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Impact of Electrical Space Heating Demand Response in Power System Operation Planning with High Penetration of Renewables

Master's Thesis

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Statement of Authentication

I hereby declare that I have written the present thesis independently, without assistance from external parties and without use of other resources than those indicated.

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Abstract

The subject of this research is to study the impact of the thermal demand on the operation power system. Therefore, a model of the electric system including the thermal loads is developed. The potential flexibility provided by power-to-heat systems is studied. It is considered a future electrification of residential space heating loads.

The operation of the power system is represented by a unit commitment including a model of the thermal behaviour of residential buildings. The objective of the unit commitment is to minimize the operation cost taking into account the generation constraints with renewable energies and the flexibility provided by the thermal loads. The different factors that affect the heating consumption are taken into account to model the thermal behaviour of residential buildings. These include heat gains due to solar radiation, internal heat gains, heat loss by transmission ventilation losses and the heat recovery for the ventilation system.

The operation planning problem is implemented through ILOG libraries and the environment ECLIPSE is used with the java language and the optimizer CPLEX.

Three different case studies are performed to understand the impact of thermal loads on the power system. Results show that including the thermal load with a non-smart operation increases the operation cost of the power system and the peak demand. However, if the energy storage capacity of the buildings is taken into account, the thermal loads can provide flexibility to the power system. When the thermal loads work in a smart operation, the operation cost is reduced, a higher penetration of renewable energy is achieved and the peak load is reduced. The potential benefits of a smart operation of the thermal loads depend on the thermal parameters of the dwellings, the number of dwellings using electricity to generate heat and the availability of renewable energy. Results also show that an electrification of the space heating loads could lead to significant reductions of the CO_2 emissions.

Acknowledgement

I would first like to thank my parents, Salva and Lupe, for their love and support and for letting me live that experience. Thank you for all you teach me and for being an example to follow. To my brother Salva for being my partner and my friend.

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Nomenclature

SU_g	is the start-up cost of unit g
SD_g	is the shut-down cost of unit g
F_g	is the fuel cost function for unit g
p_{gt}	is the thermal power generation/dispatch amount of unit g at time t
$VOLL$	is the value of loss load
δ_{it}	is the load loss at bus i at time t
P_g^{min}	is the minimum power output of generating unit g
P_g^{max}	is the capacity of generating unit g
u_{gt}	is a variable that indicates if the unit g is on at time t
$\overline{R_g}$	is the ramping-up limit of generating unit g
$S_{t,g}$	is the start-up ramping limit of generating unit g
$Rs_{t,g}$	is the secondary reserve of the unit g at time t
$Rp_{t,g}$	is the primary reserve of the unit g at time t
f_{ijt}	is the unrestricted variable, a bi-direction flow between bus i and bus j
δ_{it}	is the load-shedding loss at bus i at time t
A_i^+	is the set of flow starting at bus i
A_i^-	is the set of flow ending at bus i
R_{it}	is the renewable energy output at bus i at time t
Rrp_t	is the parameter that indicates the requirement of primary reserve
Rrs_t	is the parameter that indicates the requirement of secondary reserve
F_{ij}^{max}	is the transmission flow limit between bus i and bus j
F_g^e	is the emission function of unit g
SU_g^e	is the start-up emission of unit g at time t
SD_g^e	is the shutdown emission of unit g at time t
E^{max}	is the system emission limit
T_S	is the coefficient of solar transmission of the window (0-1)
W_C	is the shading coefficient of the window (0-1)
W_f	is the frame coefficient of the window (0-1)
S_W	is the total surface of windows of the building (m2)

$Coef$	is the non-perpendicular reduction factor
I_{sol}	is the global irradiation on horizontal surface (W/m2)
$Correc$	is the coefficient to compensate the orientation of the window
$Heat_{gain}$	is the average specific heat gain in the building (W/m2)
A	is the heated floor area in the building (m2)
U	is the average thermal transmittance of the building envelope (W/m2K)
A_{env}	is the overall surface of the envelope (m2)
$T_{out}(t)$	is the instantaneous outdoor air temperature (°K)
$T_{int}(t)$	is the instantaneous indoor air temperature (°K)
c_{pa}	is the specific heat capacity of the air (Wh/m3K)
V_c	is the sanitary air change rate (1/h)
h_{room}	is the standard value of room height (m)
Q_{heat}	is the heat provided in a building from heating equipment (W)
C	is the effective heat capacity of the building (Wh/°K)
$T_{vent}(t)$	is the temperature of supply air (°K)
H_{rec}	is the efficiency of the heat recovery unit
V_{cn}	is the natural ventilation rate (1/h)
T_{min}	is the bottom limit of temperature (°K)
T_{max}	is the upper limit of temperature (°K)
P_{max}	is the maximum power output of the heating system
Per_{hp}	is the percentage of heat provided by the heat pump
E_n	is the share of heating demand covered by electricity
COP	is the coefficient of performance of the heating system
$Units$	is the number of houses in each zone
$\sum gain$	is the sum of the different heat gains and losses in the dwelling at time *t*

1 Introduction

On December 2015 the Paris Agreement [1] was accorded in order to combat the climate change and to accelerate and intensify the actions and investments needed for a decarbonised future. The main objective is to limited global warming to well below 2°C and pursuing efforts to limit it to 1.5°C. Also, the reduction of the global emissions. For that purpose, there is a need for global emissions to peak as soon as possible and initiate rapid reductions thereafter [2].

Half of the consumption of the European Union’s energy is for heating and cooling and much of it is wasted. Most of the heating and cooling is still generated from fossil fuels, with only 18% generated by renewable energy. In order to fulfil the energy and climate goals, the consumption of fossil fuels should be reduced. At the end of 2012, in EU 45% of the energy for heating and cooling was used in the residential sector, while 36% in industry and 18% in services.

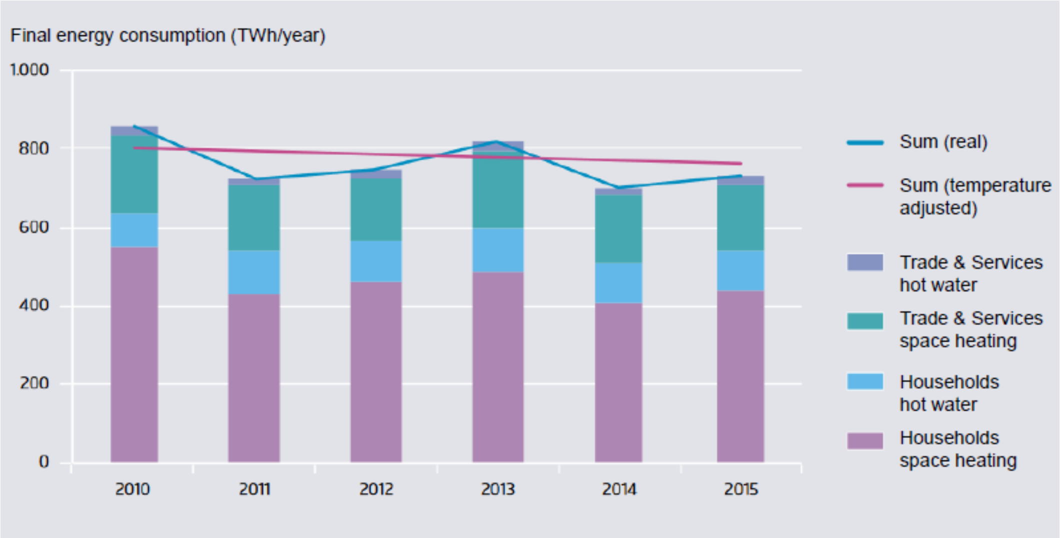


Figure 1. Final energy consumption by sector **[3]**

That is a good indicator to believe in the decarbonisation of the sector. Conversely, it means a challenge for the power grid. The decarbonisation implies reduction of the fossil fuel consumption and, as a consequence, the penetration of renewable energies and the ability to support the uncertainty that renewable energies involve. With the decarbonisation, there are savings in terms of cost-effectiveness [4]. Combining different operations strategies for electricity and heating sector can highlight the economics of these systems.

The heating sector is still a challenge for the energy transition because it has a large quantity of energy consumption that need to be change into a renewable energy generation. The renewable energy sources requires more flexibility in the system since they have an intermittent generation depending on the availability of the sources [5].

In Figure 1 the final energy use for space heating during the last years shows that the consumption is divided as follows: trade and services hot water, trade and services space heating, households hot water and households space heating. As it is shown, space heating for households have the highest part of energy consumption during the last years in EU countries.

1.1 Main objective

The objective of this research is to study the potential flexibility provided by power to heat systems for power system operation. To this end, a unit commitment model will be developed including an operation model of space heating loads. The aim of this operation model is to minimize the operation cost of the power system subject to the different constraints of the generators, transmission and the space heating loads. The impact of responsive and non-responsive operation of thermal loads in terms of cost, renewable penetration and CO_2 emissions will be studied.

1.2 Motivation

The origin of the project arises from the necessity of reduce the CO_2 emissions [1]. The penetration of the renewable energies into the power system is able to reduce CO_2 emissions in large quantity. The public generation of electricity and heating is responsible of the almost 85% of the emissions of greenhouse gasses in Germany. In addition, a quarter of the energy generated in Germany is consumed by the residential sector [6]. As residential space heating has a high energy consumption to be able to cover the heating demand, there are a strong reason to electrify the heating demand. With the addition of the thermal demands into the power system, an extra flexibility could be added to the power system and, as a result the penetration of renewable energies is possible.

2 Literature Review

In this section is going to be explained the power system operation with the objective function of the Unit Commitment and their constraints. The demand response and the importance of the space heating demand is discussed.

2.1 Power Systems Operation

Electric power systems are dynamic systems that are constantly changing. Some of the conditions can be anticipated by the system operator. However, others change without warning. Power system operation planning encompass all the decisions that are made within different periods of time of power delivery. The scheduling and operation of the system can be divided in different periods of time, such as during the day-ahead operation, hours and minutes before power delivery [7]. Dispatchable generating units are those that are controllable. While the generation units that are weather-dependent renewable are non-dispatchable generation units, as their production is uncertain. But the uncertainty also pertains to next-day demand. The day-ahead operations are based on solving the unit commitment problem with the objective of minimizing total production cost, including costs of generation, start-up and shut-down costs.

Hours before the power delivery the operator deploys reserves and acquire additional reserves if it is required. The main objective of the process is to ensure the security of the power supply, such as avoid voltage collapse, meanwhile keeping the costs as low as possible. Finally, minutes before the power delivery, the objective is to maintain the security, solving optimal power flow problem or a security-constrained optimal power flow problem. Both ensure a correct and secure functioning of the system under a likely situation in the immediate future, that are several minutes, introducing, if the system requires, preventive or corrective actions.

2.1.1 Unit Commitment

The unit commitment (UC) consists in determining the scheduling of the power generation units for a predefined planning horizon. In this phase of the planning, the on/off status of the generation units is decided so that the forecasted demand is supplied at a minimum operating cost. The resulting schedule must satisfy different technical constraints of the generating units, the load balance constraint and the operating reserve requirements. The overall objective of the UC problem is to determine the scheduling of generating units needed to minimize the total costs, to supply the demand, and to meet different technical and security constraints [7].

The electric power generation is subject to demand changes, transmission capacity and transmission conditions. Even if the real-time load follows the expectations of forecasted loads, if an outage occurs, it would cause congestions in some lines and change the original transmission flow. Meanwhile, it will affect the original power generation schedule.

2.1.1.1 Objective function

The objective function of the unit commitment is to achieve the minimum total operational cost over a planned time horizon, the maximum social welfare or the maximum total profit when the GENCO (Generation Companies) conduct bidding strategies [8].

The UC has a generic objective function composed of two cost component that are related with two stage decisions:

$$\min \sum_{g \in G} \sum_{t \in T} \left(SU_g v_{gt} + SD_g w_{gt} \right) + \sum_{g \in G} \sum_{t \in T} F_g\left(p_{gt}\right) + VOLL \sum_{i \in N} \sum_{t \in T} \delta_{it} \tag{1}$$

2.1.1.2 Constraints

The solution of the Unit commitment problem must ensure that several technical constraints on the system and generating unit level are satisfied. The generating unit constraints include the generation limits, power limits, primary and secondary reservoir limits and start-up and shut-down of thermal generators. The system constraints include the load balance, operating reserve requirements, CO_2 emission limits.

Thermal generation constraints:

Power Bounds

The generator’s output at hour t is constrained by the maximum generation limit and the minimum generation limit, as stated in eq (2). When a generator is scheduled on, the generation capacity output must be over the minimum generation limit to avoid unstable behaviour and it must be less than its maximum capacity. If the generation is scheduled to be off, its output is forced to be zero.

$$P_g^{min} u_{gt} \le p_{gt} \le P_g^{max} u_{gt} \tag{2}$$

$$p_{gt} \ge 0$$

Ramping limits

Generators can adjust the generator output, increasing or decreasing between two successive time periods. However, the outputs difference must comply with the ramping stated by eq(3) and eq (4):

$$P_{t,g} - P_{t-1,g} \le u_{t-1,g} \overline{R_g} \Delta T_t + S_{t,g} P_g^{ini} \tag{3}$$

$$P_{t-1,g} - P_{t,g} \le u_{t,g} \underline{R_g} \Delta T_t + D_{t,g} P_g^{max} \tag{4}$$

Minimum operation times

Once the generating unit is started, it must be operating for a period of time larger or the same as minimum operation time. The same restriction holds for the shutdown of the unit, once a unit is shutdown, it must remain out of service during a certain period of time.

$$u_{t,g} \ge \sum_{\tau = t - ton_g}^{t} S_{\tau,g} \tag{5}$$

$$1 - u_{t,g} \ge \sum_{\tau = t - tof_g}^{t} D_{\tau,g} \tag{6}$$

Operating reserve limits

It is important to take into account that the reserve contribution should be within the power limits of the generating unit.

$$P_{t,g} + Rp_{t,g} + Rs_{t,g} \ \leq u_{t,g} P_g^{max} \tag{7}$$

System level constraints:

Power balance

In each period of time t, the sum of the power plants generation should be sufficient to supply the demand, taking into account the transmission losses and unit consumptions. Sometimes, load loss is allowed to occur. In that case, an unserved energy penalty is reflected in the objective function.

$$\sum_{(i,j)\in A_i^+} f_{ijt} - \sum_{(i,j)\in A_i^-} f_{ijt} = \sum_{g\in G} p_{t,g} + R_{it} - D_{it}^0 + \delta_{it} \tag{8}$$

This model includes the transmission grid and also are considered the losses as a share of demand in order to sizing the needed sources to operate the system.

Operating reserve constraints

Operating reserve is one type of ancillary operations to support the power balance on the demand and supply sides.

The sources of energy provided from different reserve services are different, and the response times of reserve services can vary from a few seconds to 30 min, up to 60 min, depending on the control reserve deployment time. The operating reserve constraints are based on the time response of each resource service.

In order to satisfy the demand when there are contingencies in the power system, the system must have a primary reserve. The units that still are operating must be able to increase their power to compensate the deficit of generation. The requirement of reserve is calculated as a percentage of the demand [9].

$$\sum_{g \in GT} Rp_{t,g} \geq Rrp_t \tag{9}$$

Secondary reserve is required to maintain the balance of load and generation when there are fluctuations of load or non-dispatchable generation. Secondary reserve allows the system to quickly increase or reduce the generation. The secondary reserve requirements are calculated as 3% of the demand plus 5% of the variable generation [9].

$$\sum_{g \in GT} Rs_{t,g} \geq Rrs_t + \sum_{g \in GT \cup GF} R_{var} P_{t,g} \tag{10}$$

Transmission constraints

One of the Unit commitment problems is the power flows in a transmission network, since they can affect real-time power dispatch at a bus. Using a DC linear approximation of power flows can be simplified the calculation process. The power transmission line from bus *i* to *j* has also a flow limit, see eq (11).

$$-F_{ij}^{max} \leq f_{ijt} \leq F_{ij}^{max} \tag{11}$$

Emission constraints

Due to environmental concerns, emission limits may be imposed on the power system operation. Emission constraints can be modelled by eq (12).

$$\sum_{g \in G} \sum_{t \in T} (F_g^e(p_{gt}) u_{gt} + SU_g^e v_{gt} + SD_g^e w_{gt}) \leq E^{max} \tag{12}$$

2.2 Demand response

Demand response provides the opportunity to control the operation of the electric grid and applicate the integration of intermittent electricity generation. Through demand response the electricity consumer is able to alter its consumption in response to some incentives or changes in the price of electricity. The change of the consumption patterns is into an optimal way to match with the electricity generation [10]. Demand response refers to strategies and technologies that are able to modify the consumption patterns inducing lower electricity use at times of high market prices or when the system is threaten. The load flexibility and short term customer action are the main objectives of the demand response.

It is expected that electric vehicle increases the number of the vehicles on the roads, assuming that there will be an annual growth rate of 20% for countries without specific sales target [11]. Regarding renewable generation, the IEA Photovoltaic Energy Roadmap [12] foresee 4600GW of installed capacity by 2050 with the prices reduced to the third part since 2008. In Figure 2 is shown the foresee regional generation for the different countries.

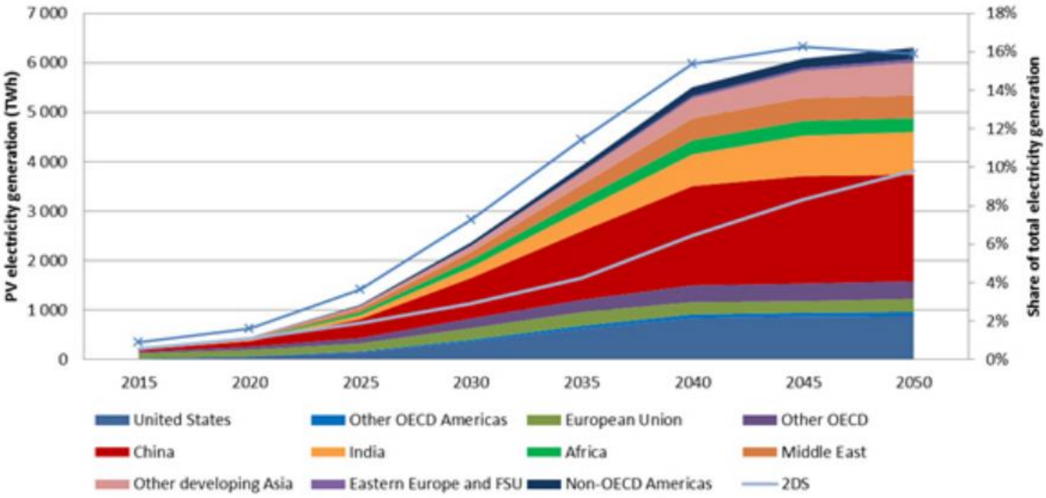


Figure 2. Regional production of PV electricity foresees

In order to facilitate the large-scale integration of intermittent electricity generation is important to match electricity supply and demand by applying Demand Side Management (DSM) measures, that comprises energy efficiency measures and permanent or regular changes in the demand pattern [10]. One of DSM measures is the Demand Response.

