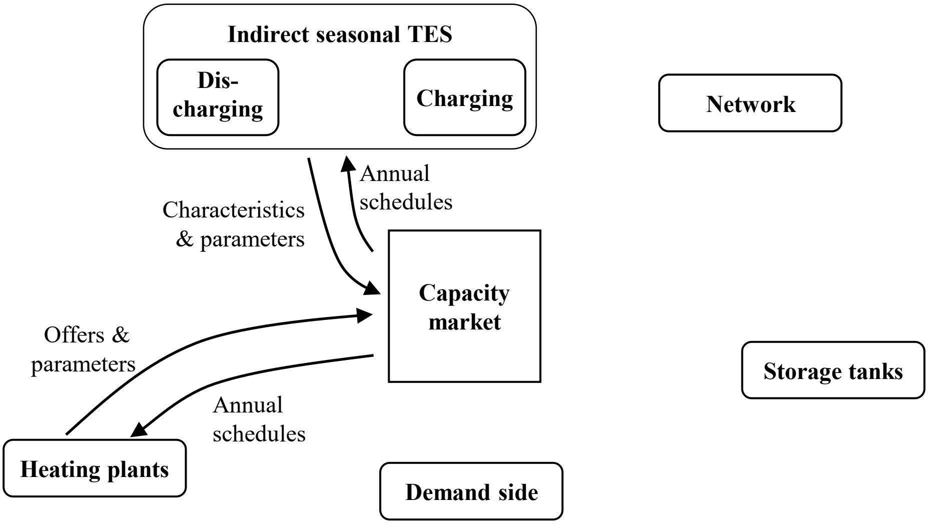

Figure 6.7: Integration of the flexible technologies into the capacity market

Flexibility in the short-term markets (day-ahead and intraday)
In the short term, the demand for flexibility results from fluctuations or failures of heating plants and forecast deviations of the demand. In addition, the same effects occur in the electricity sector, which requires compensation through CHP plants, heat pumps, and electrical heaters. Consequently, these heating plants need to adjust their production, which impacts the production of heat in the DHS as well.

Figure 6.8 depicts the integration of flexible technologies into the short-term markets.

In both short-term markets (day-ahead and intraday), the integration of the different flexibility technologies is similar.

The *heating plants* participate by bids with prices correlated to amounts and supply temperature in the required resolution. After the market clearing, they receive a schedule for the heat supply.

Seasonal TESs have two different implementations. For the *discharging process*, their production should be treated like the heating plants with bids based on temperature and amount. This is particularly necessary if indirect storage is considered and additional heating (e.g., heat pumps) is required. In contrast, the *charging process* offers flexibility which should be utilized in the short term. For consistency reasons, it is proposed to integrate this type of flexibility into the smart market dispatch model.

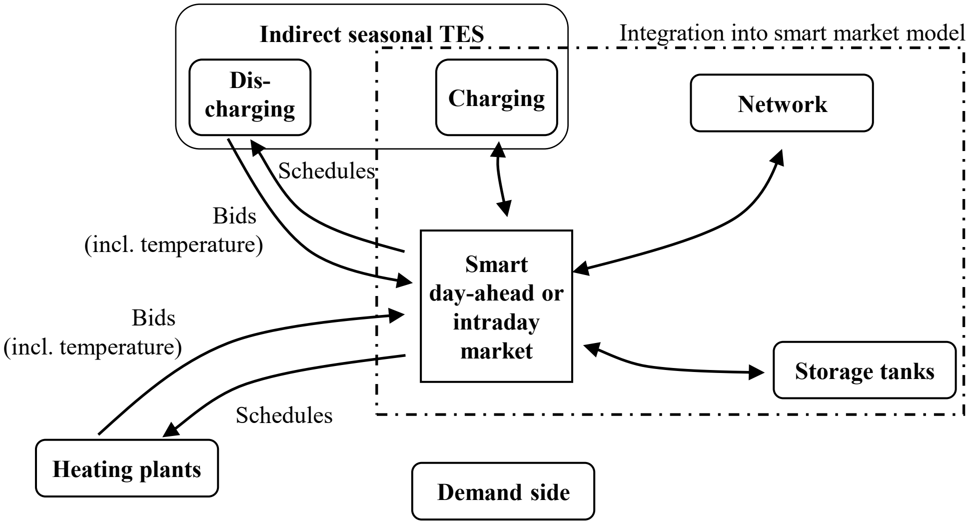

Figure 6.8: Integration of the flexible technologies into the smart short-term markets

The *network* and the *direct TESs* are also directly integrated into the dispatch model. This integration is presented separately in section 6.6.2.

The integration of the *demand side* is dependent on the concept of DSM (or vice versa). In this case, it is assumed that the demand side is integrated by DSM with dynamic pricing and therefore it is not actively integrated into the market processes. Instead, the demand side reacts to the dynamic heat prices that are provided by the smart market processes of the framework.

The main difference between the day-ahead and the intraday markets is the number of cycles and the timespan from planning to operation. The intraday market is much faster and therefore even more important for short-term flexibility technologies. To increase the resulting resolution for the supervisory control, it is proposed to set the resolution of the intraday market to 15 minutes. In contrast, the resolution of the day-ahead market is proposed to be 1 hour for two reasons. Firstly, the accuracy of the forecasts for a day-ahead timespan is lower. Secondly, since the intraday routines are made after the day-ahead planning, the lower resolution is increased anyway. Both resolutions (15 minutes and 1 hour) are recommended in relation to the standards in the electricity sector. The final decision on the resolutions of both marketplaces must be made based on experience while implementing the related routines and processes.

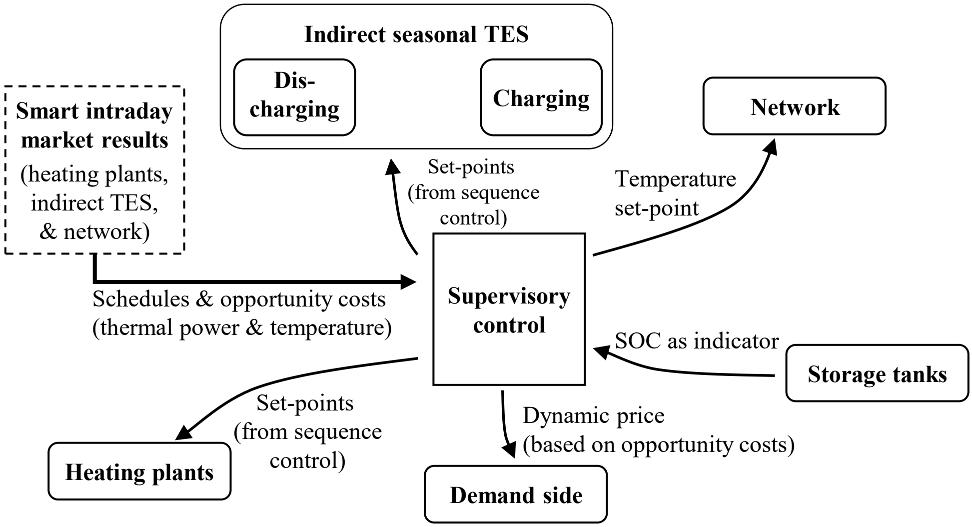

Figure 6.9: Integration of the flexible technologies into the supervisory control

Flexibility in operation (supervisory control)

The intraday market can adjust the schedules several times a day (e.g., every 4 hours) with a resolution of 15 minutes. In case of a short-term mismatch of production and consumption (e.g., through failure) between the intraday market cycles, the system must be able to intervene.

In DHSs, additionally required heat is usually supplied by HOBs. In future DHSs, this role must be defined based on dynamic economic decisions and thus it is proposed to use the opportunity costs of each technology as the basis for the decision. In this context, opportunity costs can be described as the additional costs incurred if a plant is requested to operate even though it was not planned or vice versa.

Hence, it is proposed that the supervisory control must be able to intervene by accessing the flexibility of all technologies. Figure 6.9 depicts the integration of the different technologies into the supervisory control.

The intraday market process delivers the information on the schedules and the opportunity costs for the heating plants, the indirect TESs, and the network. The supervisory control can derive the set-points for the thermal power and the supply temperature from the schedules.

The opportunity costs of the *heating plants* and the *indirect seasonal TESs* are used by the supervisory control to create a cost-ordered sequence. Through this, rapid adjustments in the case of deviations from the planned operation can be made.

The flexibility of the *network* may be used for shorter periods. If the network's supply temperature is changed, the optimal balance of supply temperature and pumping power of the smart market is left and this also results in higher costs. Further, an undersupply may be possible due to a low temperature. In addition, care must be taken to consider the temperature-changing cycles in the network that lead to earlier fatigue. But, if the costs for these effects are considered in the network's opportunity costs, its flexibility can also be included in the supervisory control.

For the integration of the *demand side* flexibility, dynamic prices are created that are based on the opportunity costs of the other technologies. By this, DSM is incentivized and can be done by independent controllers in the supplied buildings. Since such a controller reacts to price incentives, feedback to the supervisory control is not necessary.

Finally, the *storage tanks* are not included as an active component of the supervisory control but are included reactively through the differences in flow rates from production and consumption. Their energy content (represented by the SOC) should be monitored as the main indicator of the thermal energy and power balances of the DHS. This will be further investigated in section 6.6.3.

Thermal reserve

The demand for fast flexibility comes from small deviations in production and consumption through forecast uncertainty, fluctuations, and failures. Since thermal systems offer much more inertia than electrical systems, additional balancing power is not required. In DHSs, the thermal reserve is provided by the *storage tanks*. These TESs are the only components of the system that do not require an active control (considering the hydraulics proposed in chapter 4, p. 107) as they automatically buffer the difference between load and production. The amount is controlled by the equilibrium of flow rates. If the storage tanks are not fully charged or discharged, the temperature is held stable for the network's supply temperature and the heating plants' return temperature. Therefore, the temperature effects are not relevant in this timescale.

6.6.2 Integration of flexibility into the smart market dispatch model

In chapter 4, it is proposed to give the ownership (or at least the responsibility) of TESs and the network to the SB. Further, it is proposed to implement a smart market for the short-term dispatch (day-ahead and intraday). Moreover, a concept for a dispatch model of the smart market is presented as a recommendation for future implementation. The proposed dispatch model consists of two types of computation processes: *market nodes* and *transmission edges* (q.v. section 4.4.4, p. 97). The nodes form local markets, and the edges are responsible for the transmission, which can place bids at the market nodes like the heating plants. The demand is placed by forecasts. For each transmission edge, the temperature, pressure, and heat losses are considered.

In the proposed concept for the dispatch model, some of the flexible technologies are already integrated. The flexibility of the heating plants is included in the new heating plant bids. Further, the discharging process of the seasonal storages, which would require an additional heating plant (e.g., a heat pump), should be treated in the same way. The flexibility of the network should be used by the transmission edges to give them a degree of freedom for buying and selling.

Besides these three considered technologies, the integration of the direct TESs, the demand side, and the charging process of the seasonal TESs must be developed. Basically, there are two general ways in which the flexibility can be integrated into the dispatch model: by integration in the market nodes or by integration in the transmission edges. Both variants are presented and discussed in the following paragraphs. Afterward, one variant is recommended for future implementation.

Integration into the market node computation process

Figure 6.10 depicts the concept of flexible market nodes. The DSM potential, the direct TESs, and the charging process of the seasonal TESs are considered in the node. The transmission edges only include the losses for transmission (heat, temperature, and pressure). In this concept, all demand-related flexibility must be included in the clearing algorithm of the market node. This requires a market node that can optimize the bids between the timesteps by using local flexibility.

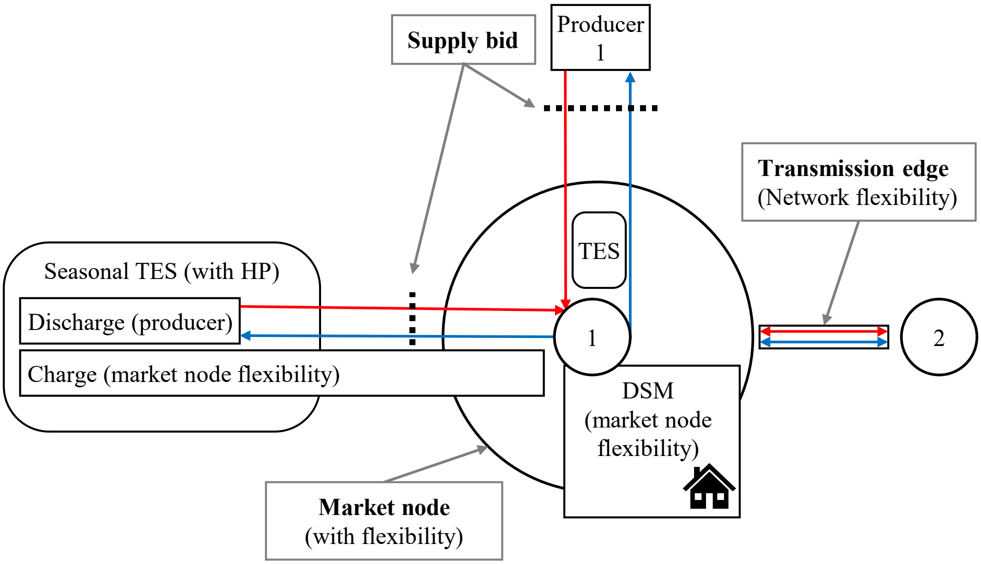

Figure 6.10: Flexibility integration into the market node computation process

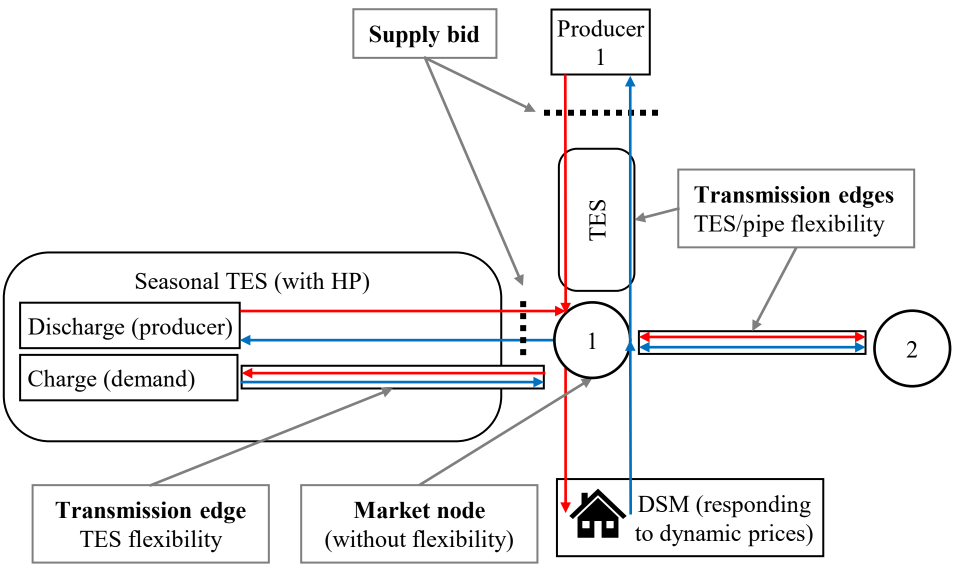

Figure 6.11: Flexibility integration into the transmission edge computation process

Integration into the transmission edge computation processes
Figure 6.11 depicts the concept which includes the flexibility in the transmission edges. In this case, a direct TES that is placed between the network and the production is treated in the same way as a pipe of the network. Thus, the transmission edge buys thermal energy at the input-sided node in times of low costs by using its flexibility. This seems plausible since some similarities between pipes and storages can be identified. For example, Jiang et al. and Leśko et al. use a TES model for modeling the flexibility of the network pipes [103], [221]. In the concept proposed here, different physical equations are required for the specific implementation of both technologies although, in relation to their similarity, they may be integrated into the same computational process.

To integrate the charging process of the seasonal TES into this variant, it should be separated into two substitution models, namely an inflexible demand combined with a flexible virtual direct TES. Through this separation, the virtual TES can be implemented as a transmission edges well.

Finally, it is proposed to integrate the customers via DSM and dynamic pricing in this variant. Through this, the complexity of the system is reduced since the demand side does not need to place bids in the local market. As an alternative, their flexibility may also be integrated as a transmission edge.

Recommendation for a concept
Both concepts would allow for integrating all types of flexibility.

The advantages of the flexibility integration into the market node are a lower number of edges (no extra TES edges) and a higher degree of freedom for the market clearing at the market node.

The advantage of the flexibility integration into the transmission edge is a lower complexity of the market node which results in several advantages. The clearing at the market node becomes time-independent and each timestep can be cleared on its own. The TES implementation in the transmission edges does not require much additional effort, because it must already be implemented for the pipe edges.

It is hypothesized that the transmission edge variant is the better concept as it is more coherent with the basic concept of the smart market as proposed in chapter 4. Therefore, it will be used for further development in this thesis. However, since it is not tested and evaluated in this thesis, the market node variant will still be an important fallback option if a future implementation of the concept leads to a dead end. Derived from the existing solutions that can be found in the literature, it is proposed that both concepts will require an iterative solving algorithm due to the non-linearity and complexity of the problem. Some of the existing concepts from the literature may be useful for the further development of the concept.

The flexibility of the heating plants is integrated by their bids on the smart market and the resulting schedules and set-points for thermal power and supply temperature. For the integration of the remaining technologies (TESs, network, and demand side) into the framework processes, the interfaces must be further specified. To do so, flexibility metrics are considered in the next section.

6.6.3 Flexibility metrics for the system operator

The previously described developments are made using general and abstract evaluations based on the literature and case studies and concepts for the integration into the framework processes are proposed. Due to the limited scope of the thesis, an implementation of the full flexibility concept is not possible. However, the first step of implementation is presented in the following, which includes the quantification of flexibility by metrics. Since the heating plants are already evaluated in detail, the other flexible technologies in the responsibility of the SB are the focus of this development. While the storage tanks are most important, the network and demand side are also relevant.

The first step, defining the flexibility is presented in section 6.2, although—related to Petersen et al.—defining flexibility does not solve the problem of its quantification [222]. While numerous ways to quantify flexibility are identified in the review, useful solutions are still lacking for some tasks [19]. Further, Lund et al. indicate that a single KPI is not available and that the selection of KPIs is related to the application case [172].

In this thesis, metrics that already exist in literature are used. The contribution is the selection and combination of the KPIs. In particular, the impact of supply temperature is focused on, which has been identified as not being sufficiently addressed in the literature.

Existing metrics in the literature

In the literature, several of the found concepts quantify flexibility (or TESs)—in the broadest sense—as the energy that can be shifted in time (or time to shift energy, power, etc.). Other concepts consider the quality (temperature) in the flexibility concept as well.

An overview of some KPIs is given by Guelpa and Verda whereby relevant examples are the energy efficiency and the exergy efficiency. The latter can be used to improve the storage design to avoid exergy losses. [166]

Another review is presented by Dahash et al. Here, the efficiency of the storage tanks is given in general as well as for the charging and discharging processes. Further, some other indicators are presented that consider the temperature gradients of the stratification and mixing effects as well as the exergy efficiency. [181]

In Annex 67 of the International Energy Agency, an overview of KPIs for flexible buildings is presented [174, p. 44]. It summarizes different KPIs from other references such as [214], [223]–[225]. [214] is introduced above and [224], [225] are used in the following. The KPIs of [223] define self-consumption factors for photovoltaics (PV) electricity consumption which are not relevant for this thesis. The article [224] presents part of the Ph.D. thesis of Reynders [226]. In both works, a relevant set of KPIs is identified with a focus on DSM. The KPIs are storage capacity, storage efficiency, power shifting capability, and the SOC. [224], [226, pp. 39–44]. All the presented KPIs in [174] do not include the supply temperature from the DHS as a variable, which can be explained by the focus of the study on the building side.

Nuytten et al. introduced a flexibility quantification. The concept consists of two types of flexibility: delayed and forced. In both cases, the flexibility is the time of shifted energy. To handle this flexibility, the authors introduced a representation with the cumulated energy demand for the minimum supply. The storage capacity is added to this minimum curve and the curve forms the maximum production. Production can be delayed (vertical shift) or forced (horizontal shift). [225]

To demonstrate the concept of Nuytten et al. [225], the principle is applied to an own consideration in figure 6.12. The blue line is the cumulative demand that is based on a demand profile [227]. The orange line is the cumulative production of a solar thermal plant in relation to the radiation from [228]. Additionally, the green line shows the sum of the demand and a fixed energy offset—the assumed capacity of a storage tank. In the beginning, the storage tank is filled with 500 kWh from the day before. The corridor between the demand (blue line) and the sum of the demand and storage tank (green line) represents the energy flexibility of the storage tank.

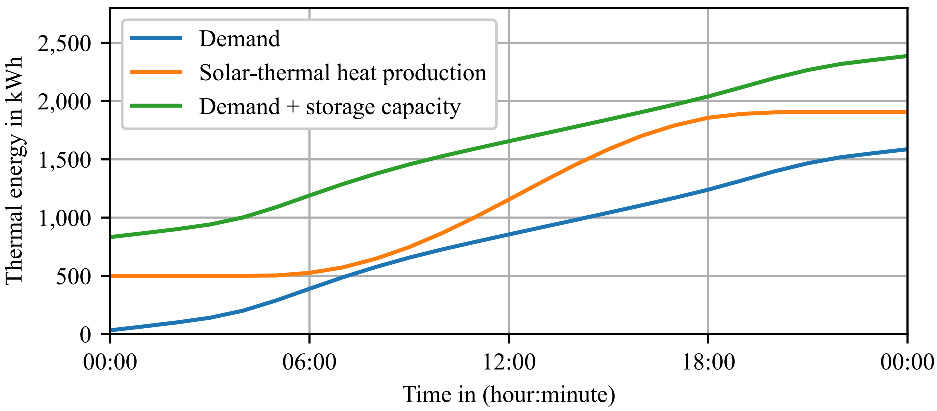

Figure 6.12: Cumulative energy related to the principle of Nuytten et al. [225] (data from [228] and [227])

The figure demonstrates the relation of thermal energy and time to quantify flexibility. In the case of a static storage capacity, such a simple concept seems sufficient for the flexibility quantification. However, if the storage potential changes over time or if the flexibility of production is in focus, more complex metrics are required.

Therefore, Ulbig and Andersson introduce four flexibility metrics [177]: power, the derivative of power (ramp), integral of power (energy), and the duration of the ramp. They present a three-dimensional visualization based on the ramp, power, and energy. [177]

The authors Yifan et al. evaluated the flexibility potential that DHSs offer for the electricity grid [229]. They classified the flexibility into "ramping", "power," and "energy capacity flexibility" related to the approach of [177].

The direction of thermal power in this thesis will be defined as production-oriented like the balancing power in the electricity grid [230] and the definition in [179]. Table 6.5 shows an overview of the sign definition in both dimensions.

Table 6.5: Sign definition for thermal power

	Positive	**Negative**
Heating plant	Increase thermal power	Reduce thermal power
Consumer	Reduce thermal power	Increase temperature
Storage	Discharge	Charge

Reynders et al. defined the "power shifting capability" as the relation of the difference between planned and shifted thermal power to its duration until a limitation is reached (e.g., by the minimum or maximum temperature) [224].

The gap in existing metrics

In existing metrics, the focus is on energy-related quantities. Even though the temperatures are mostly used in operations such as for the control of heating plants and valves, energy-related quantities are mostly used for the operational planning of plants. In these cases, temperatures are used as fixed constraints. But, as the temperature level of heat is an important characteristic, it should be considered in the flexibility metrics. This will be an important difference for the quantification of flexibility in the following.

The comparability of the different types of flexibility technologies is important and the metrics should be as simple as possible to allow for an effective implementation in operation. These requirements are included in the following identification of the flexibility metrics for sensible storage systems.

For a systematic evaluation, a thermodynamical control volume of any kind of thermal system is depicted in figure 6.13.

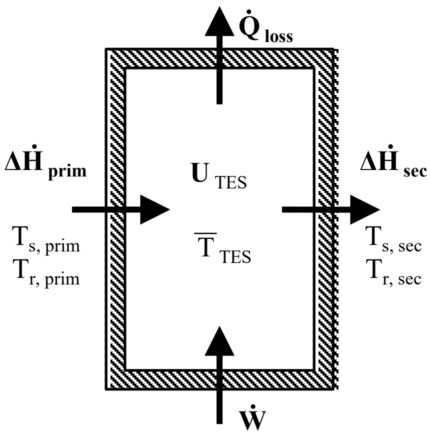

Figure 6.13: Thermodynamic control volume

Related to equation A.6 (p. 315) the inner energy (U_{TES}) is dependent on the differences of primary and secondary enthalpy flows (ΔH_{prim}, ΔH_{sec}), heat loss rates ($\dot{Q}_{\text{loss}}$), and added power ($\dot{W}$) e.g., by heat pumps. The enthalpy flows are referred to as *thermal power* in the outer context of this thesis. They are related to the mass flows and their temperatures, which are $T_{\text{s, prim}}$ and $T_{\text{r, prim}}$ on the primary side and $T_{\text{s, sec}}$ and $T_{\text{r, sec}}$ on the secondary side. The inner energy represents the whole energy level inside the control volume with the mean temperature ($\overline{T}_{\text{TES}}$). In operation, the absolute value of the inner energy is not a useful KPI. Instead, the capacity is used to define the technical boundaries of the system and the state of charge (SOC) is used to describe the state between the boundaries.

Thermal energy storage capacity

The thermal energy storage capacity represents the amount of energy that can be stored in the storage. Related to equation A.6 (p. 315), it can be defined as the difference between the inner energy from the technical maximum ($U_{\text{TES, max}}$) to the minimum ($U_{\text{TES, min}}$) in operation. In this thesis, the uppercase Greek letter Kappa (K_{TES}) will be used to avoid a mix-up with the heat capacity. The thermal energy storage capacity can be calculated using equation 6.1 in general. For sensible heat TESs, it can be calculated in relation to the TES volume (V_{TES}) with equation 6.2 using the heat capacity ($C_{\text{p, TES}}$) of the storage ($C_{\text{p, TES}} = c_{\text{p}} \cdot V_{\text{TES}} \cdot \rho$) [cf. 231, pp. 138–140].

The capacity is dependent on the maximum and minimum mean internal temperatures ($\overline{T}_{\text{TES, max}}$, $\overline{T}_{\text{TES, min}}$) whereby the main challenge lies in the definition of these temperatures. This is demonstrated by evaluating storage tanks in the subsequent section.

$$K_{\text{TES}} = U_{\text{TES, max}} - U_{\text{TES, min}} \tag{6.1}$$

$$\approx C_{\text{p, TES}} \cdot (\overline{T}_{\text{TES, max}} - \overline{T}_{\text{TES, min}}) \tag{6.2}$$

Specific implementations may need more complex computations. An example is given in [226, pp. 39–41] for buildings.

State of charge

To evaluate the current energy that is stored, the state of charge (SOC) is a commonly used KPI [cf. 232]. The thermal energy SOC can be described as the technical usable inner energy. The SOC can be calculated in absolute values (thermal energy) or relatively as a ratio to the capacity.

In this thesis, the relative SOC in relation to the TES capacity is represented by the Greek letter σ_{TES} and the relative SOC is presented in equation 6.3 [cf. 186]. The absolute usable thermal energy will be written as SOC_{TES} (q.v. equation 6.4).

$$\sigma_{\text{TES}} = \frac{U_{\text{TES}} - U_{\text{TES, min}}}{U_{\text{TES, max}} - U_{\text{TES, min}}} = \frac{U_{\text{TES}} - U_{\text{TES, min}}}{K_{\text{TES}}} \approx \frac{\overline{T}_{\text{TES}} - \overline{T}_{\text{TES, min}}}{\overline{T}_{\text{TES, max}} - \overline{T}_{\text{TES, min}}} \tag{6.3}$$

$$SOC_{\text{TES}} = K_{\text{TES}} \cdot \sigma_{\text{TES}} \tag{6.4}$$

Like the capacity, the SOC is dependent on the maximum and minimum mean internal temperatures ($\overline{T}_{\text{TES, max}}$, $\overline{T}_{\text{TES, min}}$).

In the proposed definition, the SOC represents the inner energy in relation to the thresholds of correct operation (e.g., required secondary supply temperature). In contrast to this, the inner energy difference (ΔU_{TES}) represents the stored thermal energy in comparison to the lowest system temperature ($T_{\text{r, sec}}$). It can be calculated using equation 6.5.

$$\Delta U_{\text{TES}} \approx C_{\text{p, TES}} \cdot (\overline{T}_{\text{TES}} - T_{\text{r, sec}}) \tag{6.5}$$

Again, specific implementations may need more complex computations:

Reynders used the SOC for the quantification of building flexibility whereby it is mentioned that the SOC may change even if the building's energy is constant. This is related to changes in the thresholds for minimum and maximum internal energy in relation to outer conditions. [226, pp. 43–44]

An application of the SOC KPI for network flexibility can be found in [208].

Efficiency

The thermal energy storage efficiency (η_{TES}) describes the share of discharged energy to charged energy [166]. There are different ways to define the efficiency of a TES (cf. [181], [231, p. 140]). Equation 6.6 is related to the control volume in figure 6.5 (p. 202). The efficiency represents the energy that can be recovered related to the input energy. The recovered thermal energy is the cumulated difference of enthalpy flows on the secondary side (ΔH_{sec}). The input energy is the cumulated difference of enthalpy flows on the primary side (ΔH_{prim}) and additional work. The equation can also be inverted to the non-recoverable parts. These are the heat losses (Q_{loss}) and the inner energy that cannot technically be extracted from the storage due to a temperature that is too low. The latter will be referred to as *sunk energy* ($\Delta U_{\text{TES, sunk}}$) in this thesis in accordance with the term *sunk costs*.

$$\eta_{\text{TES}} = \frac{\Delta H_{\text{sec}}}{\Delta H_{\text{prim}} + W} = 1 - \frac{Q_{\text{loss}} + \Delta U_{\text{TES, sunk}}}{\Delta H_{\text{prim}} + W} \tag{6.6}$$

The sunk energy can be calculated with equation 6.7 by using the mean minimum internal temperature and equation 6.5.

$$\Delta U_{\text{TES, sunk}} \approx C_{\text{p, TES}} \cdot (\overline{T}_{\text{TES, min}} - T_{\text{r, sec}}) \tag{6.7}$$

A specific implementation of the efficiency for DSM in buildings can be found in [224].

Effectiveness

The thermal energy storage effectiveness (ϵ_{TES}) is introduced to represent the temperature impact in an aggregating KPI. Belusko et al. used this KPI to evaluate the temperature performance of PCM TESs [233]. Previously, thermal effectiveness was used for the calculation of heat exchangers [234, p. 687].

For their evaluation, Belusko et al. treated a single TES as a heat exchanger and applied the heat exchanger effectiveness to the storage. They used the minimum required effectiveness during the discharge process to identify the storage capacity. Further, the effectiveness can be used to reduce the use of exergy. [233]

Thermal effectiveness can be understood as “temperature efficiency” [235].

Effectiveness (ϵ_{TES}) is defined in equation 6.8 for constant heat capacities [234, p. 687]. In case of a DHS, it can be related to the primary supply temperature ($T_{\text{s, prim}}$), secondary supply temperature ($T_{\text{s, sec}}$), and secondary return temperature ($T_{\text{r, sec}}$). It represents the conditions at the inputs and outputs of the system.

$$\epsilon_{\text{TES}} = \frac{T_{\text{s, sec}} - T_{\text{r, sec}}}{T_{\text{s, prim}} - T_{\text{r, sec}}} \tag{6.8}$$

There are two ways in which this quantity can be implemented in a system context, i.e., as a requirement from the demand side such as a minimum secondary supply temperature, or as a temperature potential of the primary side. In this thesis, it will be used for the requirement of the demand side. The treatment, in this case, is less complex, due to the assumption that the required temperature is known and therefore a specific value may be computed (e.g., a minimum supply temperature of 75 °C). In the other case, the potential must be calculated for the whole bandwidth (e.g., supply between 60 and 95 °C). Through this decision, the effectiveness can be used as a threshold in operation. Equation 6.9 shows the computation of the minimum effectiveness ($\epsilon_{\mathrm{TES,\,min}}$), which is required to achieve the minimum secondary supply temperature ($T_{\mathrm{s,\,sec,\,min}}$).

$$\epsilon_{\mathrm{TES,\,min}} = \frac{T_{\mathrm{s,\,sec,\,min}} - T_{\mathrm{r,\,sec}}}{T_{\mathrm{s,\,prim}} - T_{\mathrm{r,\,sec}}} \tag{6.9}$$

Variable cost factor

The variable costs for storing thermal energy cannot be calculated absolutely as they depend on the costs for the primary energy. Instead, a TES cost factor ($f_{\mathrm{TES,\,costs}}$) to compute the discharged energy's costs in relation to the primary costs can be given by equation 6.10. The factor is the reciprocal of the efficiency. In cases where additional work (e.g., by a heat pump) is used, these costs must also be considered.

$$f_{\mathrm{TES,\,costs}} = 1/\eta_{\mathrm{TES}} \tag{6.10}$$

6.7 A specific implementation of metrics for storage tanks

In the previous section, flexibility metrics are theoretically developed for all flexible technologies of the system operator. As a first and demonstrative implementation, the flexibility metrics will be applied to storage tanks. Storage tanks are the most important flexibility technology in DHSs. Besides their flexibility potential for long- and short-term storage, they can provide a thermal reserve for the smallest timespans. Further, it is common to use their SOC as an indication to control the heating plants. This is also proposed in the general integration concept for the supervisory control.

As previously shown, the SOC (q.v. equation 6.3) refers to the minimum and maximum mean temperatures. Even though it seems intuitive, it is not possible to use the system's supply and return temperatures for these mean temperatures. For example, if the storage tank would be discharged until the mean temperature equals the return temperature, this would lead to a supply temperature in operation that is too low. Vice versa, complete charging would lead to an increased return temperature. To prevent this, the lowest mean temperature is defined as the lowest temperature at the point where the supply port still has a high temperature (q.v. figure 6.14). The highest mean temperature is reached when the return port still has a low temperature (q.v. figure 6.15).