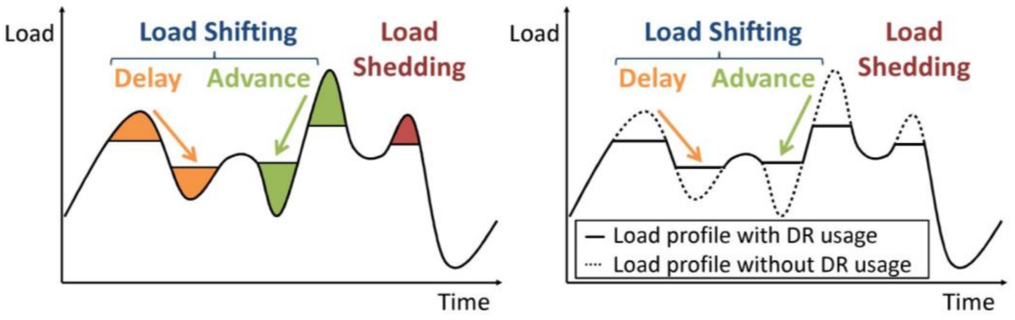


Figure 3. Mechanism and impact of the Demand Response measures load shifting and load shedding **[13]**

In Figure 3 the mechanism and impact of the demand response measures are shown. When using the demand response with the load the peaks are reduced and the consumption load is able to adapt to the generation. As a result, it is possible to change the heating demand to hours where the generation is able with renewable energies. Also, the consumption patterns changes in response of the electricity price. As a consequence, the GHG emissions could be highly reduced.

2.3 Space Heating Demand

The heating demand is thought to be the most important factor on the building heat demands. Nevertheless, it is expected that building heat demands reflect levels of energy services available, insulation and comfort, that make the heat demand of the buildings decrease [14]. In this section, the different factors that involve the space heating demand will be described.

2.3.1 Residential Space Heating demand in Europe: Current state and future perspectives

In 2015, half of the final energy demand in EU28 was used for heating and cooling, while the rest of the final energy was consumed by transport and electricity, summing up a 32% and 18% respectively [15].

The consumption of heating and cooling systems is influenced by different factors, such as demographics, the efficiency of the building, energy availability, energy policies, economic structure and climate consideration. As a result, the final energy demand for residential space heating and cooling in Europe varies a lot for the different countries. Figure 4 shows the final energy demand for different EU countries. In eleven countries more than a half of total final energy demand is used for residential space heating, having some countries such as Slovakia, Romania, Latvia and Finland more than 60% of the total energy demand aimed to heating and cooling. More than half of the total energy of Europe is consumed by Germany, France and Italy, accounting for 22%, 12% and 11.5% of the total EU energy demand respectively.

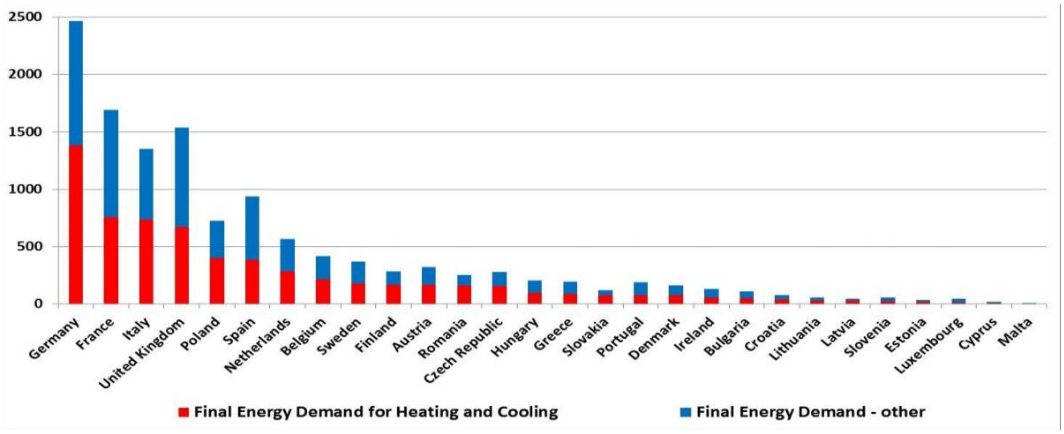


Figure 4. Final energy demand per country in EU (TWh) **[15]**

At the moment, fossil fuels are the dominant supply sources for heat demand in the EU. Coal, oil products and natural gas represent around 68% of the total supply to the building heat market. Taking into account the electricity, which sometimes it is generated by fossil fuels the percentage increases to 78%. That means that the European building sector has to take into consideration the decarbonisation of the system in the future as there are a lot of possibilities to reduce the consumption of fossil fuels. An example for reducing the use of fossil fuels could be using recovery excess heat from energy and industry activities, as well as with renewable resources [14].

In Figure 5 the final energy consumed by residential sector is shown, with both single and multifamily houses in EU in 2015. Fossil fuels dominate the supply of heating demand.

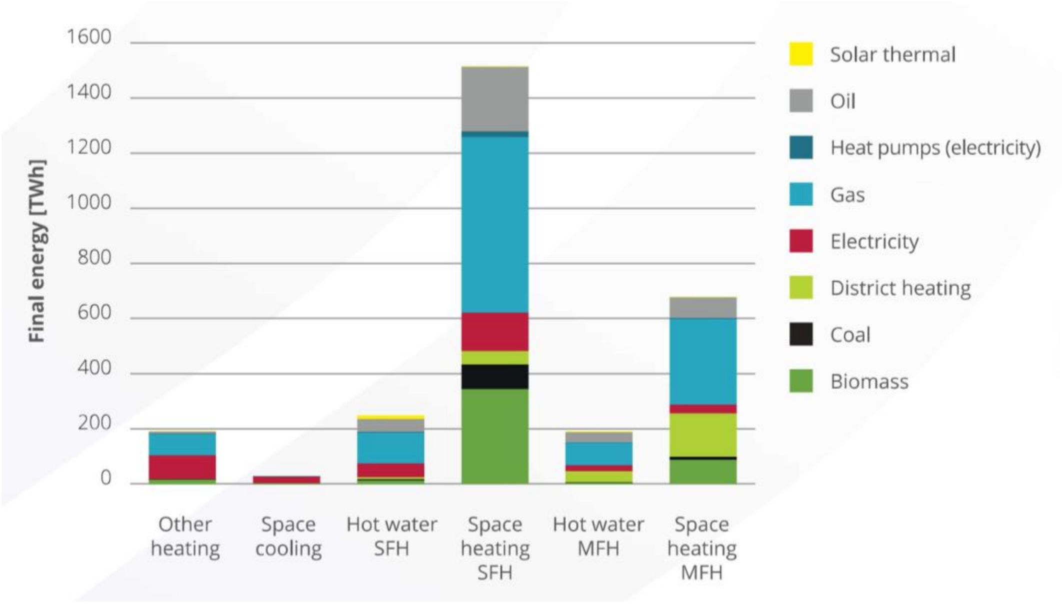


Figure 5. Residential sector by single/multifamily house in 2015 **[16]**

Figure 6 shows the final energy demand for the residential space heating in EU by 2015. The use of natural gas is considerably higher than the rest of sources in Europe, it is essentially located in north and west Europe and some central European countries such as Italy, the Netherlands and Hungary, accounting for more than half of the final energy demand for heating. The use of coal is concentrated in Poland and other countries such as the UK, Czech Republic, Sweden and Slovakia. Regarding the use of oil, countries such as Greece, Cyprus, Ireland, the UK, Belgium and Germany are the principal operators. Thermal energy issued from electricity is important in Malta and Cyprus. Due to colder climates, district heating is represented in Denmark, Lithuania, Finland, Estonia, Slovakia, Bulgaria and Latvia. Finally, in Baltic and Nordic Member States is found the highest share of renewable energy sources since their large wind availability.

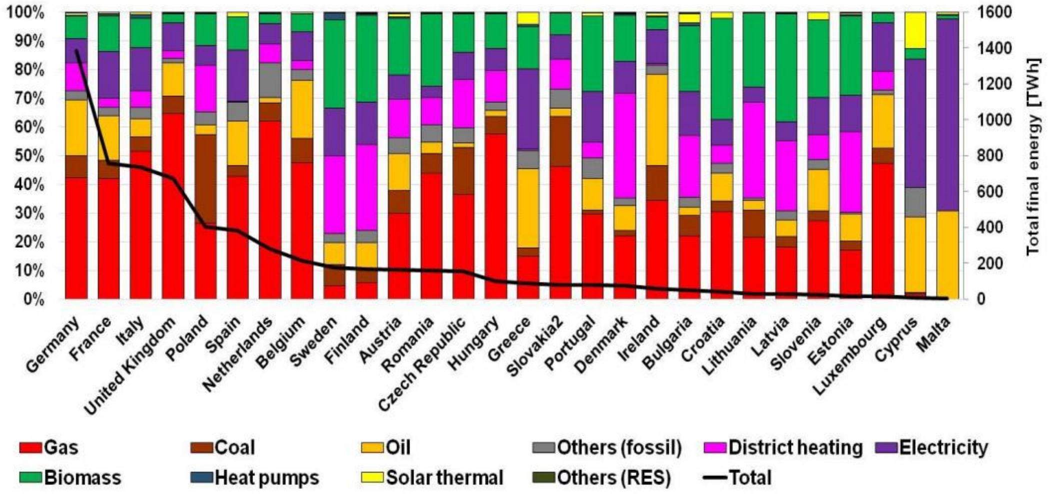


Figure 6. Final energy demand for heating and cooling per country and energy carrier in EU, 2015 **[15]**

Regarding the decarbonisation, Europe has different targets for 2020, 2030 and 2050 [15]. The strategy covers the timeframes in order to ensure a sustainable energy consumption by lowering the GHG emissions, pollution and fossil fuel dependence. The targets for 2020 defines the Europe priorities between 2010 and 2020. The priorities are reducing the GHG emissions by at least a 20%, increase the share of renewable energy at least 20% of gross final consumption and to improve the energy efficiency by at least 20%.

The framework for 2030 explains the objectives between 2021 and 2030. A mandatory target of at least a 40% reduction of GHG emissions compared to 1990 levels, a biding target of at least 27% of renewable energy and an energy efficiency increase of at least 27%.

The Energy Roadmap 2050 [16] sets out scenarios where a reduction of 80%-95% of the GHG emissions is reached by 2050 comparing with 1990 levels. The main objective is replacing the fossil fuels in the heating and cooling sector as well as in transport and power sector. To achieve the target, the electrification of the heating systems, using heat pumps and storage heaters will play a major role. The electricity can be generated by renewable energies reducing as much as possible the GHG emissions of the heating sector.

The total installed electricity generation capacity will increase from 1100 GW in 2015 to around 6000 GW by 2050 [17], as it is shown in Figure 7. By 2050 the majority of installed capacity will be constituted by solar PV with 4400 GW and wind with 960 GW. Regarding the heating sector, heat pumps, electric heating and biomass-based heating establish the majority of installed capacity by 2050. Fossil fuels will be highly reduced from the energy system by the last 5-year period leading up to 2050. The capacity of heat pumps and biomass heating will occur.

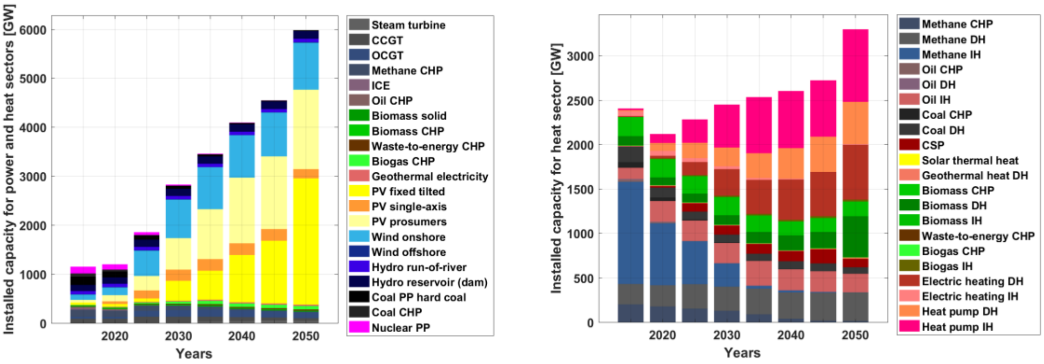


Figure 7. Technology-wise installed capacities for power (left) and heat (right) during the energy transition from 2015 to 2050 in Europe

In conclusion, residential space heating represents an important share of the total energy consumption in Europe. The heating demand is largely supplied by fossil fuels. As a consequence, the heating consumption for residential spaces are responsible for a large part of the CO_2 emissions in Europe. It is expected that in the future a large part of the heating demand will be electrified. This will add challenges to the power system, but also it will generate opportunities.

The opportunities that it could have the electrification could be the total decarbonisation since the wind and solar PV are on track to become the cheapest electricity sources. The growth of connected grids, due to the facility to transfer energy from one point to another. And finally, the creation of new business models for the power sector, in particular to blurred the difference between generation and consumption.

2.3.2 Residential power to heat options

There are several ways to convert electricity into heat. Following the categorization provided in Figure 8, there is centralized and decentralized power-to-heat options. In the first option, centralized, electricity is converted into heat at a central location. It could be distant to the point of heat demand. To distribute the heat a heating network is used. By contrast, decentralized power-to-heat transforms electricity into heat very close to the location of heat demand.

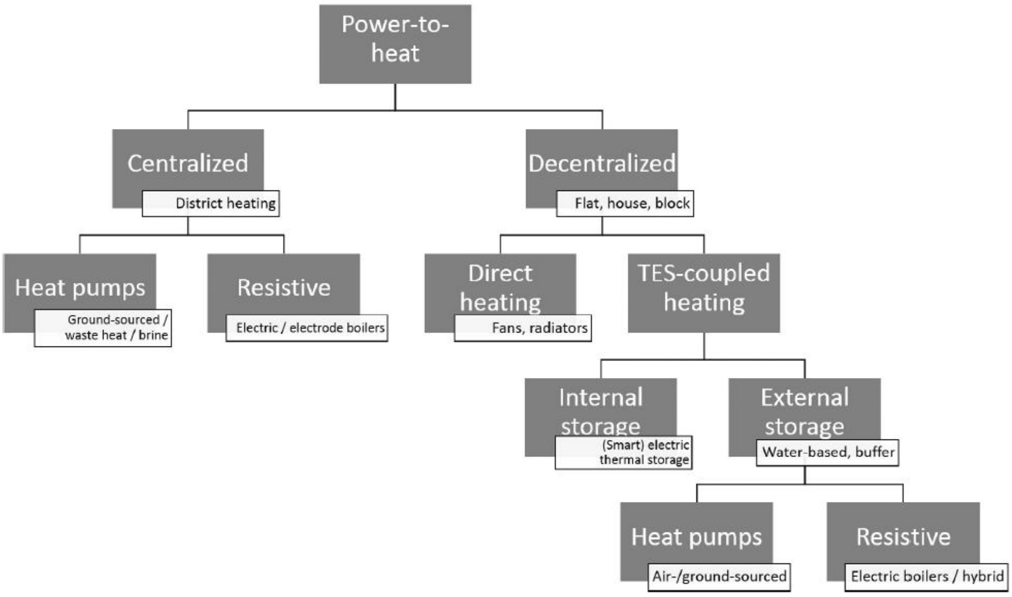


Figure 8. Categorization of residential power-to-heat options **[5]**

Regarding heat storage, district heating networks have thermal storage capacity and as a consequence the centralized options are able to storage energy in the network. The capability of storage networks can be improved with dedicated thermal storage facilities, allowing seasonal storage. By contrast, decentralized options, as they have direct heating, come without storage heating. Nevertheless, decentralized option can be combined with thermal energy storage, that can be either internal or external. Electric storage heaters are an example for internal thermal energy storage, which store in a well-insulated solid medium. If it has advanced control and communication equipment, it is referred to as smart electric thermal storage. Hot water storage elements could be an example for external thermal energy storage [5].

2.3.3 Thermal energy storage systems

The variability of the renewable generation is a challenge that makes difficult to get the fuel-efficient and cost-effective integration of large amounts of renewable energies. Wind power shows a high variability depending on the wind availability. Large ramps in generation can be observed, periods of no generation occurs where wind generation can be higher than the load [4]. Energy storage systems can provide the flexibility to the system to accommodate this variability.

Energy storage systems helps to capture energy produced when the generation exceed demands and supply energy when there is a peak demand. There are different technologies that facilitate the integration of renewable energies in the power and heat sectors, such as large heat pumps, electric boilers, heat storages in the heat sector, and electric vehicles and electric energy storage in power sector [5].

Other type of thermal energy storage is the passive heat storage, where the thermal energy is stored in the building mass or in the interior of the house and it is releases in a non-controlled way. The building is heated in hours where there is high generation availability, increasing the temperature. The energy is stored as heat in the building. When the generation availability decreases, the heating consumption is also reduced. Then, the building releases the thermal energy stored and the indoor temperature decreases. It can enable larger reductions in excess of electricity production and fuel consumption than heat accumulation tanks [4]. In addition, passive heat storage is more cost-effective than heat accumulation tanks [4].

3 Modelling of thermal loads

Thermal loads have an important impact on the behaviour of a dwelling. Moreover, it is expected that a large part of the thermal loads will be electrified in order to reduce CO_2 emissions. Adding the thermal loads into the power system would have a great impact on the operation and they have a high potential to provide flexibility due to the natural thermal storage of the buildings. For that reason, it is important to consider it into the power system operation.

In order to be able to study the flexibility that thermal loads add to the power system, is important to have a model that describes the behaviour.

The factors that affect the heating consumption are shown in Figure 9 and are those that are able to change the state of the indoor air. That factors are heat gains due to solar radiation, internal heat gains, heat loss by transmission, ventilation losses and the heat recovery for the ventilation system.

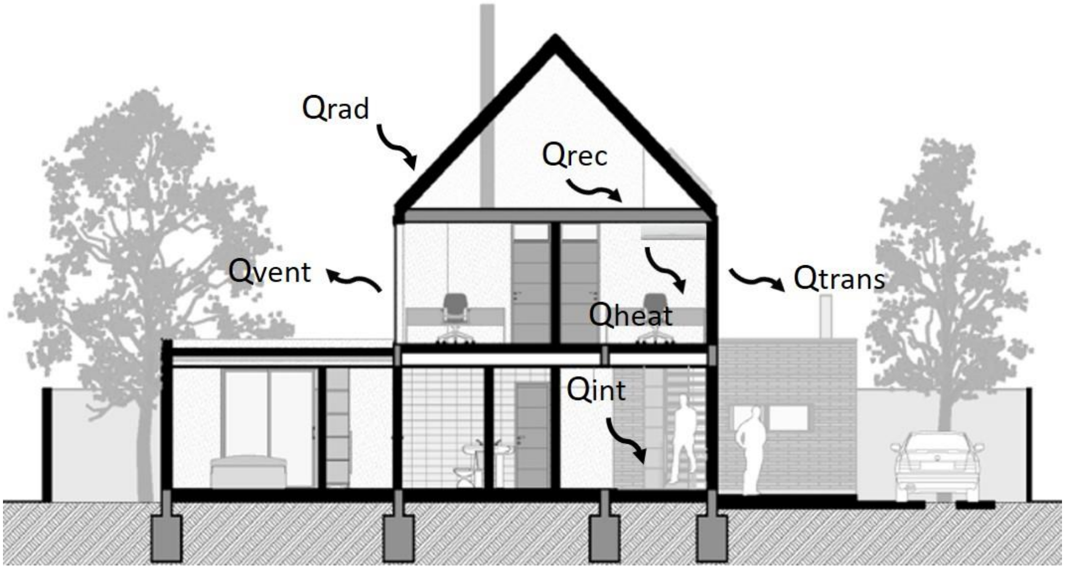


Figure 9. Distribution of the different heat gains and losses in a dwelling

As it can be seen in the previous figure, the gains that increase the temperature of the building are radiation heat gains, internal gains and the gains produced by the heat recovery. However, the losses of the building are due to ventilation losses and transmission losses.

3.1 Model of the thermal load of a dwelling

Adding a heating loads to the power system impacts the behaviour of the system in terms of generation and transmission lines flows. Therefore, it is important to take it into account within the Unit commitment problem.

In this chapter, the equations that model the thermal behaviour of the dwellings will be described.

3.1.1 Power balance constraint including space heating demand

As a heating load demand is considered for a general single or multifamily dwelling, depending on the case study, it is important to have limits and constraints to correctly model the thermal behaviour of the dwelling.

The power balance is modified in order to add the heating demand. The different gains and losses that appear in the house are included in the power balance in order to know the heating demand required.

3.1.2 Heat gains due to solar radiation

The solar radiation transmit heat into the building. The radiation goes throughout the windows and doors, heating the indoor air. A simplified model for the solar heat gains will be used. Only one window is considered, which corresponds to the total area of the building's windows. Reduction factors are included to consider the shading coefficient of the window, solar transmission of the window, frame coefficient, non-perpendicular reduction factor and the coefficient to compensate the difference in solar radiation due to the orientation of the windows.

The coefficient of solar transmission of the window indicates the percentage of solar radiation that goes throughout the window and is able to warm the indoor air. The shading coefficient of the window is used to measure the different shading objects that can be in the external part of the window, the external shading. The frame coefficient of the window is to take into account the frame of the window that does not let the sun radiation penetrate inside the house.

In addition, there are two more coefficients that are used to correct the difference in solar radiation in terms of orientation and incidence. The non-perpendicular reduction factor is used to compensate the incidence in solar radiation of each façade, while the correction factor is to compensate the orientation of the windows.

$$Q_{rad} = T_S * W_C * W_f * S_W * I_{sol} * Coef * Correc \tag{13}$$

The correction factor is calculated for each case study in Appendix 8.

3.1.3 Internal heat gains

The building has internal heat gains generated by occupants, lighting devices and electrical appliances. The internal heat gains are:

- Heat generation by light sources
- Heat generation by appliances
- Heat generation by occupants
- Heat generation by ventilation fans

To simplify the model, an average value for specific heat gain is considered to encompass the different internal heat gains that appear in a building [18]. The average internal gains factor stated in Tabula data [19] is in respect to the total heated floor area. Therefore, the internal heat gains can be computed as in eq (14).

$$Q_{int} = Heat_{gain} * A \tag{14}$$

3.1.4 Heat loss by transmission

Heat is lost by transmission through the building envelope components, such as walls, doors, windows, roof and all the elements that are in contact with the external air. The amount of heat that is loss by transmission depends on the thermal transmittance of the building, the surface of the envelope and the difference between the indoor and outdoor air temperature.

To simplify the model, the average thermal transmittance of the building is used. This factor can be calculated taking into account the transmittance of each part of the building, like walls or windows, and its area.

The equation of the transmission heat losses, at given time t can be computed as:

$$Q_{trans} = U * A_{env} * \left(T_{out}(t) - T_{int}(t)\right) \tag{15}$$

3.1.5 Ventilation losses

Due to sanitary requirements, the ventilation of the building is necessary to ensure the renovation of the air and good air quality conditions. When the ventilation takes place, convection losses appear. The losses by convection are given by the transport of heat from one area to another with different temperatures, in this case between the indoor and outdoor of the house.

The ventilation is composed by two different types. The first one is the sanitary ventilation, that involves the minimum flow rate in buildings. The second one is the natural ventilation, that occurs when the indoor air temperature exceeds the comfort limit, T_{max}. Usually natural ventilation takes place in summer and spring.

The heat loss due to sanitary ventilation is described by (16).

$$Q_{vent} = c_{pa} * V_c * A * h_{room}\left(T_{vent}(t) - T_{int}(t)\right) \quad (16)$$

The instantaneous indoor temperature, T_{int}, is defined in equation (22).

If the building does not have heat recovery from exhaust air, the temperature of supply air is equal to outdoor air temperature.

$$T_{vent}(t) = T_{out}(t) \quad (17)$$

Otherwise, if there is a heat recovery system in the building, the supply air is preheated by the heat recovery. This occurs only if the outdoor air temperature is below 15°C [18]. in that case, the temperature of supply air is defined as:

$$T_{vent}(t) = T_{out}(t) + H_{rec} * \left(T_{int}(t) - T_{out}(t)\right) \quad (18)$$

The value of the effectivity of the heat recovery depends on the heat recovery unit, but typical values are between 70% and 80% [20].

The natural ventilation, Q_{vnat}, known also as 'free cooling' is used to cool the building by means of natural ventilation. When the indoor temperature exceeds the upper comfort limit, the natural ventilation takes place. That is, when $T_{int} > T_{max}$. This type of ventilation could be carried out, for example, by opening the windows. The heat loss by natural ventilation is computed as:

$$Q_{vnat} = c_{pa} * V_{cn} * A * h_{room}\left(T_{out}(t) - T_{int}(t)\right) \quad (19)$$

T_{max} is the temperature that determine the upper temperature of the comfort range.

The total heat loss due to the ventilation results as:

$$Q_v = Q_{vent} + Q_{vnat} \tag{20}$$

In this study, the natural ventilation is not taken into account because the main focus of the project is in the heating demand.

3.1.6 Indoor air temperature

The indoor air temperature is the temperature reached in the interior of the dwelling. The model assumes the same temperature for the indoor air temperature and for all internal layers. The indoor air temperature changes in each time and it can be calculated with the differential energy balance equation:

$$C * \frac{dT_{int}(t)}{dt} = Q_{heat}(t) + Q_{rad}(t) + Q_{int}(t) + Q_{trans}(t) + Q_v(t) \tag{21}$$

Thus, integrating the equation, the indoor air temperature for each time is found as:

$$T_{int}(t) = T_{int}(t-1) + \frac{Q_{heat}(t-1)+Q_{rad}(t-1)+Q_{int}(t-1)+Q_{trans}(t-1)+Q_v(t-1)}{C} \tag{22}$$

Equation (22) includes the heat supplied in the dwelling by the heating equipment. Consequently, it is possible to calculate the indoor air temperature and the heat provided by heating equipment in each moment.

Depending on the work mode, explained in section 3.1.11, the heating demand will be switch on provided that there are heating demand, $q(t) > 0$, and the indoor air temperature is lower than the minimum temperature.

3.1.7 Temperature comfort limits

Temperature comfort limits are important to maintain the comfort of the owners. The temperature limits are as follows:

$$T_{min} < T_{int} < T_{max} \tag{23}$$

In order to optimize the behaviour of the heating system, a minimum and maximum value are defined as a comfort range of temperature. The values are 21.2 and 24°C [10], respectively.

3.1.8 Maximum capacity of the heating system

The capacity of the heating system, limits the amount of heat that can be supplied by the heating system.

$$Q_{heat}(t) \leq P_{max} \tag{24}$$

It could happen that the maximum power of the heating system is lower than the heating demand, $q(t) > P_{max}$. The indoor air temperature of the building will be lower than the bottom limit temperature, $T_{int} < T_{min}$.

3.1.9 Heat recovered

Heat recovery ventilation is also known as mechanical ventilation heat recovery (MVHR). It is an energy recovery ventilation system that works between two sources, the indoor and outdoor of the dwelling. The temperature between the sources is different and recovering part of the heat that is transferred by convection during the ventilation, it helps to reduce the heating and cooling demand in a building. The fresh air is introduced into the system and preheated before entering into the building. There are two different types of heat recovery:

- Heat recovered by heat exchanger

Part of the heating demand for the sanitary ventilation losses are recovered using a mechanical supply-exhaust ventilation system.

$$Q_{rec} = Q_{vent} * H_{rec} \tag{25}$$

- Heat recovered by exhaust air heat pump

Part of the heating demand for the sanitary ventilation losses are recovered using an exhaust air heat pump. The procedure relies upon the outdoor air temperature.

For $T_{out} < 5°C$:

$$Q_{recfvp}(t) = V_c * A * c_{pa} * h_{room} * Per_{hp} * (T_{int}(t) - 278.15) \tag{26}$$

For $T_{out} > 5°C$:

$$Q_{recfvp}(t) = V_c * A * c_{pa} * h_{room} * Per_{hp} * (T_{int}(t) - T_{out}) \tag{27}$$

If a heat recovered takes place in the system, the amount of heat recovered is added to the main equation, (22). The indoor air temperature and the heat needed to maintain the temperature will be calculated with the gains. The heat recovery helps to increase T_{vent} in eq (18).

3.1.10 Electric energy demand

The electric energy demand for the thermal load is calculated as the heat supplied to the building at each time multiplied by the share of heating demand covered by electricity, the number of dwellings and the COP of the system.

$$E_{heat}(t) = Units * Q_{heat}(t) * E_n * COP \tag{28}$$

3.1.11 Smart and non-smart operation

In order to study the flexibility that can be provided by the space heating demand, two operation modes are considered, the smart and non-smart modes. The smart operation is the one able to keep the indoor air temperature inside a comfort range. In the non-smart operation, the heating system tries to maintain the indoor air temperature to a predefined value. The difference between smart and non-smart operation is that the first is able to provide more flexibility to the power system, while the non-smart operation is more restricted.

In the non-smart case, the temperature is limited to the minimum temperature, T_{min}. to achieve this, the heat supplied to the dwelling at each time must be the necessary to reach the minimum indoor temperature in the next period of time. Because heat gains could be greater than heat losses in some hours, there will be periods where the indoor air temperature will increase over T_{min} even if the heating system is switch off. In this operation mode,

- If $C * (T_{min} - T_{int}) - \sum gain \geq 0$, then

$$Q_{heat}(t) = C * [T_{min}(t) - T_{int}(t)] - \sum gain\ (t) \tag{29}$$

- Else:

$$Q_{heat}(t) = 0 \tag{30}$$

The equation (29) makes sure the heat generated is only the necessary to keep $T_{int} = T_{min}$.

If $C * [T_{min}(t) - T_{int}(t)] - \sum gain\ (t)$ has a negative value the heat gains are higher than the losses, and the indoor temperature will increase beyond T_{min}. As a consequence, the heating is not needed.

To include this operation mode in the optimization model, the following constraints (31) - (34) must be included.

$$M_1 * I_{g,t} \geq C * [T_{min}(t) - T_{int}(t)] - \sum gain\ (t) \tag{31}$$

$$-M_1 * \left(1 - I_{g,t}\right) \leq C * [T_{min}(t) - T_{int}(t)] - \sum gain\ (t) \tag{32}$$

$$Q_{heat} \leq M_1 * I_{g,t} \tag{33}$$

$$Q_{heat} \leq C * [T_{min}(t) - T_{int}(t)] - \sum gain\ (t) - M_1 * \left(1 - I_{g,t}\right) \tag{34}$$

Therefore, Q_{heat} can only be greater than zero if $I_{g,t}$ is 1, which occurs only if the right hand side of (31) is positive. These constraints ensure the operation described by the logical relations (29) and (30).

3.2 Unit Commitment model including space heating loads

The resulting problem is described in the following equation. From eq (1) to eq (12) is described the Unit commitment problem. The equations are described and explained in section 2.1.1. The power balance equation, now contains the thermal load and the equations that defines the thermal behaviour of the building are from eq (13) to eq (34).

$$\min \textstyle\sum_{g \in G} \sum_{t \in T} \left(SU_g v_{gt} + SD_g w_{gt}\right) + \sum_{g \in G} \sum_{t \in T} F_g\left(p_{gt}\right) + VOLL \sum_{i \in N} \sum_{t \in T} \delta_{it}\ \ \forall t, g$$

(1)

$$P_g^{min} u_{gt} \ \leq\ p_{gt} \ \leq\ P_g^{max} u_{gt} \qquad \forall t, g \tag{2}$$

$$P_{t,g} - P_{t-1,g} \leq u_{t-1,g} \overline{R_g} \Delta T_t + S_{t,g} P_g^{ini} \qquad \forall t, g \tag{3}$$

$$P_{t-1,g} - P_{t,g} \leq u_{t,g} \underline{R_g} \Delta T_t + D_{t,g} P_g^{max} \qquad \forall t, g \tag{4}$$

$$u_{t,g} \geq \textstyle\sum_{\tau=t-ton_g}^{t} S_{\tau,g} \qquad \forall t, g \tag{5}$$

$$1 - u_{t,g} \geq \textstyle\sum_{\tau=t-tof_g}^{t} D_{\tau,g} \qquad \forall t, g \tag{6}$$

$$P_{t,g} + Rp_{t,g} + Rs_{t,g} \ \leq u_{t,g} P_g^{max} \qquad \forall t, g \tag{7}$$

$$\textstyle\sum_{(i,j) \in A_i^+} f_{ijt} - \sum_{(i,j) \in A_i^-} f_{ijt} = \sum_{g \in G} p_{t,g} + R_{it} - D_{it}^0 + \delta_{it}\ \forall t, g \tag{8}$$

$$\textstyle\sum_{g \in GT} Rp_{t,g} \geq Rrp_t \qquad \forall t, g \tag{9}$$

$$\sum_{g\in GT} Rs_{t,g} \geq Rrs_t + \sum_{g\in GT\cup GF} R_{var}P_{t,g} \qquad \forall t,g \tag{10}$$

$$-F_{ij}^{max} \leq f_{ijt} \leq F_{ij}^{max} \tag{11}$$

$$\sum_{g\in G}\sum_{t\in T}(F_g^e(p_{gt})u_{gt} + SU_g^e v_{gt} + SD_g^e w_{gt}) \leq E^{max} \qquad \forall t,g \tag{12}$$

$$Q_{rad} = T_S * W_C * W_f * S_W * I_{sol} * Coef * Correc \tag{13}$$

$$Q_{int} = Heat_{gain} * A \tag{14}$$

$$Q_{trans} = U * A_{env} * \left(T_{out}(t) - T_{int}(t)\right) \tag{15}$$

$$Q_{vent} = c_{pa} * V_c * A * h_{room}\left(T_{vent}(t) - T_{int}(t)\right) \tag{16}$$

For $T_{out}(t) \geq 15$°C:

$$T_{vent}(t) = T_{out}(t) \tag{17}$$

For $T_{out}(t) < 15$°C and for heat recovery:

$$T_{vent}(t) = T_{out}(t) + H_{rec} * \left(T_{int}(t) - T_{out}(t)\right) \tag{18}$$

$$Q_{vnat} = c_{pa} * V_{cn} * A * h_{room}\left(T_{out}(t) - T_{int}(t)\right) \tag{19}$$

$$Q_v = Q_{vent} + Q_{vnat} \tag{20}$$

$$T_{int}(t) = T_{int}(t-1) + \frac{Q_{heat}(t-1) + Q_{rad}(t-1) + Q_{int}(t-1) + Q_{trans}(t-1) + Q_v(t-1)}{C} \tag{22}$$

$$T_{min} < T_{int} < T_{max} \tag{23}$$

$$Q_{heat}(t) \leq P_{max} \tag{24}$$

$$E_{heat}(t) = Units * Q_{heat}(t) * E_n * COP \tag{28}$$

For $C * (T_{min} - T_{int}) - \sum gains \geq 0$:

$$Q_{heat}(t) = C * [T_{min}(t) - T_{int}(t)] - \sum gain\ (t) \tag{29}$$

For $C * (T_{min} - T_{int}) - \sum gains < 0$

$$Q_{heat}(t) = 0 \tag{30}$$

$$M_1 * I_{g,t} \geq C * [T_{min}(t) - T_{int}(t)] - \sum gain\ (t) \tag{31}$$

$$-M_1 * (1 - I_{g,t}) \leq C * [T_{min}(t) - T_{int}(t)] - \sum gain\ (t) \tag{32}$$

$$Q_{heat} \leq M_1 * I_{g,t} \tag{33}$$

$$Q_{heat} \leq C * [T_{min}(t) - T_{int}(t)] - \sum gain\ (t) - M_1 * (1 - I_{g,t}) \tag{34}$$

3.3 Implementation

The tools used to solve the Unit Commitment problem including the space heating loads are implemented in java language by using the Object Oriented Programming methodology. The problem is modelled and solved through ILOG libraries and the optimizer CPLEX.

In order to be able to start the planning process, the different data should be provided: the heating demand specifications, the generation capacity, the specification of the different generation units, solar and wind profiles, temperature and irradiance, load specifications and transmission lines specifications.

The methodology works in the following way:

1. Reading input data: the input files are read and the objects that model the system are built.
2. Problem construction: with the information of the input data, the problem is modelled.
3. Solution of the problem: the problem is solved in order to minimize the total system cost.
4. Generation of output files: the output files are written with the results of the behaviour process

Figure 10 shows the methodology block diagram.

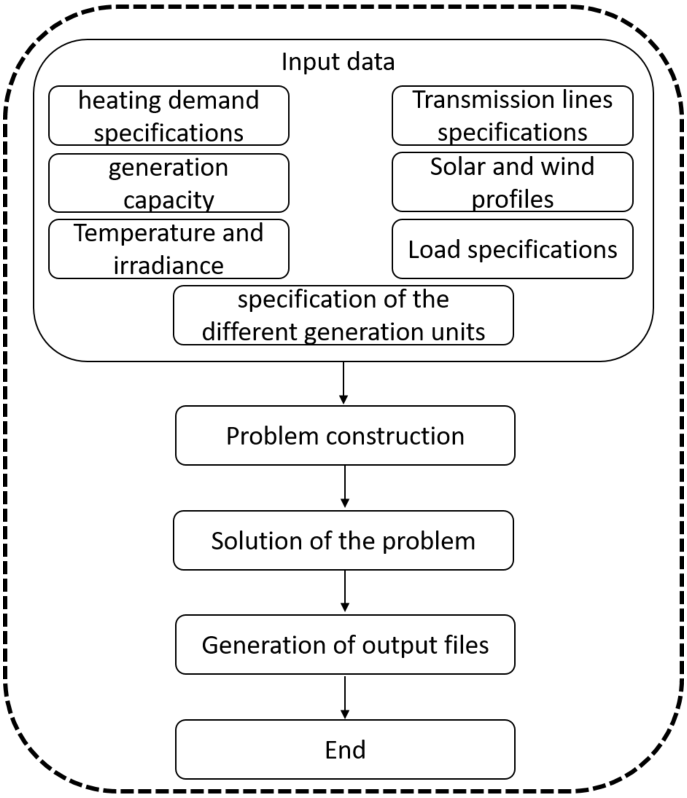


Figure 10. Block diagram of the implementation of the methodology

4 Case studies

The motivation of performing different case studies arises from the necessity to know how the thermal load will impact on the power system. The inclusion of the thermal loads in the power system will tend to increase the peak demand of the power system, this could have a negative impact on it. Nevertheless, the buildings have a natural thermal storage, which can grant flexibility to the power system.