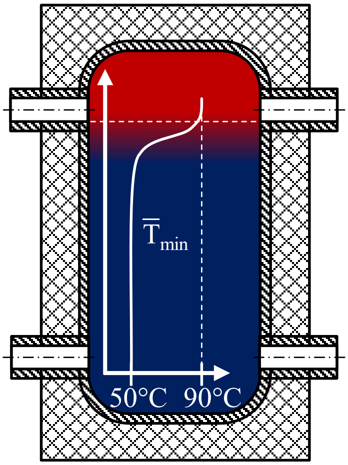

Figure 6.14: Cross-section of a tank with lowest mean temperature

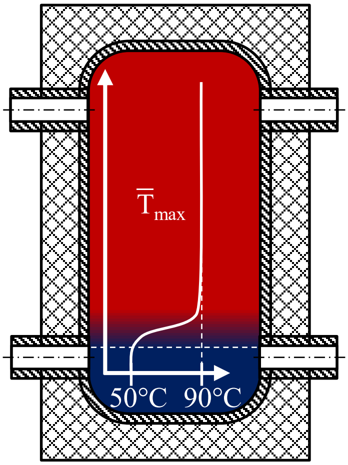

Figure 6.15: Cross-section of a tank with highest mean temperature

In practice, these mean boundary temperatures are estimated from experience in operation. In the following, a theoretical calculation for these temperatures is developed and presented.

Flexibility case studies are used for the application of the presented flexibility metrics. The evaluated devices are part of the DHS in Hamburg-Wilhelmsburg. Table 6.6 presents three case studies which are existing storage tanks with different volumes. The first two are central TESs. One is in the *Energiebunker (ENB)*, and one is in the *Energieverbund (ENV)* [78, TP1–4, p. 58]. The third one is a *domestic hot water (DHW)* tank located in a customer's building [236]. The global parameters for all three case studies can be found in table C.22 (p. 372) and variant-specific parameters are provided in table C.23 (p. 373). All variants start with the same thermocline at the middle of the height. If not stated otherwise, the primary supply temperature is set to 95 °C and the required secondary side temperature is set to 75 °C.

Table 6.6: Overview of flexibility case studies

Name	Location	Size	Rated energy (at 25 K)
storage-tank-ENV	Wilhelmsburg (Energieverbund)	$20\,m^3$	579 kWh
storage-tank-ENB	Wilhelmsburg (Energiebunker)	$2{,}025\,m^3$	57.9 MWh
storage-tank-DHW	Wilhelmsburg (Customer)	$0.91\,m^3$	26 kWh

In the following, the physical characteristics, technical boundaries, energy balances, storage duration, and flexibility KPIs will be evaluated with a special focus on the supply temperature. In a first step, a thermocline storage model is developed and validated and subsequently combined with the previously introduced flexibility metrics. This is applied to the case studies and the results are discussed.

6.7.1 Thermocline storage model

There are different ways to describe the form of the temperature in relation to the height. A typical approach is to use a thermocline (TC) regression. In this section, an existing thermocline model from [237] is extended by heat loss calculations. This new model is then combined with the flexibility metrics. Both the extended model and the combination with the flexibility metrics are novel approaches.

The thermocline model is depicted in figure 6.16. The variable z describes the relative height of the tank. The height of the thermocline is defined as z_{TC} [237].

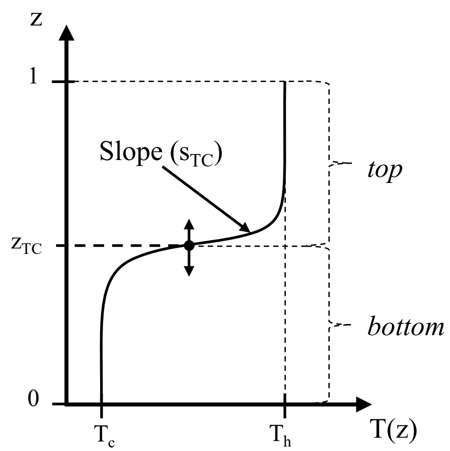

Figure 6.16: Parameters of the thermocline model

The form of the thermocline can be described by equation 6.11 [237]. Besides the height, the temperature is dependent on the slope (s_{TC}) of the function. The expression sets the inner temperature in relation to a hot reference temperature (T_{h}) and a cold reference temperature (T_{c}). For a general description, the inner temperature ($T(z)$) is transformed to a dimensionless temperature, represented by Θ in equation 6.12 [237].

$$T(z, z_{\mathrm{TC}}, s_{\mathrm{TC}}) = T_{\mathrm{c}} + \frac{T_{\mathrm{h}} - T_{\mathrm{c}}}{1 + \mathrm{e}^{(z_{\mathrm{TC}} - z)/s_{\mathrm{TC}}}} \tag{6.11}$$

$$\Theta(z, z_{\mathrm{TC}}, s_{\mathrm{TC}}) = \frac{T(z, z_{\mathrm{TC}}, s_{\mathrm{TC}}) - T_{\mathrm{c}}}{T_{\mathrm{h}} - T_{\mathrm{c}}} = \frac{1}{1 + \mathrm{e}^{(z_{\mathrm{TC}} - z)/s_{\mathrm{TC}}}} \tag{6.12}$$

The mean dimensionless temperature ($\overline{\Theta}$) of a specific height interval $[z_1, z_2]$ can be calculated using the integral shown in equation 6.13 [237]. Inserting $[0, 1]$ allows for the calculation of the mean dimensionless temperature of the whole tank ($\overline{\Theta}_{\mathrm{TES}}$) (equation 6.14).

$$\begin{aligned} \left[\overline{\Theta}(z_{\mathrm{TC}}, s_{\mathrm{TC}})\right]_{z_1}^{z_2} &= \frac{1}{z_2 - z_1} \cdot \int_{z_1}^{z_2} \left(1 + \mathrm{e}^{(z_{\mathrm{TC}} - z)/s_{\mathrm{TC}}}\right)^{-1} dz \\ &= \frac{1}{z_2 - z_1} \cdot \left(s_{\mathrm{TC}} \cdot \ln(\mathrm{e}^{(z_{\mathrm{TC}} - z_2)/s_{\mathrm{TC}}} + 1) - s_{\mathrm{TC}} \cdot \ln(\mathrm{e}^{(z_{\mathrm{TC}} - z_1)/s_{\mathrm{TC}}} + 1) - z_1 + z_2\right) \end{aligned} \tag{6.13}$$

$$\begin{aligned} \overline{\Theta}_{\mathrm{TES}}(z_{\mathrm{TC}}, s_{\mathrm{TC}}) &= \left[\overline{\Theta}(z_{\mathrm{TC}}, s_{\mathrm{TC}})\right]_0^1 \\ &= s_{\mathrm{TC}} \cdot \ln\left(\mathrm{e}^{(z_{\mathrm{TC}} - 1)/s_{\mathrm{TC}}} + 1\right) - s_{\mathrm{TC}} \cdot \ln\left(\mathrm{e}^{z_{\mathrm{TC}}/s_{\mathrm{TC}}} + 1\right) + 1 \end{aligned} \tag{6.14}$$

Rearranging equation 6.14 allows for calculating the relative thermocline height, depending on the mean inner dimensionless temperature and the current thermocline slope (equation 6.15).

$$\Rightarrow z_{\mathrm{TC}}(\overline{\Theta}_{\mathrm{TES}}, s_{\mathrm{TC}}) = s_{\mathrm{TC}} \cdot \ln\left(\frac{\mathrm{e}^{(\overline{\Theta}_{\mathrm{TES}} - 1)/s_{\mathrm{TC}}} - 1}{\mathrm{e}^{-1/s_{\mathrm{TC}}} - \mathrm{e}^{(\overline{\Theta}_{\mathrm{TES}} - 1)/s_{\mathrm{TC}}}}\right) \tag{6.15}$$

Using simulation analysis (equation 6.16), Bayón et al. showed that the thermocline slope in a standby process ($s_{\mathrm{TC,standby}}$) is related to the dimensionless time (t^*) [237]. The dimensionless time can be calculated by equation 6.17 with thermal conductivity (k), storage height (Z_{TES}), density (ρ), the specific heat capacity (c_{p}), and the storage duration from starting time (t_0) to time (t_1). Bayón et al. also introduce dynamic calculations for charging and discharging processes. In the evaluation here, only the standby process will be analyzed.

$$s_{\mathrm{TC,\,standby}}(t^*) = \frac{5}{2} \cdot \sqrt{t^*} \tag{6.16}$$

$$t^* = \frac{t_1 - t_0}{{Z_{\mathrm{TES}}}^2} \cdot \frac{k}{\rho \cdot c_{\mathrm{p}}} \tag{6.17}$$

As Bayón et al. assume that the heat losses are negligible, they are not included in the model [237]. Also, [238] and [239] demonstrate that for short periods, the heat losses have a minor impact compared to the stratification.

To analyze the long-term influence, the model will be extended by a new approach to consider the heat losses. To do so, the tank will be split into a top interval and a bottom interval divided at the thermocline height. The bottom interval is defined from $[0, z_{\mathrm{TC}}]$ and can be expressed by equation 6.18. The top interval is defined from $[z_{\mathrm{TC}}, 1]$ and can be expressed by equation 6.19.

$$\begin{aligned}\overline{\Theta}_{\mathrm{bottom}}(z_{\mathrm{TC}}, s_{\mathrm{TC}}) &= \left[\overline{\Theta}(z_{\mathrm{TC}}, s_{\mathrm{TC}})\right]_0^{z_{\mathrm{TC}}} \\ &= \frac{1}{z_{\mathrm{TC}}} \cdot \left(s_{\mathrm{TC}} \cdot \ln(2) - s_{\mathrm{TC}} \cdot \ln(\mathrm{e}^{(z_{\mathrm{TC}})/s_{\mathrm{TC}}} + 1) + z_{\mathrm{TC}}\right)\end{aligned} \tag{6.18}$$

$$\begin{aligned}\overline{\Theta}_{\mathrm{top}}(z_{\mathrm{TC}}, s_{\mathrm{TC}}) &= \left[\overline{\Theta}(z_{\mathrm{TC}}, s_{\mathrm{TC}})\right]_{z_{\mathrm{TC}}}^{1} \\ &= \frac{1}{1 - z_{\mathrm{TC}}} \cdot \left(s_{\mathrm{TC}} \cdot \ln(\mathrm{e}^{(z_{\mathrm{TC}}-1)/s_{\mathrm{TC}}} + 1) - s_{\mathrm{TC}} \cdot \ln(2) - z_{\mathrm{TC}} + 1\right)\end{aligned} \tag{6.19}$$

Applying the energy conservation principle, the mean temperatures of an interval at time (t_1) can be expressed by equation 6.20.

$$\left[\overline{T}(t_1)\right]_{z_1}^{z_2} = \left[\overline{T}(t_0)\right]_{z_1}^{z_2} - \frac{\left[\left[\dot{Q}_{\mathrm{loss}}(t)\right]_{z_1}^{z_2}\right]_{t_0}^{t_1} \cdot (t_1 - t_0)}{\left[c_p\right]_{z_1}^{z_2}} \tag{6.20}$$

The heat loss calculation is given by equation A.10 (p. 317). For the heat transfer calculation, the product of $(U_{\mathrm{loss}} \cdot A)$ is required in relation to the geometry. For the top of the tank, the product of $(U_{\mathrm{loss}} \cdot A)$ can be calculated with equation 6.21 [cf. 234, p. 100]. For the calculation, the thermal conductivity of the insulation $(k_{\mathrm{insulation}})$, its thickness $(l_{\mathrm{insulation}})$, the TES diameter (d_{TES}), and the convection heat transfer coefficient (α_{air}) is needed.

$$(U_{\mathrm{loss}} \cdot A)_{\mathrm{top}} = \frac{1}{\frac{l_{\mathrm{insulation}}}{k_{\mathrm{insulation}}} + \frac{1}{\alpha_{air}}} \cdot \frac{\pi}{4} \cdot d_{\mathrm{TES}} \tag{6.21}$$

For the side wall of the tank, the product of $(U_{\mathrm{loss}} \cdot A)$ can be calculated using equation 6.22 [240].

$$(U_{\mathrm{loss}} \cdot A)_{wall} = \frac{\pi \cdot Z_{\mathrm{TES}}}{\frac{1}{2 \cdot k_{\mathrm{insulation}}} \cdot \ln\left(\frac{d_{\mathrm{TES}} + 2 \cdot l_{\mathrm{insulation}}}{d_{\mathrm{TES}}}\right) + \frac{1}{\alpha_{\mathrm{air}} \cdot (d_{\mathrm{TES}} + 2 \cdot l_{\mathrm{insulation}})}} \tag{6.22}$$

The described equations enable the calculation of the mean bottom and top inner temperatures ($\overline{T}_{\mathrm{TES,\,bottom}}$ and $\overline{T}_{\mathrm{TES,\,top}}$) at the time t_1.

Pizzolato et al. evaluated the influence of heat losses and time on the thermocline via fluid dynamic simulations [241]. Their resulting figure 6.17 shows that the heat losses do not influence the form of the thermocline but impact the hot water temperature instead. A similar phenomenon was demonstrated during tests in [242].

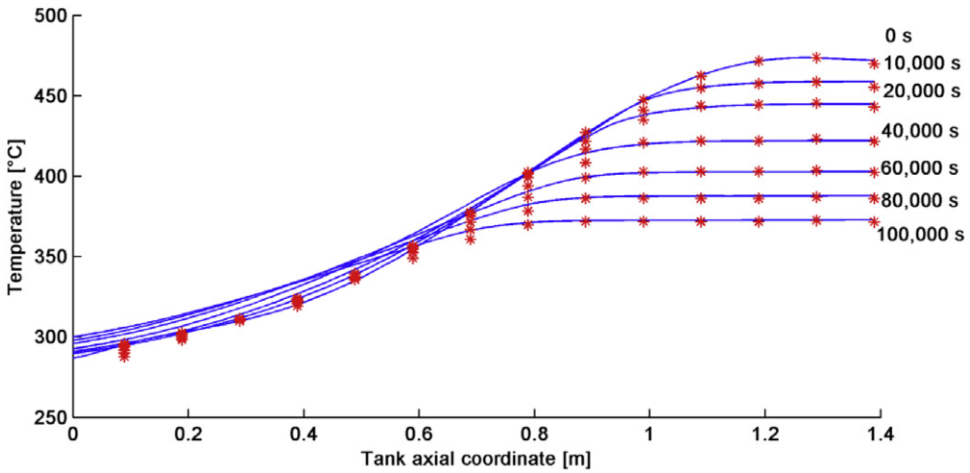

Figure 6.17: Storage tank standby process [241]

Based on these results from [241], [242], it is assumed that the heat losses do not influence the height or slope of the thermocline and, consequently, the heat losses do not affect the dimensionless temperature. Instead, in relation to the energy conservation equation, the losses must reduce the inner temperature. These conditions lead to a new approach.

The thermocline model has four coefficients: the slope (s_{TC}), the height (z_{TC}), and a hot (T_{h}) and a cold reference temperature (T_{c}) (q.v. equation 6.11, p. 231). Since the slope and height are assumed to not be affected by the losses, the reference temperatures must change to ensure energy conservation.

As the dimensionless temperature will not be affected, it can be set equally at the two points of time t_0 and t_1 (equation 6.23). From this, the equation for the hot temperature can be developed in dependence on the cold temperature (equation 6.24).

$$\overline{\Theta}_{\mathrm{top}}(t_0) \overset{!}{=} \overline{\Theta}_{\mathrm{top}}(t_1) = \frac{\overline{T}_{\mathrm{TES,\,top}}(t_1) - T_{\mathrm{c}}(t_1)}{T_{\mathrm{h}}(t_1) - T_{\mathrm{c}}(t_1)} \tag{6.23}$$

$$\Rightarrow T_{\mathrm{h}}(t_1) = T_{\mathrm{c}}(t_1) \cdot \left(1 - \frac{1}{\overline{\Theta}_{\mathrm{top}}(t_0)}\right) + \frac{T_{\mathrm{h}}(t_1)}{\overline{\Theta}_{\mathrm{top}}(t_0)} \tag{6.24}$$

In the same way, the equation for the mean bottom dimensionless temperature can be derived (equation 6.25). By inserting equation 6.24, the cold temperature can be calculated independently from the hot temperature (equation 6.26).

$$\overline{\Theta}_{\mathrm{bottom}}(t_0) \overset{!}{=} \overline{\Theta}_{\mathrm{bottom}}(t_1) = \frac{\overline{T}_{\mathrm{TES,\,bottom}}(t_1) - T_{\mathrm{c}}(t_1)}{T_{\mathrm{h}}(t_1) - T_{\mathrm{c}}(t_1)} \tag{6.25}$$

$$\Rightarrow T_{\mathrm{c}}(t_1) = \frac{\overline{\Theta}_{\mathrm{top}}(t_0) \cdot \overline{T}_{\mathrm{TES,\,bottom}}(t_1) - \overline{\Theta}_{\mathrm{bottom}}(t_0) \cdot \overline{T}_{\mathrm{TES,\,top}}(t_1)}{\overline{\Theta}_{\mathrm{top}}(t_0) - \overline{\Theta}_{\mathrm{bottom}}(t_0)} \tag{6.26}$$

Through this, the state of the storage tank in the standby process can be described by the slope depending on time, the hot and cold reference temperatures, and the mean inner temperature. All other quantities can be derived from these states.

Like the models in chapter 5, the model is implemented in the programming language Python using the packages Pandas [68] and NumPy [70]. The implementation of the models allows for independently enabling or disabling the diffusivity and the heat losses.

6.7.2 Validation of the model

For the validation of the implementation, the first case study *storage-tank-ENV* is used. The data can be found in tables C.22 and C.23 (pp. 372–373).

For the first step of the validation, the heat losses are disabled so that the implementation of the stratification model can be compared to the reference used in [237]. The data of the article was read from [237, Fig 8] using a graphic program and its coordination system. The data must be transferred from a dimensionless temperature to the temperature used for the case studies. The cold dimensionless temperature of 0.75 is applied to 50 °C and the hot dimensionless temperature of 1 is set to 95 °C. The data is depicted in figure 6.18 as dots. The thermoclines are presented in an intuitive way: the height is on the y-axis and the temperature is given on the x-axis. The result of the model data is given by the lines at the same relative times. A slight inaccuracy in the relative time can be identified at 20.43 hours, which is related to the pattern of time in the implemented model. Its impact is negligible.

The results of the model fit the data from the reference. This indicates that the implementation of the thermocline equations is correct and through this, they can be verified.

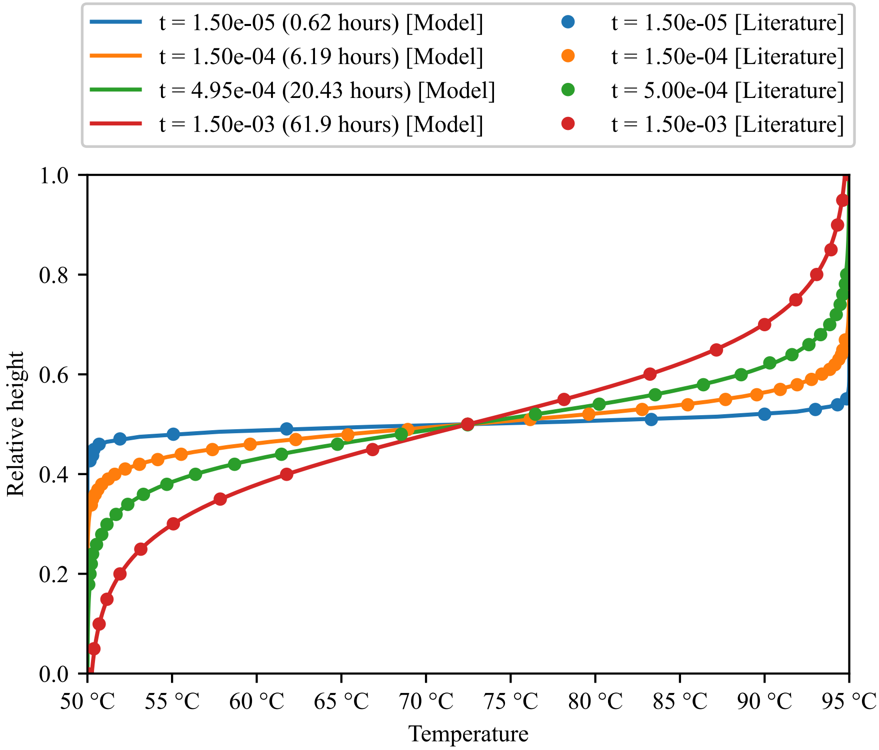

Figure 6.18: Comparison of the model results and external data from [237]

In the next step, the isolated impact of the diffusivity and of the heat losses are compared with the full model. The result of three calculation variants can be seen in figure 6.19. All variations show the thermocline after 0.62 hours, 6.19 hours, 12.38 hours, 20.43 hours, 61.9 hours, and 167.75 hours (≈ 1 week). The times are related to the relative times of the reference used [237] and, therefore, they are not given as integers.

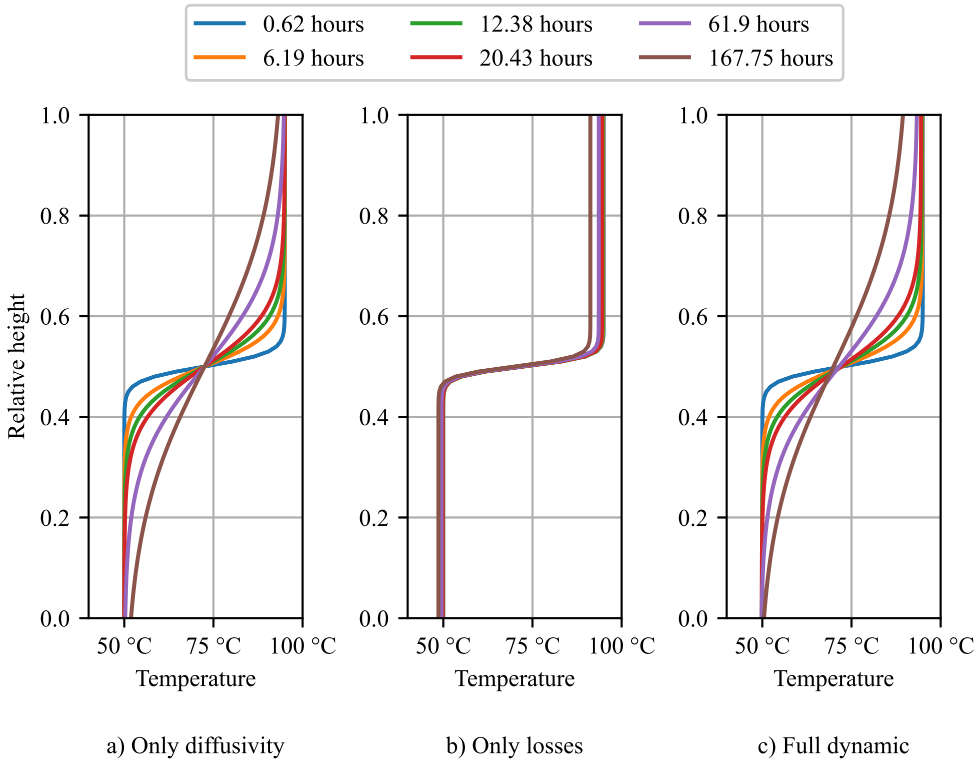

Figure 6.19: Impact of diffusivity and losses on the storage tank's thermocline

The plot on the left (a) shows the influences of the diffusivity on the thermocline. In particular, the slope of the thermocline increases while the height of the thermocline stays constant. This figure depicts the same results as figure 6.18. After the longest timespan of approximately 1 week, the cold temperature (at the bottom) increases, and the hot temperature (at the top) decreases.

In contrast, plot (b) shows the impact of the heat losses. This effect does not impact the form of the thermocline and the hot and cold temperatures both decrease. The impact on the hot temperature is higher which seems plausible due to greater heat losses at high temperatures.

The plot on the right (c) combines both influences whereby the height of the thermocline stays the same. The hot temperature decreases more pronouncedly than in the other cases due to the addition of both effects while the cold temperature stays (roughly) equal due to the compensation of both effects.

The behavior of all variants can be explained by the known effects. Therefore, the model is considered plausible in relation to the modeling assumptions.

6.7.3 A new combination of flexibility metrics and the storage model

In this subsection, the relationship between the thermocline model and the flexibility metrics will be presented. This combination is a novel approach and has not been found in the literature.

In the first step, the TES capacity should be computed. It is related to the minimum and maximum mean temperatures, which can be technically achieved in operation. It is also described above that these temperature thresholds, and hence the capacity, may change during operation and thus by time (t). For this evaluation of the steady-state standby process, it is assumed that the time impact on the maximum mean temperature is not relevant for evaluating the capacity after the charging process has ended. In contrast, the time dependency of the minimum mean temperature is much more relevant for the discharging process, because it defines the lower threshold. This results in equation 6.27.

$$K_{\text{TES}}(t) = C_{\text{p, TES}} \cdot \left(\overline{T}_{\text{TES, max}} - \overline{T}_{\text{TES, min}}(t)\right) \tag{6.27}$$

To compute the maximum mean temperature at the beginning of the standby process (equation 6.28), the dimensionless temperature (equation 6.12, p. 231) is used. In this case, the hot temperature equals the supply temperature, and the return temperature equals the cold temperature. Further, the thermocline slope after charging as well as the lowest possible thermocline height is required. The latter is unknown and must be determined.

$$\overline{T}_{\text{TES, max}} = T_{\text{r, sec}} + (T_{\text{s, prim}} - T_{\text{r, sec}}) \cdot \overline{\Theta}_{\text{TES}}(z_{\text{TC, min}}, s_{\text{TC}}(t_0)) \tag{6.28}$$

The minimum mean temperature can be computed in the same way (equation 6.29). In contrast to the maximum temperature, time-variable values for the hot and cold temperatures and for the thermocline slope are used.

$$\overline{T}_{\text{TES, min}}(t) = T_{\text{c}}(t) + (T_{\text{h}}(t) - T_{\text{c}}(t)) \cdot \overline{\Theta}_{\text{TES}}(z_{\text{TC, max}}, s_{\text{TC}}(t)) \tag{6.29}$$

All required variables can be calculated using the equations that are presented in section 6.7.1. The only unknown variables are the minimum ($z_{\text{TC, min}}$) and maximum ($z_{\text{TC, max}}$) heights of the thermocline. To compute the heights, the equation for the dimensionless temperature (equation 6.12, p. 231) can be rearranged to allow for the calculation of the thermocline height (equation 6.30). This equation can then be used to calculate the minimum height that would be allowed for stable operation boundaries (equation 6.31). The minimum height defines the maximum internal energy when the maximum allowed primary return temperature ($T_{\text{r, prim, max}}$) is not yet exceeded at ($z = 0$). In contrast, the maximum thermocline height is defined by the minimum internal energy when the secondary supply temperature ($T_{\text{s, sec, min}}$) has not yet fallen below the minimum required temperature at ($z = 1$) (equation 6.32).

$$z_{\mathrm{TC}}(z, s_{\mathrm{TC}}) = \ln\left(\frac{1}{\Theta(z)} - 1\right) \cdot s_{\mathrm{TC}} + z \tag{6.30}$$

$$z_{\mathrm{TC,\,min}}(s_{\mathrm{TC}}) = \ln\left(\frac{T_{\mathrm{h}} - T_{\mathrm{c}}}{T_{\mathrm{r,\,prim,\,max}} - T_{\mathrm{c}}} - 1\right) \cdot s_{\mathrm{TC}} + 0 \tag{6.31}$$

$$z_{\mathrm{TC,\,max}}(s_{\mathrm{TC}}) = \ln\left(\frac{T_{\mathrm{h}} - T_{\mathrm{c}}}{T_{\mathrm{s,\,sec,\,min}} - T_{\mathrm{c}}} - 1\right) \cdot s_{\mathrm{TC}} + 1 \tag{6.32}$$

With these equations, it is now possible to calculate the time impact on the capacity in the standby process of storage tanks. For demonstration purposes, an example with input parameters from the variant *storage-tank-ENV* is depicted in figure 6.20.

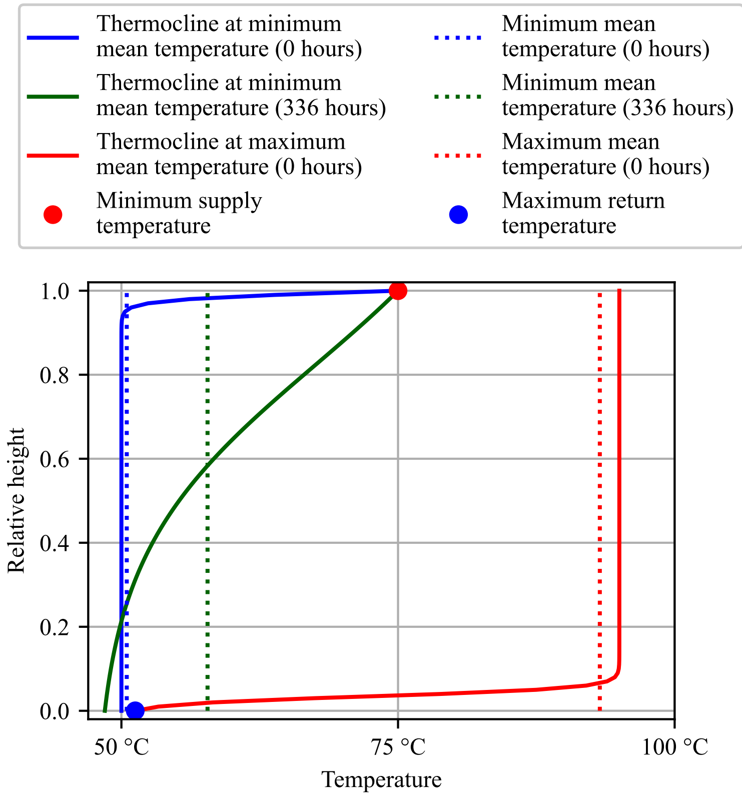

Figure 6.20: Minimum and maximum mean temperatures

The maximum temperature curve is given as a solid red line at 0 hours. The maximum primary return temperature (blue dot) is set to 1.25 K over 50 °C. This value represents half of the resolution proposed for the smart market (2.5 K). The solid blue line represents the thermocline of the empty storage if the tank would be instantaneously discharged. It can also be seen that the required secondary supply temperature is set to 75 °C (red dot). The solid green line represents the thermocline if the tank is discharged after 336 hours. Even though the primary return temperature is slightly lower than 50 °C, a large part of the volume of the tank is now filled with sunk energy (represented by the difference between the blue and green lines). The mean temperatures of all three thermoclines are shown with dotted lines in the same colors.

Based on these temperatures and findings, the other flexibility KPIs can be formulated. In the case of the storage tank, all the quantities are time-dependent, and the relative SOC can be calculated based on the minimum and maximum temperatures in the same way as for the capacity (equation 6.33). The mean inner temperature is known. The absolute SOC can be calculated using both KPIs (equation 6.34). The efficiency is the ratio of enthalpy that could be discharged and the previously charged enthalpy (equation 6.35). After one cycle, although the remaining heat that could not be discharged is not lost, it cannot be (directly) used in the DHS.

$$\sigma_{\text{TES}}(t) = \frac{\overline{T}_{\text{TES}}(t) - \overline{T}_{\text{TES, min}}(t)}{\overline{T}_{\text{TES, max}} - \overline{T}_{\text{TES, min}}(t)} \tag{6.33}$$

$$SOC_{\text{TES}}(t) = K_{\text{TES}}(t) \cdot \sigma_{\text{TES}}(t) \tag{6.34}$$

$$\eta_{\text{TES, discharge}}(t) = \frac{\Delta H_{\text{sec}}(t)}{\Delta H_{\text{prim}}} \approx \frac{\overline{T}_{\text{TES}}(t) - \overline{T}_{\text{TES, min}}(t)}{\overline{T}_{\text{TES}}(t_0) - \overline{T}_{\text{TES, min}}(t_0)} \tag{6.35}$$

The core of this concept is that the thermocline model allows for a forecast of the minimum inner energy by projecting the current slope to an empty TES that still fulfills the temperature limitations. Figure 6.21 illustrates this *projection* by showing the intersection of the minimum secondary supply temperature ($T_{\text{s, sec, min}}$) with the thermocline.

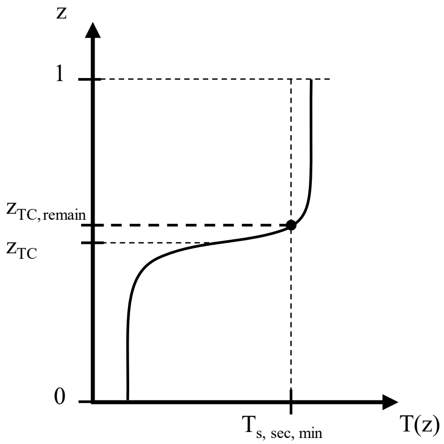

Figure 6.21: Remaining height of the thermocline

Through the continuous form of the dimensionless temperature (equation 6.12, p. 231), a reverse calculation of the height related to the dimensionless temperature at the minimum supply temperature ($\Theta_{\mathrm{s,\,sec,\,min}}$) can be performed. It is used to calculate the remaining height ($z_{\mathrm{TC,\,remain}}$) (equation 6.36).

$$z_{\mathrm{TC,\,remain}}(\Theta_{s,\,\mathrm{sec,\,min}}) = z_{\mathrm{TC}} - \ln\left(\frac{1}{\Theta_{s,\,\mathrm{sec,\,min}}} - 1\right) \cdot s_{\mathrm{TC}} \tag{6.36}$$

Using equation 6.13 (p. 231) allows for the calculation of the mean dimensionless inner temperature of the remaining top layer in the interval $[z_{\mathrm{TC,\,remain}},\, 1]$. Applying equation 6.11 (p. 231) allows for calculating $\overline{T}_{\mathrm{TES,\,remain}}$, which is needed to calculate the remaining mean output effectiveness of the tank ($\bar{\epsilon}_{\mathrm{TES,\,remain}}$). $\bar{\epsilon}_{\mathrm{TES,\,remain}}$ represents the mean effectiveness during the remaining discharging progress (equation 6.37).

$$\bar{\epsilon}_{\mathrm{TES,\,remain}}(t) = \frac{\overline{T}_{\mathrm{TES,\,remain}}(t) - T_{\mathrm{r,\,sec}}}{T_{\mathrm{s,\,prim}} - T_{\mathrm{r,\,sec}}} \tag{6.37}$$

If $\bar{\epsilon}_{\mathrm{TES,\,remain}}$ is higher than the minimum required effectiveness ($\bar{\epsilon}_{\mathrm{TES,\,min}}$), the storage can be discharged.