The first case studies the behaviour of an efficient single-family dwelling for a week. The second case study is similar to the first one but using an inefficient single-family dwelling. Finally, the third case study analyses a system with a more detailed modelling of the building stock. The period of time studied in the third case is the whole heating demand period of the year, namely 24 weeks.

Each case study involves different situations and variables. Moreover, three different scenarios are considered in each case study. The purpose is to analyse which scenario is more profitable for the system and to study how the system reacts in front of each situation. The scenario X-5 of the e-Highway 2050 project [16]. The input data is obtained from the scenario X-5 Large Scale RES and low emissions gives the priority to large scale renewable energy systems, alongside with centralized storage solutions. Fossil fuel generation completes the energy mix, but CO_2 intensive technologies are not widely spread.

4.1 Description of the test system

The case studies are based on a future projection of the German power system by the year 2030. The input data is obtained from the project e-Highway 2050 [16]. The system under study consists of the power system coupled to thermal loads that are supplied by electric heating devices such as heat pumps, electric boilers, etc.

The power system is composed by different generators, loads and thermal loads. The system consists of an electric grid, where the generators generate electricity and supply it to the grid. The generators are distributed around the country and are powered by lignite, coal, gas and renewable energies. Once the electricity is generated, their distribution on the different consumption points is done. The electricity consumption considers the current use, electric vehicles and non-residential heating. Additionally, thermal loads for residential space heating are considered. The space heating requirements of each dwelling are modelled and scaled to the number of dwellings in each node of the power system.

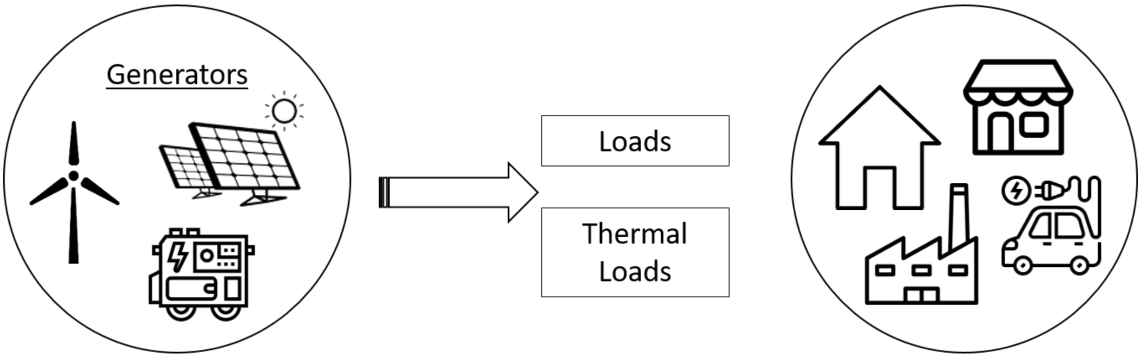


Figure 11. Scheme of the structure of the case studies

4.2 Germany by 2030

The future projection of the German power system is obtained from the e-Highway 2050 project [21].

In order to organize the generation and consumption, Germany is divided into seven different zones. Figure 12 shows how the power system is divided. For modelling different names are taken for each one of the zones, being the relation as:

Zone 0 → 31DE
Zone 1 → 32DE
Zone 2 → 33DE
Zone 3 → 34DE
Zone 4 → 35DE
Zone 5 → 36DE
Zone 6 → 37DE

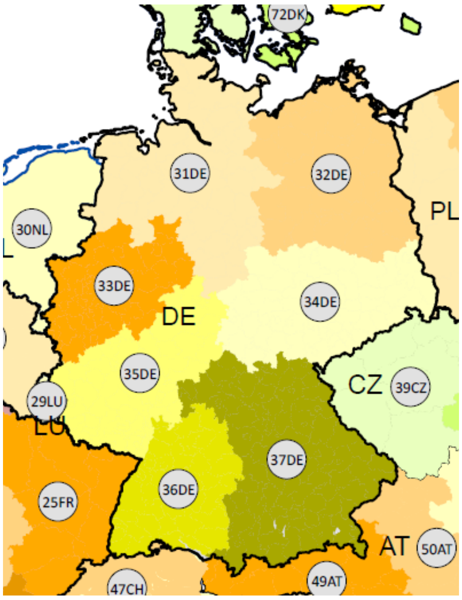


Figure 12. Division of the country in different zones

The generation units comprise thermal and renewable generators. Thermal generators include lignite units, coal units, open cycle gas units (OCGT) and combined cycle gas units (CCGT). Renewable generators include, wind, solar, biomass and run on river generators. Pumped hydro storage plants are not considered in the case study.

4.2.1 Installed capacity

Figure 13 shows the installed capacity for each zone of the power system by the year 2030 obtained from [21]. Each zone has different generators installed, conventional and non-conventional.

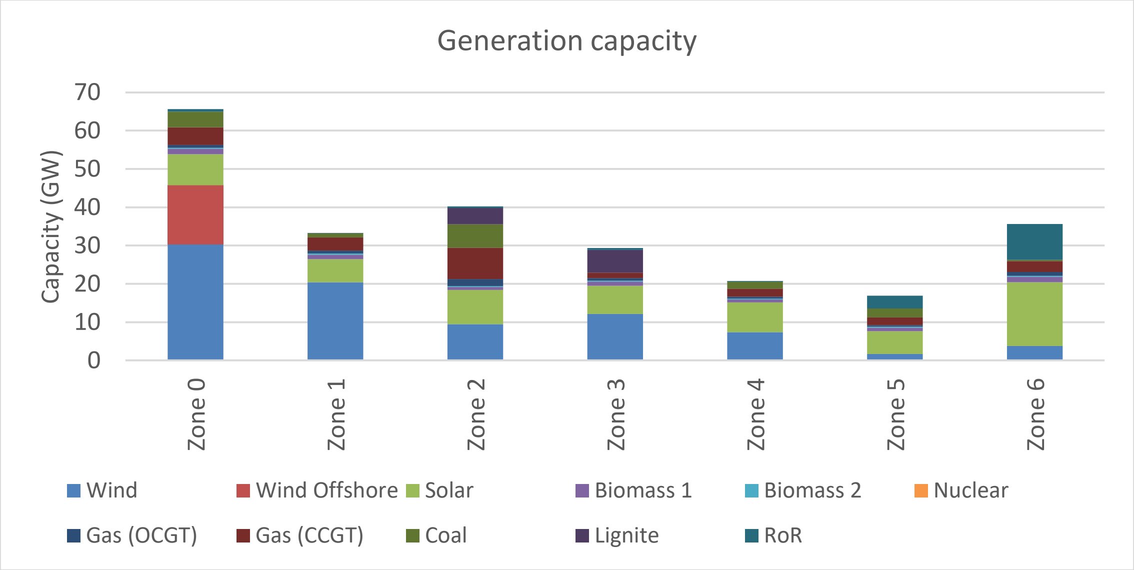


Figure 13. Generation capacity per zone and type of generation

As it can be seen the installed capacity of wind and solar energy is predominant in the system. Offshore wind energy has an important development in Zone 0, which corresponds to the North Sea. The total share renewable generation is 74%. In the graphic, the wind capacity is divided into onshore and offshore wind. Biomass is divided into two types with different characteristics and costs. The generation with biomass 2 is more expensive than with biomass 1. As it is said in the previous section, the gas is also divided into OCGT and CCGT. The hydraulic generation is present as generation with Run of River plants.

The capacity installed of wind is 40% of the total capacity, being 34% of the total from onshore wind and 6% from offshore wind generation. The percentage of wind capacity installed is the highest share of the total. The following highest share of capacity installed is from renewable sources too, 24% of solar capacity. The run on river generators have 6% of the installed capacity and biomass has 4%. On the other side, conventional generators have a total capacity installed of 22%.

Each type of generator is modelled by a generic unit with corresponding operational cost, and technical parameters. The technical parameters are the efficiency, maximum and minimum output power, ramp rates, CO_2 emissions and operation times.

4.2.2 Future load

Future load projection is also obtained from data of the e-Highway 2050 project [21]. The total load for year 2030 sums up to 508.71 TWh. A 7% of the total load corresponds to residential space heating.

The difference of consumption between zones is determined by demographic factors such as the number of inhabitants per zone [21]. Regarding residential heat consumption, it depends on the outdoor air temperature, the solar radiation and, also, the number of dwellings per zone.

Load profiles for current use are obtained from real data of 2016 for Germany [2] and scaled to the total yearly load. Fixed loads for electric vehicles and non-residential space heating are obtained from the e-Highway 2050 project [16].

Figure 14 shows the foresee load consumption for 2030. The highest consumption appears in zone 6, with a total load consumption of 152.29 TWh. The second zone with high load consumption is zone 3, with 80.54 TWh of total load consumption. The two zones with highest load consumption do not correspond to the zones with highest generation capacity. The transmission is in charge to be able to allow the required energy imports and exports between zones.

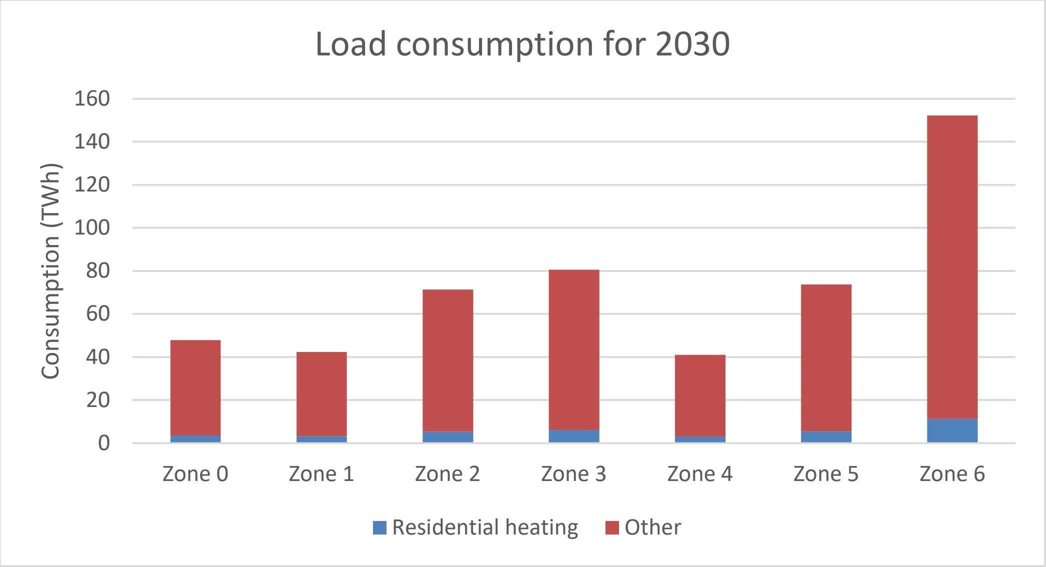


Figure 14. Load consumption for 2030

4.2.3 Radiation and temperature time series

Solar radiation and outdoor temperature are external factors that affect the requirement of space heating of the dwelling. The solar radiation and temperature time series are taken from real data of 2016 for Germany from the European Commission PVGIS [22]. The data is given as an hourly record per zone.

Figure 15 shows the irradiance profile during the year 2016 in Germany for each zone. Figure 16 shows the variation of temperature during 2016 for each zone. The average temperature for heating moths that are from October to April is 4.8°C, while for non-heating months is 17.22°C [22].

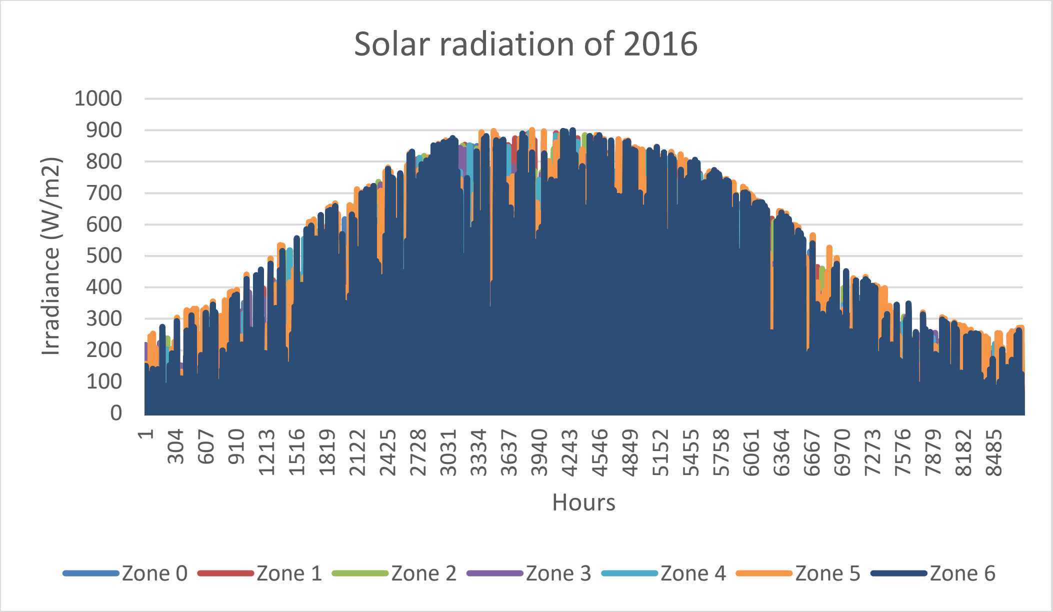


Figure 15. Profile of solar radiation of 2016

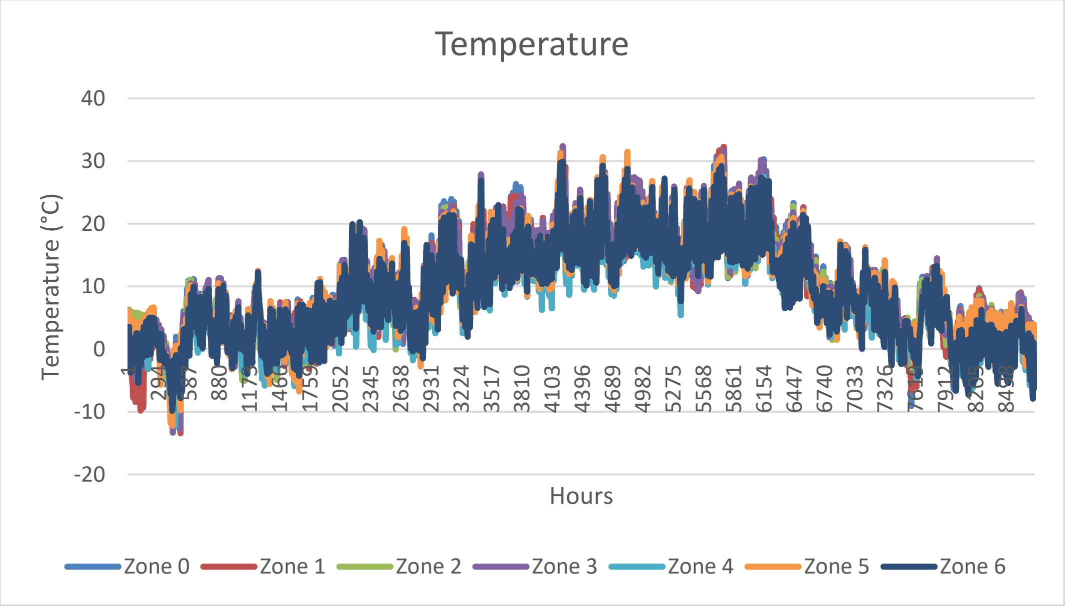


Figure 16. Profile of temperature of 2016

4.3 Case study 1

The first case study consists on analysing the behaviour of a single-family dwelling for one week. For this illustrative case a representative efficient house will be considered. The different coefficients that allow to model the thermal behaviour of the house are taken from the Tabula project [19] and are presented in Appendix 1. The sixth week of the year is selected to simulate the behaviour of the power system coupled to the thermal loads.

Three different scenarios are considered to study the impact of thermal loads on the power system operation:

- Scenario 1: the first scenario analyses the power system without residential thermal load. The loads consist of electricity demand for current use, electric vehicles and non-residential heating with fixed profiles.
- Scenario 2: the second scenario analyses the power system including residential thermal load. The heating system seeks to maintain the indoor temperature fixed at certain level.
- Scenario 3: the third scenario also considers the thermal load in the power system. In this case, the thermal load can provide flexibility by increasing or decreasing the consumption. The indoor temperature can vary within a comfort range.

Regarding thermal loads, the electricity consumption of each zone is calculated as the consumption of each single dwelling of the zone scaled by the number of dwellings. In order to model the thermal behaviour of a single dwelling, the house type DE.N.SFH.12.Gen.ReEx.001.001 is selected from [19]. This corresponds to a typical German house built on 2016, with a high efficiency standard. The data of this single-family house can be found in Appendix 1.

The heating system of the single-family house consists of a heat pump. According to e-Highway 2050 [21], the recommendations for data use indicate that the average heat pump size in individual houses for residential sector must be from 8 to 12 KW. A commercial heat pump is selected in order to get a more accurate approximation of the thermal behaviour of the house. To be consistent with e-Highway 2050 project, a heat pump of 12 kW is selected. The heat pump is from ORIONAIR, model AHUW126A0+H12SNE. Its average COP is 4.46. The datasheet of the heat pump can be found in Appendix 5.

The heat recovery system used for preheat the air in the ventilation system is a commercial model from S&P. The model is CADB-HE DI 04 PRO-REG with an 87% of recovery efficiency, see Appendix 7. The efficiency of the heat recovery system is higher than the typical values, which are around 70% to 80% [20]. This consideration is taken because in 2030 the expected typical efficiency values should be higher than those observed today. For the case study 1 the heat is recovered by a heat exchanger.

4.3.1 Calculation of the number of houses

The number of single-family houses using electricity to generate heat is obtained by considering the foresee annual consumption for residential heat for 2030. The annual consumption for residential heat is shown in Table 1.

Table 1. Foresee annual consumption per zone

2030 consumption (TWh)	
Zone 4	3.03611044
Zone 5	5.46149383
Zone 2	5.28502327
Zone 3	5.97232549
Zone 0	3.54199757
Zone 1	3.13346411
Zone 6	11.2935981

Considering the annual consumption of each house, 12980 kWh/year, and the COP of the heat pump, the number of houses can be calculated. Table 2 shows the number of single dwellings per zone. In the model, the heat requirements of each individual dwelling is scaled to the number of dwellings per zone as started in equation (28).

Table 2. Number of single dwellings per zone. Case Study 1

Single dwellings units	
Zone 0	1217050
Zone 1	1076676
Zone 2	1815963
Zone 3	2052124
Zone 4	1043224
Zone 5	1876600
Zone 6	3880543

4.3.2 Scenario 1. System without heating load

The first scenario corresponds to the power system without consideration of the residential thermal loads. The loads in this scenario consists of the electricity demand for current use, electric vehicles with a fixed charge profile and non-residential heating as stated in the e-Highway 2050 project. The operation planning of the system is performed by solving the Unit Commitment problem presented in section 2.1.1 with the aim of minimizing the total operation cost.

Since no thermal loads are considered, the indoor temperature of the dwelling does not have any restriction. There is no possibility for adding flexibility to the system.

Operation Cost

The process of generating electricity has different costs that all together conform the operation cost. The generation cost comprises the fuel cost, and the non-fuel variable and fixed costs. The start-up and shut-down costs, that are the costs for switching on and off the different generating units.

Table 3 shows the operation cost of the system for the sixth week of the year. The total operation cost of the system for the sixth week of the year is 55.317.334,92€. While the generation cost corresponds to a 90.34% of the total cost. The start-up and shut-down costs corresponds to a 9.62% of the total.

Table 3. Operation cost. Case Study 1-Scenario 1

Scenario 1: System without heating load	
Generation Cost	49,975,226.46 €
Start-up/Shut-down Cost	5,323,150.00 €
Operation Cost	**55,317,334.92 €**

Electricity generation

Figure 17 shows the electricity generation per source for the studied week. The load for this case is mainly supplied by wind, accounting for 7,740.74GWh of electricity generated. Conventional sources such as lignite, coal and gas, generate 1,046.2 GWh, 593.83 GWh and 78.25 GWh, respectively. The rest of non-conventional sources have also an impact on the generation, with solar supplying 399.71 GWh, biomass 442.98 GWh and hydro 250.03 GWh.

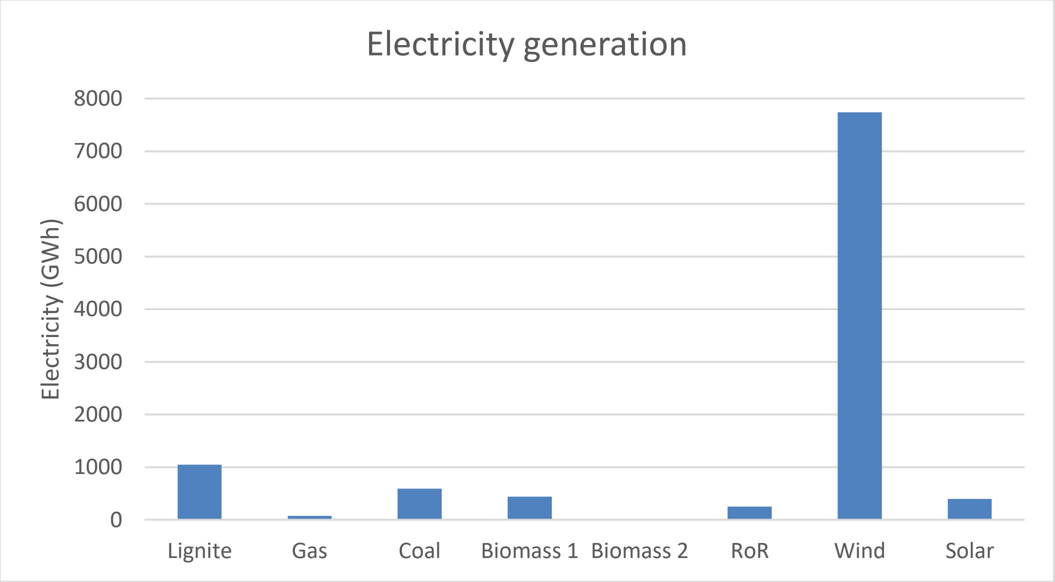


Figure 17. Electricity generation per source of generation. Case Study 1-Scenario 1

Hourly operation

Figure 18 shows the weekly operation of the power system. The amount of electricity generated is exactly the same as the load demanded for the week. Due to the high availability of wind during the week, the major part of the demand is covered by wind. There is a base demand that is covered by lignite. Even in the hours of high wind availability, lignite remains to operate. This is due to the high start-up cost and long minimum operation times. For that reason, it is better to generate with lignite even if its cost is higher than to generate with renewable units. When the wind is not able to supply the demand, other renewable units, gas and coal units are switch on to generate the remaining electricity.

In some hours of the week, renewable energy curtailment is observed. Sometimes, this occurs due to high surplus of renewables. However, in other hours, renewable energy curtailment occurs because inflexible thermal generators cannot reduce the generation due to technical restrictions such as minimum output power and operation times.

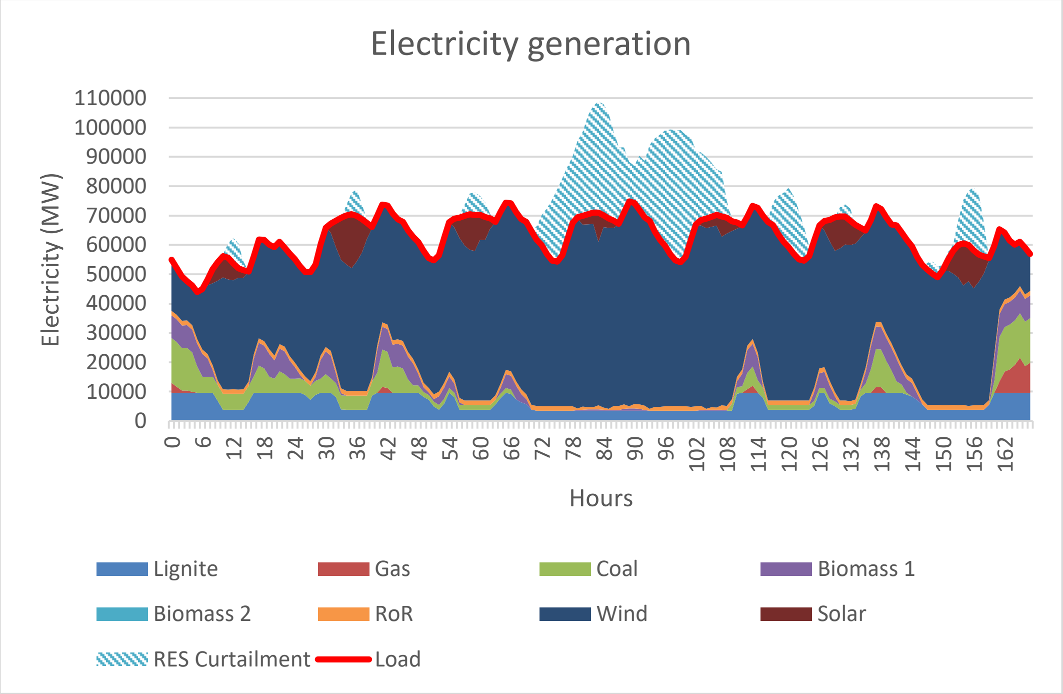


Figure 18. Electricity generated per source, load and RES Curtailment. Case Study 1-Scenario 1

4.3.3 Scenario 2. System with heating load, no smart case

In this scenario, loads for residential space heating are considered in addition to the loads for current use, electric vehicles and non-residential heating. Heating load corresponds to the thermal demand for the usage in residential space heating, such as heat pumps, radiators or radiant floor to convert electric energy into thermal energy.

When the heating load takes place, the modelling of thermal behaviour of the dwelling must be included in the system. The different gains and losses that the dwelling has are important to determine the consumption of the house. The gains are those that appear due to the effect of solar radiation, internal heat gains and heat recovered by the heat exchanger. By contrast, the losses are those that are generated by transmission and ventilation, as detailed in section 3.1.

The operation mode for the thermal loads is a non-smart operation. This means that the system tries to maintain the indoor air temperature to a fixed value. In this case, the value is set as 21.2°C. In some hours the heat gains due to solar radiation and internal gains are high enough to balance the heat losses. Therefore, the indoor air temperature could increase over the set point. If this is the case, no heating would be required and the heating demand is set to zero, as explained in section 3.1.11.

Operation cost

When the heating load is included in the system, there is a necessity of generate more electricity to be able to supply the demand. Therefore, the operation cost is increased compared to the first scenario.

Table 4. Operation cost. Case study 1-Scenario 2

Scenario 2: System with heating load, no smart case	
Generation Cost	63,449,668.36 €
Start-up/Shut-down Cost	6,995,250.00 €
Operation Cost	**70,444,918.36 €**

Electricity generation

Figure 19 shows the total generation per source. As in scenario 1, the load is mainly supplied by wind, generating 7,944.55 GWh. The rest of renewable electricity generated such as solar, biomass and hydro have a generation of 430.98 GWh, 543.45 GWh and 256.17 GWh, respectively. The generation with conventional sources has been increased, accounting for a 1,143.89 GWh for lignite, 185.94 GWh for gas and 909.49 GWh for coal.

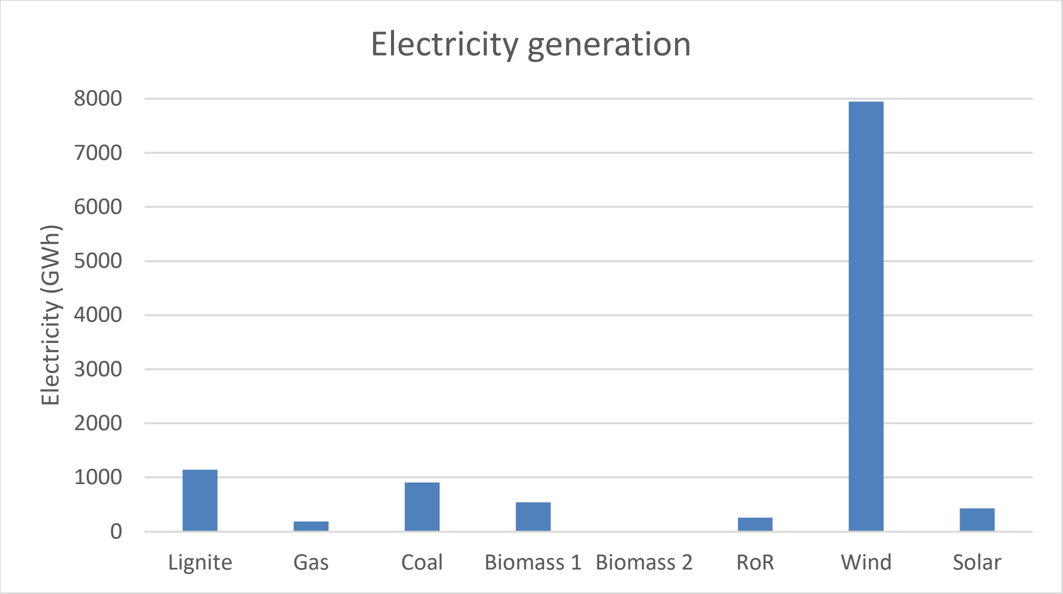


Figure 19. Electricity generation per source of generation. Case Study 1-Scenario 2

Hourly operation

Figure 20 shows the amount of electricity generated, and also the load and thermal load demanded. The major part of the demand is covered by wind, due its high availability. As in the scenario 1, a base demand is covered by lignite. The rest of the generating units are turned on when there is an excess of demand that wind and lignite are not able to cover. Comparing the hourly operation of the scenario 1 with scenario 2, scenario 2 has more hours where the gas and coal generation is required. The generation peaks are higher than the generation peaks of the scenario 1.

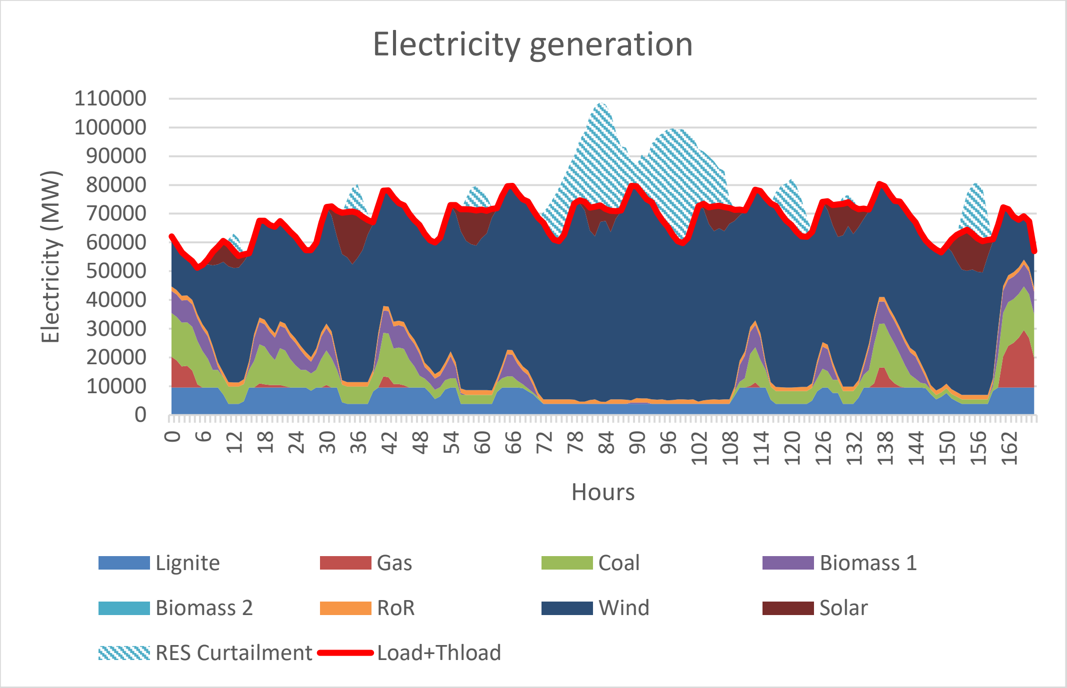


Figure 20. Electricity generated per source, load and RES Curtailment. Case Study 1-Scenario 2

Hourly indoor temperature

Figure 21 displays the indoor temperature at each instant of the week. As it can be seen, the indoor air temperature is set most of the time to 21.2°C. In some hours, the indoor air temperature has peaks higher than the minimum value of 21.2°C. These peaks of temperature appear mostly during the day when the sun radiation has a direct impact on the single dwelling and warms up the indoor air. Also, the internal gains help to warm up the dwelling.

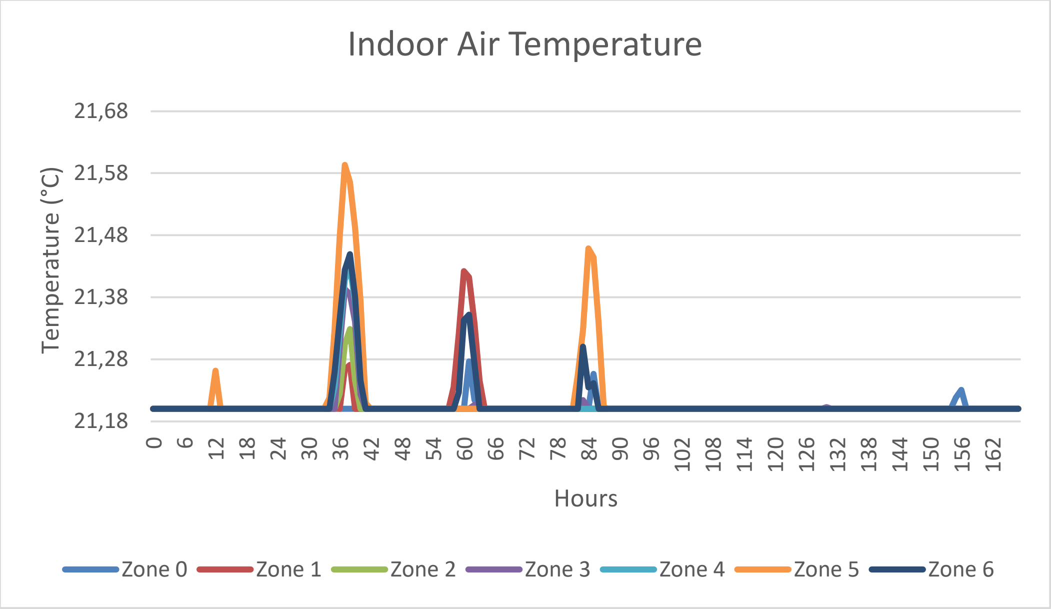


Figure 21. Indoor air temperature. Case Study 1-Scenario 2

In Figure 22 the heat generated to maintain the temperature in the dwelling is shown. The heating consumption, is directly related with indoor the temperature. When the heat gains and losses of the house are not able to maintain the indoor temperature in the limit, a heating supply is needed. Conversely, when the heat gains are enough to maintain the dwelling warm, the heating consumption is reduced.

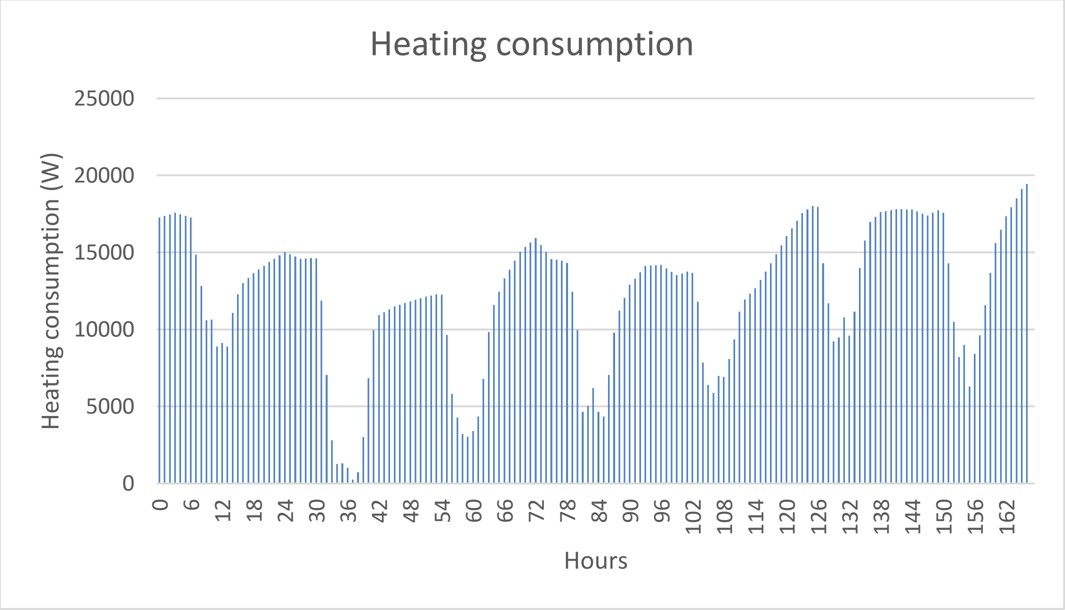


Figure 22. Heating consumption. Case Study 1-Scenario 2

4.3.4 Scenario 3. System with heating load, smart case

The third scenario of the case study 1 represents the behaviour of the power system with different generators, different loads and different heating loads for each zone. The input data is the same as described at the beginning of the section, yet the system responds to the heating demand smarter than in scenario 2. In contrast with scenario 2, the indoor air temperature can vary in a range of temperature. Therefore, temperature range is limited by a maximum and minimum temperature, which corresponds to 21.2°C and 24°C. The system is able to determine when the dwelling needs to be warmed and at which temperature. This operation allows to provide flexibility to the power system.