In this subsection, the thermocline model and the flexibility metrics are combined. Due to this combination, the temperature behavior of the storage tank becomes predictable. This is innovative because the approach shown enables the inclusion of the temperature dynamics into capacity, SOC, efficiency, and effectiveness calculations by considering a thermocline that is projected to the empty storage. The thresholds for the storage operation are defined by a dynamic temperature characteristic in contrast to typical solutions that only consider energy thresholds or fixed temperature boundaries.

The new combination closes a gap between the local control, which is mostly based on temperature measurements, and the operational planning, which is mostly based on energy-related metrics. Through the new combination, the capacity and the SOC are more related to the real temperature-based operation.

6.7.4 Results of application to case studies

In this subsection, the flexibility metrics are applied to the case studies.

Time impact on flexibility metrics

In the first evaluation, the *storage-tank-ENV* is used to demonstrate all technical flexibility KPIs. Figure 6.22 depicts the flexibility KPIs over time. The left side (a) shows energy quantities, and the right side (b) shows dimensionless quantities. The cost factor will be presented later in a separate evaluation.

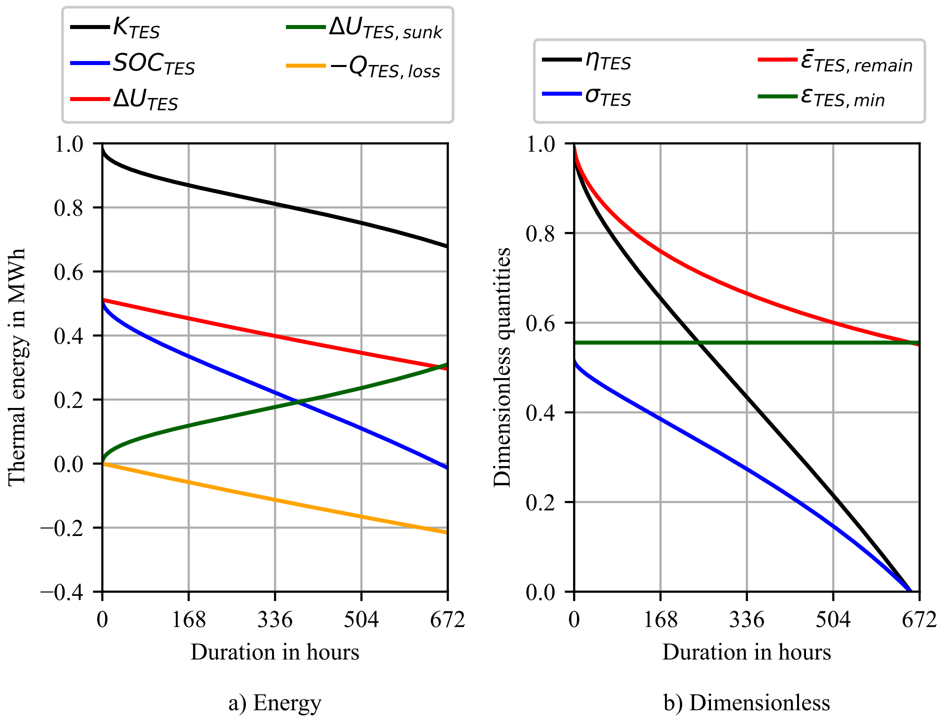

Figure 6.22: Flexibility metrics for storage tank evaluation

On the energy side (left), the TES capacity (black) decreases over time through the diffusivity. The difference between the internal energy and the energy of the empty storage (red) decreases through the thermal losses (yellow). At the same time, the SOC (blue) rapidly decreases from 500 kWh through the diffusion and the thermal losses. At around 670 hours, the TES can be considered empty due to the poor temperature distribution inside the tank. At this point in time, the sunk energy (green) equals the inner energy difference (red).

The right side presents the relative quantities. The required minimal effectiveness (green) is related to the minimum required secondary supply temperature and is a constant external boundary. The remaining effectiveness (red) starts with almost 100 %. This means that there is almost no temperature reduction through the charging process in short times. After 670 hours, the mean remaining effectiveness is lower than the required effectiveness. The TES can thus be considered empty, and the efficiency (black) behaves identically. In the beginning, the efficiency is almost 1 and decreases until it is almost 0 at around 670 hours. The relative SOC begins at 0.5 (initial value) and decreases to 0 at 670 hours.

Temperature impact on the capacity

Figure 6.23 depicts the TES capacity related to the primary supply temperature and the required secondary supply temperature.

The three variants (a–c) have almost the same form of the data, even though the scale is quite different. The different capacities are at a maximum of approximately 1 MWh for the 20 m$^{(}$3) variant (a), approximately 100 MWh for the 2,000 m$^{(}$3) variant (b), and 0.045 MWh for the 1 m$^{(}$3) variant (c). The influence of the primary supply temperature is almost linear. The higher the temperature, the higher the capacity is while the influence of the required secondary temperature is much smaller. Only if the secondary temperature is near to the primary supply temperature is the capacity reduced. A higher secondary supply temperature above the primary supply temperature is not possible. The largest capacity can be achieved in the combination of a high primary and a low secondary supply temperature.

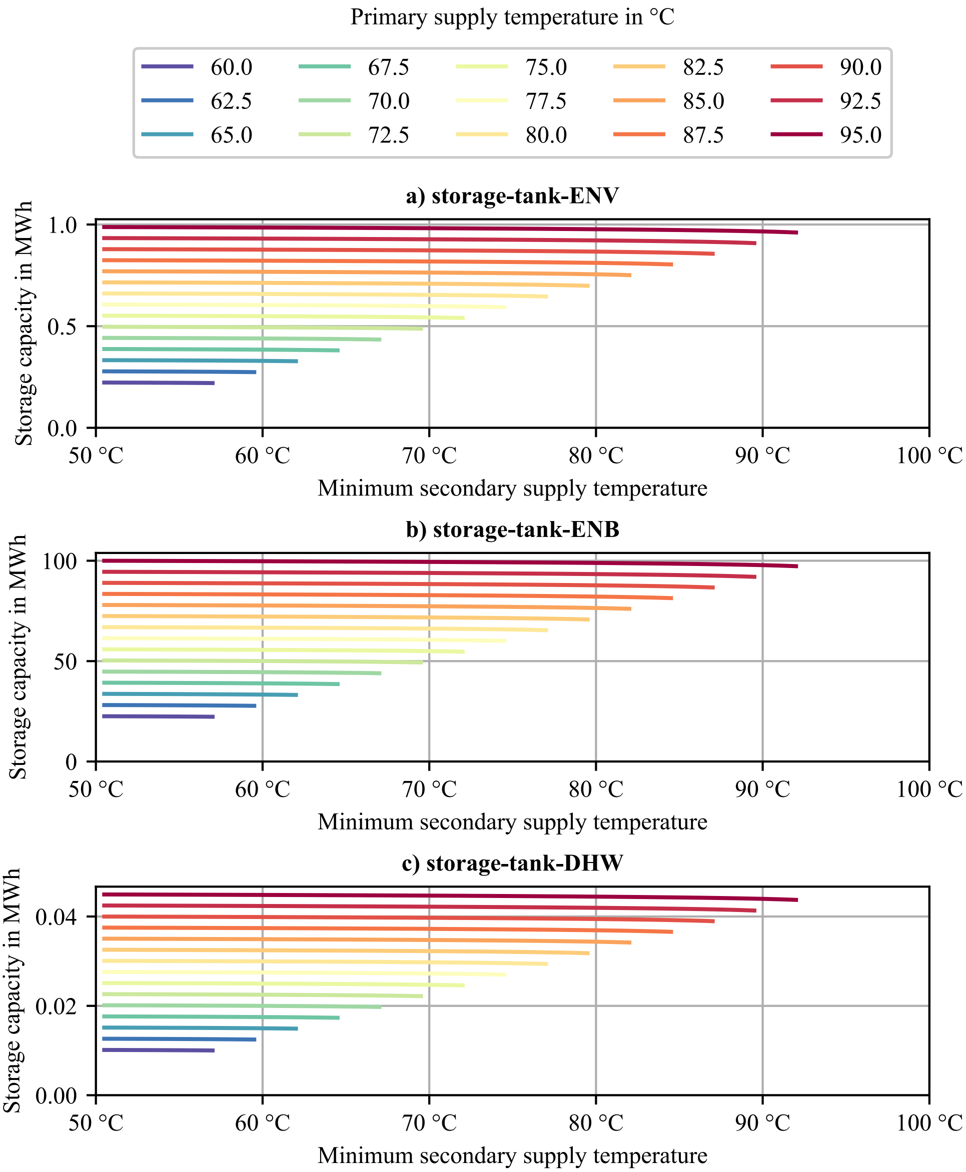

Figure 6.23: Maximum TES capacity for storage tank variants under initial conditions

Temperature impact on the efficiency

Figure 6.24 presents the time until the efficiency has fallen below 80 %.

The figure allows for evaluating the best time scale for storing heat in relation to the size of each storage. Like in the figure before, the form of the results is similar, although the absolute values are different. The maximum time for variant (a) is around 500 hours. The largest TES (b) allows for a longer storage duration of more than 4,000 hours. The small TES (c) has a maximum duration of approximately 80 hours until the efficiency falls below 80 %. Its efficiency falls much faster than that of the other two with increasing minimum secondary temperature. Due to the small timescale of the last variant, uncertainties resulting from the numerical concept become visible by unsmooth curves. In contrast to the capacity, the minimum required secondary supply temperature has a stronger impact on the storage time. Medium or high secondary supply temperatures significantly reduce the storage time. The maximum values which are described above are valid for a secondary supply temperature that is almost on the return temperature level. In the case of 90 °C (prim.) to 75 °C (sec), the time would approximately be 100 hours, 1,000 hours, and less than 10 hours for the three variants.

A lower primary supply temperature also reduces the storage time. As a result, the impact of the system's temperature should be included in storage tank operation and the secondary side supply temperature should be set as low as possible to increase the capacity and to increase the storage time.

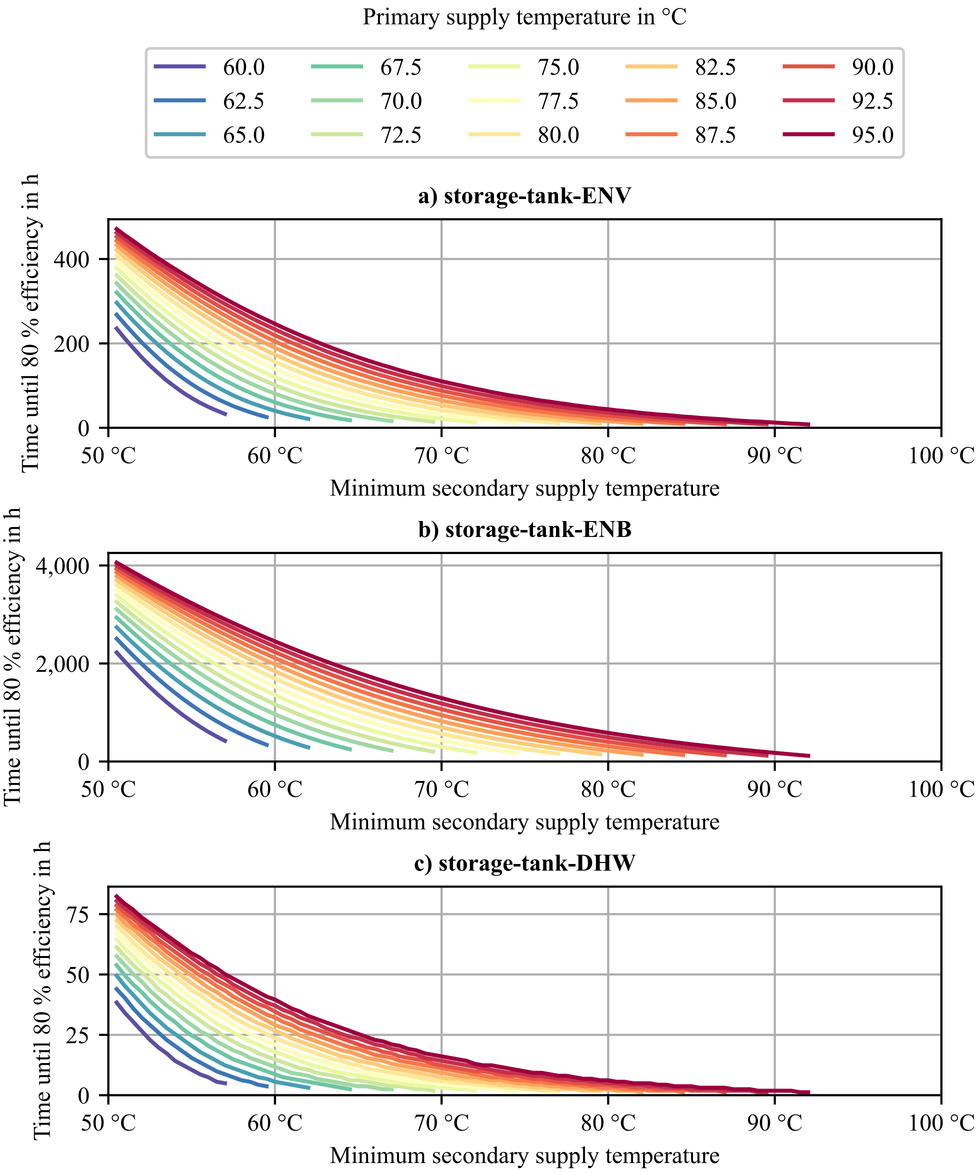

Figure 6.24: Time until efficiency is less than 80 % for storage tank variants

Time impact on the cost factor

Figure 6.25 presents the cost factor for the three evaluated variants in relation to storage duration. In all cases, the primary (charging) temperature is set to 95 °C. The cost factor would be 1 if the full heat could be used at the required secondary temperature level. The minimum secondary temperature is chosen as 75 °C. In addition, two variants of the *storage-tank-ENV* are shown for a lower (60 °C) and a higher (90 °C) minimum secondary temperature. The time is presented on a logarithmic scale.

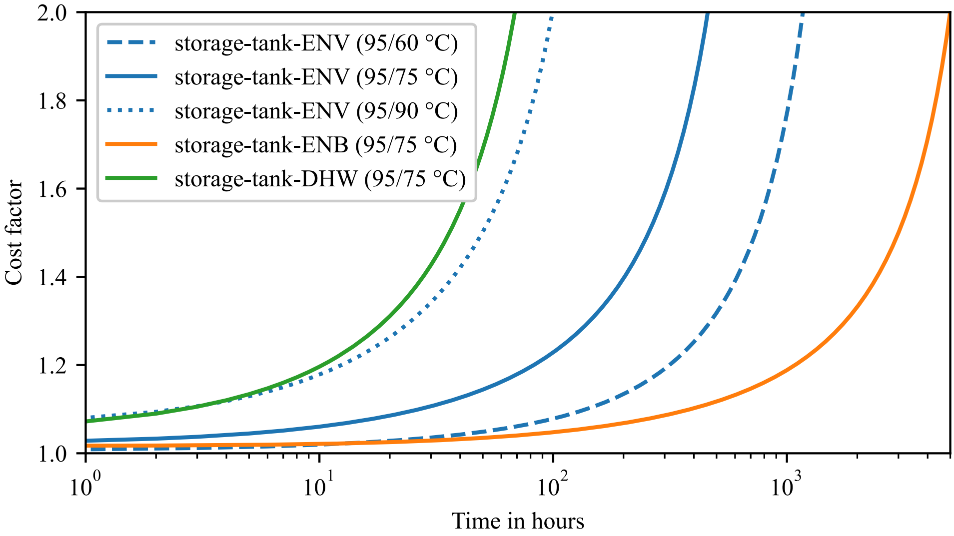

Figure 6.25: Time dependency of the cost factor (considering heat losses and required temperature)

In the first step, the three different TESs are compared (solid lines). They all have a similar form but different timescales. The DHW tank starts at a higher cost factor (1.07) after 1 hour and has a rapid increase in the factor. A cost factor of 1.25 (80 % efficiency) is achieved after 15 hours. After 68 hours, the costs for the heat are doubled. The storage tank of the Energieverbund (ENV) starts at 1.03 (after the first hour). After 114 hours, the costs are at 1.25 (0.25 % increase) while after approximately 460 hours, the costs are doubled. The Energiebunker (ENB) tank starts at 1.02, achieves a cost factor of 1.25 after 1420 hours, and after 5,000 hours, the costs are doubled. It can be concluded that under the same temperature constraints, the size of the storage is important for the time impact on the variable cost of heat. The larger the storage is, the longer the heat can be stored at the same costs (e.g., a 25 % cost increase results in 15, 114, or 1,420 hours for the three variants).

In the next step, the impact of the secondary side temperature is focused on. If the storage tank of the ENV is charged at 95 °C and discharged until 60 °C (dashed line), the storage can be used for much longer storage durations. For example, after 1,160 hours the costs are double in contrast to 460 hours for 75 °C. If a temperature of 90 °C (dotted line) is required, this time span is reduced to 100 hours. If a cost increase of 25 % is accepted, the heat can be stored for 19 hours at 90 °C, 114 hours at 75 °C, and 393 hours at 60 °C. This demonstrates the impact of the secondary side temperature (respectively the temperature difference of the primary and secondary sides).

The three different TESs cases demonstrate that different utilizations of flexibility are needed depending on the size of the tank. For shorter timespans ($<$ 24 hours), the DHW storage tank has a much higher factor. Therefore, shifting a full day does not seem to be a suitable application for this tank. Such small tanks are suitable for reserve (load smoothing) and may be relevant for intraday applications.

At low temperature differences (dotted line), the medium-sized storage tank ENV can only be used for short-term applications such as reserve or intraday flexibility. The lower the secondary side temperature required, the better this TES can be integrated into long(er)-term applications such as day-ahead or even longer planning processes.

Finally, the large TES from ENB can be used for long timescales. For seasonal flexibility at low costs, larger tanks, or a combination with temperature-increasing heating plants like a heat pump or others are necessary.

For all variants, it is important to mention that the remaining heat in the storage at a temperature level that is too low is not considered in the cost factor. The degradation of the thermocline and the mixing effects result in wasted storage potential. The operational strategies of all tanks should consider useful mechanisms that allow for the utilization of this heat to increase the cost factor. This includes design concepts with heat pumps for storage tanks. An alternative would be forced overcharging or undercharging. During times of overcharging, it must be accepted to increase the return temperature of the DHS while during times of undercharging, the supply temperature may be lower than needed or it must be embedded in the smart market mechanism.

6.7.5 Discussion of the specific implementation and results

In this subsection, the results of the specific implementation for the storage tanks are discussed. It is successfully demonstrated that it is possible to implement the flexibility metrics for storage tanks with the proposed thermocline model. The chosen existing thermocline model is based on a validated model and is extended in this thesis by the calculation of heat losses. The model implementation has been verified by comparing its results with data from the literature and by evaluating their plausibility. The chosen flexibility metrics have been combined with this model. This combination is innovative due to the inclusion of the temperature behavior of the storage.

The new storage tank stratification model is based on an existing and validated model from literature. This model is limited due to its graphical approach since it assumes a continuous stratification and neglects heat losses. The implementation of the existing model for the thesis is validated by a comparison of the model's results with given case study data. Since the existing model does not include heat losses, the model is extended to a new model with heat losses. This extension is derived by using thermodynamic equations. This extension is verified by an isolated comparison of the different effects of the original model (considering the degeneration of the thermocline), the new feature (considering heat losses only) as well as the combined effects. The results are evaluated as plausible. Due to the continuous stratification approach of the basic model, the new model can only be applied to the here presented stand-by application and not to dynamic charging and discharging processes.

The main goal of the application is to demonstrate the flexibility metrics and the importance of including the supply temperature in their evaluation. The flexibility metrics are successfully applied to three storage tanks of the DHS in Hamburg-Wilhelmsburg. The results show that the diffusion results in a degeneration of the thermocline. The effect of the degeneration is more relevant compared to the heat losses in shorter timespans (e.g., in the first 24 hours for the ENV TES). The degenerated thermocline and heat losses impact all KPIs. It can be shown that the capacity and SOC are both decreasing. Furthermore, it is shown that the chosen primary and secondary supply temperatures have a massive impact on the capacity and the efficiency of the TES. The proposed approach shows that the storage has the highest potential if high primary temperatures are available and low temperatures are needed.

Due to the problem of fluctuating variable costs for the primary heat, absolute values for the costs of storing heat cannot be calculated. Instead, a cost factor is introduced that describes a relative increase in costs and which is based on the efficiency (ratio of thermal energy for discharging to charging). Based on this factor, it is shown that the degeneration and the heat losses impact the variable costs for storing heat in a nonlinear way.

With the help of the thermocline model, a projection from the current physical state (e.g., a medium height of the thermocline) to the discharged state (maximum height of the thermocline) can be made. By including this projection into the flexibility metrics, a dynamic form of the thermocline is considered. It is expected that this approach leads to more precise metrics than those concepts with fixed temperature thresholds for minimum and maximum mean temperatures. The thresholds for the discharge process are based on the required secondary supply temperature and on the projection of a medium charged TES compared to the discharged TES. This approach is novel and differs from existing solutions. The effectiveness is used as an indicator for this threshold.

If these temperature thresholds would not be considered, the efficiency would only consider the heat losses and not the sunk inner energy. In this case, the storage duration would be increased. Figure 6.26 shows the cost factor for this alternative approach. The blue lines are superimposed and thus only one blue line can be seen.

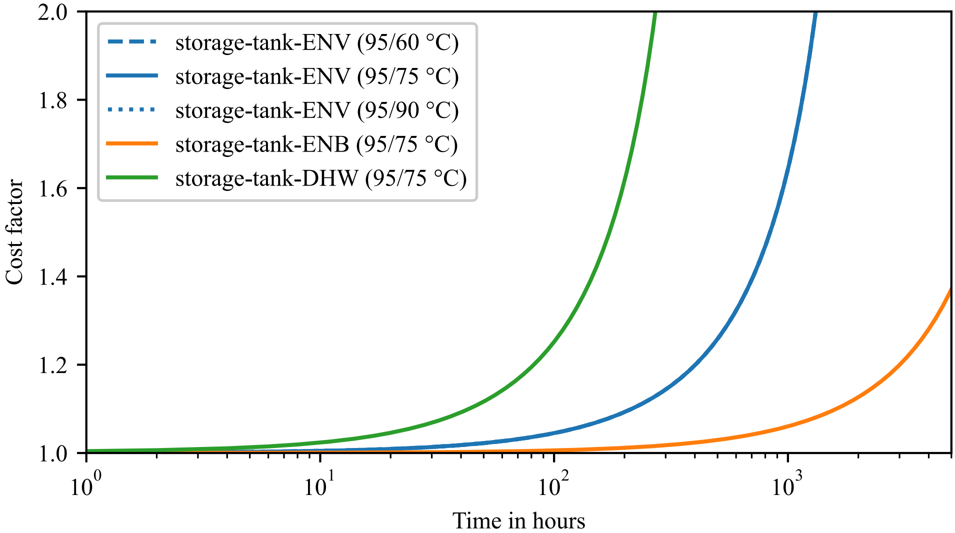

Figure 6.26: Time dependency of the cost factor (considering heat losses only)

The times for an increase of costs to 125 % are 99 hours (previously 15 hours), 480 hours (previously 114 hours), and 3,600 hours (previously 1,420 hours). The doubling of the costs of the ENB variant is not shown in this plot. The cost factor is 1.37 at 5,000 hours. Further, the three temperature variants of the ENV TES are identical and the required supply temperature has no relevance under these circumstances. However, in practice, this would lead to a misunderstanding of the state of the TESs. They would store the thermal energy, but it cannot be used under the required temperature conditions. In such a case, the TESs should be combined with a heat pump to deliver the required temperature.

The results show that the inner temperature profile and the primary and secondary temperature must be considered in the planning and operation of flexibility. A special focus for further developments should be given to control strategies that allow for regeneration of the thermocline. An example to achieve this is a complete discharge of the TES in times of low temperature demand and parallel production of high temperature. Further, the developed KPIs should be implemented in monitoring tools. In particular, the capacity should be monitored to evaluate whether regeneration of the thermocline is necessary. Through this, the capacity in existing storages can be increased. The proposed SOC calculation can also be used in operation to indicate the state of the whole system. In this way, over- and underproduction can rapidly be detected. These findings must be considered in the implementation of the smart market and the related control algorithms. The impact of temperature on variable costs may be considered in two ways, namely as fixed thresholds (e.g., a required secondary temperature) like in the presented concept or also by variable pricing whereby the variable pricing would be the preferrable concept. However, it is rather complex to optimize costs in temperature and time because these two quantities are not independent. Nevertheless, the shown metrics are a supporting component for such a strategy.

6.8 Discussion of the general flexibility results

In this chapter, several results are elaborated. In the first step, flexibility is defined. The term is split into flexibility demand and potential. Further, the existing definition of flexibility is extended by a temperature dimension that should be included in DHSs. Afterward, the requirements and possible integrations for flexibility potential are systematically analyzed. As a result, a new method for the integration of flexible technologies into the framework is developed, which is based on three parts: a general integration, a smart market integration, and flexibility metrics.

The general part of the method allows for optimal integration into the proposed framework in relation to the best storage duration. For each individual type of flexibility technology, the integration into the capacity, day-ahead, and intraday market and into the supervisory control and thermal reserve is proposed. The assignment is based on findings from the literature as well as from an own qualitative evaluation of the individual technologies.

In the next step, the planning of indirect storages must be integrated into the capacity market planning procedures. For their feed-in, the combination of the indirect storage and the heating plant must be further investigated in relation to their variable costs with the method from chapter 5.

The implementation of the different types of flexibility will require further development. For example, for the implementation of DSM, some of the presented existing concepts may be used. But for the integration, dynamic real-time pricing for the opportunity costs including the transmission costs must be developed.

Through the specific part of the method, the flexible technologies are integrated into the smart market of chapter 4. The smart market dispatch model consists of two different internal components: nodes and edges. The nodes are markets at important t-pieces in the network while the edges are the transmission pipes between the nodes. In the algorithms, they are represented by computation processes that buy heat from one market node and sell it at another market node. For the integration in the dispatch model, mainly two different concepts are discussed: the integration of the flexibility into the market nodes versus the integration into the transmission edges. Finally, the integration into the transmission edges is regarded as being more coherent with the previously developed mechanisms and it may be easier to implement e.g., due to the similarities of pipes and TESs. The integration of flexibility into the smart market and in all other parts of the framework supports competition as well as a possible unbundling of heat production from the SB. The smart market concept allows the temperature of the flexible technologies to be taken into account.

Further metrics are required for the implementation and for the interfaces from the smart markets to the operation and control systems. This applies, in particular, to the technical elements of the system operator (SB): storage tanks, network, and demand side. To facilitate the integration, flexibility metrics are identified. All of the identified KPIs can be found in the literature, but the final combination of the selected KPIs, which is presented in this chapter, is not found in the literature. The combination of the KPIs and the focus on the supply temperature impact is a novel approach. The metrics include the impact of temperature in the quantification. Besides technical KPIs, the variable cost factor allows for a representation of costs in relation to the storage duration or temperature.

The new combination of flexibility metrics is applied to the technology of storage tanks. The application demonstrates that temperature has a significant impact on storage capacity, efficiency, and duration. This validates the hypothesis that temperature must be included in all parts of the framework. Through these results, the objectives of this chapter—the integration of flexibility into the framework—can be regarded as having been achieved.

The verification of the model is done by a comparison with the referenced model, and it is based on a plausibility check for the new approach to heat loss calculation. In a future step, the results of the case study must be further validated. To do so, the final model and its parameters would require a comparison with a real storage tank. This may lead to a different quantity of results. Nevertheless, the qualitative results would not be affected.

For storage tanks, the results of the application can be used directly in the implementation. To do so, the developed KPIs should be implemented in planning procedures: storing heat creates heat losses and the heat losses create costs. Therefore, the benefit of storing heat must compensate for the costs. To create this benefit, dynamic variable costs for heat production are required as an incentive to optimize the costs of heat production and the costs of storing it. Further, the metrics can be used for operational monitoring systems as the chosen metrics can be used for the evaluation of the states of flexibility in operation. For example, the capacity of the storage tanks may be monitored to identify bad stratification. Such an implementation will require further development in terms of regression and state estimation. Particularly for the storage tank, the model should be extended to include more dynamics in operation.

The application of the metrics to other technologies than storage tanks is not investigated in this thesis. Even though the storage tanks are the most important technology, this can lead to a biased view. Therefore, further research is required to apply the metrics to other technologies. It is expected that the metrics can be applied to the network due to the physical similarity of pipes and tanks. Further, it is expected that the metrics can be applied to the demand side. The reason for this expectation is that similar KPIs have been applied for DSM in [226]. In contrast to this, the metrics cannot be applied to the heating plants since they have no internal capacity or SOC. Instead, their flexibility in relation to thermal power and supply temperature is already integrated into the smart market bids as presented in chapter 5. The most challenging application is expected for the indirect seasonal TESs. However, the proposed separate treatment of the discharging and charging process may simplify the application.

Finally, further research is required for the interaction with the electrical reserve capacity market and the framework. For such an interaction, the opportunity costs may be used to quantify the costs of participation in the reserve capacity market. For example, a call of a CHP for reserve capacity may be treated as another demand for flexibility (deviation) on the heating side although the detailed planning and compensation require further research.

Concluding, the proposed general part of the method is the first full approach to combine a flexibility treatment of all relevant technologies and a market-based concept in DHSs. The proposed concept is developed and builds on findings in the literature. Therefore, the resulting framework is regarded as being consistent with these findings. Since the presented concept is only one possibility among numerous alternatives, the proposed details for its implementation require further evaluation and research.

The next step is to start the implementation of the markets, especially the smart market, by including the described concepts. The presented concepts form the theoretical foundation for this implementation and challenges and alternatives for the integration may arise during implementation. Finally, only through implementation can the developed concept be fully validated.

6.9 Conclusion of the flexibility integration

In the context of the transition in district heating systems (DHSs) towards 4th generation district heating (4GDH), increasing numbers of heating plants with fluctuating production, dependency on fluctuating electricity prices, or even a seasonal mismatch of production and consumption will challenge the resilience of the system. An advantage of the district heating (DH) sector is that it provides several technologies that can contribute to the flexibility of all energy sectors. These flexible technologies can be heating plants, the demand side, and the piping of the network, as well as direct and indirect thermal energy storages (TESs).

In the literature, numerous concepts exist that deal with a single flexible technology. As shown in this chapter, some studies evaluate possible combinations of the technologies. A comprehensive approach, however, which allows for utilizing all types of flexible technologies at all locations to improve the management the DHS, cannot be found. Therefore, the main objective of this chapter is to develop a new concept for the integration of the flexibility of relevant technologies into the proposed framework (q.v. chapter 4).

In this chapter, several results are achieved. Firstly, a new definition of the term flexibility for DHSs is developed. The definition for thermal flexibility in DHSs includes temperature and energy flexibility as well as the demand and potential of flexibility. In a subsequent step, the requirements for a new flexibility integration concept are analyzed with a focus on both demand and potential. Based on the requirements, existing solutions for the flexibility integration are reviewed and a gap is identified as a generic and systematic flexibility concept that considers all available types of flexibility for a market-based system management cannot be found. To fill this gap, the relevant technologies are evaluated individually. Based on this technology-specific evaluation and the reviewed integration concepts, a new concept is developed which consists of three parts:

The first part of the new concept is the general flexibility integration. It includes a novel and systematic classification of the different technologies by their optimal storage duration. It is shown that the different types of flexible technologies should be used for different purposes and durations (e.g., seasonal or short-term purposes) in relation to their energy and temperature losses. The result of this part is the assignment of the five different types of flexible technologies to the different processes of the framework (namely capacity market, day-ahead market, intraday market, operation, and thermal reserve). Further, it is specified how the different types of technologies must be managed in the framework processes. Through this systematic development, the resulting framework is now able to access the flexibility of the relevant technologies in a systemic way. If competition is introduced to a DHS, the planning procedures ensure that the flexibility is integrated in a system-serving way. In most cases, it can be recommended to place the responsibility for the flexibility with the system operator. This enables the system operator to reduce the costs for purchasing heat by using the physical adaptability of the whole DHS.

The second part is the integration of flexible technologies into the smart market concept. It is proposed to integrate the flexibility of the direct TESs, the demand side, and the pipes of the network directly into the smart market model. Further, it is proposed to integrate the flexibility of the heating plants and of the discharging process of seasonal indirect TESs as bids for heating plants. The smart market concept allows for considering the temperature of the flexible technologies. By this, the system operator can use the thermal flexibility of the system to minimize all variable costs such as the costs for heat purchase and for heat losses. For further information about the smart market concept q.v. chapter 4.

The third part supports the smart market by the identification and concretization of flexibility metrics (capacity, efficiency, effectiveness, state of charge (SOC), and a variable cost factor) for TESs, the network, and the demand side. The metrics are demonstrated by the application of these flexibility metrics to existing storage tanks of the DHS in Hamburg-Wilhelmsburg. It is shown that they help to abstract and understand the thermodynamic processes in the DHS. Further, it demonstrates the impact of temperature on the quantification of flexibility and thus it emphasizes the importance of the inclusion of the temperature dimension into the thermal flexibility definition.

The presented integration of flexibility and its detailed steps is the first comprehensive concept. However, it is only one possible variant and open questions concerning the proposed concept are discussed. This discussion shows that the presented concept requires further development and implementation. The most relevant open implementation is the smart market algorithm based on the concepts presented in this and previous chapters. If the proposed smart market model and algorithm can be implemented and if all mathematical issues can be solved in a reasonable computation time, one of the main disadvantages of competition (the loss of the system-serving character of DHSs) is countered.

The presented flexibility integration is the fourth step of the framework approach and contributes to the framework. Through this last step, a coherent and comprehensive framework is worked out which is concluded in chapter 7.

Chapter 7

Thesis conclusion

In this chapter, the results of the thesis are summarized and discussed. Thereafter, the main contributions are presented. Furthermore, the limitations of the results are determined and discussed and recommendations for future research are derived.

7.1 Level of achievement

The thesis aimed to develop a comprehensive methodology for the transition to 4^{th} generation district heating (4GDH) in an economically efficient way. To do so, four specific objectives were defined and have been achieved in this work.

Objective 1

The first objective was set on the identification of existing methodologies that facilitate the transition. This was achieved through the classification of existing methods and concepts as well as by the identification of a possible scientific gap.

The objective is achieved in chapter 2 by presenting systematic literature research. In a first step, the requirements for the transition are identified. The most important requirements are a reduction of temperature and an overcoming of the established business logic that supports centralized, fossil, and combustion-based plants with high temperatures. In a second step, eight district heating (DH) scopes are proposed to classify the activities in the different fields of district heating systems (DHSs). It is a synthesis of the findings from the literature and the author's practical experience in DH development and research. The DH scopes show the different fields in DH and their interrelation. These *DH scopes* are *preconditions* (DH scope I), *policies* (DH scope II), *heat strategy* (DH scope III), *organization* (DH scope IV), *design* (DH scope V), *operative planning* (DH scope VI), *operation* (DH scope VII), and *evaluation* (DH scope VIII). In a third step, the developed DH scopes are used to classify the findings of the literature review. By assigning the different findings to these scopes, a gap is identified as a methodology is lacking that covers the activities of the scopes design, operative planning, and operation and that facilitates the transition toward 4GDH. Such a methodology must ensure that the requirements of the renewable technologies fit into the planning activities and the economic conditions that currently support the established heating technologies.

The literature research was carried out according to the described DH scopes, which enables a systematic classification of existing and upcoming publications. By applying these DH scopes, a systematic identification of the pending research issues is ensured. Based on the novel DH scopes and the identification of the research gap, it can be concluded that the first objective is achieved in the context of this thesis.

Objective 2

The second objective was set on the development of a framework for the DH scopes design, operative planning, and operation to fill the identified gap concerning a comprehensive methodology. The methodology should facilitate the transition to 4GDH in an economically efficient way. This includes the investigation of new roles and the consideration of the physics to connect all subsystems of the DHS in a system-serving way.

The second objective is achieved in chapter 4 by the development of a comprehensive and coherent framework. Since the transition methodology aims toward achieving a systemic perspective, the framework approach and the resulting framework are complex. Despite this complexity, the development can be broken down into two steps.

The first step is the development of the *basic framework structure*. This includes the identification of optimal organizational conditions (DH scope IV) for the transition as well as the identification of the required internal *framework processes* and their interrelation. As analyzed in chapter 2, the lock-in effect on the established business logic is a relevant barrier. Further, in chapter 3 it is shown that a good framework is continuously learning and improving. Due to the advantages of introducing competition in the context of the transition (integration of external surplus heat sources, specific capabilities of some types of heating plants, and an economy of scope and scale), it is proposed to introduce competition to create an adaptable environment for the transition. To prevent discrimination against external producers, an unbundling of system operation and independent production is also proposed. Hence, the DH operator is transformed into a single buyer that is responsible for the network and the customers as well as for the overall system operation. Its new purpose is to ensure a reliable and cost-efficient heat supply. By only being focused on the network and customers, the single buyer can aim to reduce the heat demand and the temperature and by this, it can aim for a continuously growing share of renewable heat sources. These are strong arguments for the introduction of competition to facilitate the transition towards 4GDH while keeping the system economically efficient. Since the extension of a DHS is only local and compared to the electricity system much smaller, further steps to introduce competition (e.g., through introducing retail competition) are not considered reasonable at the current stage. However, such considerations could follow, provided that an introduction of the single buyer can be successfully demonstrated and that this further step is economically efficient at the local dimension. Since a quantitative proof of the benefits of competition is not part of this thesis, it was decided to develop a framework that allows for full vertical integration, the unbundled single buyer, and a mixed model. Besides potentially disproportionate costs for introducing competition, there are further issues when introducing competition to the DHS: suboptimization, the market power of independent producers, and high risks for investments in new plants. To achieve the aim of an economically efficient and transition-facilitating framework, these issues must be solved in the development. To face these challenges, the following framework processes are introduced: a *capacity market*, *smart short-term markets*, and a harmonized *control and operation process*. These processes are specified by the second step—the *individual framework process development*.

To face the challenge of high market power and investment risks, a capacity market is introduced as a *first framework process* that is relevant for the design decisions (DH scope V). Participation is optional for the independent producers. This capacity market should operate regularly in an annual cycle. In this market, long-term contracts are concluded between the single buyer and the producers. The core part is a mechanism for a fixed thermal power price and rules for the energy price. On the one hand, this reduces the risks for investments. On the other hand, this concept secures predictable prices for the single buyer due to long-term contracts. By the regular evaluation of the existing heating plants combination, a continuous adaption to new regulations and market conditions is possible. Further, the single buyer can now control the amount of renewable heat production on an annual basis, by privileging renewable heating plants with a high price for thermal power and a low energy price. With this mechanism, the fulfillment of ecological goals becomes an intrinsic characteristic of the economic processes and through this, no extra ecological constraint is necessary for the short-term planning.

In addition to the capacity market, the *second and third framework processes* consist of two smart short-term markets: a day-ahead and an intraday market. These markets secure the operative planning (DH scope VI) and are synchronized with the electricity markets. A smart market model and algorithm are introduced that considers all costs in the price clearing of the market. These costs are for transportation (pumping and heat losses) and temperature. The latter is accomplished by novel bids for the producers which include a correlation of the price to the potentially delivered thermal power and supply temperature. These bids prevent the issue of suboptimization by applying the cost-by-cause principle which translates the conditions for an overall optimum into economic mechanisms for the subsystems.

The combination of the capacity market and the short-term markets requires a solution that allows long-term contracts to be concluded while at the same time being able to react flexibly to short-term cost fluctuations (such as electricity prices). Therefore, this thesis proposes an interface between the capacity and short-term markets. Firstly, the participation on the short-term markets is obligatory for all producers—those with long-term contracts and free producers. Secondly, free producers (without a long-term contract from the capacity market) will be paid according to the system marginal price. Thirdly, the payment for the contract-related producers will be organized by the mechanism of contract for differences. The advantage of this solution is illustrated by the following example: Given a heating network where sufficient generation capacity is covered by long-term contracts. Now, free producers are connected to the network at their own expense and without long-term contracts. To be able to sell their heat, these free producers must place their bids on the short-term market below the variable prices of the contract for differences of the existing producers. However, the free producers must refinance their fixed costs through the revenues from these bids. If a new technology is still more economical, the single buyer and the heat customers benefit from a more favorable heat price. In this case, the producers with long-term contracts cannot sell their heat and are not paid for the thermal energy. However, they receive the thermal power price agreed on the capacity market, which allows them to cover their fixed costs for standby. Thus, the capacity market minimizes the risk for a long-term investment while the short-term market is opened for competition.

The operation (DH scope VII) forms the *fourth framework process* whereby the results of the intraday market serve as the scheduling for the heating plants. These schedules include the thermal power and the minimum supply temperature. Both variables can be translated into set-points at the control platforms, and they can be transferred to the local control systems. For the communicational connection as well as for the hydraulic interface, standards combined with explicit responsibility for all subsystems are given by the new framework. Further, it is defined how a hierarchical control concept should compensate for deviations from the schedule that occur in between the intraday market routines. Such a complementary control system is a requirement for the introduction of a schedule-driven operation. Finally, the interface to the evaluation process (DH scope VIII) is developed that is needed to identify potential mismatches between the market results and real operation.

The outer conditions and the inner framework processes, mechanisms, and their interfaces form the new comprehensive framework. It is proposed to introduce competition to break up the established fossil business logic. Different processes are introduced to avoid suboptimization, market power, and investment risks. The most important of these is the introduction of a capacity market and smart short-term markets in combination with backbone control algorithms. All processes serve the purpose of translating ecological and technical constraints into economic mechanisms. These mechanisms are validated (q.v. chapter 4) against the defined requirements (q.v. chapter 2). The proposed framework is the first full scientific concept that connects the DH scopes of design, operative planning, and operation with the aim to facilitate the transition to 4GDH with high economic efficiency. It serves as a foundation or a starting point for further research, development, and implementation. The framework can be applied to competitive environments and also to vertically integrated DHSs. In any case, the transparency can be increased. By this, it can be concluded that the developed framework fulfills the second objective to facilitate the transition in an economically efficient way.

Objective 3

The third objective was set to evaluate the supply temperature impact on the costs of heat production. Through this, the temperature relevance for the new framework should be evaluated and the heating plants should be integrated into the new framework.

The third objective is achieved in chapter 5. Here, existing methods are reviewed that can evaluate the supply temperature impact on the average variable cost of production. Because no method can be found that fits the requirements, a new method is developed. This method is then applied to existing and planned heating plants of the case study DHS in Hamburg-Wilhelmsburg. The results of the case studies show that the supply temperature and the part load ratio have a relevant impact on maximum thermal power and on the average variable costs of some types of plants such as heat pumps.

This shows that including the supply temperature in the framework is reasonable. Due to the evaluation of the variable costs, it can be concluded that the bids for the smart market should include the temperature correlation to integrate the heating plants of the possibly unbundled producers in a system-serving way. As the presented evaluation focuses on variable costs, the fixed costs are treated as sunk costs. For the consideration of the temperature in the capacity market, the new method can be used as a starting point for further developments. Since the temperature impact is considered relevant, it is recommended to integrate the supply temperature into all marketplaces. By these presented achievements, the third objective can be considered as being achieved in the context of this thesis.

Objective 4

The fourth objective was set to integrate flexibility into the framework. To accomplish this, existing concepts should be analyzed, and the final integration should aim to access the full flexibility in an efficient and systemic way.

The fourth objective is achieved in chapter 6. Firstly, a new definition for the term *flexibility* in the context of DHSs is proposed which includes the temperature as a further degree of freedom in addition to thermal energy. Secondly, existing concepts that deal with the integration of flexibility are reviewed. Thirdly, as no concept can be found that fits the requirements, a new concept for the integration of flexibility is developed which consists of three steps. In the first step, the identified flexible technologies are assigned to the framework processes. The flexible technologies are heating plants, the network, the demand side, direct thermal energy storages (TESs), and indirect (mostly seasonal) TESs. Further, it is specified how the different technologies are integrated into the different processes of the framework. In the second step, the specific implementation of the smart market model is proposed. In the third step, a set of flexibility metrics is compiled from existing key performance indicators (KPIs) from the literature. Here, the innovation is the novel combination of the KPIs and the inclusion of temperature in all of them. Finally, the metrics are subsequently applied to existing storage tanks of the case study DHS in Hamburg-Wilhelmsburg. The results of the application highlight the relevance of temperature in the flexibility treatment.

In this thesis, all relevant flexible technologies are integrated into the new framework which forms a first overall concept. It serves as a foundation for further development, implementation, and validation. As the developed integration considers all parts of the DHS (heating plants, network, the demand side, and TESs) and since it considers the temperature in all steps, all technologies are integrated in a system-serving way. Utilizing the flexibility of the whole DHS improves the system management and enables the system operator to minimize all variable costs (heat purchase and network operation). Therefore, the concept can be evaluated as being systemic and thus, the fourth objective can be considered as achieved in the context of this thesis.

Level of achievement of the research aim
The lacking transition methodology (chapter 2) is elaborated by the new framework approach (chapter 3) in four steps. The approach is built upon the newly developed structure of DH scopes. This structure of DH scopes ensures that the new framework is developed coherently and that all framework processes are systematically linked. The four steps of the approach are applied in chapters 4 to 6. The resulting framework ties established tools and principles and newly developed methods together. It is comprehensive since all relevant technologies and physical conditions are considered. The framework serves as a foundation for the further evaluation of introducing competition since it proposes processes and mechanisms that eliminate the most relevant counterarguments against the competition (suboptimization, market power, and risk for investments). If introducing competition can be validated as economically efficient, introducing the new organizational structure can act as one component to resolve the identified lock-in effect to the established business logic.

As the new framework can be implemented independently from the final organizational structure, the framework supports the integration of the renewable heat sources in any case while it secures a transparent and economically efficient system. Since the individual objectives are achieved, it can be concluded that the thesis makes an important contribution to fulfilling the central research aim. While developing the framework in this thesis, several contributions are made which will be described in the following section.

7.2 Contributions

The main contribution of the thesis is a grand synthesis of existing theories and methods into a comprehensive framework for the DH scopes of design, operative planning, and operation that facilitates the transition to 4GDH. In detail, the following contributions are made:

Specific outputs
The main output of the thesis is the proposed framework with its organizational structure, framework processes, interfaces, and mechanisms as well as the underlying methods and concepts. The most relevant of these underlying concepts are the structure of DH scopes, the capacity market, the concept of a smart market algorithm, the operational structure, the method for determining the variable costs of heating plants, as well as the flexibility metrics, and the extended storage tank model. The framework or parts of it could be implemented by DH companies, or it may be used as an orientation for strategical or political decisions as well as for further research to facilitate the transition to 4GDH.

Besides the presented framework and the specific underlying methods, this thesis delivered the following outputs in the form of publications, congress presentations, and contributions to research projects:

With its concepts and methods, this thesis contributes to the research project *Smart Heat Grid Hamburg* [25]. This research project aims to practically implement 4GDH innovations in the DHS in Hamburg-Wilhelmsburg. The DHS serves as a case study site for this thesis and, in return, the thesis contributes the specific results of the applications (chapters 5 and 6) to the research project. Further, the thesis provides theoretical methods and the new framework as central results for this research project.

As a part of this research project, the conference paper *Design of a Smart Thermal Grid in the Wilhelmsburg district of Hamburg: Challenges and approaches* was published by Lorenzen et al. [12]. The paper focuses on practical implementations of innovations to facilitate the transition in the DHS in the district Hamburg-Wilhelmsburg and it describes the case study DHS in Hamburg-Wilhelmsburg. The paper has benefited from several parts of this thesis. Firstly, it introduces the two main paths of DH research, namely increasing the share of renewable heat production and the compensation of fluctuations in the electrical system. Secondly, it summarizes the relevant heating technologies. Finally, this thesis provided initial standards for hydraulic circuits and the relevance of standardization for smart control concepts.

An early concept of the new framework was published in the international DH magazine *Hot/Cool* with the title *A district heating market mechanism: Markets as a mature concept for a modern district heating infrastructure* [79]. The publication emphasizes the relevance of markets for the transition. Furthermore, it introduces the framework concept (called the *market cascade*) of the capacity and smart short-term markets. In this publication, the first concepts of the underlying mechanisms are proposed.

The method and parts of the case studies of the heating plant integration (chapter 5) are published in Elsevier's journal *Applied Energy* [75]. The article *Variable cost evaluation of heating plants in DHSs considering the temperature impact* shows that a method that adequately includes the impact of the supply temperature in the evaluation of variable costs of heat is lacking. Further, the paper presents a novel method that fills this gap. The method is applied to a case study involving heating plants that are existent or planned in the DHS in Hamburg-Wilhelmsburg. The results of the paper are included in chapter 5.

An early proposal for the flexibility definition was presented at the *4^{th} International Conference on Smart Energy Systems and 4^{th} Generation District Heating* in Aalborg, Denmark. The oral presentation under the title *Flexibility in district heating systems – A suitable definition and model to describe the temperature and* *energy flexibility* introduces the temperature aspect into the understanding of flexibility in DHSs (q.v. chapter 6) [243].

In the paper *Design of a district heating roadmap for Hamburg,* Kicherer, Lorenzen and Schäfers present a new method for the development of a heat strategy in Elsevier's Journal *Smart Energy* [244]. By the application of the method, a strategy for the transformation of Hamburg's largest DHS is developed. This thesis contributed to the paper's method by defining and computing flexibility and considering temperature aspects.

Finally, the novel framework of this thesis served as a blueprint for parts of a new research proposal *Reallabor: Integrierte WärmeWende Wilhelmsburg – Integrierter Wärmemarkt* (*Living Lab: Integrated Heating Transition Wilhelmsburg—Integrated Heat Market*) [26]. In this research project, which commenced in August 2020, the proposed framework will be partly implemented and tested. Further, it is planned to implement the capacity market, the smart markets, and the control concepts in the DHS in Hamburg-Wilhelmsburg.

Problem-solving

The transition to 4GDH is a broad topic and a large research field. It is too large to be solved within one Ph.D. thesis. However, with the new methodology and several specific developments and investigations, this thesis contributes to the transition. Since the thesis aims to provide a general methodology, it is not focused on the transition of a specific DHS and hence the resulting framework provides standardized conditions that can be applied to every DHS, and which secure an economically efficient transition. Introducing competition and the framework empowers small-scale DHSs and operating companies to access the knowledge and capital of all companies in the DH market. The new framework connects the different relevant activities, and it allows for competition. In this way, it forms the conditions for an agile and self-enhancing system.

However, the introduction of the framework itself does not secure a successful transition; rather, the successful transition must be additionally facilitated through the support of activities in the other higher-level scopes. This means that it requires an acceptance of the customers (DH scope I), transition supporting policies (DH scope II), and facilitating regional heat strategies (DH scope III). The new structure and introduction of DH scopes can help to identify the right measures and the best fitting scope.

Filling gaps

The first identified gap is that a structure for the different fields of DH research is lacking. This is provided by the introduction of the structure of DH scopes in chapter 3.

The second identified gap is a lacking methodology for the DH scopes of design, operative planning, and operation. A strong contribution is made in the whole thesis and particularly in chapter 4 to fill this gap. The different subordinated methods are tested with their application to case studies and through this, they are validated. With the development of the framework and the new methods, the identified gap of a lacking methodology is filled. This new framework forms a foundation for further research.

Another gap is identified for the evaluation of the average variable cost of heat production in relation to the supply temperature. For this, a method is developed and tested in chapter 5. Finally, a gap is identified for a coherent flexibility integration. Here, a new method has also been developed and tested. All the developments are related to each other and therefore, they are evaluated as coherent.

Relation to existing theories

The main contribution—the framework—is a synthesis of partly existing theories and derived concepts. Furthermore, own innovations are also introduced to fill the gap. These innovations are tested and validated wherever possible. For example, the competition models are related to the historical development in electrical systems. Further, this is combined with experiences from DHSs that operate, even today, with unbundled system operators (e.g., the DHS in Copenhagen).

Most of these developments and the syntheses are built upon existing theories and thus are based on verified knowledge. In turn, this thesis aligns with these theories. For example, as demonstrated by the interview with Fjernvarme Fyn, single mechanisms of the proposed capacity market are existent and already performed regularly in DHSs today.

However, there are also some aspects of the results that may challenge existing theories. Most importantly, the introduction of a competitive environment is seen critically in the DH sector due to the described concerns of non-reasonable transaction costs, suboptimization, market power, and the risk for investments. The developed framework aims to address these concerns in the light of a successful transition. However, further research is required for a final recommendation in favor of or against competition and in favor of or against unbundling of system operation and production. From the perspective of the electricity sector, the selected competition model might not be considered far-reaching since retail competition is not yet included. However, the undbundled single buyer model represents a good compromise between the status quo from both—the DH and electricity sector—and forms a starting point for the introduction of competition. In case of implementation, it is therefore recommended that this process is evaluated regularly to derive further steps.

The conceptualized smart market model is another break from existing concepts. Here, an implementation is required and finally, a comparison with alternative existing models like those based on mixed integer linear programming (MILP) is necessary.

Practical applications

Besides scientific contributions, this thesis presents several results that can be applied in practice to support the transition to a fossil-free energy supply.

In particular, the new structure of eight DH scopes should be emphasized (q.v. chapter 3), which provides a guidance for all stakeholders involved in the transition or implementation of DHSs (e.g., policy makers, municipalities, or DHS operators). The interconnections of the different activities and technologies in a smart thermal grid and the resulting complexity demonstrate the value of such a systematically developed structure.

This also applies to the developed framework (q.v. chapter 4). For new DHSs, the results of this thesis provide a blueprint for a possible organizational structure and the implementation of processes. In existing DHSs, the realistic application is not necessarily a one-to-one implementation of the framework. Rather, it is suitable to support continuous improvements and an associated learning process for the transition. The framework can be used by all stakeholders to analyze the existing processes and to derive improvements. DH companies can use it as orientation in the overall system context when solving individual problems. Policymakers and municipalities can use the framework as a target system for the transition of the DH sector.

Besides the orientation provided by the framework and structure of DH scopes, many other specific suggestions from this thesis can be practically applied. The most relevant ones are presented in the next sections in relation to the DH scopes in reverse order—following the recommendation of a bottom-up learning process (q.v. chapter 3).

Evaluation scope (VIII): The results of the thesis show that the evaluation of the DH operation and its processes is the basis for a further learning process. On a technical level, this means that operational data must be measured, monitored, and archived. The thesis identified the relevant measurements that can be directly implemented in practice (e.g., the measurement of temperatures and all energy balances for each individual heating plant and substation).

Operation scope (VII): This thesis presents an operational hierarchy that can be used to implement sufficient control systems and to identify the responsibility of agents. The proposals for hydraulic and control standards can be used when planning new plants and integrating them in a system-serving way. The developed flexibility metrics can be directly implemented to improve the operation of storage tanks. They contribute to the improvement of the missing compatibility of energy-based metrics in the operative planning processes, and temperature measurements, which are used to control the charging and discharging processes of storage tanks in the field. These metrics can be directly implemented in existing control systems.

Operative planning scope (VI): For the operative planning processes, it is also proposed to consider the temperature by its integration into the smart market model. Since this model has not been implemented yet, it cannot be directly applied in practice now. But if the concept will be implemented in the future, including temperature and transportation costs in one market model will lead to higher economic efficiency and greater cost transparency.

In contrast to that, the results from the heating plant evaluation (q.v. chapter 5) and the flexibility evaluation (q.v. chapter 6) can be directly used in practice. Here, the numerical results can be used for the evaluated case studies in the DHS in Hamburg-Wilhelmsburg. Further, the applied methods can be directly applied to any other plant or technology.

Further, the discussed interface between the capacity market and the short-term markets also contributes to existing processes in vertically integrated utilities. The proposed price mechanisms can be directly implemented in internal business case calculations to identify the benefits of reducing temperature to integrate renewable heating plants.

Design and organization scopes (V and IV): The proposed capacity market can be implemented in existing or new DHSs. However, even if no third-party access is introduced, the proposed processes support a more systematical planning process and a continuous enhancement process. It can be combined with the identified existing planning tools. By implementing these processes, the whole system can be evaluated regularly considering the planning of seasonal storages and ecological goals.

Even today, the DH companies may introduce competition in their systems without a change of the legislation. Processes for this step are proposed here, which can be directly implemented. Even though this might be seen critical by DHS companies today, there are several advantages to open the systems in the process of transition to 4GDH. Depending on the technology and size of the plants, the motives are different. One example is the installation of a deep geothermal plant which may be provided by a specialized third party. The construction and operation of such a plant require specific expertise. In addition, such a technology requires high investments which are often too high for small DH companies. Also, an external company has more possibilities to split the risk of a geothermal discovery to several DHSs. In such a case, the concepts developed in this thesis can be used. However, it is important to implement a balanced level of complexity of the framework processes depending on the number of heating plants and the size of the network.

Heat strategy, policies, and preconditions scopes (III–I): Even though this thesis is not focused on these DH scopes, practical applications for them can be derived from the results. Since these scopes form the conditions for a possible implementation, the framework can be used as an overview of required processes and a possible target system. In order to develop comprehensive heat strategies, municipalities can use the framework as orientation for an organizational structure and required processes when creating new DHSs or enhancing existing DHSs and their utilities. Required changes of policies should be identified by further investigations. The range for possible changes is wide. It starts with initiating small supporting steps such as forcing the DH companies to split the customers' bills into costs for transmission and production and ends with forcing the implementation of a new framework.

7.3 Boundaries of the work

Like all scientific works, this work is bounded by a given scope in terms of time and extent.

For this thesis, a liberalized market in a non-regulated market environment is assumed and thus a transition supporting framework in a fully regulated environment may look quite different in comparison to the framework developed in this thesis. Further, it is assumed that the framework and its processes can be implemented in any existing DHS—independently of the existing organization and ownership structure. In practice, such an implementation will require an individual implementation strategy.

This thesis aims to find solutions that fulfill the systemic perspective. Due to the limitations in scope, it is not possible to solve a number of issues, especially to address the new questions that arise during the development of the framework. In addition, a large number of development decisions are made in this thesis and some details of the development are thus based on the author's experience and subsequently only represent one possible solution among many alternatives.

On the specific level, simplifications and assumptions are applied in the implemented models. The most important global simplifications and resulting limitations are discussed in section 3.3, whereby the assumption of a constant return temperature is one of the most relevant simplifications. The models use established steady-state equations, which are given in the respective chapters and in appendix A. In addition, the temperature dependence of the input variables is also evaluated in appendix A.

The limitations of the heating plant models are described in section 5.3 and discussed in section 5.5.5. The constant return temperature and the steady-state implementation may be given as the most relevant limitation. Further limitations of the individual heating plant models are plant-specific and depend on the individual implementation and parameters (q.v. section 5.5.5).

The limitations of the storage tank model are discussed in section 6.7.5. The basic model is a validated model from literature which neglects heat losses. This limitation was removed by the new extension in this thesis (q.v. section 6.7.1). However, the basic model is a graphical regression model that represents a continuous stratification in the storage tank. This limits the model to typical storage tanks with a bottom and a top connection. Further, the model cannot be used for dynamic considerations like charging, discharging and other forced mixing processes. Since an idealized standby process does not have these effects, this limitation is not relevant for the presented evaluation.

On the global level, the most relevant boundaries may result from open implementations of the proposed processes and the framework itself. The capacity market is described with its main mechanisms and the macroeconomic basics that are applied, but an implementation of the framework processes in specific DHS companies must be developed. This is even more relevant for the smart short-term markets. Here, just one possible smart market model and one solving algorithm are extensively described including the integration of unbundled producers and the integration of different types of flexible technologies.

This thesis provides strong arguments and a coherent overall picture that competition is a great accelerator for the transition. Thus, based on research and the fundamentals of macroeconomics, the introduction of competition is very likely to have a positive impact on the transition progress. The provision of quantitative proof concerning whether the introduction of competition and the unbundling of heating plants from the system is beneficial in comparison to a vertically integrated utility on a macroeconomic basis is not the objective of this thesis. Therefore, further research is required for this evaluation.

7.4 Recommendations for future research

Based on the boundaries of the work, future research foci can be proposed to facilitate the transition in DHSs. The framework and its subordinate processes require further specific investigation. This is described in detail in chapters 4 to 6. Here, the most relevant recommendations are summarized.

The capacity market and thus the design scope require further research to combine existing tools for planning and designing DHSs. Here, many tools are available in the literature, but the different tools are not part of a coherent toolbox, i.e., one that uses the same database.

The smart market model requires research to develop mathematical models and implement the models and their algorithms. In addition, the inputs for the smart markets must be further investigated. The market requires two inputs: bids from the producer side and forecasts from the demand side. Through the developed method for the bids that consider the supply temperature impact, this thesis contributes to the producer side. In the same way, a forecast for the consumers is needed that also considers the required supply temperature. Its temporal resolution must be high to fit the smart market resolution. Further, the specific implementation of the flexibility metrics will require further investigation for those technologies that are not considered in the flexibility evaluation.

For the operational scope, the control algorithms require further investigation for which many solutions are available (such as model predictive control (MPC)). These existing concepts must be integrated into the framework. To do so, the interfaces between the markets and the control systems as well as between the control systems themselves must be further developed and standardized. The controls of the heating plants should require set-points for thermal power (part load ratio) and supply temperature. Due to the smart market concept and the unbundling of the heating plants from the rest of the DHS, proper network operation and monitoring are required, to make the costs of transport transparent. This is relevant because these costs are used for economic decisions in a competitive environment, and it must be avoided to discriminate against producers because of missing system information. One technology for such detailed system monitoring is state estimation.

Besides these specific developments and implementations, the framework as a whole requires further investigation. As a first step, the framework should be implemented for a specific DHS and a specific DH company. In this step, further shortcomings in the developed framework may be identified, the whole framework may be improved, and its practical application may be validated.

Finally, the introduction of competition and unbundling must be quantified on a macroeconomic level. Such a quantification must compare the additional transaction costs of the framework operation and the additional administrative costs when separating production and system operation on the one hand with the increasing economic efficiency on the other hand. The boundary condition for the evaluation is a sufficient transition towards 4GDH within the goals of the Paris Climate Agreement and not the status quo of fossil heat supply. Further, the evaluation must consider economies of scale and scope due to the introduction of competition in many DHSs (i.e., all DHSs in Germany). This is relevant for the independent heat producers and the market operation. To create transparency as a first step, it would be advisable for DHS operators to be required by law to separate the costs of heat production and distribution on the customer bill.

As described in section 7.2, the proposed framework was used as the basis for a research proposal. Based on this proposal, a new research project (*Integrierter Wärmemarkt*) started in August 2020. As part of this project, the proposed framework will be partly implemented and tested, and through this, the concept of this thesis is further developed and validated.

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Appendix A

Introduction to theoretical concepts underlying the thesis

This thesis combines approaches from different fields of research including district heating (DH) technology, thermodynamics, heat transfer, hydraulics, macroeconomics, and competition theory. As interested readers might only have a part of the background knowledge in these fields, a brief summary of the relevant theoretical basics is provided in this chapter. Further, since there are different meanings assigned to the same terms in the various disciplines, terms and conditions are defined to unify the wording in addition to the definitions given by the glossary. General assumptions are made to support the reader with global constants. In contrast to the review of the state of the art in chapter 2, this chapter delivers concepts that are independent of current research.

The chapter is organized into three sections. Firstly, the general DH technology is introduced, and terms are defined. Technical assumptions and limitations are discussed which are used in the whole thesis. Secondly, the basics of macroeconomics are presented. Finally, the basics of the relevant algorithms are presented.

A.1 Fundamentals of district heating technology

This thesis focuses on DH only and thus district cooling systems or combined district heating and cooling (DHC) systems are not considered. Before the DH technologies can be presented, one issue must be pointed out. Sulzer et al. show that the vocabulary of the DH sector is not standardized [1]. As this thesis only focuses on heating and not on district cooling, some topics that are discussed in [1] are not relevant and therefore not all recommendations are applied. However, it is important to define some terms for a clear wording in this thesis. The most relevant definitions are provided in the glossary. In addition, terms are clarified with more context in this chapter.

A.1.1 Terms and definitions in district heating

A *district heating system (DHS)* is a heating system on a large scale (e.g., for a district or a whole city). It delivers heat from one or more heat sources through a network of pipes to the location(s) of heat demand. The distribution is realized by a network that consists of (at least) two pipes [107, p. 26]. A simplified system and the most relevant terms are illustrated in figure A.1.

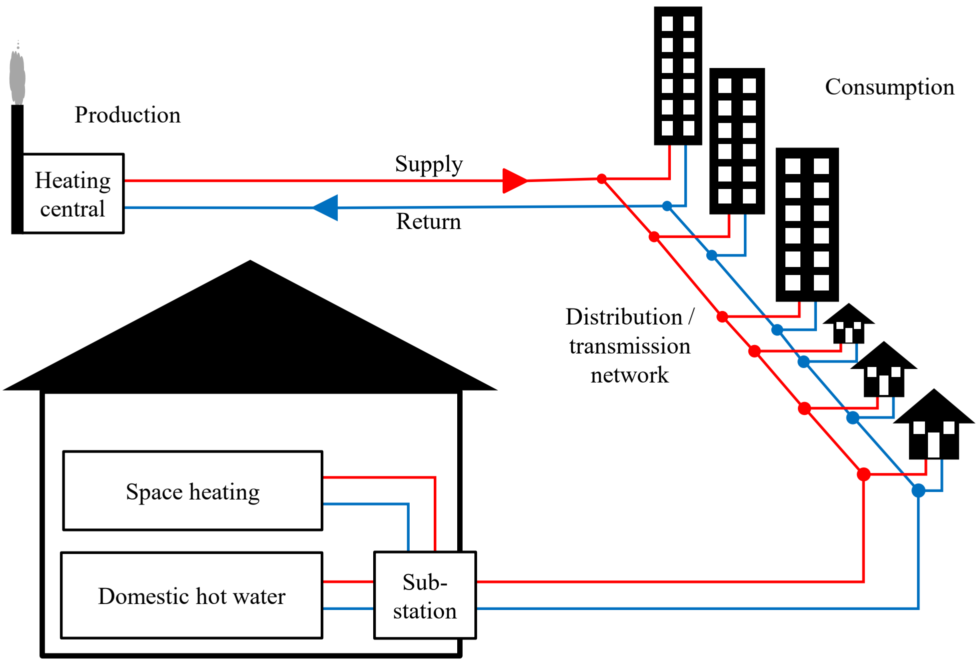

Figure A.1: Overview of a district heating system

In district heating systems (DHSs), a *network of pipes* connects the heating plants and the customers. In electrical systems, the network consists of two different levels. The larger connections are called *transmission lines* and the smaller and local connections are called *distribution lines* [245]. As most DHSs only have a local scale, it is unusual to differentiate between the two layers.