Operation cost

The operation cost in scenario 3 is reduced compared to scenario 2. This is due to flexibility provided by the smart operation of the thermal load. A part of the demand is shifted to be supplied by renewable energies. Therefore, the operation cost is reduced. Also, the flexibility provided by thermal loads allows to reduce start-up costs. The operation costs of the scenario 3 are shown in Table 5.

Table 5. Operation cost. Case Study 1-Scenario 3

Scenario 3: System with heating load and smart case	
Generation Cost	54,447,055.29 €
Start-up/Shut-down Cost	4,679,000.00 €
Operation Cost	**59,126,055.29 €**

Electricity generation

Figure 23 shows the amount of electricity per source of generation in scenario 3. The electricity generated is mainly by wind, summing up for 8,260.98 GWh. The other renewable sources used in the electricity generation have 439.92 GWh for solar, 555.23 GWh for biomass and 254.09 GWh for hydro generation. The generation with coal and gas has been decreased with respect to scenario 2, generating 669.8 GWh and 112.05 GWh, respectively. The generation with lignite is 1,201.35 GWh.

In this scenario, the power system has more flexibility and part of the heating demand can be adapted to periods where there are more renewable energies available.

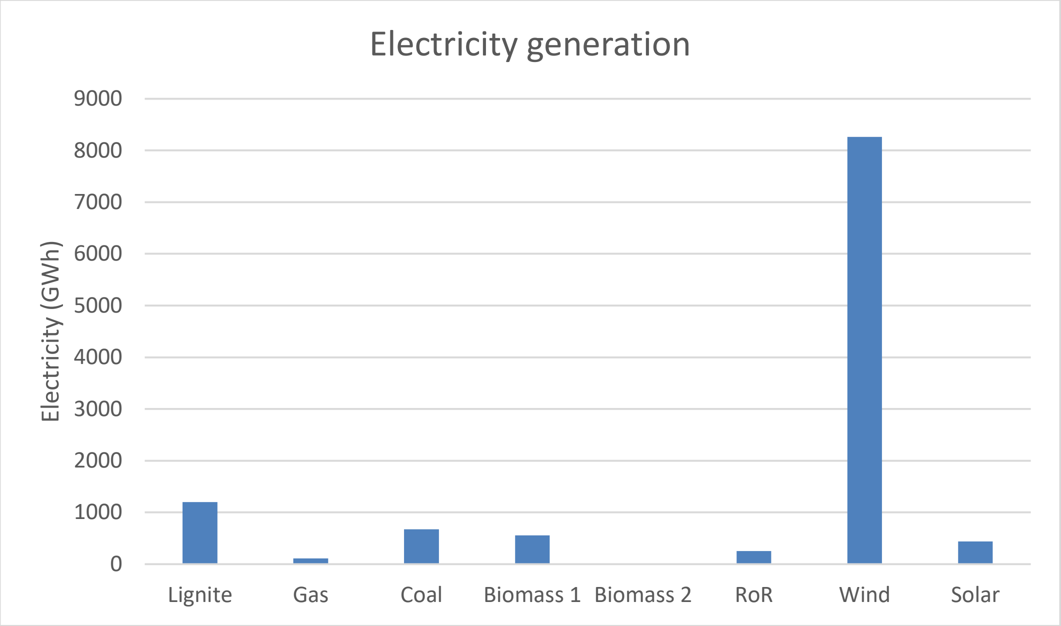


Figure 23. Electricity generation per source of generation. Case Study 1-Scenario 3

Hourly operation

Figure 24 expose the weekly operation of the power system. The space heating demand is adapted to the hours where there is more renewable capacity to supply the demand. The demand presents a pattern following the available renewable capacity. Therefore, the renewable curtailment is significantly reduced. This can be achieved by the flexible operation of the thermal load.

The electricity generation in the smart case scenario almost fits perfectly with renewable capacity. There are few hours where the generation could be supplied by renewable energies. However, due to the start-up and shut-down restrictions the generation is supplied by conventional sources. Also, there is a high surplus of wind at that hours.

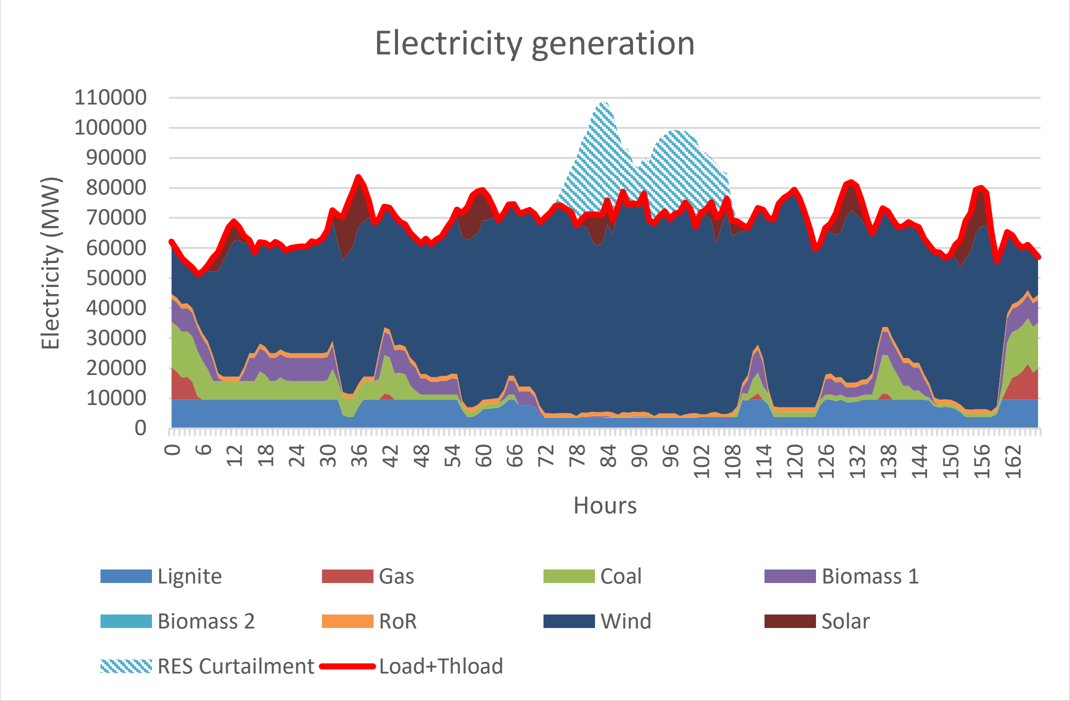


Figure 24. Electricity generated per source, load and RES Curtailment. Case Study 1-Scenario 3

Hourly indoor temperature

Regarding the indoor temperature in the dwelling, the operation range is, as said, between 21.2°C and 24°C. The system operation is free to supply with heat the indoor space when the gains are not able to maintain the temperature beyond the minimum temperature. As a result, indoor air temperature has a permanent temperature variation. Figure 25 shows the behaviour of the temperature during the week. The temperature varies inside the range of work depending on the gains and losses that the dwelling has and also the heating the system is adding. The temperature never is out of the boundaries.

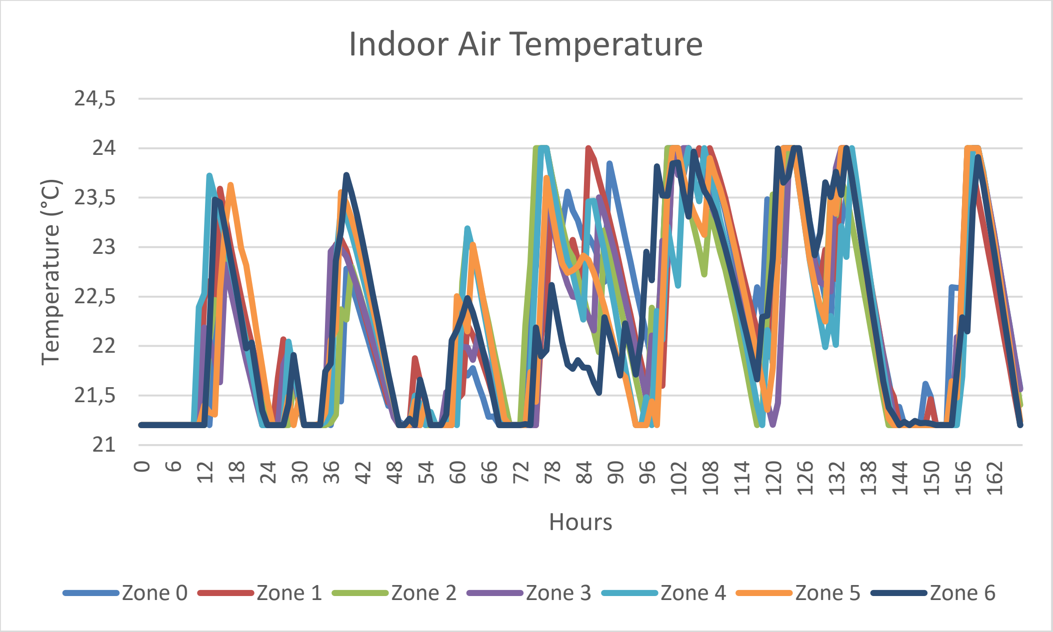


Figure 25. Indoor air temperature. Case Study 1-Scenario 3

The system works in a smart way, the thermal load increases in hours where there is high availability on renewable energies. On the contrary, thermal load demand decreases in hours of low availability. With that, it is added flexibility to the system. As a result, the heating consumption is reduced since the temperature is able to work in a wider range than before. When the temperature decreases the peaks of heating consumption appear. The dwelling is working as a battery. It stores energy by increasing the indoor temperature in times of high wind availability. Then, the thermal energy is released in hours where there is less wind availability. It corresponds to the hours where the indoor temperature is decreasing and there is no heating consumption.

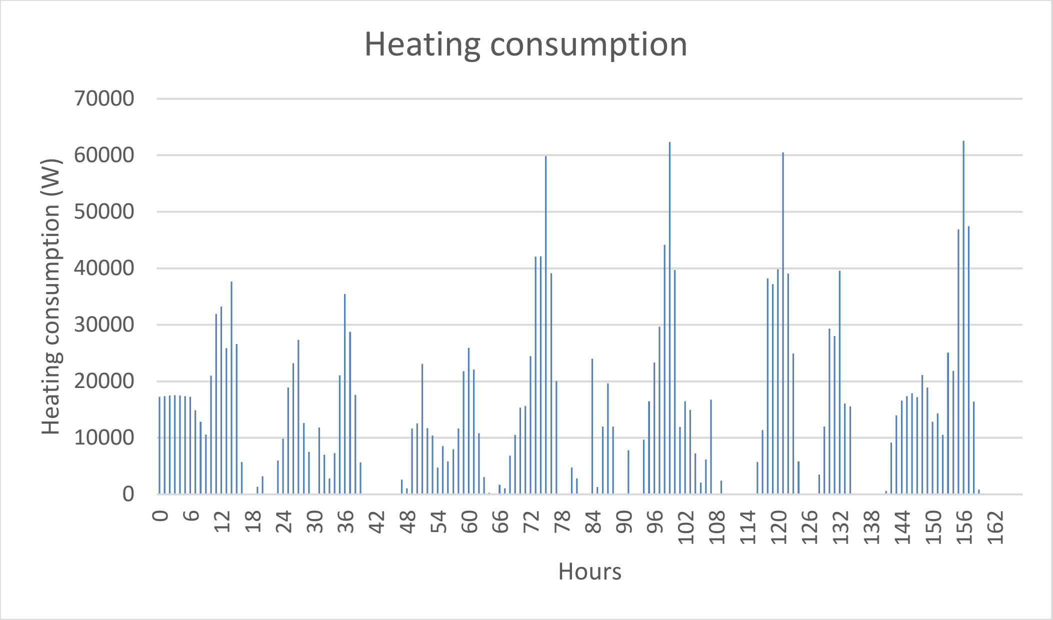


Figure 26. Heating consumption. Case Study 1-Scenario 3

4.3.5 Results analysis

The comparison of the three different scenarios will allow to understand the impact of the operation of thermal loads in the power system. Results are analysed in terms of system costs, electricity generation, CO_2 emissions, and the impact on the net load.

System costs

Table 6 shows the costs generated by the three scenarios. The first scenario does not have thermal load, as a result the generation cost is lower than scenarios 2 and 3. In scenario 2, the inclusion of the thermal load to the power system increases the operation cost by 27.35% with respect of the first scenario.

The third scenario adds flexibility to the system. Therefore, a higher share of electricity demand can be supplied by renewable energies. The smart operation allows to reduce the operation cost by 16.07% compared to the second scenario. Moreover, the start-up cost reduction allows an increment of the lifespan of thermal generation units and reduces the maintenance requirements.

Table 6. System costs Case Study 1

	Operation Cost	**Generation Cost**	**Start-up/Shut-down Cost**
Scenario 1: System without heating load	55,317,334.92 €	49,975,226.46 €	5,323,150.00 €
Scenario 2: System with heating load, no smart case	70,444,918.36 €	63,449,668.36 €	6,995,250.00 €
Scenario 3: System with heating load and smart case	59,126,055.29 €	54,447,055.29 €	4,679,000.00 €

Electricity generation

The electricity generation is different between scenario 1 and scenarios 2 and 3, since the demands are different depending on the working mode. Taking as a base case the first scenario, the addition of the thermal load increases electricity demand by 8%.

Figure 27 shows the electricity generation by source in each scenario. In both scenarios 2 and 3 the generation with wind has increased compared with scenario 1. Moreover, due to the increased flexibility, the third scenario uses a share of wind 3% higher than in scenario 2. The rest of the renewable energies have small variations in terms of generation. Regarding conventional generation units, in scenario 3, the lignite has a bigger share than scenario 2 and the generation with coal and gas has decreased.

With the addition of the thermal load the RES Curtailment is reduced a 18.38% for scenario 2 and 43.02% for scenario 3.

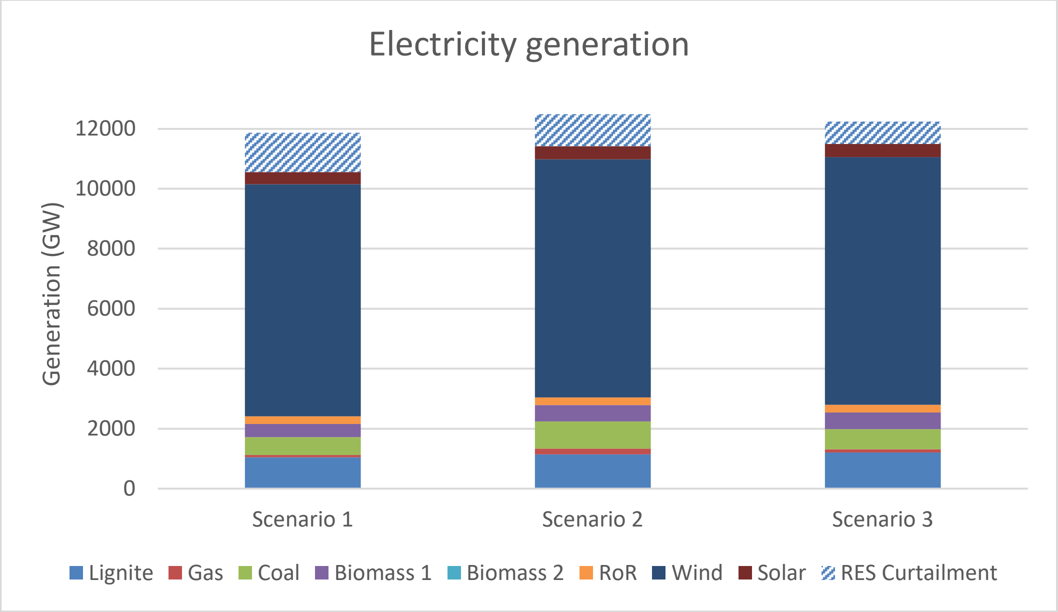


Figure 27. Electricity generation comparison per source. Case Study 1

CO_2 emissions

The CO_2 emissions produced by conventional generation units have a large impact on the environment. To reduce CO_2 emissions, it is important to electrify the thermal demands as described in section 2.3. Therefore, it is important to be able to quantify the emissions in each scenario.

The first scenario only takes into account the electricity generated to cover the load demand. Nevertheless, not only the load demand is the one that it is important to take into account regarding emissions, but also the emissions produced by thermal demand have to be quantified. Although the thermal load is not supplied by the electric generation units it is supplied by other thermal heat generation units. To be able to quantify it, it is supposed that the thermal load is covered by the current heat generation system. The thermal load is multiplied by an average emission coefficient. That coefficient is calculated taking into account the energy consumed in Germany by space heating in 2016, 706 TWh, and the CO_2 emissions in Germany of space heating in 2016, 142 Mio tones CO_2. The value of the average emission coefficient is 0.2009 tn CO_2/MWh.

Table 7 shows the CO_2 emissions per scenario. Regarding the first scenario, the CO_2 emissions are more than 2 million tonnes. When thermal loads are supplied by electricity, the emissions are reduced by 18.6% for the second scenario and 25.2% for the third scenario. This large reduction is achieved because a significant part of the thermal load would be supplied by renewable energy.

Table 7. CO_2 emissions. Case Study 1

CO_2 emissions (tn)	
Scenario 1: System without heating load	2.223.487,50
Scenario 2: System with heating load, no smart case	1.810.519,64
Scenario 3: System with heating load and smart case	1.663.761,83

Net load

The net load is the difference between the total load and the available renewable power. In order to see the impact, the values are ordered from higher values to lower values. The positive values meant the load plus the thermal load are higher than the renewable power available, while the negative values meant that there is more renewable power than loads. Figure 28 shows the net load of the three scenarios. The base scenario, scenario 1, has a demand lower than the other scenarios, because it does not consider the thermal load. When there is thermal demand in scenario 2, the net load curve moves up and has higher load in almost all hours. Also, the peak demand is increased.

The flexibility provided by the smart case can be observed in the net load change.

The demand peak is reduced compared to scenario 2, and it is similar to the first scenario without heating load. Also, the curve of net demand flattens, reducing the consumption in hours of high demand and increasing it in hours of less demand.

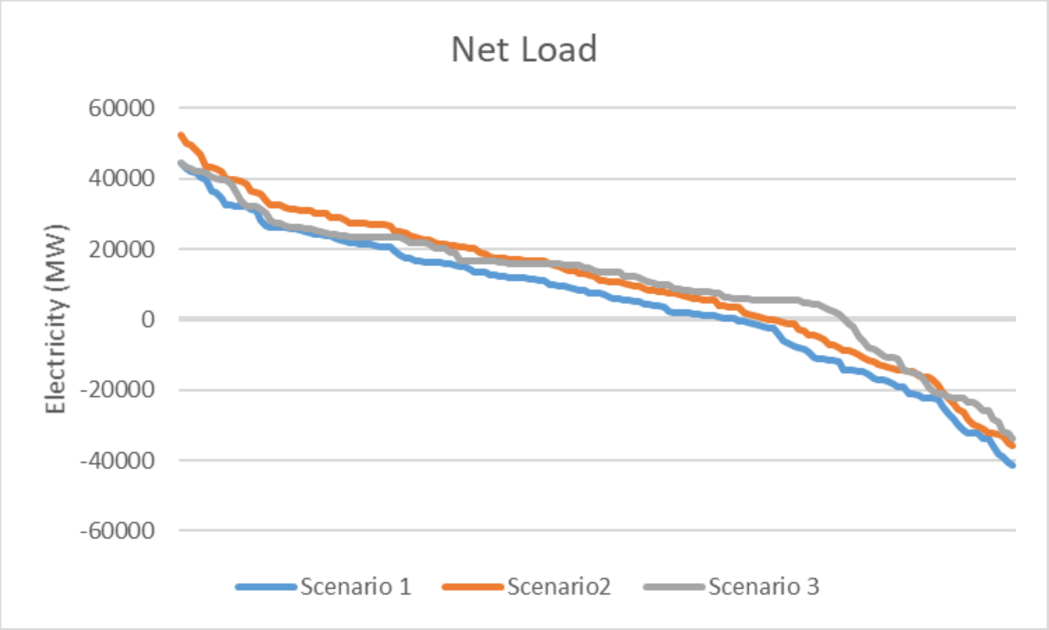


Figure 28. Net load. Case Study 1

4.4 Case study 2: Sensibility on the building type

The second case study, as the first case study, consists on analysing the behaviour of a single-family for one week. The difference with the first case study is the type of single-family used. The different coefficients that allow to model the thermal behaviour of the house are taken from the Tabula project [19] and are presented in Appendix 2. As in the case study 1, the sixth week of the year is selected to simulate the behaviour of the system. Three different scenarios are considered to study the impact of thermal loads on the power system operation:

- Scenario 1: the first scenario analyses the power system without residential thermal load. This scenario is the same as the scenario 1 from the case study 1.
- Scenario 2: the second scenario analyses the power system including the thermal load. The heating system tries to maintain the indoor temperature at certain level.
- Scenario 3: the third scenario also considers the thermal load in the power system. The thermal load is able to add flexibility by changing the consumption. The indoor temperature can vary within a comfort range.

Regarding thermal loads, the electricity consumption of each zone is calculated as the consumption of each single dwelling of the zone scaled by the number of dwellings. In order to model the thermal behaviour, the house type DE.N.SFH.04.Gen.ReEx.001.001 is selected from [19]. This corresponds to a typical German house built between 1946 and 1957. Comparing with case study 1, this house is considered as inefficient. The data of the house can be found in Appendix 2.

The heating system of the single-family house also consists of a heat pump. The same heat pump that in section 4.3 is used. The heat pump is from ORIONAIR, model AHUW126A0+H12SNE. Its COP is 4.46, see Appendix 5.

The heat recovery used for preheat the temperature in the ventilation is also defined in section 4.3.

4.4.1 Calculation of the number of houses

The number of the houses can be calculated considering the annual consumption of each house, summing up to 31561 kWh/year, and the COP of the heat pump. It is considered the foresee annual consumption for residential heat for 2030, see Table 1. In Table 8 is shown the number of single dwellings per zone.

Table 8. Number **of single dwellings per zone. Case Study 2**

Single dwellings units	
Zone 0	500533
Zone 1	442801
Zone 2	746846
Zone 3	843971
Zone 4	429044
Zone 5	771784
Zone 6	1595940

4.4.2 Scenario 1. System without heating load

In the first scenario the power system does not consider the residential thermal loads. This scenario is the same as scenario 1 from case study 1 since the difference between both case studies is the type of single-family dwelling.

4.4.3 Scenario 2. System with heating load, no smart case

In the second scenario, the loads for residential space heating are considered. As a result, the behaviour of loads for current use, electric vehicles, non-residential heating and thermal loads are included in the system.

The operation mode for the thermal loads is a non-smart operation. The system tries to maintain the indoor air temperature to a fixed value set as 21,2°C. when the indoor temperature is beyond the et point no heating would be required.

Operation cost

Table 9 shows the operation, the generation and, start-up and shut-down costs. The total operation cost in scenario 2 is a 33.6% higher than scenario 1 due to the addition of the thermal load. The start-up and shut-down costs are 8,6% of the total operation cost. Comparing with case study 1, the operation cost is a 18.18% higher.

Table 9. Operation cost. Case Study 2-Scenario 2

Scenario 2: System with heating load, no smart case	
Generation Cost	76,152,372.32 €
Start-up/Shut-down Cost	7,133,600.00 €
Operation Cost	**83,285,972.32 €**

Electricity generation

Figure 29 shows the electricity generation per source of generation. Most of the load is supplied by wind, generating 8,143.03 GWh, a 5.2% more than in scenario 1. The rest of renewable electricity generated such as solar hydro and biomass is higher than the electricity generated in scenario 1, summing up 446.01 GWh, 259.12 GWh and 603.79 GWh, respectively. The generation with conventional sources has been increased comparing with scenario 1, accounting for 1,212.27 GWh for lignite, 288.95 GWh for gas and 1,082.93 GWh for coal.

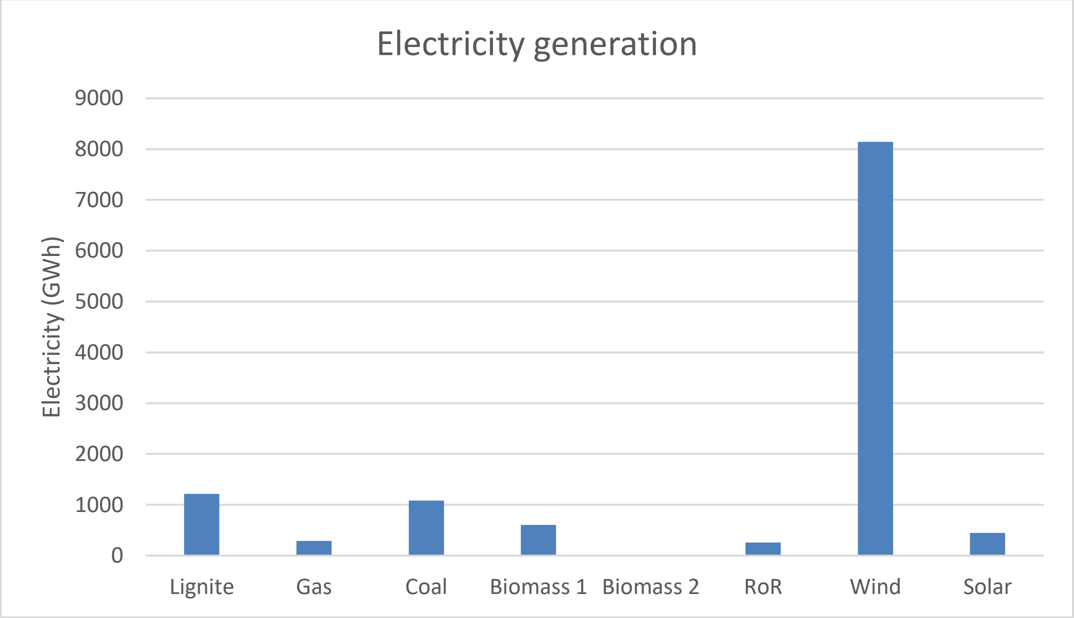


Figure 29. Electricity generation per source of generation. Case Study 2-Scenario 2

Hourly operation

Figure 30 shows the electricity generated, the load and thermal load and the RES curtailment. The major part of the electricity generated is covered by wind. As in the scenario 1, a base demand is covered by lignite. The rest of the generating units are turned on when the demand is not covered by wind. Comparing the hourly operation of the scenario 1 with scenario 2, scenario 2 has more hours where the gas and coal generation is required. The generation peaks are higher than the generation peaks of the scenario 1.

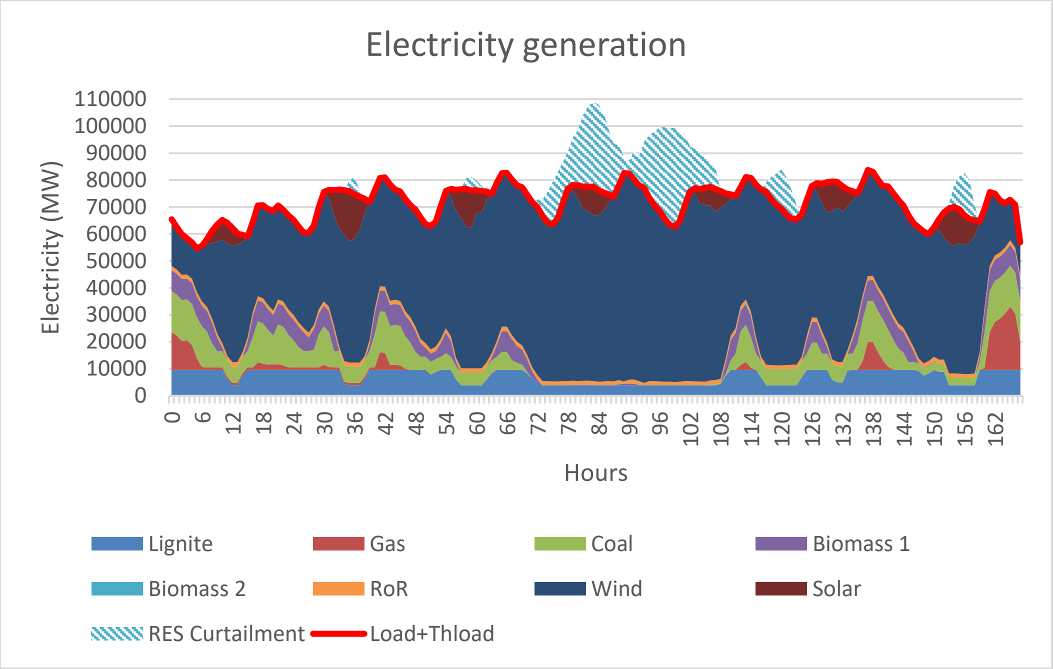


Figure 30. Electricity generated per source, load and RES Curtailment. Case Study 2-Scenario 2

Hourly indoor temperature

In Figure 31 the indoor air temperature during the week is shown. The temperature during the week is fixed at 21.2°C. The peaks of temperature observed in the scenario 2 of case study 1 are not observed for this case. This is because the type of single-family dwelling used in this case study is less efficient than in the first case study. Hence, the gains are not able to overcome the heat losses. The heating load is always required and maintaining the temperature at 21.2°C.

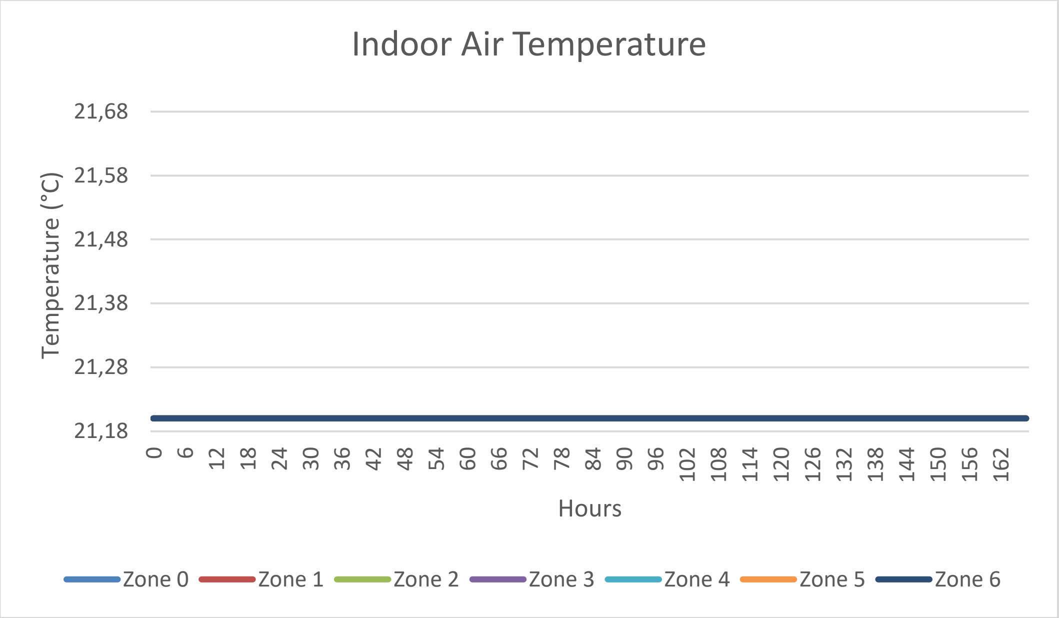


Figure 31. Indoor air temperature. Case Study 2-Scenario 2

Regarding the heating consumption, due to the inefficiency of the house the heating supply is required during the whole week. There is a small reduction at the hours where the gains are high, that is during the day. The heating consumption behaviour is showed in Figure 32.

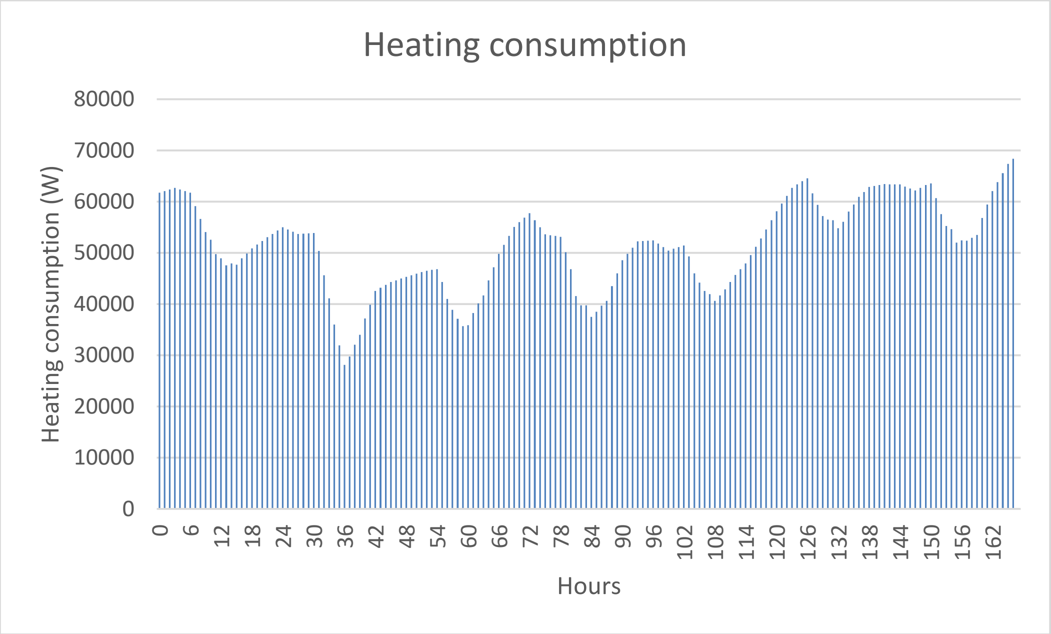


Figure 32. Heating consumption. Case Study 2-Scenario 2

4.4.4 Scenario 3. System with heating load, smart case

The third scenario presents the behaviour of the power system responding to a heating demand smarter than in scenario 2. The range of temperature at which the indoor air temperature can vary is from 21.2°C to 24°C. As explained in section 4.3.4 this operation allows to provide flexibility to the power system.

Operation cost

The operation cost in scenario 3 is reduced a 6.4% compared with scenario 2. The flexibility provided by the smart operation lets part of the demand be generated by renewable energies. As a consequence, part of the operation cost is reduced.

Table 10. Operation cost. Case Study 2-Scenario 3

Scenario 1: System without heating load	
Generation Cost	49,975,226.46 €
Start-up/Shut-down Cost	5,323,150.00 €
Operation Cost	**55,317,334.92 €**

Electricity generation

Figure 33 shows the electricity generated per source of generation. The electricity generated is mainly supplied by wind, summing up for 8,311.65 GWh, a 2.07% more wind generated than in scenario 2. The rest of renewable energies have more generation than in scenario 2, reaching a 661.95 GWh for biomass, 424.87 GWh for solar and 252.78 GWh for hydro. The generation with coal and gas decreases compared to scenario 2, corresponding to 993.41 GWh and 227.38 GWh, respectively. The generation with lignite has increased compared to scenario 2, generating 1,261.44 GWh. The power system has adapted part of the heating demand to periods where there are more renewable energies, such as periods with high wind availability.

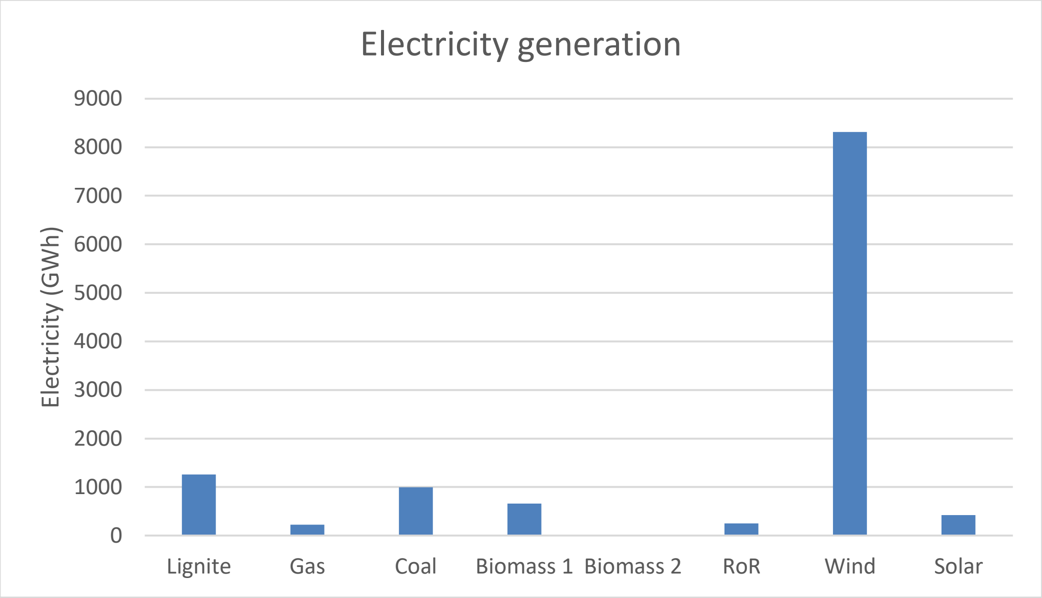


Figure 33. Electricity generation per source of generation. Case Study 2-Scenario 3

Hourly operation

As it can be seen in Figure 34, the hourly demand is adapted to the hours where there is renewable capacity to supply the demand. There is still part of the generation supplied by lignite but the demand is requested at different hours than in scenario 2. The smart operation of the thermal loads allows a higher penetration of renewable energy. Comparing case study 2-scenario 3 with case study 1-scenario 3, there are less hours in case study 2 where the base of lignite and the wind are enough to cover the demand. Therefore, the renewable curtailment is reduced in some hours while in others the dwelling is not able to add the flexibility needed to take advantage of the renewable capacity. Also, a higher use of gas and coal is observed.