Residential heat consumers mostly have two types of demand: *domestic hot water (DHW)* and *space heating* [107, p. 12]. A *substation* is a connection between the network and the consumer, and it transfers the heat from the DHS to the building's internal heating system [4].

If a building is a *producer* at one point in time and a *consumer* at another point in time, it is called a *prosumer*. In this case, the bidirectional substation should be called an *energy transfer station* related to [1].

In DHSs, diverse types of pipes are used. They can be characterized between the material, geometry, structure, and laying. Pipes in DHSs have in common that they have an internal pipe surrounded by insulation (q.v. figure A.2). The inner pipe material can be metal (mostly steel) or plastics, and the thickness of the insulation (geometry) determines the heat losses. An example of a different structure is the twin-pipe in which the supply and return pipes are enclosed by common insulation. Another variable is the laying methods of the pipe. Pipes can be located on concrete sockets in the air, in special media channels, or simply in the ground [2, pp. 271–343].

Figure A.2: Example of a bonded pipe [246, p. 2]

The different characteristics influence the calculation and parameters of the heat and pressure losses [107]. In the context of this thesis, only one type of pipe will be referred to, namely the bonded pipe system which is the most commonly used type. The most commonly used laying method is direct burial [2, p. 284].

A.1.2 Piping and instrumentation diagram

Heating systems are illustrated using a piping and instrumentation (P&I) diagram that represents the hydraulics and the control scheme. The rules and the official symbols are defined by several standards (e.g., DIN4747 [106]). P&I diagrams provide the main basis for the planning and construction phase of DHSs. In this thesis, they are used to illustrate the hydraulic system in a simplified way. This includes the omission of details that are not necessary to explain the functional principle. These could be ancillary facilities such as water treatment plants, venting taps, or pressure balance vessels. A simple example is given in figure A.3. The P&I diagram shows the piping as colored lines and hydraulic components and instruments as symbols. Control loops are illustrated by black dotted lines, while the supply pipes are illustrated as solid red lines and return pipes as solid blue lines.

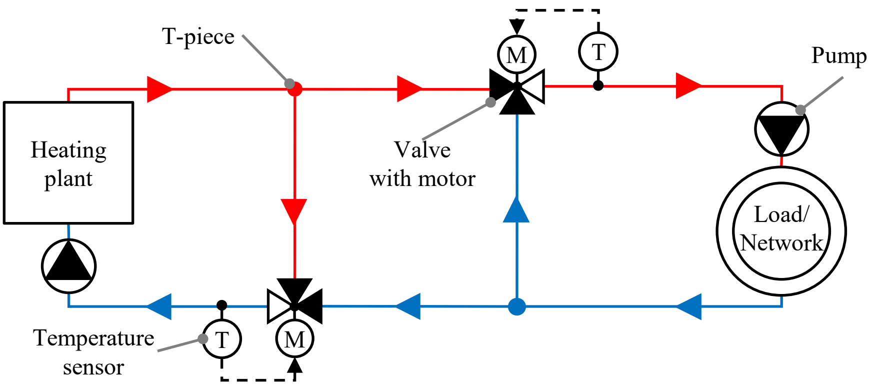

Figure A.3: Exemplary P&I diagram

The figure shows several components. On the left side, the heating plant (rectangle) heats the water which is transferred through the supply pipe and divided by the T-piece. To the right, the pipe is connected to a three-way valve which is driven by a motor (M). On the side represented by a white triangle, the valve is always open. In its right direction, a temperature sensor (T) is placed. The sensor is used to control the valve (black dotted line). Following the supply pipe, a pump is placed to supply a load or the network (two concentric circles). After the consumption, the temperature is reduced and led to another T-piece.

A.1.3 DH control systems

For the introduction of control systems, four different levels can be defined: component-level (e.g., a pump), aggregate-level (e.g., a heating plant), subsystem-level (e.g., a heating central, customer's building, or network), and the system-level for all implemented parts of the DHS. Figure A.4 presents an overview of a simple DHS.

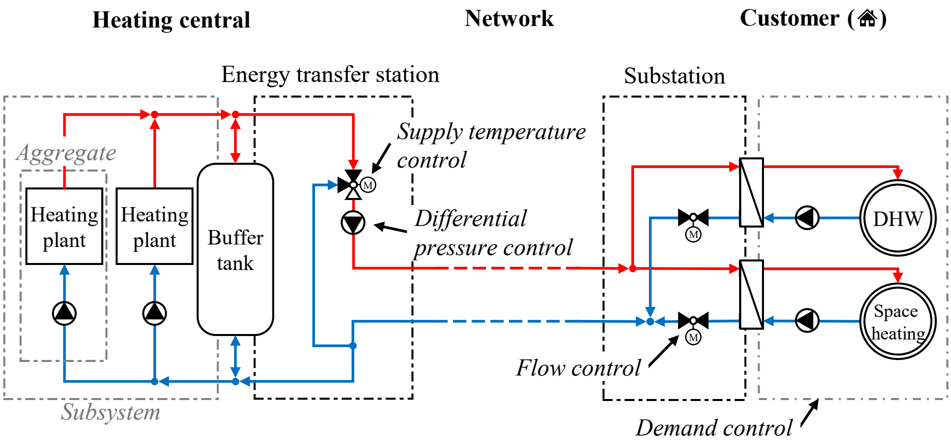

Figure A.4: Exemplary control structure

Controls in DHSs mainly consist of four different variables. The *heat demand* is given by the building's internal controls and the *flow control* is executed by the substation's control valve to supply the load. In the heating central, the *differential pressure* is controlled by frequency-controlled pumps. The network's *supply temperature* is also controlled in the heating central (e.g., by mixing valves). [2, pp. 469–471]

The most efficient control for the network is a *variable flow and variable supply temperature control*. The supply temperature is mostly chosen by a correlation of a set-value and ambient temperature. The set-point for the differential pressure of the network pumps is set by a measurement at one or more customers with the furthest distance. The most frequently used strategy for the heating plants is a *sequence control* based on variable costs whereby the return temperature is set by the customer's internal heating system. [42, pp. 18–20, 26]

If production is fed into the grid at more than one point, one heating central must be defined as the *primary* one. This primary point of feed-in controls the differential pressure and the other (*secondary*) points of feed-in require a centralized set-point for a feed-in flow rate. [cf. 247, p. 55]

A.1.4 General equations and constraints

The fields of thermodynamics, heat transfer, hydraulics, power systems, and economics are important for this thesis. These fields use different terms for the same purposes which can lead to confusion and thus definitions are provided to determine the meaning of the expressions used in the context of this thesis.

Thermodynamic equations

The first law of thermodynamics (*the conservation equation*) expresses the change of the system's total energy by work (W). Work is a form of energy transfer to or from a system and can result in increasing the internal energy of a system (U). The internal energy includes small-scale energy such as atomic vibrations. Heat (Q) is the energy that is transferred through the border of a thermodynamic system from higher to lower temperatures. If the change of the kinetic and potential energy of the system is negligible, the equation can be simplified to equation A.1, which describes the change of heat between states 1 and 2. [cf. 5, pp. 38–40, 66–68]

$$Q_{12} = W_{12} + (U_1 - U_2) \tag{A.1}$$

In an open system for steady-state and incompressible flow, the Eulerian description of the conservation equation of mass applies and can be described as shown in equation A.2 for $\dot{m}$ as the *mass flow rate* (derivative with respect to time) [5, p. 241].

$$\sum_{\text{Outlet Ports}} \dot{m}_{\text{out, o}} - \sum_{\text{Inlet Ports}} \dot{m}_{\text{in, i}} = 0 \tag{A.2}$$

The sum of the internal energy with the pressure work (W_p) is defined as *enthalpy* (H) in equation A.3 [5, p. 38].

$$H = U + W_\text{p} \tag{A.3}$$

Through division by mass, the enthalpy can be expressed as specific enthalpy (h) in equation A.4 and internal energy can be expressed as specific internal energy (u) in equation A.5 [5, p. 244].

$$h = H/m \tag{A.4}$$

$$u = U/m \tag{A.5}$$

Using these equations, and under the conditions of a steady-state process, control volume with fixed boundaries, no internal heat production, and the negligence of the kinetic and potential energy of the system, the first law of thermodynamics for open systems can be reduced to equation A.6 where $\dot{Q}$ is the *rate of heat transfer* (the derivative of heat with respect to time) and W_s is the shaft work.

$$\sum_{\mathrm{i}}(\dot{m}_{\mathrm{in,i}} \cdot h_{\mathrm{in,i}}) + \sum \dot{Q} = \sum \dot{W}_{\mathrm{s}} + \sum_{\mathrm{o}}(\dot{m}_{\mathrm{out,o}} \cdot h_{\mathrm{out,o}}) + \frac{d}{dt}(m \cdot u) \tag{A.6}$$

In thermodynamics, power ($\dot{W}$) is the rate of energy transfer by work, which is defined in equation A.7 [5, p. 57]. For further discussion of the term *power* q.v. the glossary.

$$\dot{W} = \frac{dW}{dt} \tag{A.7}$$

One way to add heat to a thermodynamic system is by the combustion of a fuel. In this process, *gross calorific value (GCV)* is the amount of heat produced by the full combustion (e.g., of natural gas) if the enthalpy of the steam in the exhaust gas is used [248, p. 403]. If the enthalpy of the steam is not used, the heat is equivalent to the *net calorific value (NCV)* [248, p. 403]. For natural gas (type H) the ratio of gross calorific value (GCV) to net calorific value (NCV) is 1.1 [249].

Thermodynamic properties

A thermodynamic system has properties like pressure (p), density (ρ), temperature (T), enthalpy (H) and specific heat capacity (c_{p}) [5, p. 40]. Heat and work are not observable characteristics of the system [5, p. 35].

The *specific heat capacity* is used to express the increase of temperature depending on the amount of heat in a homogenous phase [cf. 5, p. 38]. Under constant pressure, the specific heat can be calculated by equation A.8 [5, p. 40] with the specific enthalpy (h).

$$c_{\mathrm{p}} = \left(\frac{\partial h}{\partial T}\right)_{\mathrm{p}} \tag{A.8}$$

In this thesis, the specific heat capacity is assumed as constant with a mean value of 4.192 kJ/(kg.K). The calculation is based on the numbers provided in [250, pp. 176–177]. Figure A.5 shows the comparison of the original values and the mean value. In the relevant temperature range between 50 and 95 °C, the maximum deviation of the mean value is 0.45 %. As it is lower than 1 %, it is decided to use the constant value which reduces the complexity of all related calculations.

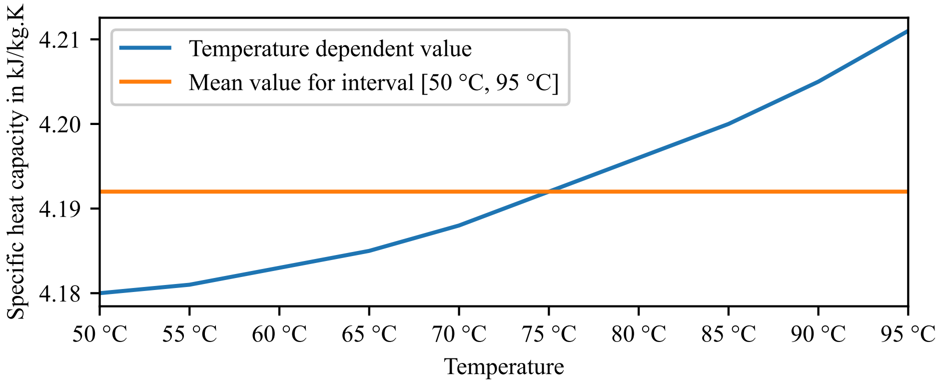

Figure A.5: Specific heat capacity of water (data from [250, pp. 176–195])

The *density* has a temperature dependency that is not neglected in this thesis. Figure A.6 depicts the density and the mean value in correlation to the temperature. If the density would be assumed as constant with the mean value of 977 kg/m^3 in the range of 50 to 95 °C, the maximum deviation is approximately 1.4 %. Since the deviation is above 1 %, an interpolation based on the data of [250, pp. 176–177] will be used. In contrast, the volume expansion is neglected. It is not necessary for the calculation of the thermal balance, and it makes the calculation more complex. While components for volume balancing such as pressure balance vessels should be included in the constructions, they are not part of this thesis.

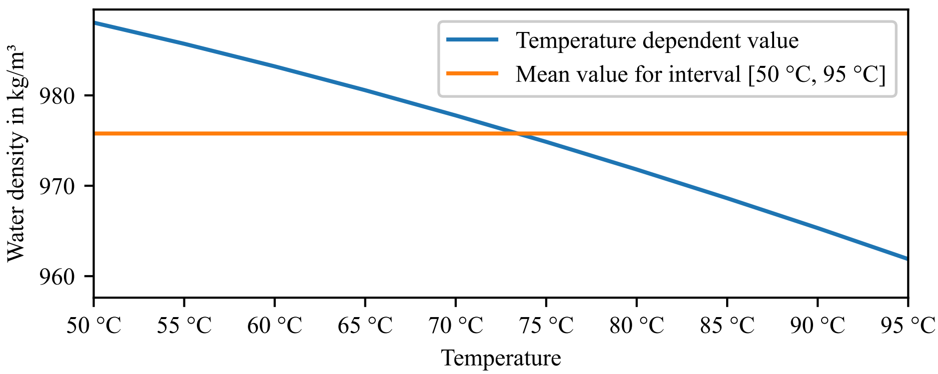

Figure A.6: Density of water (data from [250, pp. 176–177])

Temperature can be expressed by T in K (Kelvin) or ϑ in °C (degree Celsius) whereby Kelvin is the absolute scale. Both can be converted by applying equation A.9. [5, p. 38]

$$T = \vartheta + 273.15\,\mathrm{K} \tag{A.9}$$

Heat transfer

For the calculation of losses and mixing effects, some fundamental theoretical concepts from the heat transfer discipline are required whereby heat transfer describes the process of exchanging energy between two objects by conduction, convection, and radiation [234, pp. 2–13].

The *thermal conductivity of water* is relevant for the later presented evaluation of thermal energy storages (TESs) and its temperature dependence is shown in figure A.7. In the temperature range between 50 and 95 °C, the maximum deviation is approximately 3 % for the mean value of 0.6585 W/(m.K). Therefore, the temperature impact is not neglected, and the calculation is based on the values provided in [250, pp. 176–177].

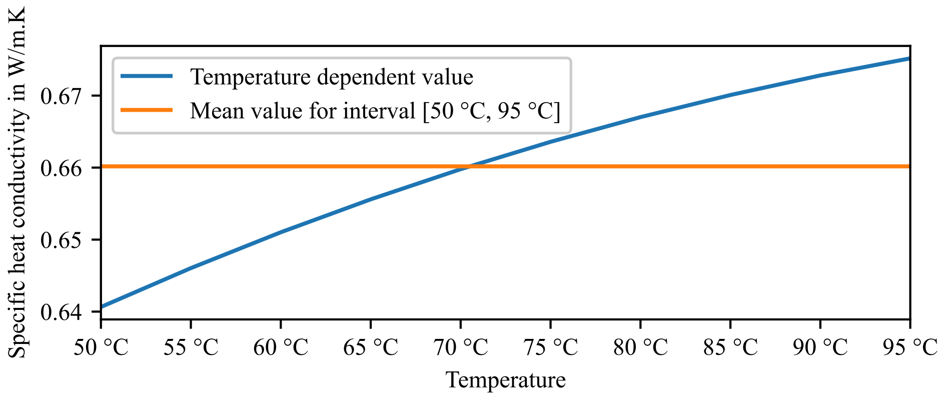

Figure A.7: Thermal conductivity of water (data from [250, pp. 176–195])

In practice, the *thermal transmittance* (U_{loss}) is often used to simplify the calculation of heat losses. It summarizes the effect of the three forms of transfer on equation A.10 [234, p. 100]. A is the geometric characteristics area, T_{fluid} is the temperature of the inner fluid, and T_{surr} is the temperature of the surroundings.

$$\dot{Q}_{\mathrm{loss}} = U_{\mathrm{loss}} \cdot A \cdot (T_{\mathrm{surr}} - T_{\mathrm{fluid}}) \tag{A.10}$$

Due to the importance of pipes, their *heat loss* calculation will also be presented in this section. This calculation can be performed using several approaches. It is possible to calculate the delay and losses by differential equations or by a numerical approach. In this thesis, the thermal calculation is performed using a numerical quasi-stationary calculation. Figure A.8 depicts the geometry in the radial direction.

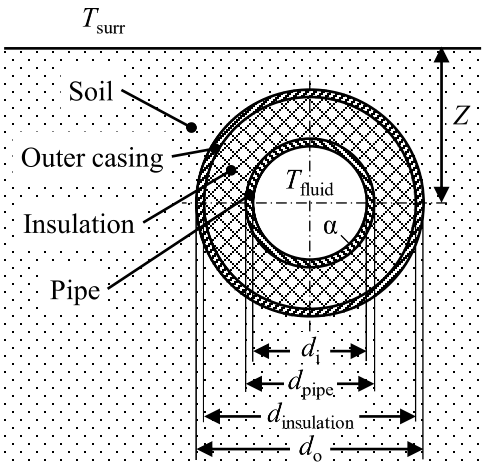

Figure A.8: Cross-section of a bonded pipe in a direct burial laying [cf. 107, p. 57]

The media with the inner temperature (T_{fluid}) is at the center and it is enclosed by a steel pipe [2, p. 284]. The pipe has the outer diameter (d_{pipe}) and the inner diameter (d_{i}). It is surrounded by insulation made of e.g., polyurethane foam [2, p. 284]. The insulation has a thermal conductivity ($k_{\text{insulation}}$) and an outer diameter ($d_{\text{insulation}}$) and it is covered by a casing pipe made of polyethylene [2, p. 284]. In the case of direct burial laying, the thermal conductivity of the soil (k_{soil}) and the depth of the pipe (Z) have an important influence as the deeper the pipes, the more independent the losses are of the ambient temperature (T_{surr}). [107, pp. 57–63]

There are several approaches for calculating the losses of an insulated pipe in the ground. For example, effects such as the temperature exchange from the supply to the return pipe can be considered. For this thesis, the calculation from [107, p. 58] will be used that was applied in the previous modeling in [203]. Referring to [107, p. 58], the insulation material only has the relevant resistance for the heat transfer to the surrounding soil and therefore the conduction of the steel pipe, the casing pipe, the radiation, and the convection can be neglected. The heat losses through the insulation and the ground ($\dot{Q}_{\text{loss}}$) can be calculated with equations A.10 and A.11.

$$(U_{\text{loss}} \cdot A)_{\text{pipe}} = l \cdot \frac{2 \cdot \pi \cdot k_{\text{soil}}}{\frac{k_{\text{soil}}}{k_{\text{insulation}}} \cdot \ln(\frac{d_{\text{insulation}}}{d_{\text{pipe}}}) + \operatorname{arccosh}(\frac{2 \cdot Z}{d_{\text{insulation}}})} \tag{A.11}$$

Hydraulics

In fluid dynamics, *volume flow* is written using a "Q". To avoid a mix-up with heat (Q), the thermodynamic writing $\dot{V}$ is used for the volume flow rates. Furthermore, to avoid confusion between height in fluid dynamics and specific enthalpy in thermodynamics (h), *height* will be written as coordinate Z.

The term *distribution* in DHSs describes the convective heat transfer through the pipe network. Convective heat transfer describes the transfer of heat with a movement of a fluid [5, p. 435]. In most cases, the medium for heat transport is desalinated water or steam [107, p. 1]. In this thesis, only liquid water systems are considered and thus the heat transfer can be described through mass transport with the two main properties: temperature and mass flow rate. Temperature changes can be expressed by the equations above.

The mass flow rate is a result of a pressure difference from location 1 to location 2 in a hydraulic system and can be described by the Bernoulli equation including pressure work and pressure loss [cf. 251, p. 45] in equation A.12.

$$p_1 + \Delta p_{\text{tot}} + \rho \cdot g \cdot Z_1 + \frac{1}{2} \cdot \rho \cdot {v_1}^2 = p_2 + \Delta p + \rho \cdot g \cdot Z_2 + \frac{1}{2} \cdot \rho \cdot {v_2}^2 \tag{A.12}$$

The equation consists of several summands. The static pressure (p) (with the index of the location) is on both sides. The term ($\rho \cdot g \cdot z$) describes the pressure that results from a height difference (Z) with the gravitational acceleration (g). The term ($\frac{1}{2} \cdot \rho \cdot v^2$) is the dynamic pressure that includes fluid velocity (v). The total pressure change (Δp_{tot}) represents the pressure difference when energy is added to the system (e.g., by a pump) and the equivalent on the right side is the pressure drop (Δp) that results from the friction of the flow. In a closed system, the dynamic and potential pressure is identical on both sides of the pump and therefore the total pressure for the pump can be calculated by the pressure drop of the system.

The *pressure drop of a single component* of a hydraulic system can be calculated with equation A.13 [cf. 251, p. 178] which includes the fluid velocity and the pressure loss coefficient (ζ).

$$\Delta p = \zeta \cdot \rho \cdot \frac{v^2}{2} \tag{A.13}$$

Inserting ($v = \dot{m}/\rho \cdot A$) allows for switching from the fluid velocity to the mass flow rate (equation A.14) whereby A is the cross-section area inside the pipe.

$$\Delta p = \dot{m}^2 \cdot \frac{1}{2 \cdot A^2 \cdot \rho} \cdot \zeta \tag{A.14}$$

The last part of the term can be summarized as a *hydraulic resistance* (R). By this, equation A.15 becomes an analogy to Ohm's law [121, p. 17]. Analog to Ohm's law, resistances in a row and in series can be calculated with the law of Kirchhoff. In electrical systems, the voltage is equal to the product of resistance and current. In contrast, in hydraulic systems, the pressure difference is equal to the product of the hydraulic resistance and the square of the flow rate, which makes this dependency non-linear.

$$\Delta p = \dot{m}^2 \cdot R \tag{A.15}$$

The *Reynolds number* (Re) is required for the calculation of the pressure loss coefficients of the different components. It is a dimensionless number that represents a threshold at which a flow changes from laminar to turbulent [252, p. 6] and is calculated with equation A.16 [121, p. 33] where η_{water} represents the dynamic viscosity.

$$Re = \frac{\rho \cdot v \cdot d}{\eta_{\text{water}}} = \frac{4 \cdot \dot{V} \cdot \rho}{\eta_{\text{water}} \cdot \pi \cdot d} = \frac{4 \cdot \dot{m}}{\eta_{\text{water}} \cdot \pi \cdot d} \tag{A.16}$$

If the value obtained is below the critical Reynolds Number (Re_{crit}) of approximately 2300, the flow pattern is laminar [252, p. 6]. Otherwise, it is turbulent.

The *dynamic viscosity* depends on temperature and density and can be calculated using equation A.17 [250, p. 357], [121, p. 77]. The equation is valid for water between 0 and 200 °C.

$$\begin{aligned} \eta_{\text{water},0..200\,^\circ\text{C}} &= \frac{0.00006896 \cdot \text{Pa} \cdot \text{s}}{\rho} \cdot exp\left(0.45047 \cdot x^{\frac{1}{3}} + 1.39753 \cdot x^{\frac{4}{3}}\right) \\ \text{with } x &= \frac{613.181 - T}{T - 63.697} \end{aligned} \tag{A.17}$$

The *pressure calculation of the pipe* is based on the pressure loss coefficient (ζ_λ). The coefficient calculation (q.v. equation A.18) is dependent on the friction factor (λ) including the length (l) and the inner diameter (d_{i}) [121, pp. 36–37], [122, p. 175].

$$\zeta_\lambda = \lambda \cdot \frac{l}{d_{\text{i}}} \tag{A.18}$$

The *friction factor* depends on the characteristics of the pipe and the flow regime whereby the flow regime can be proven by the Reynolds number. In the case of a laminar flow pattern ($Re < Re_{\text{crit}}$) the friction factor is calculated using equation A.19. [122, p. 175]

$$\lambda = \frac{64}{Re} \tag{A.19}$$

In the case of a turbulent flow pattern, the friction factor is calculated using equation A.20 which includes the surface roughness (ϵ_{surf}). In this case, it must be calculated by an iteration for which an initial value of 0.02 is proposed by the literature. [122, p. 175]

$$\frac{1}{\sqrt{\lambda}} = -2 \cdot lg\left(\frac{2.51}{Re \cdot \sqrt{\lambda}} + \frac{\epsilon_{\text{surf}}}{d_{\text{i}} \cdot 3.71}\right) \tag{A.20}$$

The *surface roughness* of the pipes has a wide range and is dependent on the material and the age of the pipe. New steel pipes have a surface roughness of around 0.025 mm. Through corrosion, it could increase to 0.5 mm with light rust and 1.0 mm for heavy rust. Unless otherwise specified, surface roughness of 0.05 mm is chosen for this thesis, which is a value for steel with a good finish. [121, p. 35]

The pressure calculation of other components such as heat exchangers is simplified in this thesis by a quadratic regression. Due to the typically highly turbulent flow rates in hydraulic systems, the pressure drop has a nearly quadratic form in most applications [126, p. 248]. Therefore, equation A.21 is used with a quadratic (b_2) and a constant (b_0) coefficient.

$$\Delta p = b_2 \cdot \dot{V}^2 + b_0 \tag{A.21}$$

A.2 Basics of macroeconomics

In this section, the required basics of macroeconomics are introduced. Since this thesis represents a cross-section of different disciplines, the following introduction serves as a basis for those readers who do not have an economic background. To do so, the different types of costs are presented in the first subsection. In the second subsection, the basics of competition are presented and thirdly, different competition models are introduced. Finally, the basics of centralized trading are described.

A.2.1 The different types of costs

In the following, the cost metrics that are relevant in the economic context of this thesis will be briefly introduced.

When producing a good, the *production costs* can be split into fixed and variable costs. *Fixed costs* represent those costs that must be paid independently of the amount of production within certain limits while *variable costs* depend on the produced amount. The sum of the variable costs of all produced units and the fixed costs is called the *total costs*. [253, p.45]

In DHSs, the largest part of the fixed costs are the capital costs, and they are often assigned to the cost for the size (*thermal power costs*). The costs for staff also belong to the fixed costs as they must be paid independently of the operation. The variable costs, such as the costs for fuels, are related to the production of the amount of heat (*thermal energy costs*).

Marginal costs are the costs that must be paid to buy or produce an additional unit of a good [254, pp. 36–37]. The opposite is *marginal benefits*, which are the benefits of selling an additional unit of a good [254, pp. 36–37]. Mathematically described, the (long-run) marginal costs are approximately equal to the derivative of the total costs [255, p. 374]. As the production capacity cannot be changed immediately, the short-run marginal costs are related to the variable costs [255, p. 374]. In this short-run case, the capital costs can be seen as sunk costs.

The concept of *sunk costs* is used to describe expenditures that are based on a decision in the past and are obligatory to be paid independently of newer decisions [254, pp. 35–36]. An example in the DH context is the capital costs for the pipes of the network after they are installed. The concept of sunk costs is abstract as is the concept of opportunity costs. *Opportunity costs* represent the theoretical loss of benefit that could be achieved by the decision for the next-best alternative [254, pp. 33–35] and they are required to compare different choices. *External costs* are another abstract type of cost and represent the costs that are not paid by a firm that produces or sells a good, but instead, these costs are paid by society (e.g., in the case of emissions) [253, p. 45].

In the context of competition, *transaction costs* are relevant and represent the expenditure for trading. This includes costs for trading (such as information and execution) and costs for the transmission of the good (transportation and handover). [253, p.45]

A.2.2 Fundamentals of competition in macroeconomics

The transmission and distribution (network operation) in the DHS can be considered a *natural monopoly* [84]. Such a natural monopoly is given if a single company can provide a good more cost-effectively than several companies under competition [83, p. 44].

A *vertically integrated utility* means that one company produces, transmits, and distributes the energy to the customers [85, p. 1].

Both vertically integrated companies and monopolies tend to become economically inefficient. Monopolies have a low competitive pressure, which reduces the incentive to increase the work intensity while vertically integrated companies have higher organizational costs for the larger organization e.g., through the bureaucracy. This effect is also called *diseconomies of scope.* [83, pp. 123, 129]

Furthermore, the introduction of competition induces costs, namely *transaction costs*, and their avoidance is the main motivation for the vertical integration. If they can be compensated by a reduction of economic inefficiencies, a competitive environment is beneficial. [83, pp. 125-129]

There are two main mechanisms to increase the economic efficiency of a single company, namely economy of scale and economy of scope. *Economy of scale* means that average total costs of production are reduced if a higher output is generated while *economy of scope* means that a company can generate advantages by combining diverse markets. For example, it can apply the knowledge from one specific product to another product, thereby resulting in lower costs e.g., for product development. [83, pp. 109, 128]

A.2.3 Competition models in natural monopolies (electrical system)

In contrast to the DH sector, the electricity sector has undergone a process of transformation from a monopoly structure to a liberalized market. In the following, four different market structures and their related roles are presented.

Vertically integrated utility as a monopoly

The traditional model for electricity supply is a *vertically integrated utility* with no access to other producers (q.v. figure A.9). This vertically integrated utility provides all steps of the electricity supply including generation, transmission, and distribution. In this model, the consumers are supplied by this single company (monopoly), and they have no choice but to change the supplier. Due to the absence of competition in this model, the vertically integrated utility would thus be able to exploit its market power and therefore a regulator is needed that prevents this exploitation. Furthermore, monopolies tend to become economically inefficient. As all processes are internal, there is only a low level of transparency regarding the costs which forms a barrier for the regulator to identify the potential for economic improvement. [85, pp. 2–4]

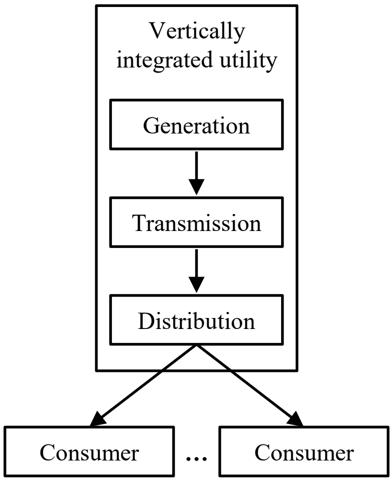

Figure A.9: Vertically integrated utility as a monopoly [cf. 85, p. 3]

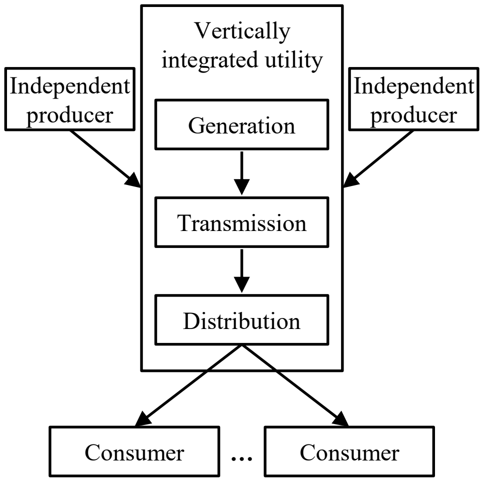

Figure A.10: Vertically integrated utility with independent producers [cf. 85, p. 4]

Vertically integrated utility and independent producers

The first step of introducing competition is to allow for access to third-party companies for the generation (q.v. figure A.10). These third-party producers are called *independent power producers*. In this model, the vertically integrated utility still supplies all consumers, but it can buy electricity from independent power producers. Through this *single buyer (SB)* model, competition is introduced on the generation side. As the vertically integrated utility still owns the generation plants, it will have no interest in growing competition and therefore legislation is needed to force the vertically integrated utility to buy electricity from the independent producers. This leads to the issue of finding an optimal price for the production as the vertically integrated utility tries to pay little to prevent the expansion of the independent producers. On the other hand, the independent producers try to get high prices, and thus the regulator must decide on the price. However, this approach could still be inefficient due to the lack of transparency. [85, pp. 4–5]

Wholesale competition
The issue of the identification of the best price for production can be solved if the vertically integrated utility is broken up as a wholesale market structure that can then be implemented as depicted in figure A.11 whereby the producers are now completely unbundled from the transmission. These *generation companies* sell their electricity on a wholesale market. In this market, *distribution companies* (and *large customers*) buy the electricity and sell it to the consumers. [85, p. 5]

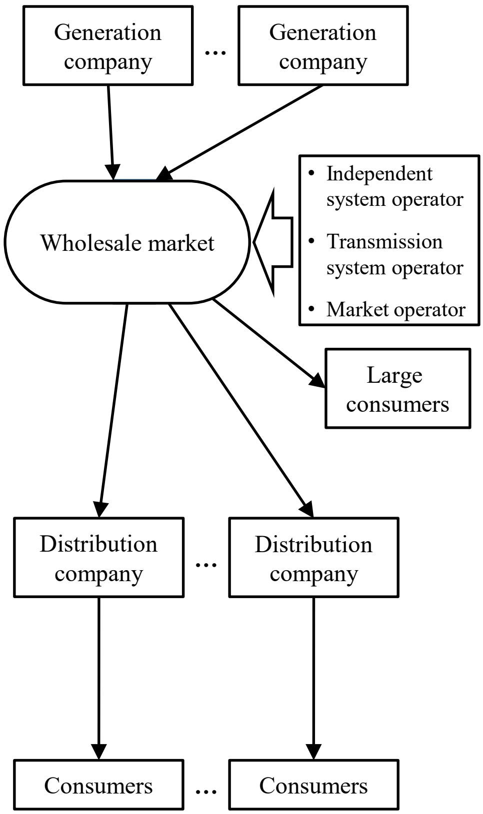

Figure A.11: Wholesale market structure [cf. 85, p. 5]

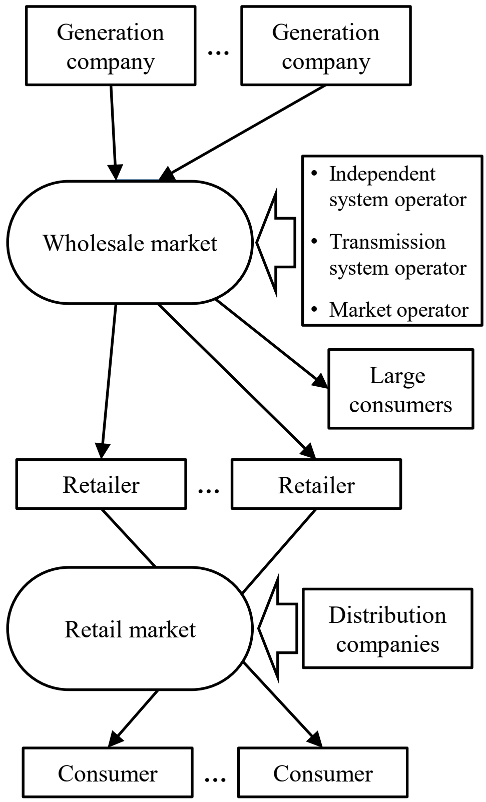

Figure A.12: Retail competition structure [cf. 85, p. 6]

New roles are introduced in this model. An *independent system operator* that is independent of the other market participants is needed for the operation of the system. Further, a *transmission system operator* is required that operates the transmission lines and a *market operator* is needed to operate the wholesale market.

These three roles may be integrated into a single company or in separate companies. In the electrical system, the independent system operator and the transmission operator are often combined whereas the market operator is a separate company that may operate in different markets. [85, p. 5]

This model provides full competition on the production side. However, on the consumer side, there is still no choice for different suppliers and thus there is still no competition. Therefore, retail must still be regulated. [85, p. 5]

Retail competition

The fourth model introduces *retail competition* by the introduction of a retail market (q.v. figure A.12). To do so, the previously presented model is extended by *retailers* that buy the electricity on the wholesale market and sell it to the consumers in the retail market. In this model, only the distribution and transmission companies remain monopolies. Further separation is not efficient, because the networks are natural monopolies. In this model, the regulator is required to monitor the investment decisions for the network. Due to the introduction of competition for the retailers, no regulation is required for the consumer prices and in this way, this model leads to economically efficient prices. [85, p. 6]

A.2.4 Fundamentals of centralized (electricity) trading

If a good is produced in a competitive environment, the price for the good is a result of the equilibrium of demand and supply. In centralized markets, the price for a good can be determined systematically. There are many different types of markets. In the following, some fundamentals in the context of electricity markets will be presented. For each timestep, the market equilibrium of demand and supply should be found. Suppliers send their offers to the market, where these are sorted by an increasing price to a supply curve (q.v. figure A.13). In normal markets, the demand is placed in the same way, but with a decreasing price. An issue of the demand side in electricity systems is that it is not strongly dependent on the price in the short term, and this means that a higher or a lower price has no strong impact on the quantity of the demanded electricity. Such a demand is called *inelastic*. The demand is typically forecasted, and due to its inelasticity, its price curve is an almost vertical line. In the market clearing, all offers below or equal to the forecasted amount are taken. This intersection of the supply and demand curve is called the *market equilibrium* and the price at the equilibrium is called the *system marginal price*, which represents the minimum price to supply the required demand. [85, p. 57]

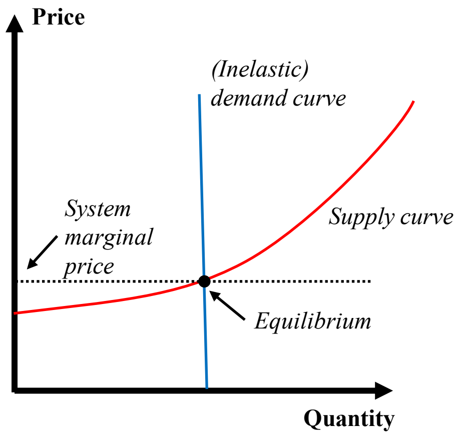

Figure A.13: Principle of the market equilibrium [cf. 85, pp. 23, 57]

The payment of the suppliers can be accomplished in two different ways: *pay-as-bid* or by the system marginal price. The experience in the electricity markets has shown that payment at the system marginal price is more efficient. In this case, the producers place their bids at their (short-run) marginal costs. Their benefits are generated from the difference between the system marginal price and their marginal costs. Further, these benefits can be used for refinancing the fixed costs. If the payment would be made on a pay-as-bid scheme, the suppliers would try to place their bids in relation to a forecast of the system marginal price. This leads to a higher system marginal price and hence to a market inefficiency. [85, p. 57]

A.3 Algorithms

In the literature review (presented in chapter 2), the following algorithms were found in several references, which shows that they have great relevance in DH research. Furthermore, a basic understanding of the principles is required to follow the developments and discussions of market approaches (e.g., in chapter 4). The task of the algorithms is mostly the optimization of decision variables.

The term optimization describes a mathematical problem, which is to identify the minimum (e.g., of costs) or the maximum (e.g., of benefits). In complex systems, many variables can be changed inside some limitations. Several algorithms are available to identify the optimum. [256, pp. 1–2]

For a brief overview, the most relevant algorithms will be introduced in the following. The first one is *mixed-integer programming*. Thereafter, three algorithms from the field of artificial intelligence are briefly described (*evolutionary algorithms*, *neural networks*, and *fuzzy logic*).

Mixed-integer programming

One approach to systematically identifying the optimal set of decisions is called mathematical programming. In this method, different inputs are combined into a mathematical model that describes the optimization problem. The inputs are parameters, variables, constraints, and the objective function while the parameters are fixed inputs. The (decision) variables can be of different kinds such as continuous, binary, or integer. The constraints limit the range of the variables, and they are given as inequalities. Examples are bounds or balances. Finally, an objective function is formulated that should be minimized or maximized. After the model is formulated, it is given to a computational solver. [257, pp. 1–2, 35–40, 43–48, 49, 20]

The required type of programming is related to the type of optimization problem. If the optimization problem can be expressed by linear functions, it is called *linear programming.* If the variables of linear programming are partly integer and partly continuous variables, it is called *mixed integer linear programming (MILP).* As soon as one of the included functions is nonlinear, the problem must be solved by *mixed integer nonlinear programming (MINLP).* [257, pp. 17, 52, 56]

Evolutionary/genetic algorithms

The concept of *evolutionary algorithms* is inspired by the evolution of a population in nature. It is a stochastic algorithm, which is based on the resulting values of functions. Therefore, the used functions must not be directly implemented in the optimization algorithm which means that there are no restrictions on the linearity or other aspects of the functions. There are different variants of evolutionary algorithms (e.g., evolutionary and genetic algorithms). The differences are not relevant in this thesis and the terms *evolutionary* and *genetic* are thus used synonymously. [258]

Internally, the algorithm has the structure outlined here. In the first step, a population is initialized. This means that different variants (individuals) with different values for the variables are created. After this, the results are evaluated. In the next step, a loop is started until the termination criterion is reached (i.e., the best solution is identified). In this loop, those individuals are selected that should be reproduced with slight modifications (mutations). The resulting offspring is evaluated again, and the individuals that should survive are selected. In this way, the best solution is selected in each loop pass. [258]

Neural networks
Artificial neural networks (or simply *neural networks*) are machine learning algorithms based on an empirical model. Before the application of the algorithm, the neural network must be trained with data for the independent and the objective dependent variable(s). Internally, the algorithm is based on neurons that represent weights between different internal (hidden) variables. The application of neural networks can be diverse. For example, they are often used for forecasts or predictions. [259]

Fuzzy logic systems
Fuzzy logic systems are based on fuzzy sets. In contrast to traditional sets, an element can be partly assigned to a set and thus fuzzy logic can be used to model systems that can only be described qualitatively. The advantage is that they can be used to describe systems that cannot be described in a mathematically exact way. The fuzzy logic is based on heuristics and works with uncertainties. It is applied to systems that are too complex, non-linear, or that cannot be described sufficiently due to lacking knowledge. Due to its ability to decide on such systems, it is also used in control systems. [260]

A.4 Conclusion of the underlying theoretical concepts

In this chapter, the relevant fundamentals of district heating systems (DHSs) are presented. This includes the technical basics of DHSs, thermodynamics, heat transfer, and hydraulics. Further, basic aspects of macroeconomics are introduced, which include the definition of costs and the fundamentals of competition. In addition, basic algorithms are presented that are discussed during the framework development.

As a part of these fundamentals, this chapter provides definitions of some terms that are inconsistently used in the literature. On the one hand, this depends on the different scientific disciplines that are applied in this thesis such as thermodynamics, heat transfer, hydraulics, macroeconomics, and district heating (DH) technology. On the other hand, the vocabulary in the DH sector is also used inconsistently in the literature. To avoid a mix-up, definitions are proposed, and assumptions are presented for this thesis. Besides facilitating a clear understanding of this thesis, these clarifications are a contribution to the scientific community that focuses on DHSs, and they also contribute to a harmonization of the different disciplines.

Appendix B

Interviews with Danish DH companies

This chapter provides the documentation of the interviews with the four Danish DH companies.

Protocol: Interview at VEKS

Date: 14/02/2019; 13:00 – 15:30;
Place: Roskildevej 175, 2620 Albertslund
Author: Peter Lorenzen

Participants

VEKS: Lars Gullev (CEO)
Hamburg University of Applied Sciences: Peter Lorenzen

Content

The following document includes the content of the interview. Lars Gullev used a presentation during the meeting. All relevant information from the slides and other documents used in the interview are included in this document. References to the presentation are highlighted by [1]. The "VEKS Annual Report 2017" is referenced as [2] and the VEKS Environmental Report 2016 "Miljøredegørelse 2016"as [3]. All non-cited comments are directly from the interview.

The protocol is structured by the contents. It begins with the general structure of the Greater Copenhagen DHS (District Heating System), the interconnection with VEKS and the transition to become CO_2 neutral. Additionally, an industrial surplus heat plant, a biogas plant and a pit storage project is introduced.

General structure in Greater Copenhagen

Figure 1 shows a map of the DHS in Greater Copenhagen.

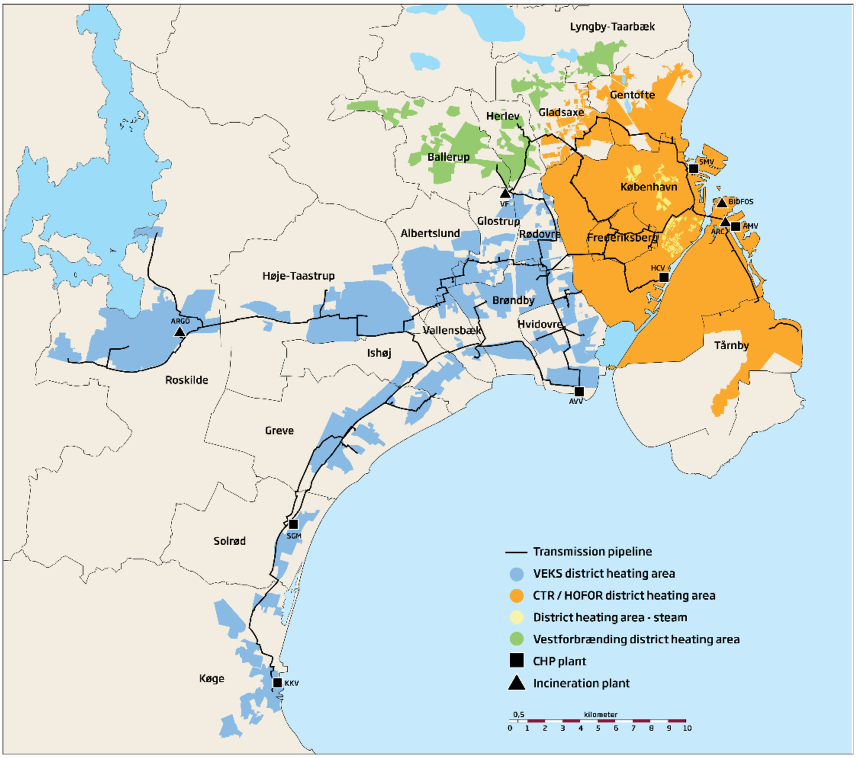

Figure 1: *District heating networks in the Copenhagen area [2, p. 46]*

The DHS in Greater Copenhagen is a very large one with a complex structure at the technical and the property level. The width is about 40 km and it connects about 500,000 end-users with 34,500 TJ (9,600 GWh) of annual energy consumption. It is spread over 19 municipalities. The system includes 4 systems at the transmission grid level and for almost every municipality an own distribution grid. [1, p. 9]

The transmission grids are separated from the distribution grids by heat exchangers. Therefore it is an indirect system. The transmission grid has a high pressure of 25 bar and 120 °C as the maximum supply temperature. The distribution grids have 6-10 bar and a maximum temperature lower than 100 °C. The diameters in the transmission grid are between DN 200 and 800.

The four transmission systems are VEKS, CTR, Vestforbraending and the steam system, which are all organized in single companies. The steam system is in a process of conversion to warm water system (lower than 100 °C). The biggest heat generation plants are connected to the transmission grid at the higher temperature level. Some smaller generators are connected to the distribution grids. The bigger plants are the following CHP plants: KKV (VEKS), SGM (VEKS), AVV (VEKS and CTR), HCV (CTR), AMV (CTR) and SMV (CTR). Additionally, there are the waste incineration plants: ARGO (VEKS), VF (VEKS and CTR), BIOFOS (CTR) and ARC (CTR).

VEKS

VEKS is a partnership of 12 municipalities. It includes 350,000 tax-payers and 170,000 end-users. The annual energy consumption is 9,000 TJ (2,500 GWh). It was established in 1984 with the purpose to utilize surplus heat from CHP and waste incineration plants. The main challenge in the beginning was to find the right company structure, because building the transmission system needed a lot of capital. Only 0.2 % of the needed capital was available. The solution was a communal partnership including the liability of each individual municipality for the total loan debt. Resulting from this structure, there was only a small risk for the creditor which reduced the capital costs. For example the rating from Moodys was AA1. As a result VEKS got capital from international creditors with optimal interest conditions. [1, p. 8-14]

Concerning the technical side it is important to mention that the peak load generation is done in every transmission grid. In the VEKS part it is generated by natural gas and oil fired boilers – and one biomass fired boiler (wood pellets). These are centralized controlled by VEKS.

Transition to renewable generation

The goal for the whole Copenhagen system is to be CO_2 neutral in 2025. VEKS has an important role in the transition process of the whole grid. On the generation side a bundle of measures has been realized or started. The existing coal fired CHP plants are converted to wood pellet fired CHP plants and woodchip fired CHP plants are built [22-31]:

- KKV (Køge) 2012: VEKS bought a woodchip fired CHP plant with 60 MJ/s heat and 25 MW electrical power.
- AVV2 2014: DONG Energy upgraded from 75 to 100 % wood pellets (480 MJ/s).
- SGM 2015: VEKS built a biogas CHP plant with 3 MJ/s and 3 MW power.
- AVV 2016: changed to 100 % wood pellets fired CHP (932 MJ/s heat, 797 MW el).
- Bio4 2019: HOFOR takes a woodchip fired CHP (400 MJ/s, 150 MW el) plant into operation.
- AVV1 2033: rebuilding the unit to 100 % wood pellets (350 MJ/s).

As before, the waste incineration CHP plants are included in the heat mix. In addition, there are two big electrical heaters with 80 MW and 40 MW operated by CTR. Every decision for new investments and new plants is in competition with life extension costs for the existing plants. Therefore, new generators have to be cheaper than the life extension of existing generators. This is possible because all generators will be converted to renewable sources by 2025 at the latest. At that point the competition will be between different renewable generators and not between conventional and renewable generators.

In the context of the transition to neutral CO_2 emissions the reduction of the grid temperature is also an important point. Figure 2 shows the reduction of the return temperature in the last years. VEKS has started with 55 °C and has now less than 48 °C.

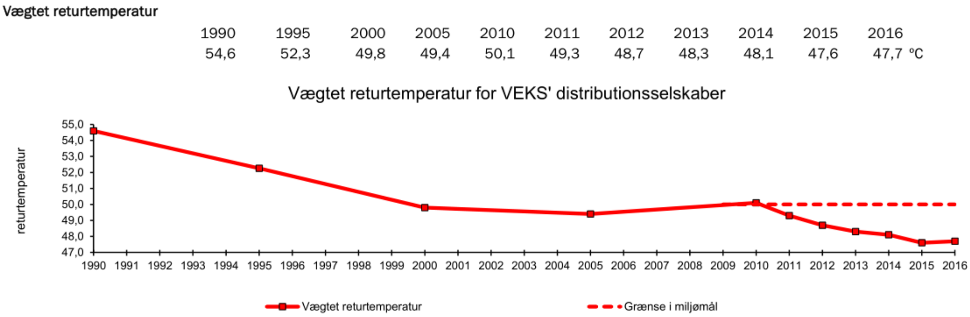

Figure 2*: VEKS: "Miljøredegørelse 2016", (Environmental Report 2016), p. 17*

This was achieved by different measures. One solution is the use of incentive prices. These are used on the one hand between transmission grid and distribution grids and on the other hand between customers and distribution grid. The limit is 55 °C between the grid operators. A lower temperature will be rewarded with a bonus, a higher temperature will be penalized. As shown in the figure, most distribution systems get a bonus at the moment.

To sensitize also the tenants and the landlords a competition for the best "cooler" is rewarded. The winner is published in the press. By this, the topic of low return temperatures gets public attention. Additionally employees of heating companies can take part in training classes. 90 % of the costs for such classes are integrated in the heat price of the customers. Therefore the participants pay only ~30 €/day for a class. In this price also food is included. These conditions make this offer very interesting and result in a high participation rate.

Besides lowering the return temperature, the first distribution company connected to VEKS has set the goal to change the distribution system from 1963-73 to a DHS of the 4th generation. This results in a supply temperature of 60 °C in 2026. The long-time goal for VEKS is to reduce the flow temperature in the transmission-system in respect to the needed flow temperature in the connected distribution systems.

Industrial Surplus Heat Plant with CP Kelko

In the following text the realization of the industrial surplus heat project in the Køge distribution system is introduced. The Køge distribution system is operated by VEKS. The first part focusses the contractual situation which was the harder part in the realization. The contract negotiations took 2 years. After this the realization was done in one year. The industrial company built the heat exchanger and the heat pump. The DH-operator built a new DH connection [1, p. 37]. Because of the location of the factory, the connection to the distribution net changes the flow direction and the diameters as well as the narrowing of the existing pipes do not fit to this situation.

The industrial company CP Kelco produces pectin from orange peels [1, p. 35]. They use natural gas to fire the processes. Later in the production process, there is surplus heat that was cooled down by cooling towers before the installation [37]. The trigger for the contact with the DH-Company was a noise problem of these cooling towers. The company planned to invest in anti-noise measures. By using the heat for the DHS, the cooling towers would not be needed in normal operation mode. That is the reason why contract negotiations started. However, in the beginning of the negotiations, the short periods for the return of investment (< 3 a) in the industry on the one hand and the long term periods in the DHS (> 10 a) on the other hand were a barrier for investments. Further, the US-American company CP Kelco could not guarantee that the factory will be there for more than 3 years. Also the confidentiality of the company was a barrier in the beginning.

The solution for these problems was a transparent communication culture and the philosophy of open books. This worked because the overall profit in a short term was not sufficient. The focus was on finding a solution for the short term return on investment of the industry to make the project possible. The investments to the plants of the industry partner had to be made by the industry because the state of Denmark pays subsidies for industrial energy efficiency measures. This subsidy can only paid to industrial companies and not to the DH-operator. This was the reason for the model of ownership. Otherwise it would be easier to realize the investments by the DH operator with long term return on investment.

To fulfill these boundary conditions and the short return on investment periods for the industry the following agreement was committed that is divided in three periods (see table 1):

In the first period the capital costs for the investments of the industrial company are repaid. Therefore, they have a settlement price that has the level of the VEKS substitution price. The time is about 3 - 4 years until the investment is repaid. [1, p. 40]

The second period is used for the repayment of the capital costs of VEKS for the pipes and other investments in the DHS. The settlement price is the sum of operating costs and a surplus heat charge. The payback time is planned with 3 years. [1, p. 40]

In the third period the benefits are split between the partners weighted to the share of the investments. The settlement price is the sum of operating costs and the surplus heat charge, but less than the VEKS substitution price. [1, p. 41]

Phase	**VEKS**	**CP Kelko**	**Settlement price**
1	0	Substitution price	Substitution price
2	Surplus heat charge	Operating costs	Substitution price
3	(Share on investments) x surplus heat charge → reduces the consumer heat price	Operating costs + (1 - share on investments) x surplus heat charge	Substitution price

Table 1: *Price agreement [1, p. 40-41]*

With this model, the public company guarantees for the investments to the power plants. In return the industry surplus energy price is limited by the substitution price of VEKS. Further, the solution fulfills the climate goals for VEKS and CP Kelco [1, p. 44].

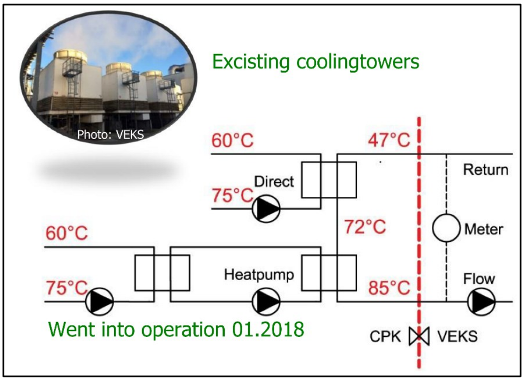

Figure 3: *Utilization of surplus heat to Køge distribution system [1, p. 38]*

The technical concept of the plant is shown in figure 3. The first temperature increase results from the heat exchanger. If the temperature is not high enough, a heat pump is used to increase the temperature further. The plant can be used most of the year without the heat pump. The set points for temperature and power are transmitted by VEKS and controlled by the industrial company. The amount of energy is about 150 TJ/a (42GWh/a) and the average COP is about 18.5 [1, p. 38]. The thermal power is between 8.5 MJ/s in winter and 4-5 MJ/s in summer.

The Biogas Plant in Solrød

Near the industrial surplus plant a new biogas plant was built in Solrød that uses the waste of the pectin production, besides other materials. Table 2 shows the different materials and their amount for the biogas plant. The plant produces biogas that can be buffered before it is transported closer to the DHS via a pipeline.

At the DHS, a CHP plant is converting the biogas to electricity and heat. The heat production is about 100 TJ/a (28 GWh). The thermal power is 3.7 MJ/s and the electrical power is 3.0 MW. [1, p. 47]

Raw material	To the biogas plant tons/year	Calculated methane production 1,000 m^3/year	Contribution to the project
Manure	53,200	578.8 (9.5 %)	Gas production and process stability
Seaweed	7,400	31.6 (0.5 %)	Nutrients and improved water quality
CP Kelco (citrus)	79,400	4,514.8 (**75 %**)	Gas production
Industrial residues	60,000	918.7 (15 %)	Gas production and nutrients
Total	**200,000**	**6,000 (100 %)**	Benefits for the environment

Table 2: *Solrød biogas plant: Raw material, methane production and contributions to project [1, p. 46]*

The biogas plant uses 80,000 tons of orange peel, 53,000 tons of pig manure, 7,400 tons of seaweed and 60,000 tons of industrial residues per year [1, p. 45].

The fraction is used afterwards to replace the fertilizer for the fields [1, p. 49]. Especially the utilization of the seaweed has a lot of benefits for the nature at the bay and the environment by reducing the load of nutrients [1, p. 47].

Thermal Pit storage

Another new project currently planned is the realization of a big pit storage. It is located in the area of Høje Tastrup. The pit storage is connected to the VEKS transmission grid and can be loaded with 90 °C and 30 MW by the transmission grid. The discharging can also be done with 30 MW but to the distribution grid in Høje Tastrup at 75 °C. [1, p. 50]

The site is a former gravel pit. The volume is about 70,000 m³. The capital costs are divided between the different shareholders (transmission grid operators and generation plant operators) in the same share as the forecasted share of benefits.

Protocol: Interview at Fjernvarme Fyn

Date: 14/02/2019; 9:00 – 10:30;
Place: Havnegade 120, 5000 Odense
Author: Peter Lorenzen

Participants

Fjernvarme Fyn: Jesper Wonsbek Buck, Jan Wæhrens
Hamburg University of Applied Sciences: Peter Lorenzen

Content

The following document includes the content of the interview. Jesper Buck and Jan Wæhrens used presentations during the meeting. All relevant information from the slides in the interview are included in this document. References to the presentation “Welcome to Fjernvarme Fyn”, Kim Winther, 19. November are highlighted by [1]. An additional presentation about the modelling methodology is referenced as [2]. All non-cited comments are directly from the interview.

The protocol is structured by the contents. In the first part, an overview of the DHS in Fyn is given. After this, the methodology to find a solution for replacing the coal fired CHP plant is explained. In the end, a project utilizing surplus heat from a datacenter is summarized.

Structure of the DHS in Odense

The Odense DHS is shown in figure 1. The DHS supplies about 90.000 households. The maximum heat demand is 850 MW and the annual demand is 2.6 Mio MWh. [1, p. 4]

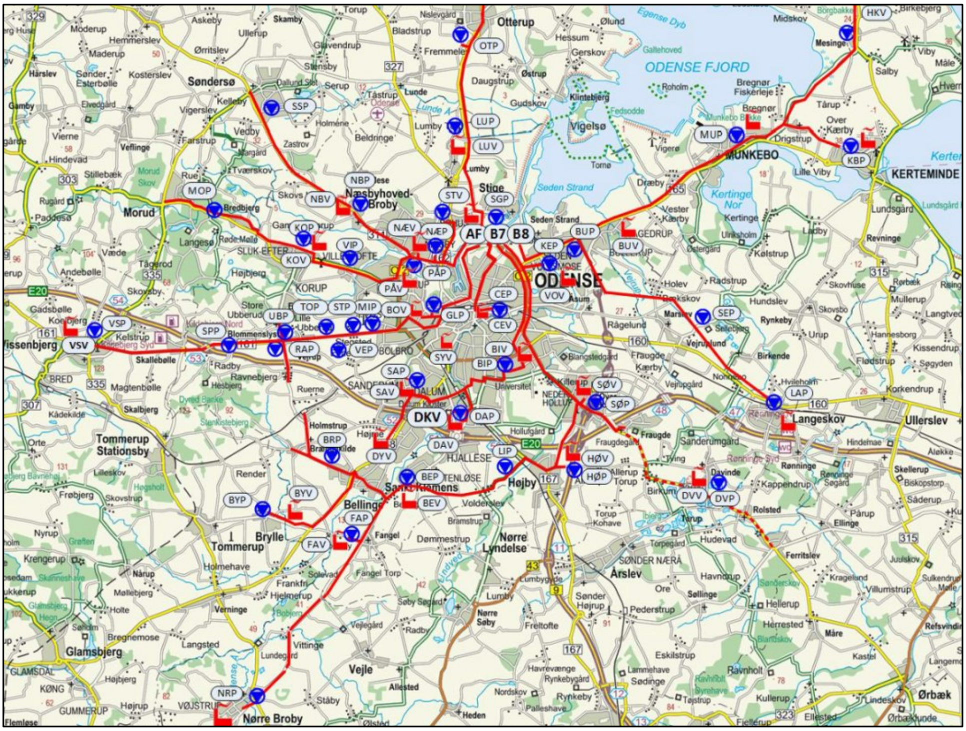

Figure 1: *District heating network in the Odense area [1, p. 4]*

The DHS consists of a transmission grid and distribution grids. The transmission grid (red lines) is based on 8 high pressure lines with 10 to 16 bar (max. 25 bar), 90 to 75 °C and 120 km length. The distribution grid has 2 to 5 bar (max. 6 bar), 90 to 70°C and 2.200 km length. The two grid levels are directly connected without heat exchangers. The whole grid (transmission and distribution) as well as all power plants belong to companies that are owned by the municipal Fjernvarme Fyn Holding.

Fjernvarme Fyn is always working on lowering the supply temperature. At the moment, there are some critical consumers, which need the high temperature.

The heat generation mix is approximately 40-45 % centralized coal, 22 % straw with the lowest marginal heat price, 23 % waste, 11 % woodchips, 1 % gasoil and natural gas, 3% biomass and 1% industrial surplus heat[1, p. 8]. Approximately 30 % of the waste is imported. The coal CHP, waste incineration and straw plants and a storage tank are connected to the transmission grid. The other smaller plants are connected to the distribution grids.

The generators are listed in the following [1, p. 7]:

- FYV 7 - Coal CHP plant: 490-610 MJ/s heat / 322-376 MW electricity
- FYV 8 - Straw CHP plant: 88-120 MJ/s heat / 32 MW electricity
- FFA CHP 11-13 – waste incineration plant: 105 MJ/s heat / 50 MW electricity
- Dalum – Woodchip CHP plant
- 2 natural gas CHP plants
- 22 Peakload generators (oil/gas)
- Surplus heat – Datacenter
- Biogas

Figure 2 shows the heat production at the DHS in Fyn. At the moment, the coal fired CHP has a high share in the annual heat demand. Nevertheless, the coal fired plant is planned to be phased out until 2025. Therefore, different supply scenarios are developed by Fjernvarme Fyn.

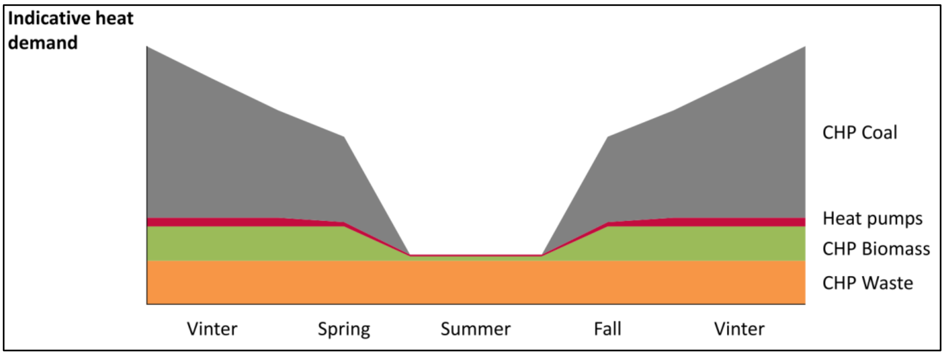

Figure 2: *Heat production at Fjernvarme Fyn [1, p. 6]*

Methodology to find a solution for replacing the coal fired CHP plant

The planning for the DHS is based on two steps with different planning tools: Investment planning based on scenario definitions and schedule optimization. The tools are internally developed by Fjernvarme Fyn. In general, the heat production is prioritized by the marginal costs including taxes [1, p. 6].

For all scenarios, the same standard expectations are used. They are generated by inputs of different sources. In the business development process, they are aggregated to standardized assumptions that are used for the modelling tools. [2, p. 1]

The expectations consist of the following categories [2, p. 1]: Price forecasts, heat demand, technology catalog, future taxes & subsidies and existing plants.

The modeling uses these expectations as inputs for the investment modeling. This is done with two different tools. The LCE model is an Excel tool that uses the annual duration curve and includes plant investments and marginal costs. The second tool is the BID model. It uses a dual-simplex solver in Matlab. It is more complex than the Excel tool and considers investments, hourly marginal costs, storage capacities, ramps, solar generation and different CHP modes (with and without bypass). The result of this step is to choose the technology and the optimal capacity. [2, p. 2-4]

In the last step the POP model is used to have a more precise schedule optimization. It includes the results from the first step as a fixed generator setting. The POP model is comparable to the BID model, but does not include the investments. In return, it includes more details and uses a MILP solver. [2, p. 2, 4] To include an optimal heat accumulator scheduling the state of charge of the first hour of the planning process has at least the same value as the last hour.

The POP model is also used for the real time trading and coordination of the generators.

The results of these scenario analyses show the preferred solution for the coal substitution. It is a combination of large heat pumps with synergies to a CHP biomass unit and a large heat accumulator. The peak load should be supplied by gas and electric boilers. [1, p. 11]

The biggest challenge with this plant setting is the leak in the summer demand, which could be fixed by an increase of the summer load or by heat accumulators [1, p. 6].

Hydraulic bottlenecks are not implemented to the modelling of the scenario planning, yet. It is planned to include them with a flow-matrix.

Data center

In 2020 a Facebook data center will be connected to the DHS. The size is 120.000 m². The heat pump will provide 70 °C to the DHS in the distribution grid. The profile of this heat source is forecasted as almost base load.

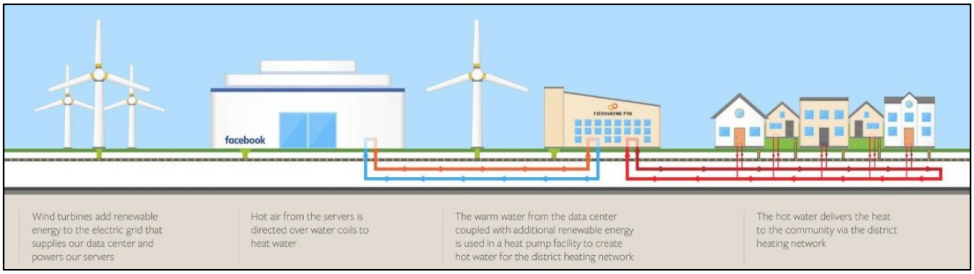

Figure 3: *Heat recovery process of the datacenter [1, p. 9]*

The data center is owned and operated by Facebook. The heat pump plant is planned and owned by the DH Company. Both are supplied with renewable electricity. The amount of heat is 100,000 MWh.

The use of datacenters as a heat source is very efficient for the overall energy consumption. Therefore, new datacenters should always be located near cities with a DHS. Datacenters normally have emergency electricity generators with a capacity of the total power of the datacenter. They could be used for electricity system services, in times they are not needed for the datacenters.

Protocol: Meeting/Interview at HOFOR

Date: 15/02/2019; 11:30 – 13:50;
Place: Ørestads Boulevard 35, 2300 Copenhagen
Author: Peter Lorenzen

Participants

HOFOR: Nick Bjørn Andersen (senior consultant planning), Bjarke Gudmann Kyhn (scenario planning), Kristian Honoré (Energy Lab Nordhavn), Tore Gad Kjeld (Energy Lab Nordhavn/heat pumps)
Hamburg University of Applied Sciences: Peter Lorenzen

Content

The following document includes the content of the interview. Kristian Honoré started with a presentation about the research project in Nordhavn with the slides that are referenced by [1]. Tore Gad Kjeld explained the utilization of a heat pump in the Nordhavn project for primary reserve capacity with the presentation "Feasibility and limitations of flexible operation of large-scale ammonia heat pumps" from Wiebke Meesenburg, Denmark Technical University (DTU) Mechanical Engineering that will be referenced by [2]. Bjarke Gudmann Kyhn and Nick Bjørn Andersen presented HOFOR's strategy for the utilization of excess heat with slides [3]. All non-cited comments are directly from the interview. The protocol is structured by these contents.

Nordhavn

Nordhavn is a new district built in Copenhagen. The harbor area is developed into a new mixed residential and commercial district. It is planned to have 40,000 inhabitants in 2050. At the moment, 2000 inhabitants live in this area [1, p. 2].

The development of this district into a sustainable city is supported by the research project "Energylab Nordhavn" including different commercial, municipal and scientific partners. The project's budget is 19 Mio € including 11 Mio € from the Danish State. [1, p. 4]

The research project has 10 work packages with different topics, e.g. smart charging of cars, power grid operation and a showroom to integrate the inhabitants into the development of a smart city. In the context of the interview, the flexibility of heating and cooling grids (5 & 10), flexible buildings (3 & 5) and integrated markets (8) are the most relevant working packages. [1, p. 6]

The flexibility of the district heating pipes was analyzed to provide storage potential for surplus heat import and exchange. A demonstration was done in two parts of the grid. For the experiment, the supply temperature was increased with a delta of 15 K. The results showed that it is possible to store the heat in the DH pipes. The main advantage is that there is no need for additional investment for this storage capacity. But for the utilization of this potential a good load forecast is necessary. [1, p. 11]

Moreover, in the project, central heat accumulators are planned to be used in a smart way to optimize the operation with a maximum benefit from electricity and heat prices. [1, p. 12]

One very important focus of the project is the integration of flexible heat customers. Therefore, the heat capacity of the buildings should be used to reduce peak-loads and to provide balancing and flexibility services for the overall integrated energy system. The peak load reduction is planned by specific peak hours. In these situations, the power is lowered via a remote control. The indoor temperatures of some rooms are measured to prevent a room temperature that is too low. [1, p. 9-10]

The research of flexible customers is just in the beginning. The scheduling process is therefore not solved completely. At the moment, a commercial tools from LeanHeat in Finland (www.leanheat.com) is tested. It is implemented in 9 pilot buildings. The results will be published in the Nordhavn project context. An alternative is NODA from Sweden (www.noda.se) but it's not tested at the moment. At the moment, the flexible customers are not integrated in the overall Copenhagen scheduling process at Varmelast. This could be one of several future solutions. As a recent result, the flexibility has a time range up to three or five hours. There are many different reasons to utilize the existing flexibility of the buildings. It can be used to prevent short term peak loads or to have optimal schedule for heat pumps on the electricity side. Besides this, the monitoring and measurement increase the efficiency and detect failures in the system. Through the availability of the information, the accounting and the detection for maintenance demand could be automatized so that no service personal has to check all substations providently. Besides all technical and economic advantages, a smart DH product increases the transparency and the interaction with the customer. Therefore, changes in supply conditions and contracts are needed.

Heat pump

As one part of the Nordhavn project, HOFOR, in cooperation with the Denmark Technical University, analyzes the utilization of heat pumps to provide primary energy reserve for the compensation of fluctuating generation inducted by wind power plants. [2, p. 4]

Large scaled heat pumps were chosen because of their larger amount of power, the higher flexibility in the combination with DHS, the professional management and the lower specific control costs. The only disadvantages are slower start-up times and ramps as well the design for base load operation. To overcome these problems, different tests and simulations have been carried out to find better technical solutions for flexible large-scale heat pumps. [2, p. 5]

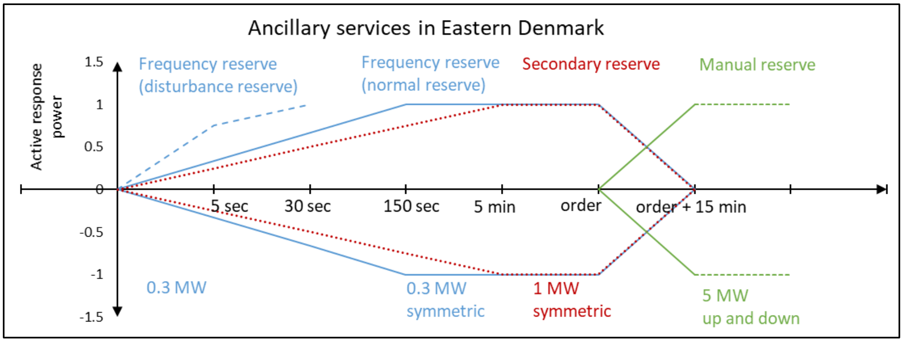

Figure 1: *Regulation services in Denmark [2, p. 7]*

Figure 1 shows the regulation services in Eastern Denmark where Copenhagen is located. The frequency reserve has a maximum time of 150 s. In the project, a participation with a large-scale heat pump in this market is analyzed. The market is very interesting because the more complex to deliver service, the higher the prices [2, p. 8]. For example, the FCR-D is the fastest reserve, but FCR-N is better paid – this is because FCR-D is in one direction whereas FCR-N is in both direction.

The analysis is done by DTU in simulations and a prototype plant of 800 kW (thermal power) with HOFOR in Nordhavn. The detailed results of the heat pump behavior depending on temperatures, ramps, power variations and COPs can be found in [2]. In summary, the results for the utilization of a heat pump for electrical ancillary services are [2, p. 19-20]:

The participation in the tertiary reserve is possible without any technical changes. The participation in the secondary reserve could be done in part load operation (20 – 100 %). Some little technical improvements should be made. The participation in the primary reserve with less than 150 s ramping time needs some improvements to the heat pump. The design should be changed to avoid damages by fluid entering the compressor. The necessary ramps must be enabled. To solve this, a combination of a large-scale heat pump and direct electrical heating can be a good solution for this special case. In addition, also a "cold start" seems to be possible as the heat exchanger on the warm side are always relatively warm due to the insulation of the units. So it is rather a variation of different warm start-ups.

Surplus heat utilization

Besides the topics in Nordhavn, HOFOR analyzes possibilities for other renewable sources besides waste incineration and biomass (woodchips and pellets).

In the Copenhagen area, there are no huge production industries. Surplus heat sources are distributed between many smaller industries. The potential of surplus heat in the Copenhagen area is shown in table 1. [3, p. 1]

Types	Potential MW	Goal in 2028 MW
Industrial processes	10,2	9,6
Super markets	10	2,9
Computer servers	10	5,4
ATES	8	8,1
District Cooling	37,6	5
Sum	**75,8**	**31**

Table 1: *Production capacity for excess heat in Copenhagen [3, p. 1]*

The table shows the highest potential for district cooling with about 37.6 MW. However, the goal until 2028 is set to 5 MW. In contrast, the potential for industrial processes is estimated to be about 10 MW and it is planned to utilize almost all of this potential until 2028. The reason is that sources that are highly distributed and on a low temperature level are harder to implement than more centralized sources on a high temperature level. The forecast of HOFOR's excess heat goal is shown in figure 2.

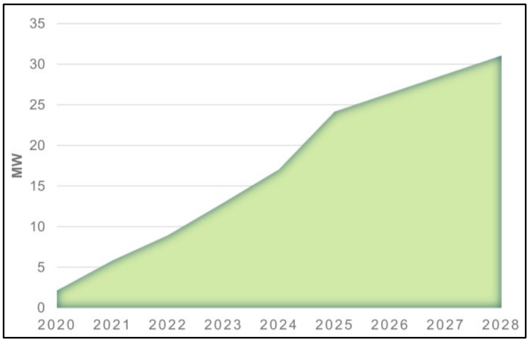

Figure 2: *Forecast for excess heat utilization in the HOFOR distribution area [3, p. 2]*

The utilization of surplus heat is not as easy as using other heat sources. Even though the legal and regulation framework has been improved in Denmark, there are still barriers for this kind of heat source. One of the main reasons is the size of the plants with is between 0.1 and 5 MW and results in higher grade of distribution as well as higher investments. In addition, the need of a heat pump in most cases and the competition with modern CHP with a power of 550 MW are other barriers. [3, p. 2]

In addition to the shown potential of industrial surplus heat, HOFOR conducts many other potential analyses regarding new heat sources. The short term plan is to get rid of fossil heat sources until 2025. The long term plan is to reduce the amount of biomass and waste incineration as well – seeking utilization of geothermal heat.

Protocol: Interview at Varmelast

Date: 15/02/2019; 08:30 – 11:00;
Place: Stæhr Johansens Vej 38, 2000 Frederiksberg
Author: Peter Lorenzen

Participants

Varmelast: Helga Hubeck-Graudal
Hamburg University of Applied Sciences: Peter Lorenzen

Content

The following document includes the content of the interview. Helga Hubeck-Graudal used two presentations during the meeting. All relevant information from the slides are included in this document. References to the presentation "The District Heating System in Greater Copenhagen Area - in a free power market", 05.10.2018 are highlighted by [1]. References to the presentation "Hovedstadsområdets fjernvarmesystem i et frit elmarked", 11.12.2017 are highlighted by [2]. All non-cited comments are directly from the interview. The protocol is structured by the contents. It begins with the general structure of the Greater Copenhagen DHS (District Heating System) and the role of Varmelast. Further, a general overview of the scheduling process is given before the processes for the day ahead, the intraday and the balancing scheduling is explained.

Overview of the Greater Copenhagen DHS and the role of Varmelast

In the Greater Copenhagen DHS different big scaled plants are connected to the transmission grids. Varmelast coordinates these plants and the interconnection of the different transmission grids based on the marginal costs. Varmelast is not included into the process of investment and grid development. Some small renewable energy plants and industry surplus heat plants feed into the distribution grids. They are not taken into account in this coordination process and seen as a load reduction for the purchase of heat from the transmission grid to the distributing company. Some other renewable or surplus heat plants are owned by the transmission companies or the transmission companies have contracts with them (currently around 20 MJ/s in total). These plants have traditionally been prioritized like waste, but it is the aim to include future plants in Varmelast's load dispatch optimization.

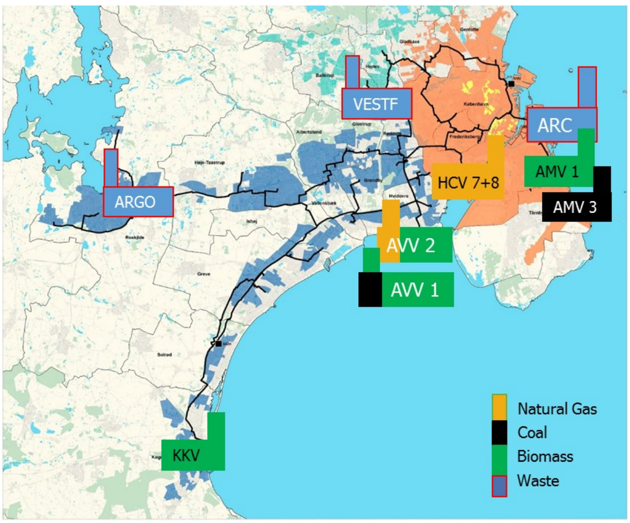

Figure 1: *Generation plants connected to the transmission level in 2017 [see 2, p. 4 (translated)]*

Figure 1 shows all generation plants that are connected to the transmission level. The plants are the following [1, p. 4]:

- 4 Combined Heat & Power plants (CHP-plants)
  owned by two companies (Ørsted and HOFOR Energy Production) 1.700 MJ/s*.
  In 2019 a new plant will be commissioned that increases the capacity to around 1900 MJ/s.
- 3 Waste incineration (CHP) 400 MJ/s
- Reserve and peak load Heat-Only-Boilers 1.400 MJ/s
- 2 Heat Accumulators 3.000 MWh*

*updated by [2, p. 4].

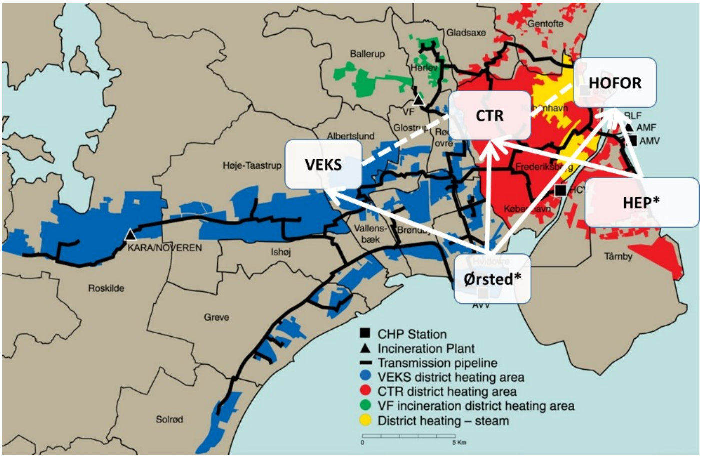

Figure 2: *Interaction of different companies in one DHS [see 1, p. 9] with (*) updated company names*

The Greater Copenhagen DHS consists of several companies. The transmission grids that are included in the scheduling process of Varmelast are owned by VEKS, CTR and HOFOR. The steam DHS is the main part of the system that HOFOR owns. However, once the steam network is fully phased out, HOFOR will remain in possession of some relatively short transmission pipe lengths that extend from one of the plants to those distribution areas that have been converted from steam to water. This part of the network is still operated by CTR though. So even though HOFOR owns the transmission grid the operator is CTR.

Two companies Ørsted and HEP ("HOFOR Energiproduktion") own the big CHP plants that are connected to the transmission grids. Because of the conditions of the electrical market, Ørsted and HEP are not allowed to know each other's marginal costs.

VEKS is mainly a transmission grid operator, but also possess and operate a minor share of the distribution grids in their area. VEKS has also become a producer when they bought the small power plant Køge Kraftvarmeværk way south of Copenhagen, even though the plant is very small. Moreover, CTR recently installed an electric boiler, and more are being projected. The boiler is being managed by an external power trader. So even though CTR is not a power producer, they now indirectly participate in the power trading market as well. Although the DH companies are trying to separate the different areas of their business, the system is becoming more complex with a higher grade of decentralization.

The results of a strategic analysis (2006) showed that the cheapest green district heating could be realized if the DH companies are responsible for heat load dispatch in a cost-based market. Therefore, Varmelast was established as a cooperative between all these DH-companies. The DH-companies have their own contracts with each other (see figure 3). Varmelast has the role as an independent overall system cost-minimizing instance. The payment for heat production is covered by separate contracts with VEKS, CTR and HOFOR on the consumer side and Ørsted and HEP on the generation side. The payment between producers and DH-companies is not regarded in the planning process of Varmelast. [1, p. 6-8]

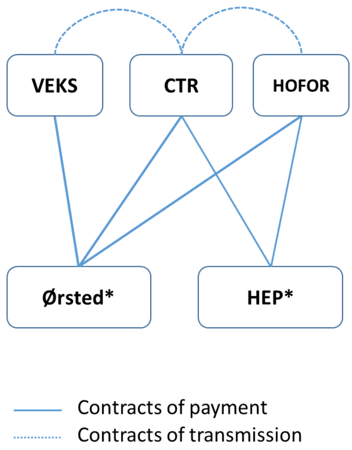

Figure 3: *Contracts of the different companies [see 1, p. 8] with (*) changed company names*

Overview of scheduling processes

The plants that were introduced before have the following general priority as shown in figure 4. The waste incineration plants have the highest priority. This a political priority because the waste has to be incinerated. Nevertheless it is also an energy source with very low variable costs since waste incineration plants receive a gate fee for removing the waste. If the plants would be included in the optimization process introduced later, they would mostly get the priority they already have.

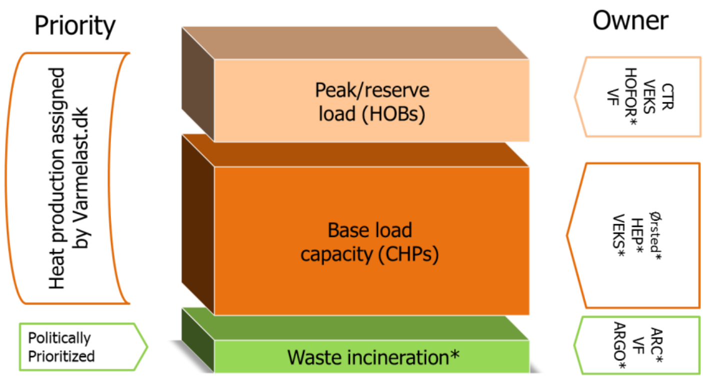

Figure 4: *Priority of the different generator types [see 1, p. 14] with (*) changed labels from [2, p. 6]*

Because of the must-run condition of the waste incineration plants their production is forecasted and not optimized. Even though their turbines could be bypassed for a higher share of heat, they are not yet included in the planning algorithms. It was agreed in 2018 that turbine bypass, heat pumps and flue gas condensation at the waste incineration plants should be included in the planning in the future, and work towards this goal is ongoing.

All three waste incineration plants import waste because they get paid to receive the waste. It's not prohibited by law to import waste during the summer, but the five municipalities that own ARC have decided that it may not import waste during the summer, because the ARC plant is oversized (230 now and before 100 MW).

Depending on energy prices at different energy markets at the Nordpool energy exchange and at Energinet.dk, the CHP plants are planned and have therefore the second priority. Figure 5 shows the most important electricity markets for the producers in the DHS. At the Nordpool there is a day ahead spot market and a continuous intraday market. System services for Energinet.dk are manual reserve and FNR reserve that are planned day ahead and the balancing power that is planned continuously 45 minutes before it is needed.

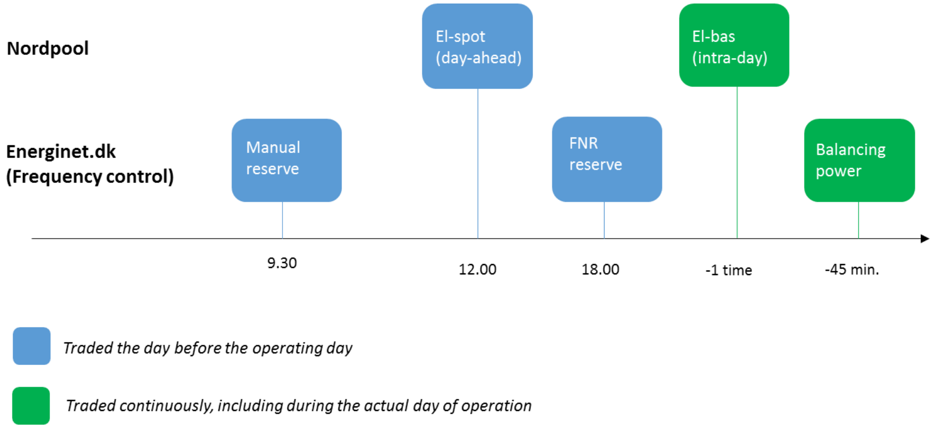

Figure 5: *Electricity markets I for eastern Denmark (DK2) [see 2, p. 13 (translated)]*

The planning process at Varmelast for the DHS side for these generators includes different steps. In the first step a day ahead planning is done with a planning scope of 48 hours. Only the first 24 hours of this scope are binding. Afterwards 6 intraday planning and trading cycles are made. By this, the forecast insecurity of the load and the prices is compensated. New and in the process of introduction is the participation at balancing power markets. The different planning scopes are explained in the following section. But before, the general conditions in all steps are explained.

For all planning phases, some boundary conditions are identical. The price is found by a MILP-solver based on GAMS. The planning tool was built and is maintained by an external consultant. The hydraulic grids are integrated as power bottlenecks manually included based on the grid situation and the knowhow of the employees. The biggest bottleneck is between the VEKS and the CTR system. Most distribution grids are just modelled as sinks, in case they have no transmission purpose. The complex system is shown in figure 6. The CTR hot water grid is shown in yellow, VEKS in green and the steam system in red. Two heat accumulators are visualized as cylinders. The black arrows show the grid bottlenecks. The small rectangles are the generators divided in blocks. The connections are represented by edges and nodes.

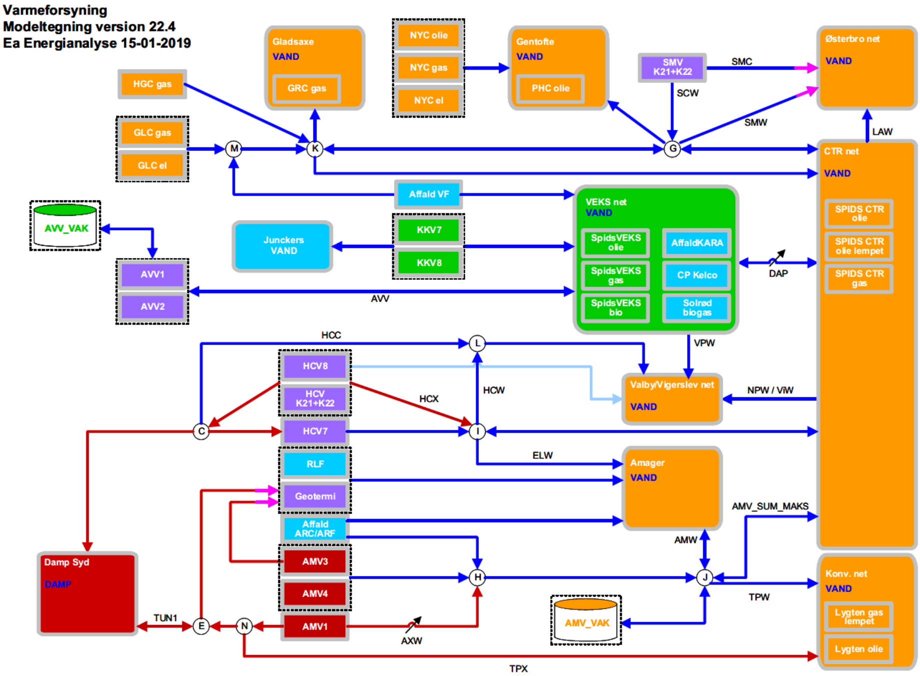

***Figure 6:** GUI and visualization of the scheduling model [1, p. 18]*

On the generation side, the model includes technical restrictions like minimal running times and ramps etc. In the optimization only variable heat costs are considered. They include the costs for fuel, CO_2 emissions, operation, maintenance and energy taxes and are reduced by the revenues from the electricity side. [1, p. 10]

The load side as well as the generation of the waste incineration are forecasted. The load that is taken for the optimization is reduced by the generation of the waste incineration plants. The generation that is connected at the distribution level is not included in the planning process. It is considered as a load reduction directly also in the measurement.

In the context of the transition to more decentralized heat generators and the increasing number of small scale generators in the distribution grid, new challenges have to be solved in this methodology. Even today new generators on the distribution level reduce the heat demand that the distribution companies buy from the transmission grids. That causes a surplus of heat especially from the waste incineration in the summer time. One reason is the structure of prices between the transmission grids and the distribution grids. This price has been an annual average price. In summer, it is easy to generate heat at the distribution level by own plants of the local heat supplier, even though the costs for the heat from the waste incineration might be lower. Because of this, a new price system was introduced consisting of a fixed part and a variable part. The variable part is planned to have a seasonal price summer/winter. The overall development is changing to more dynamic prices.

After the schedules are made, they are spread to all participants. The bottleneck between the two main transition grids (a pump station) is controlled by CTR.

Afterwards Varmelast compares the schedules and the realized production [1, p. 21].

Day ahead scheduling

Figure 7 shows the day ahead planning cycle. It consists of 6 steps.

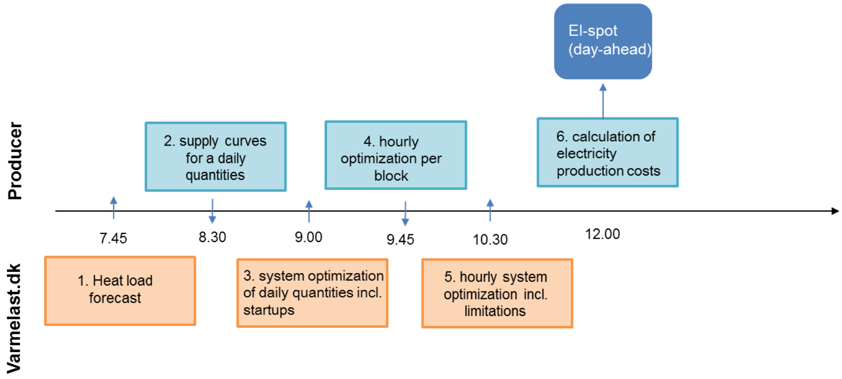

***Figure 7:** Day ahead planning process [see 2, p. 15 (translated)]*

1. A heat load forecast is made by a consultant for the whole grid. They include the whole historic demand and in addition the demand of the last day, the outer temperature and other weather conditions. They use self-learning algorithms (neuronal networks). Because they don't include holidays and other special conditions, the forecast is corrected by Varmelast. The overall forecast is spread by Varmelast for the different supply areas in a top down approach. The distribution is divided by the share of the annual consumption.
2. In the second step, the supply companies calculate discrete supply curves for a daily sum generation. The function is the energy price depending on the amount of heat and potential start-up costs. This daily amount ensures that the right generators are included in the planning process [1, p. 16]. Capacities that are not available (planned maintenance etc.) are not included.
3. Based on this information Varmelast calculates the cheapest plants on a daily basis [1, p. 17].
4. In the next step the generation companies do an hourly based scheduling for the fixed daily energy amount. They also include differential costs to give Varmelast the possibility to adjust each schedule.
5. With this information Varmelast does the hourly system optimization including the limitations of the hydraulic network.
6. The producers calculate their electricity prices and bid their electrcity to the Nordpool.

The power production that is tied to the heat order is offered at Nordpool at the market's lowest possible bidding price to make sure that the bid is accepted. If Nordpool's final electricity price is below the producer's marginal costs, the producer gets compensated by the DH companies. If the electricity price is so low that peak load generation will be cheaper, the producer will switch as much load as possible from the CHP plants to their own boilers (without turning off the CHP plants), and if necessary Varmelast will switch even more load to the boilers owned by the DH companies.

The whole process is finished before 12 o' clock, because the heat production has to be planned before the bid on the power market [1, p. 13].

Even though the process is done in a daily frequency 48 hours are planned in the system. The reason for that is the capacity of the heat accumulators. Figure 8 shows the planned heat accumulator content on top of the forecast of electricity prices. If the prices for only one day would be considered, the accumulator would be loaded at the end of the first day. But with the higher prices at the end of the second day, the better solution is to reserve the capacity for the second day.

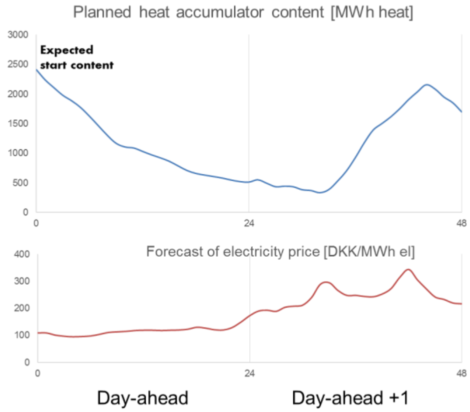

Figure 8: *Heat accumulator optimization over 48 hours [see 2, p. 16 (translated)]*

The accumulators have different behaviors in different seasons. In the summer they are mainly used for the waste incineration. Additional starts and stops of CHP plants or boilers are accepted, because the generation from waste is politically prioritized. [1, p. 25]

In the winter the reduction of morning peaks is important to prevent expensive peak load generation. Therefore the accumulators have to be filled until 6 o' clock. An exception are extreme electricity prices. If low electricity prices result in higher heat costs than the peak load generators, the storage is used to prevent these peaks. Also the heat demand forecast error has a higher absolute value in winter. [1, p. 27]

In autumn and spring it is possible to use them to shift to the cheapest generation depending on fluctuating electricity prices. In addition, the waste incineration generation has to be used to reduce the peak generation. [1, p. 30]

Intraday scheduling

To compensate the load forecast insecurity and failures of generators, 6 times a day an intraday scheduling process is done. The process is shown in figure 9. The planning is based on differential costs to the last schedule. For the intraday planning, the same model is used as the one for the day-ahead planning. The inputs for the tool are prepared by Varmelast. The 24 h execution is done by CTR and approved by VEKS [1, p. 20].

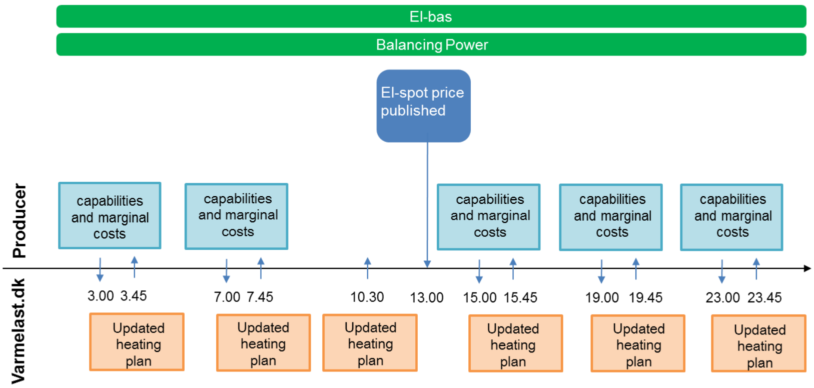

Figure 9: *Intraday heat control [see 2, p. 27 (translated)]*

Balancing power scheduling

The sale of reserves requires that the CHP producer is able to regulate their power both up and down to support the electrical system. In order to do so, they cannot produce at their maximum. However, the DH companies pay for the right to use the major part of the heat capacity at the power plants. Therefore, the ability to sell reserves is limited to two cases: 1) plants on which the DH company does not have a right to the entire capacity, and 2) situations (typically the summer) where it is extremely unlikely that Varmelast will order maximum heat production from a plant.

As a new market, balancing power at the secondary reserve market should be accessed. The existing heat accumulators should be used partly for that. The constraints are given by an additional contract. The new procedure will allow each CHP producer to partially use the heat accumulator located at their own CHP site. In brief, the procedure allows the producer to regulate up or down in the next hour if they expect to be able to perform the opposite regulation within the next 9 hours, while expecting to make an overall positive revenue from both actions and while respecting the confines of the heat accumulator. The producers should not actively make the later counter-regulation themselves; only if they are demanded to do so by CTR/Varmelast in an intraday regulation (because conditions may easily change within 9 hours). The new procedure will be implemented on October 1st 2019.

Appendix C

Case study input data

In this appendix, the input data and parameters of the case studies are described. The appendix includes *general input data* in appendix C.1, specific parameters for the *heating plants* in appendix C.2, and specific parameters for the *flexible technologies* in appendix C.3.

C.1 General input data

The general input data includes the three parts: weather data, electricity costs, and gas costs.

C.1.1 Weather data

For the evaluation of the case studies, the ambient temperature, and the global solar irradiance for Hamburg of the year 2019 are used from [261]. The data is shown in figure C.1

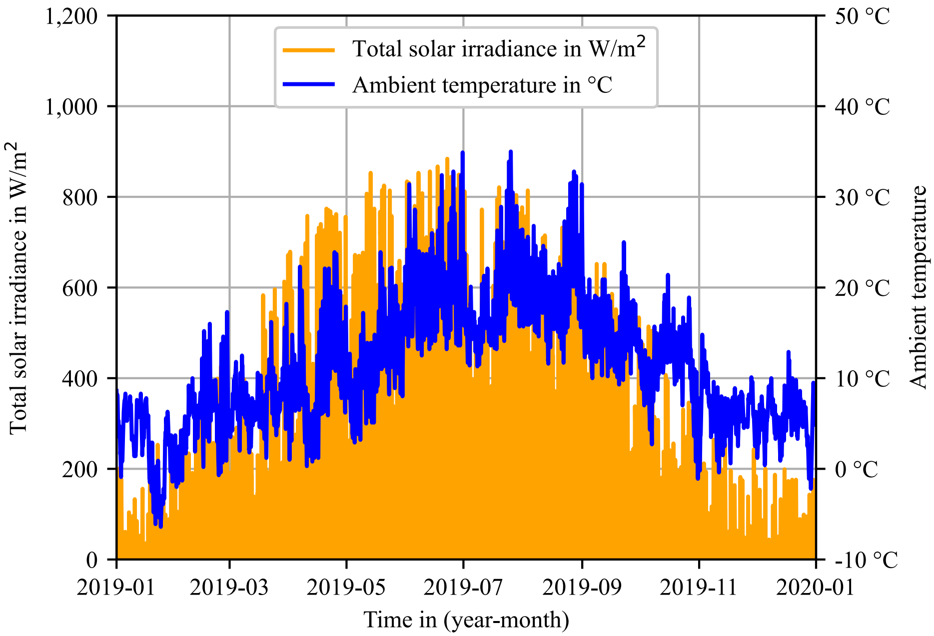

Figure C.1: Hourly data for ambient temperature and global solar irradiance for Hamburg in 2019 (data from [261])

C.1.2 Electricity costs

Since the case study location is Hamburg in Germany, the German electricity costs are used. Besides the procurement costs, the electricity costs consist of different taxes, levies, and grid fees in Germany [262]. The magnitude of the different taxes and levies depends on the type of usage and the annual consumption. Therefore, the different parts of the electricity costs are introduced in detail in the following paragraphs.

Taxes and levies

Table C.1 shows the different levies and taxes for electrical energy in Germany in the year 2019.

Table C.1: Levies and taxes for electricity consumption for 2019 (overview from [262])

Type	Costs in €/MWh (<100 MWh/a)	Costs in €/MWh (> 100 MWh/a)	Reference
Electricity tax	20.50	20.50	[263]
Renewable energy levy (*EEG*)	64.10	64.10	[264]
CHP levy (*KWKG*)	2.80	2.80	[265]
Distribution grid levy (*StromNEV*)	3.05	3.05	[266]
Defeatable loads levy	0.05	0.05	[267]
Offshore grid levy	4.16	4.16	[268]
Concession levy	23.90	1.10	[269]
Sum of levies and taxes (except VAT)	**122.03**	**99.23**	

In contrast to the energy-intensive industry, the heating sector is not excepted from these levies [270, § 63, § 64, appendix 4]. But if high amounts of energy are consumed (> 100 MWh/a), the concession levy is reduced. Since value added tax (VAT) must not be paid for commercial purchase, it is not relevant for the cost calculation of electrical energy.

Electricity grid fees

Table C.2 presents the electricity grid fees for Hamburg.

Table C.2: Grid fees for electricity consumption in Hamburg for 2019 (data from [271] and [272])

Type Grid / Voltage level	Max. run-time in hours/a	Max. consumption in kVA	Max. production in kVA	Energy price in €/MWh
Low	2,500	100	100	47.7
Low	–	100	100	35.6
Low/Medium	2,500	540	270	41.2
Low/Medium	–	540	270	15.4
Medium	2,500	1,500	1,000	29.0
Medium	–	1,500	1,000	14.7
Medium/High	2,500	12,000	9,000	21.4
Medium/High	–	12,000	9,000	10.0
High	2,500	–	–	21.5
High	–	–	–	7.4

The grid fees consists of three elements for power, energy, and metering. Since the evaluations in this thesis focus on variable costs, the fee for energy is the only relevant part. The costs can be selected by the grid connection (voltage level) which can be estimated by the maximum power of consumption or production. Further, the maximum run-time is relevant with a threshold at 2500 h/a.

Electricity price

Figure C.2 depicts the daily mean day-ahead electricity prices for the year 2019 in an sorted order [273]. As part of the evaluation of the variable costs, the sensitivity to the electricity price should be analyzed. Therefore, three different values are used: a mean value, a moderate high value (at the position of 10 %), and a moderate low value (at the position of 90 %). These three values are highlighted by the lines in figure C.2.

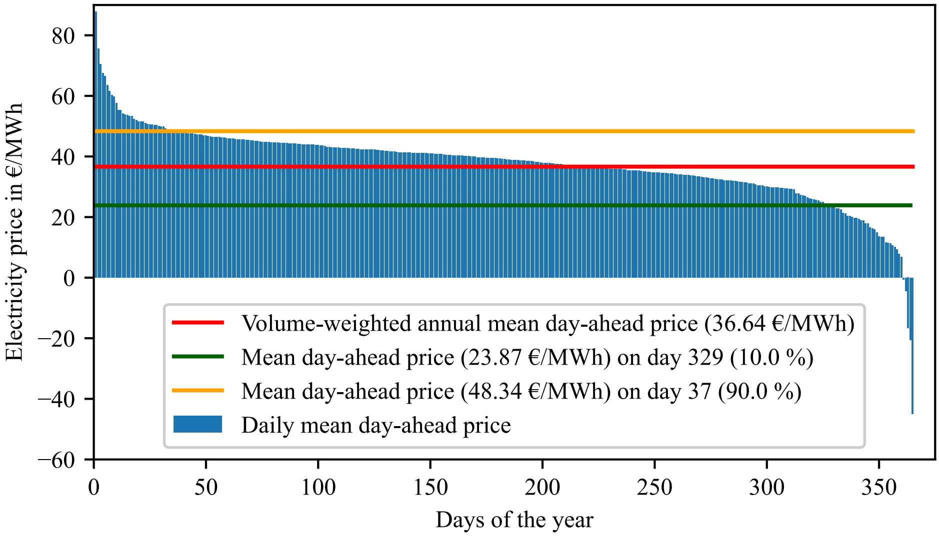

Figure C.2: Daily mean day-ahead electricity prices, sorted by price (data from [273], [159])

Since these prices are wholesale prices, additional costs must be considered for buying and selling activities. Table C.3 presents the costs for distribution (in case of electricity production) and the costs for procurement (in case of consumption.)

Table C.3: Further electricity price elements

Quantity	Value	Unit	Reference & comment
Share of energy distribution costs	10	%	In relation to the wholesale price; Assumption
Share of margin for procurement	20	%	In relation to the wholesale price; Assumption

C.1.3 Gas costs

For the calculation of the gas costs, the energy per volume and the factor to convert the gross calorific value (GCV) to net calorific value (NCV) are needed (table C.4). Since biomethane is transmitted in the natural gas grid, the costs for the infrastructure and its physics are identical with those of natural gas.

Table C.4: Energy of natural gas

Quantity	Value	Unit	Reference
GCV per norm-cubic-meter of H-gas	11.42	$kwh_{GCV}/m^3{}_{norm}$	[249]
GCV per NCV for natural gas	1.1	–	[249]

Like the costs for electricity, the gas costs consist of different cost elements. The wholesale price is given in the case study parameter tables (q.v. appendix C.2, p. 359). Table C.5 shows the energy taxes, concession levies, and procurement margin, that must be paid in addition to the wholesale price and the gas grid fees.

Table C.5: Natural gas cost elements (overview from [274])

Quantity	Value	Unit	Reference & comment
Concession levy	0.3	€/MWh_{GCV}	[275]; Interpreted as industrial customer
Energy tax	5.5	€/MWh_{GCV}	[276]
Share of margin for procurement	20	%	In relation to the wholesale price; Assumption

Furthermore, grid fees must be paid which are divided into the three parts energy, base, and measurement. Since the evaluation in this thesis is focused on variable costs, the energy related fees are the only relevant ones. Their amount depends on the annual consumption (table C.6).

Table C.6: Gas grid energy fees for Hamburg for 2019 [277]

Maximum energy consumption (in MWh_{GCV}/a)	Energy Costs (in €/MWh_{GCV})
2,500	2.32
6,000	1.76
11,000	1.35
–	0.47

C.2 Case study parameters for the heating plant evaluation

In this section, the input parameters for the heating plant case studies are given. For each heating plant type, the *global* input parameters are given in a first table. These parameters are used for all variants of the heating plant type. In additional tables, the specific *variant* input parameters are given.

C.2.1 Solar thermal input parameters

The global parameters for all solar thermal plant variants are given in table C.7. The variant-specific parameters for the variant *ST-ETC* are given in table C.8 and the parameters for variant *ST-FPC* are given in table C.9.

Table C.7: Global parameters for the solar thermal plants

Quantity	**Value**	**Unit**	**Reference & comment**
Heat exchanger return temperature gradient ($\Delta T_{\text{HEX, r}}$)	3	K	Assumption
Heat exchanger supply temperature gradient ($\Delta T_{\text{HEX, s}}$)	3	K	Assumption
Maximum ambient temperature (ϑ_a)	35	°C	[261] (rounded)
Maximum production temperature	150	°C	Assumed for plant dimensioning
Maximum total solar irradiance (G_t)	900	W/m^2	[261] (rounded)
Minimum return temperature (ϑ_r)	50	°C	Assumed for plant dimensioning according to the global assumptions (q.v. section 3.3.1, p. 51)
Minimum temperature difference	25	K	Assumed for plant dimensioning
Minimum thermal PLR (PLR)	0.02	–	Assumption
Pipe surface roughness (ϵ_{surf})	$5 \cdot 10^{-5}$	m	[121, p. 35] (steel, good finish)

Table C.8: Parameters for solar thermal plant variant *ST-ETC*[1]

Quantity	**Value**	**Unit**	**Reference & comment**
Collector area (A_{coll})	3.9	m^2	[129] (weighted mean of both collector types)
Collector efficiency (linear coefficient) (a_1)	0.613	$W/(m^2.K)$	[129]
Collector efficiency (quadratic coefficient) (a_2)	0.003	$W/(m^2.K^2)$	[129]
Collector length	2.058	m	[129]
Collector pressure drop (quadratic coefficient) (b_2)	1.5	$MPa.(l/s)^{-2}$	[127, p. 74]; Pressure drop at 2 l/min is 13 mbar resp. 19 mbar resulting in a mean pressure drop of 16.6 mbar for both types; Coefficients are determined by quadratic regression
Collector type	Ritter XL 34/50 P		315 collectors of the types (Aqua Plasma) *XL 34 P* (share 2/5) and *XL 50 P* (share 3/5) [128]
Collector width	2.5439	m	[129] (weighted mean of both collector types)
Heat exchanger pressure drop (quadratic coefficient) (b_2)	1	$kPa.(l/s)^{-2}$	[278, p. 95]; Size is estimated by rough calculation; Type *AQ4* offers the needed temperature gradient with acceptable pressure losses for the given maximum flow rate; Pressure loss coefficients are determined by quadratic regression from maximum pressure at maximum flow rate
Nominal collector efficiency (η_0)	0.687	–	[129]
Nominal pump efficiency ($\eta_{pump,\,nom}$)	0.72	–	Pump *Grundfoss TPE 50–290/2* selected by maximum flow rate and pressure difference [279]
Number of panels in a row	5	–	The maximum surface for one row should be approximately 17 m^2 [cf. 127, p. 29]; It is estimated that each row consists of 2 panels of the type *XL 35 P* and 3 panels of the type *XL 50 P*
Number of parallel rows	63	–	Estimated from satellite picture [280]; One row is missing due to the chimney

Ratio ground width to collector width	2	–	Estimated from satellite picture [280]

Table C.9: Parameters for solar thermal plant variant *ST-FPC*

Quantity	Value	Unit	Reference & comment
Collector area (A_{coll})	13.61	m^2	[281]
Collector efficiency (linear coefficient) (a_1)	2.27	$W/(m^2.K)$	[281]
Collector efficiency (quadratic coefficient) (a_2)	0.018	$W/(m^2.K^2)$	[281]
Collector length	2.28	m	[281]
Collector pressure drop (quadratic coefficient) (b_2)	14	$kPa.(l/s)^{-2}$	Coefficient determined by regression using data from [282, p. 268]
Collector type	HT–SolarBoost 35/10		One of the leading companies for large-scale solar thermal plants connected to district heating systems (DHSs) [131]
Collector width	5.97	m	[281]
Heat exchanger pressure drop (quadratic coefficient) (b_2)	1	$kPa.(l/s)^{-2}$	Assuming the same size like for the *ST-ETC* variant; Data from [278, p. 95]
Nominal collector efficiency (η_0)	0.773	–	[281]
Nominal pump efficiency ($\eta_{\text{pump, nom}}$)	0.72	–	Assuming the same size like the *ST-ETC* variant; Data from [279]
Number of panels in a row	10	–	Determined by pressure loss calculation: 20 panels would lead to a pressure drop of more than 10 bar, 15 to 4.4 bar and 10 lead to 1.4 bar (evaluated as acceptable)
Number of parallel rows	9	–	Results in the same overall collector area as the *ST-ETC* variant

[1] Some of these parameters were previously published in [75].

Ratio ground area to collector area	4	–	[124, Fact sheet 2.2, p. 2]; The parameter is used to estimate the pipe lengths
Ratio ground width to collector width	1.1	–	It is assumed that 10 % space is needed between the panels

C.2.2 Geothermal input parameters

In this subsection, the input parameters for the geothermal plants are given. For the calculation of the costs for wear, the investment of this heating plant type is required. Therefore, the subsurface investment is given in table C.10 and the surface investment is given in table C.11.

Table C.10: Geothermal subsurface investment (in 1,000 €)

Type	4,000 m well	3,000 m well	Reference & comment
Well doublet	16,000	12,000	[134, pp. 386, 388]
Reservoir engineering	1,500	1,000	[134, pp. 386, 388]
Down-hole pump	500	500	[134, p. 386]
Other costs (project planning etc.)	1,800	1,350	10 % of investment [134, p. 386]
Sum of subsurface investment	**19,800**	**14,850**	

Table C.11: Geothermal surface investment (in 1,000 €)

Type	17.9 MW	11.2 MW	9.3 MW	Reference & comment
Geoth. fluid loop	250	250	250	[134, p. 386]
Heating plant unit	1,790	1,120	930	100 €/kW [134, p. 382]
Other costs (project planning etc.)	204	137	118	10 % of investment [134, p. 386]
Sum of surface investment	**2,244**	**1,507**	**1,298**	

The global parameters for all geothermal plant variants are given in table C.12. The variant-specific parameters for the three different variants are given in tables C.13 to C.15.

Table C.12: Global parameters for the geothermal plants[2]

Quantity	Value	Unit	Reference & comment
Density of geothermal fluid (ρ)	1,147	kg/m^3	[134, p. 363]; Value depends on water chemistry and temperature; Assumed to be constant due to missing specific information
Geothermal productivity index (PI)	$8.33 \cdot 10^{-9}$	$m^3/(s.Pa)$	[134, p. 363]; Assumption; Depends on geological characteristics
Heat exchanger return temperature gradient ($\Delta T_{HEX,r}$)	3	K	Assumption
Heat exchanger supply temperature gradient ($\Delta T_{HEX,s}$)	3	K	Assumption
Interpolation flow rates ($\dot{V}$)	[10, 20, 30, 40, 50, 60, 70]	l/s	[136, p. 150]
Interpolation pressure losses (Δp_{loss})	[1.0, 2.0, 4.4, 8.1, 12.2, 17.6, 23.8]	bar	[136, p. 220] (7 inch (155 mm) Diameter); Used for validation
Minimum return temperature (ϑ_r)	50	°C	Assumed for plant dimensioning
Minimum thermal PLR (PLR)	0.1	–	Assumption to typical pump characteristics
Minimum well head pressure (p_{WH})	10	bar	[134, p. 364]; Assumption; Defined by geochemistry
Nominal efficiency of down-hole pump ($\eta_{pump,nom}$)	0.75	–	[134, p. 364]; Given by pump characteristics
Nominal flow rate of down-hole pump ($\dot{V}_{pump,nom}$)	70	l/s	Maximum value of interpolation flow rates
Planned annual operation	7,500	h/a	[134, p. 385]

Specific heat capacity of geothermal fluid (c_p)	3.5	kJ/(kg.K)	[134, p. 363]; Assumption; Value depends on water chemistry and temperature; Assumed to be constant due to missing specific information
Static fluid layer height (Z_SFL)	100	m	Given by geological characteristics, plausibility check q.v. section 5.3.2 (p. 146)
Subsurface maintenance costs as share of investment	1.5	%/a	[134, p. 385]
Surface maintenance costs as share of investment	6	%/a	[134, p. 385]
Thermal conductivity of the ground (k)	4	W/(m.K)	[137]; Typical value for liquid dominated well
Well diameter (d_i)	0.155	m	Assumption related to [136, p. 220]
Well surface roughness (ϵ_surf)	$1.3 \cdot 10^{-5}$	m	Assumption; Verified by comparison with [136, p. 220]

Table C.13: Parameters for geothermal plant variant *GT-130/60*

Quantity	**Value**	**Unit**	**Reference & comment**
Interpolation production temperatures	[93.8, 109.7, 115.9, 119.2, 121.3, 122.7, 123.7]	°C	Q.v. figure 5.8 (p. 161)
Maximum production temperature	123.7	°C	Q.v. figure 5.8 (p. 161)
Minimum injection temperature	60	°C	Assumption related to [134]
Reservoir temperature	130	°C	[136, p. 150]
Subsurface investment	19,800,000	€	Q.v. table C.10
Well depth	4,000	m	Data from [134, pp. 384, 386] (*power plant 1*)

[2] Some of these parameters were previously published in [75].

Table C.14: Parameters for geothermal plant variant *GT-96/50*

Quantity	**Value**	**Unit**	**Reference & comment**
Interpolation production temperature	[75.6, 85.0, 88.6, 90.5, 91.6, 92.4, 92.9]	°C	Q.v. figure 5.8 (p. 161)
Maximum production temperature	92.9	°C	Q.v. figure 5.8 (p. 161)
Minimum injection temperature	50	°C	Assumption related to [134]
Reservoir temperature	96.4	°C	[136, p. 150]
Subsurface investment	14,850,000	€	Q.v. table C.10
Well depth	3,000	m	Variant

Table C.15: Parameters for geothermal plant variant *GT-96/60*

Quantity	**Value**	**Unit**	**Reference & comment**
Interpolation production temperature	[75.6, 85.0, 88.6, 90.5, 91.6, 92.4, 92.9]	°C	Q.v. figure 5.8 (p. 161)
Maximum production temperature	92.9	°C	Q.v. figure 5.8 (p. 161)
Minimum injection temperature	60	°C	Assumption related to [134]
Reservoir temperature	96.4	°C	[136, p. 150]
Subsurface investment	14,850,000	€	Q.v. table C.10
Well depth	3,000	m	Variant

C.2.3 Industrial surplus heat input parameters

All parameters for the industrial surplus heating plant are given in table C.16.

Table C.16: Parameters for the industrial surplus heating plant[3]

Quantity	Value	Unit	Reference & comment
Distance of industry to DHS	300	m	[146, p. 16]
Heat exchanger pressure drop (quadratic coefficient) (b_2)	1	kPa.(l/s)$^{-2}$	[278, p. 95]; Size is estimated by rough calculation; Type *AQ4* offers the needed temperature gradient with acceptable pressure losses for the given maximum flow rate; Pressure loss coefficients are determined by quadratic regression from maximum pressure at maximum flow rate
Maximum thermal power of the chilling process ($\dot{Q}_{\mathrm{max}}$)	200	kW	Average surplus potential, given by Hamburg Energie GmbH
Maximum thermal power of the exhaust gas process ($\dot{Q}_{\mathrm{max}}$)	100	kW	Average surplus potential, given by Hamburg Energie GmbH
Minimum thermal power of the chilling process ($\dot{Q}_{\mathrm{min}}$)	0	kW	It is assumed that an additional cooling possibility is given; Therefore the cooling process can be adjusted between 0 and full thermal power
Minimum thermal power of the exhaust gas process ($\dot{Q}_{\mathrm{min}}$)	100	kW	It is assumed, that only the full or no thermal power can be extracted from this process; Related to the high temperature, the heat exchanger would get damaged, if only part of the heat would be extracted
Nominal efficiency of pump ($\eta_{\mathrm{pump,\,nom}}$)	0.7	–	Assumption to typical value
Secondary supply temperature of the chilling process (ϑ_{s})	75	°C	Assumption related to [283, p. 4]
Secondary supply temperature of the exhaust gas process (ϑ_{s})	95	°C	High temperatures from exhaust gas are possible [cf. 283, p. 4]; For low-cost system design, a temperature below 100 °C is assumed

Surface roughness of pipe (ϵ_{surf})	$5 \cdot 10^{-5}$	m	[121, p. 35] (steel, good finish)

C.2.4 Heat-pump input parameters

All parameters for the heat pump plants are given in table C.17.

Table C.17: Parameters for the heat pumps

Quantity	Value	Unit	Reference & comment
Interpolation COP relation ($f_{COP,PLR}$)	[0.0, 0.286, 0.467, … 0.986, 0.993, 1.0]	–	[149, Fig. 8]; COP from figure was normalized to maximum COP
Interpolation PLRs (PLR)	[0.0, 0.05, 0.1, … 0.8, 0.9, 1.0]	–	
Maximum supply temperature (ϑ_s)	90	°C	Given for numerous heat pumps in [148, table 1]
Maximum thermal power ($\dot{Q}_{max}$)	2,000	kW	Assumption
Minimum thermal PLR ($\dot{Q}_{min}$)	0.1	–	[150]
Second law efficiency (f_{Lorenz})	0.5	–	[148]; Second law efficiency (Lorenz-factor) can be up to 50 %
Return temperature gradient ($\Delta T_{HEX,r}$)	3	K	Assumption
Supply temperature gradient ($\Delta T_{HEX,s}$)	3	K	Assumption

[3] Some of these parameters were previously published in [75].

C.2.5 CHP plants input parameters

All parameters for the combined heat and power (CHP) plant variants are given in table C.18.

Table C.18: Parameters for the CHP plants

Quantity	Value	Unit	Reference & comment
Bonus for small-scale CHP management ($bonus_{\mathrm{management}}$)	2	€/MWh$_{\mathrm{el}}$	[284]; Annual value for 2019
Fixed subsidy for electrical energy grid feed-in ($subsidy_{\mathrm{fixed}}$)	180	€/MWh$_{\mathrm{el}}$	[285, §27]; Basic subsidy (110 €/MWh$_{\mathrm{el}}$), bonus for cultivated biomass (50 €/MWh$_{\mathrm{el}}$), bonus for gas treatment (mean magnitude) (20 €/MWh$_{\mathrm{el}}$)
Fuel type	biomethane		[286]
Hourly costs for maintenance	2.55	€/h	[287]
Interpolation PLRs (PLR)	[0.25, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0]	–	
Interpolation scaling factor for electrical efficiency ($f_{\eta_{\mathrm{el}},\mathrm{PLR}}$)	[0.645, 0.695, 0.78, 0.85, 0.905, 0.945, 0.97, 0.99, 1.0]	–	[154, Fig. 9a]
Interpolation scaling factor for thermal efficiency ($f_{\eta_{\mathrm{th}},\mathrm{PLR}}$)	[1.09, 1.07, 1.04, 1.02, 1.01, 1.005, 1.0, 1.0, 1.0,]	–	[154, Fig. 9a]
Maximum electrical power consumption	11	kVA	[288, p. 1]
Maximum supply temperature (ϑ_{s})	90	°C	[289]
Maximum thermal power ($\dot{Q}_{\mathrm{max}}$)	652	kW	[289] (GG530)
Minimum thermal PLR (PLR)	0.511	–	[288, p. 1]
Nominal electrical efficiency (NCV) ($\eta_{\mathrm{el,\,nom}}$)	0.406	–	[289] (GG530)
Nominal supply temperature ($\vartheta_{\mathrm{s,\,nom}}$)	70	°C	Assumption: 20 K below max. temperature
Nominal thermal efficiency (NCV) ($\eta_{\mathrm{th,\,nom}}$)	0.498	–	[289] (GG530)

Planned annual operation	6,650	h/a	[287]
Reference value for market bonus calculation ($\overline{py}_{\mathrm{reference}}$)	37.7	€/MWh$_{\mathrm{el}}$	[284]; According to the German law for renewable energy *EEG*
Scaling factor for thermal efficiency related to supply temperature ($f_{\eta_{\mathrm{th}},\mathrm{T_s}}$)	0.98	–	[155, Fig. 6] (Dachs); Electrical efficiency is not influenced by higher temperatures; Thermal efficiency is decreasing approx. 2 % with increasing supply temperature of 20 K

C.2.6 Heat only boilers input parameters

All parameters for the heat only boilers (HOBs) are given in table C.19.

Table C.19: Parameters for the HOBs

Quantity	Value	Unit	Reference & comment
Interpolation PLRs (PLR)	[0.03, 0.04, 0.05, … 0.8, 0.9, 1.0]	–	Data from [161, Fig. 2.8] (*boiler 1*)
Interpolation thermal efficiencies (GCV) ($\eta_{\mathrm{th,\,PLR}}$)	[0.727, 0.795, 0.836, … 0.836, 0.817, 0.799]	–	Data from [161, Fig. 2.8] (*boiler 1*); Data is adjusted to the higher return temperature of 50 °C by data from [161, Fig. 2.6]
Maximum electrical power consumption of the fan	3	kVA	[290, p. 24]; Size fits to boiler
Maximum supply temperature (ϑ_{s})	100	°C	[291, p. 3] (type *1400*)
Maximum thermal power ($\dot{Q}_{\mathrm{max}}$)	1,280	kW	[291, p. 3]; Size assumed to type *1400*
Minimum thermal PLR (PLR)	0.1	–	Assumption based on highly decreasing efficiency below 10 % [cf. 161, Fig. 2.8]
Nominal supply temperature ($\vartheta_{\mathrm{s,\,nom}}$)	70	°C	Data from [161, Fig. 2.8] (*boiler 1*)

C.3 Case study parameters for the flexibility evaluation

In this section, the input parameters of the flexibility case studies are given. For each flexible technology, the *global* input parameters are given in a first table. These parameters are used for all variants. In additional tables, specific *variant* input parameters are given.

C.3.1 Seasonal storage input parameters

All parameters for the seasonal thermal energy storage (TES) are given in table C.20.

Table C.20: Parameters for the ATES

Quantity	Value	Unit	Reference & comment
Electricity consumption down-hole pump	16.8	MWh_{el}/a	265 MWh_{el}/a is given for low temperature with 4 K [292]; Linear/conservative approach: scaled with temperature difference of (77 °C–14 °C) for high temperature ATES
Maximum electrical power consumption	203	kVA	Sum of maximum electrical power for the heat pump (at lowest COP) and for the down-hole-pump
Rated TES capacity (K_{TES})	2,856	MWh	Discharged thermal energy [cf. 292, Fig. 3]
Second law efficiency (f_{Lorenz})	0.5	–	Second law efficiency (Lorenz-factor) can be up to 50 % [cf. 148]
Return temperature gradient ($\Delta T_{HEX,r}$)	3	K	Assumption
Source return temperature ($\vartheta_{r,source}$)	14	°C	[195], [197]
Supply temperature gradient ($\Delta T_{HEX,s}$)	3	K	Assumption

C.3.2 Pipe network input parameters

All parameters for the network evaluation are given in table C.21.

Table C.21: Parameters for the pipes

Quantity	**Value**	**Unit**	**Reference & comment**
Ambient temperature (ϑ_a)	11.3	°C	Mean value from figure C.1 (p. 354)
Burial depth of the pipe (Z)	0.65	m	[293, p. 104]
Inner diameter (d_i)	0.21	m	[2, p. 320] (DN200, Series 3)
Length (l)	3,000	m	Variant
Outer diameter of the insulation ($d_{insulation}$)	0.39	m	[2, p. 320] (DN200, Series 3)
Thermal conductivity of the insulation ($k_{insulation}$)	0.025	W/(m.K)	[2, p. 315]
Thermal conductivity of the soil (k_{soil})	0.5	W/(m.K)	[294, p. 26]
Time interval for heat loss calculation	0.25	h	Verified as sufficient by tests of different intervals

C.3.3 Storage tank input parameters

The global parameters for all storage tank variants are given in table C.22. The variant-specific parameters are given in table C.23.

Table C.22: Global parameters for the storage tanks

Quantity	**Value**	**Unit**	**Reference & comment**
Ambient temperature (ϑ_a)	20	°C	Assumed for temperature in heating central
Convection heat transfer coefficient (α_{air})	3.5	W/(m^2.K)	[240]
Initial relative thermocline height (z_{TC})	0.5	–	50 % is chosen to allow for comparison with [237]
Initial thermocline slope (s_{TC})	0.009682	–	Dimensionless time set to $1.5 \cdot 10^{-5}$ to allow for comparison with [237]
Maximum temperature difference for primary return	1.25	K	Assumption; Half of the temperature resolution
Thermal conductivity of the insulation ($k_{insulation}$)	0.035	W/(m.K)	[240]
Time interval for heat loss calculation	0.619	h	Interval of 1 hour is verified as sufficient by a test of different intervals; 0.619 hours is chosen to allow for comparison with [237]

Table C.23: Parameters for the storage tank variants

Quantity	Variant	Value	Unit	Reference & comment
Inner tank height (Z_{TES})	storage-tank-ENB	19.5	m	From nameplate in the *Energiebunker*
Inner tank volume (V_{TES})	storage-tank-ENB	2,025	m^3	Calculated by height and diameter from nameplate in the *Energiebunker*
Insulation thickness ($l_{\text{insulation}}$)	storage-tank-ENB	0.27	m	[240]
Rated TES capacity (K_{TES})	storage-tank-ENB	57.9	MWh	Difference of mean temperature assumed as 25 K at 75°C
Inner tank height (Z_{TES})	storage-tank-ENV	4.9	m	[295] (type *LZO 20.000*)
Inner tank volume (V_{TES})	storage-tank-ENV	20	m^3	[295] (type *LZO 20.000*)
Insulation thickness ($l_{\text{insulation}}$)	storage-tank-ENV	0.2	m	[295] (type *LZO 20.000*)
Rated TES capacity (K_{TES})	storage-tank-ENV	0.572	MWh	Difference of mean temperature assumed as 25 K at 75°C
Inner tank height (Z_{TES})	storage-tank-DHW	1.73	m	[236]
Inner tank volume (V_{TES})	storage-tank-DHW	0.91	m^3	[236]
Insulation thickness ($l_{\text{insulation}}$)	storage-tank-DHW	0.13	m	[236]
Rated TES capacity (K_{TES})	storage-tank-DHW	0.026	MWh	Difference of mean temperature assumed as 25 K at 75°C

Appendix D

Flexibility definitions

Table D.1 shows the identified definitions of the term *flexibility* as well as an own abstraction of their meaning.

Table D.1: Flexibility definitions

1.	Denholm and Hand: "System flexibility can be described as the general characteristic of the ability of the aggregated set of generators to respond to the variation and uncertainty in net load." [167]		
=	the ability	to respond to	variation and uncertainty in production and consumption
2.	Li et al.: "The flexibility of IEDHS [integrated electricity and district heating systems] refers to the ability to respond to system changes and uncertainties of supply and demand side resources." [168]		
=	the ability	to respond to	variation and uncertainty in production and consumption
3.	Huber, Dimkova, and Hamacher: "Flexibility is the ability of a power system to respond to changes in power demand and generation." [169]		
=	the ability	to respond to	changes in production and consumption
4.	Cochran et al.: "Flexibility of operation—the ability of a power system to respond to change in demand and supply—is a characteristic of all power systems." [170]		

= the ability to respond to changes in production and consumption

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5. Six et al.: "The flexibility of a [heat pump (HP)] in smart or intelligent grids can be seen in two different ways. Delay of (a part of) the electricity consumption of the HP over a limited period, although there is a demand for [space heating (SH)] and/or domestic hot water (DHW). [..] Forced electricity consumption of the HP over a certain period although there is no or low demand for SH and/or DHW." [171]

= the ability to delay or force consumption

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6. Vandermeulen, van der Heijde, and Helsen: "A possible definition of flexibility is the ability to speed up or delay the injection or extraction of energy into or from a system." [19]

= the ability to delay or force feed-in and feed-out

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7. Lund et al.: "The electric system is built in such a way that it has up to a certain point a capability to cope with uncertainty and variability in both demand and supply of power." [172]

= the ability to adapt to variation and uncertainty in production and consumption

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8. Corsten and Gössinger: "Adaptability of production systems to changing conditions" [173, translated from German]

= the ability to adapt to changing conditions

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9. Finck et al.: "Energy flexibility can be seen as the ability to manage a building's demand and generation according to local climate conditions, user needs and grid requirements." [174]

= the ability to modify production and consumption

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10. Sneum and Sandberg: "In this study, flexibility is characterised by the ability of a DH-technology to provide frequent increases or decreases in its consumption or production of electricity according to signals from the electricity system, such as the use of P2H [power to heat] during hours when electricity prices are low, CHP electricity production during hours when electricity prices are high and the use of HS [heat storage] to supply heat when demanded." [175]

= the ability to modify production and consumption

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11. Fischer et al.: "In a power system context flexibility is seen as the ability to modify energy generation or consumption of a system in response to external signals." [176]

= the ability	to modify	production and consumption	in response to external signals

12. Ulbig and Andersson: "Operational flexibility is the technical ability of a power system unit to modulate electrical power feed-in to the grid and/or power outfeed from the grid over time." [177]

= the ability	to modify	feed-in and feed-out	

13. Hammer, Sejkora, and Kienberger: "[Temperature-flexible operation:] The novel feature is to switch off the district heating network in low-load times with particularly high specific heat losses, to prevent the heat losses, while simultaneously serving the heat demand of the consumers from decentralised heat storages." [178]

= the ability	to switch off	and serve from decentralized storages	

14. Bertsch et al.: "By definition, flexibility is the capability to balance rapid changes in renewable generation and forecast errors within a power system." [296]

= the ability	to balance	variation and uncertainty in production and consumption	

15. Petersen et al.: "The flexibility of a given system is a unique, innate, state and time dependent quality. In conversation it is therefore sometimes said that flexibility is the ability to deviate from the plan. That characterization of flexibility is very insightful, but it still leaves us with the problem of defining both the ability to deviate and the plan." [222]

= the ability	to deviate	from the plan	

16. MacDougall et al.: "A device has flexibility if it is capable of shifting its production or consumption of energy in time within the boundaries of end-user comfort requirements and without the primary goal to change its total energy production or consumption." [193]

= the ability	to shift	production and consumption	respecting comfort

17. Nuytten et al.: "The flexibility of the installation allows for changes in the energy use over time and is a valuable property when the supply of energy has an increasingly intermittent character." [225]

= a property	allowing for	changes in energy use	

18. Finck et al.: "It can also be understood as a building property, if it is seen as the margin in which the building can be operated while respecting its functional requirements (Clauß et al., 2017)." [174]

= a property	providing	margin for operation	respecting comfort

19. Finck et al.: “On the other hand, energy flexibility can be regarded as a service which can be provided. In that sense, energy flexibility will allow for demand side management/load control and demand response based on the requirements of the surrounding grids.” [174]

=	a service	provided to	the surrounding grid	

20. Tahersima, Madsen, and Andersen: “Our suggested framework is to measure flexibility of a single house in terms of the energy that can be shifted without violating its comfort settings.” [212]

=	energy	shifted		respecting comfort

21. Stinner, Huchtemann, and Müller: “Positive flexibility is needed if the load is higher than the generation from renewable sources and negative flexibility is needed if the renewable generation exceeds the load.” [179]

=	a need	to balance	production and consumption	