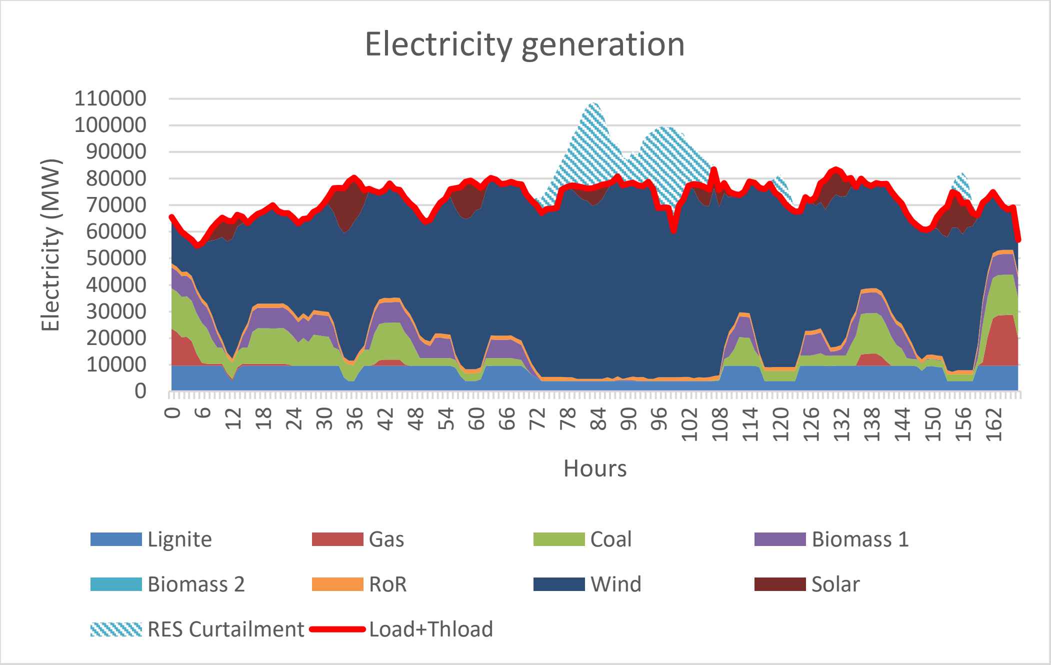


Figure 34. Electricity generated per source, load and RES Curtailment. Case Study 2-Scenario 3

Hourly indoor temperature

The system operation is free to supply with heat the indoor space to maintain the temperature inside the operation range, between 21.2°C and 24°C. Figure 35 shows the permanent variation of the temperature. As this house is less efficient than the house from case study 1, the gains and also the thermal inertia are not able to maintain the temperature for so many hours without heating support. In Figure 36 the heating consumption is shown. As a consequence of the inefficiency, there is heating consumption during all the hours of the week.

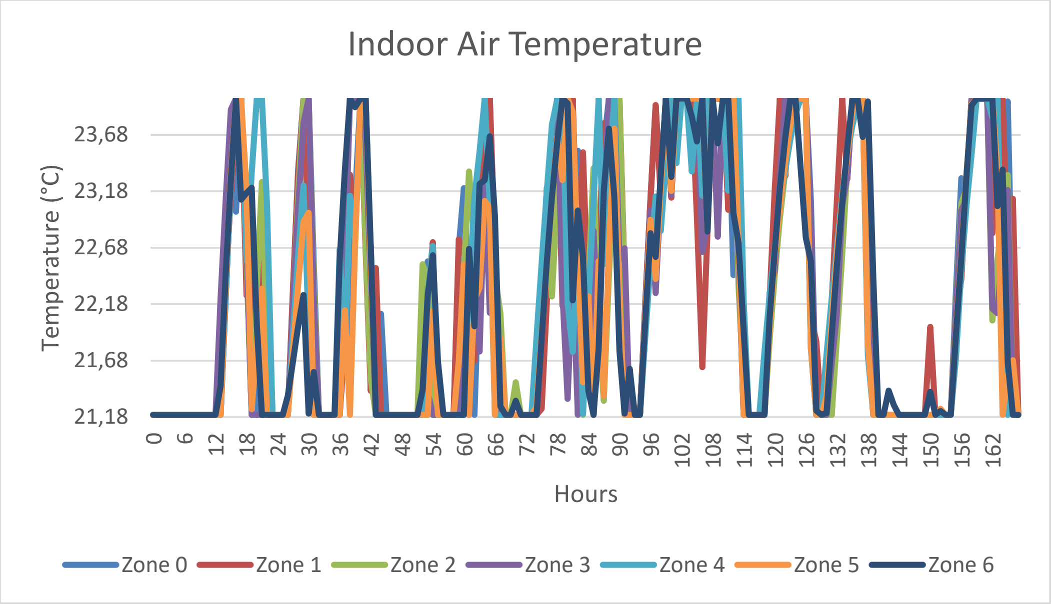


Figure 35. Indoor air temperature. Case Study 2-Scenario 3

When the system works in a smart way, the heating consumption has more peaks since the system is shifting the consumption constantly. The heating consumption is shown in Figure 36.

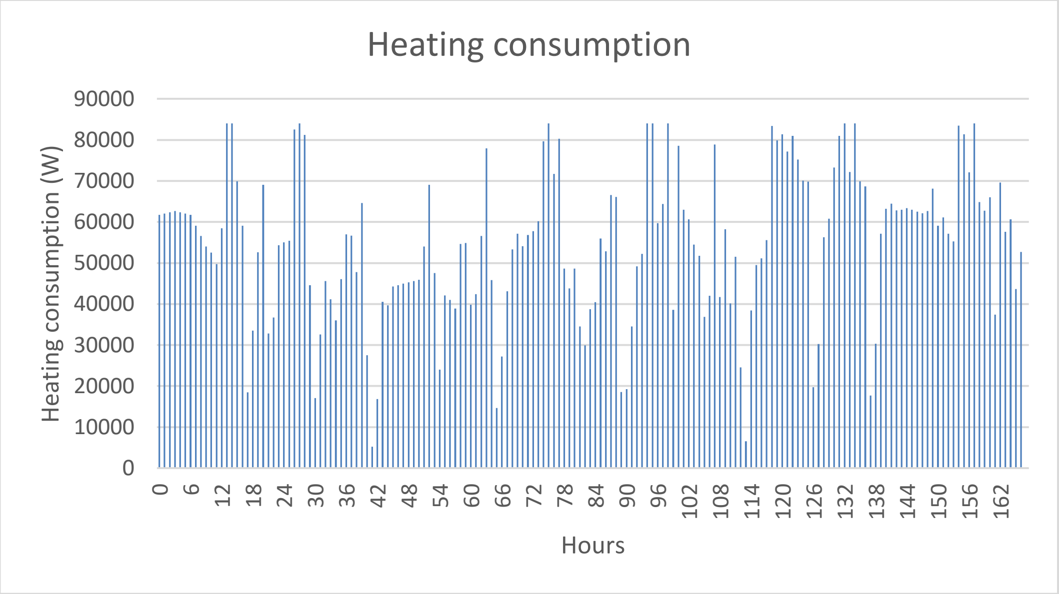


Figure 36. Heating consumption. Case Study 2-Scenario 3

4.4.5 Results analysis

As a result of the case study 2, an analysis in terms of system costs, electricity generation, CO_2 emissions, and the impact on the net load is done.

System costs

Table 11 shows the three different operation costs. As happened in the first case study, scenario 1 does not include the thermal load. Therefore, the operation cost is lower than in the other scenarios.

Adding the thermal load to the power system, from scenario 1 to scenario 2, the generation cost increases a 34.37%. This value is higher than in case study 1 since the considered house is less efficient. In scenario 3, the operation cost is reduced in a 6.38% with respect to scenario 2. Moreover, the start-up and shut-down costs are reduced almost to the same costs as the generation without the thermal load. Comparing to the case study 1, the benefits obtained by operating the system in a smarted way are lower.

Table 11. System costs Case Study 2

	Operation Cost	**Generation Cost**	**Start-up/Shut-down Cost**
Scenario 1: System without heating load	55,317,334.92 €	49,975,226.46 €	5,323,150.00 €
Scenario 2: System with heating load, no smart case	83,285,972.32 €	76,152,372.32 €	7,133,600.00 €
Scenario 3: System with heating load and smart case	77,969,416.92 €	72,381,366.92 €	5,588,050.00 €

Electricity generation

Figure 37 shows the electricity generation by source in each scenario. The increase of the different generation units when thermal load is added makes that in scenario 2 there are less MWh generated with wind, having a share of 5% less of wind generation than in scenario 1. The rest of the renewable energies have small variations in terms of generation. Regarding conventional generation units, the generation with gas and coal increases when the thermal load is added to the system. Comparing scenario 2 and 3, the generation with wind increases from scenario 2 to 3 while the generation with coal decreases slightly.

In case study 1, the difference when adding the smart operation is higher than in case study 2. The generation with coal decreases from scenario 2 to 3, and the generation with wind increases from scenario 2 to scenario 3.

With the addition of the thermal load the RES Curtailment is reduced a 34.87% for scenario 2 and 45.63% for scenario 3.

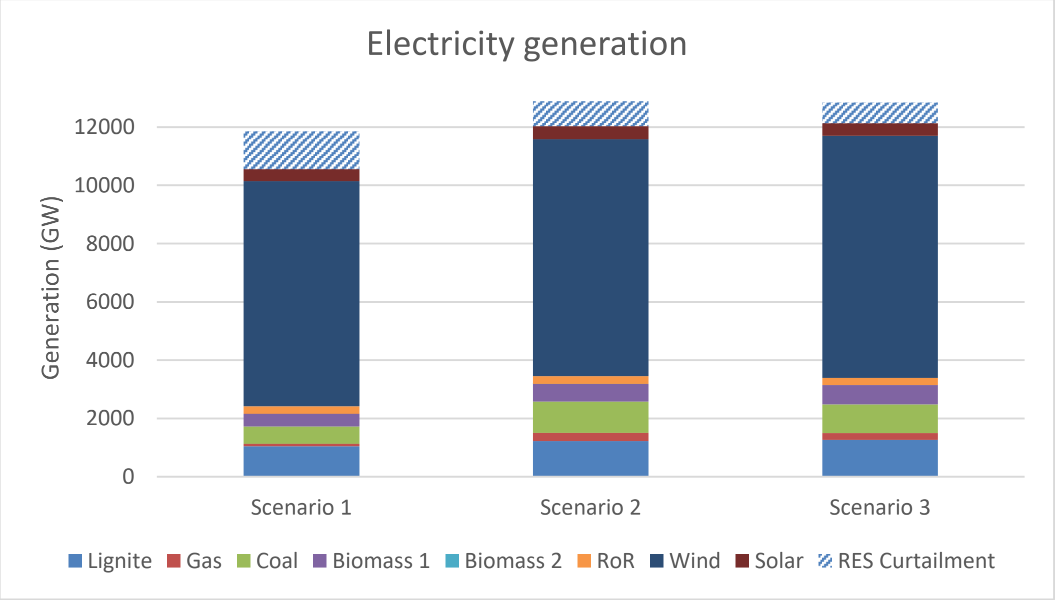


Figure 37. Electricity generation comparison per source. Case Study 2

CO_2 emissions

Table 12 shows the CO_2 emissions per scenario. Regarding the first scenario, the CO_2 emissions are almost 3 million tonnes. When thermal loads are supplied by electricity generation, the emissions are reduced by 26.7% for the second scenario and 28.1% for the third scenario. This large reduction is achieved because a significant part of the thermal load would be supplied by renewable energy. Comparing with case study 1, the CO_2 emissions in case study 2 have increased since the house is less efficient and needs more heat contribution.

Table 12. CO_2 emissions. Case Study 2

CO_2 emissions (tn)	
Scenario 1: System without heating load	2,781,138.23
Scenario 2: System with heating load, no smart case	2,038,560.53
Scenario 3: System with heating load and smart case	1,998,695.35

Net load

Figure 38 shows the net load of the three scenarios. As scenario 1 does not consider thermal load, the total demand is lower than scenario 2 and 3. The net load curve moves up when the thermal demand is added to the power system.

Comparing with the third scenario of the first case study, the addition of the smart case has not such as significant impact on the power system. Nevertheless, the peak load is reduced and the smart operation allows to slightly reduce the consumption in the hours of high demand and to increase it in the hours of lower demand.

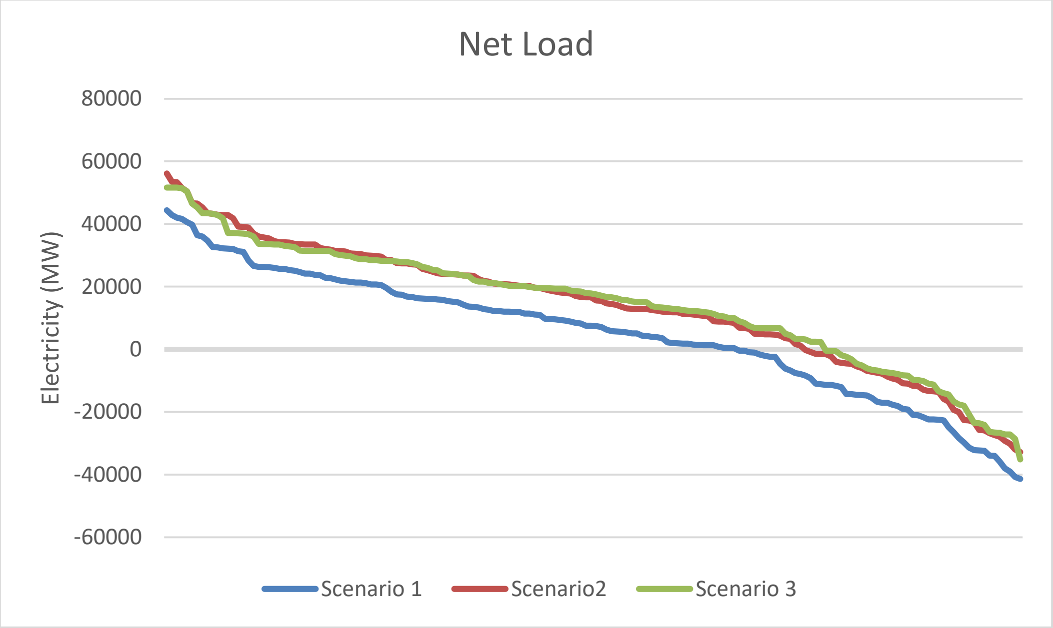


Figure 38. Net load. Case Study 2

4.5 Case study 3

The third case study consists on analysing the behaviour of a single and multi-family dwelling for the whole heating demand period of the year, concretely 24 weeks. For this case, two representative types of houses will be considered. The coefficients that enable to model the thermal behaviour of the two types of houses are taken from the Tabula project [19] and are presented in Appendix 3 for the single-family dwelling, and in Appendix 4 for the multi-family dwelling. The weeks selected to simulate the behaviour of the power system are from the first to the twelfth and from the fortieth to the fifty-second week of the year.

Three different scenarios are considered to study the impact of thermal loads on the power system operation:

- Scenario 1: the first scenario analyses the power system without residential thermal load. The loads consist of electricity demand for current use, electric vehicles and non-residential heating with fixed profiles.
- Scenario 2: the second scenario analyses the power system including residential thermal load. The heating system seeks to maintain the indoor temperature fixed at certain level.
- Scenario 3: the third scenario also considers the thermal load in the power system. In this case, the thermal load can provide flexibility by increasing or decreasing the consumption. The indoor temperature can vary within a comfort range.

With regard to thermal loads, the electricity consumption of each zone is calculated as the consumption of each single and multi-family house of the zone scaled by the number of dwellings. To be able to select the two representative houses for the case study, the data of the building stock for Germany from Tabula model [19] is taken. In that report, the German building stock is modelled with 6 representative houses, 3 single-family units and 3 multi-family units. To reduce this model to two representative houses, the weighted average of the energy used for heating for both single and multi-family houses is calculated. Hereafter, it is considered a heating consumption reduction of a 25% by the year 2030 [23]. With that results, the houses with the closet value of annual energy use are selected from [19] for each type. The houses type DE.N.SFH.09.Gen.ReEx.001.002 and DE.N.MFH.09.Gen.ReEx.001.001 are selected from [19]. These correspond to a

German house built between 1995 and 2001. The data of these single and multi-family houses can be found in Appendix 3 and Appendix 4, respectively. The share of single and multi-family houses is 83% and 17%, respectively.

The heating system of the dwellings consist of a heat pump. To be consistent with e-Highway 2050 [21], the heat pump selected for the single-family dwelling is the same as defined in section 4.3. Regarding the heat pump used for the multi-family dwelling, e-Highway 2050 recommends to use a heat pump sized from 10 to 500 kW. A commercial single and multi-family heat pump is selected in order to be consistent with e-Highway 2050 project, a heat pump of 68.9 kW is selected. The heat pump is from Dimplex, model WI 65TU. Its average COP is 6.2. the data sheet of the heat pump can be found in Appendix 6.

The heat recovery system used for preheat the air in the ventilation system is the same as described in section 4.3.

4.5.1 Calculation of the number of houses

The number of single and multi-family houses using electricity to generate heat is obtained considering the foresee annual consumption for residential heat for 2030. The annual consumption for residential heat is shown in Table 1.

As the case study considers two different type of houses. The number of units of each type is calculated taking into account the percentage of single and multi-family houses, their annual consumption, the COP of the heat pumps and the total annual consumption per zone. Table 13 shows the number of units per zone and type of house.

Table 13. Number of single and multi-family dwellings per zone. Case Study 3

Single and multifamily dwellings units		
	SFH	MFH
Zone 0	660071	135195
Zone 1	583939	119602
Zone 2	984894	201725
Zone 3	1112977	227959
Zone 4	565797	115886
Zone 5	1017781	208461
Zone 6	2104627	431068

4.5.2 Scenario 1. System without heating load

The first scenario of the case study 3 corresponds to the power system without consideration of the residential thermal loads. The functionality of the scenario is the same as described in section 0.

Operation cost

The total operation cost of the system for the whole heating demand period of the year is 2,904 M€. While the generation cost corresponds to a 95.03% of the total cost. The start-up and shut-down costs corresponds to a 4.97% of the total.

Table 14. Operation cost. Case Study 3-Scenario 1

Scenario 1: System without heating load	
Generation Cost	2,759,872,772.18 €
Start-up/Shut-down Cost	144,481,400.00 €
Operation Cost	**2,904,354,172.18 €**

Electricity generation

Figure 39 shows the electricity generation per source of generation. The load for this case is mainly supplied by wind, generating 105,167.9 GWh. Conventional sources such as lignite, coal and gas, generate 33,751.7 GWh, 32,571.7 GWh and 17,209.5 GWh, respectively. The rest of non-conventional a generation of 11,875.1 GWh, 19,376.5 GWh and 6,502.3 GWh for solar, biomass and hydro, respectively.

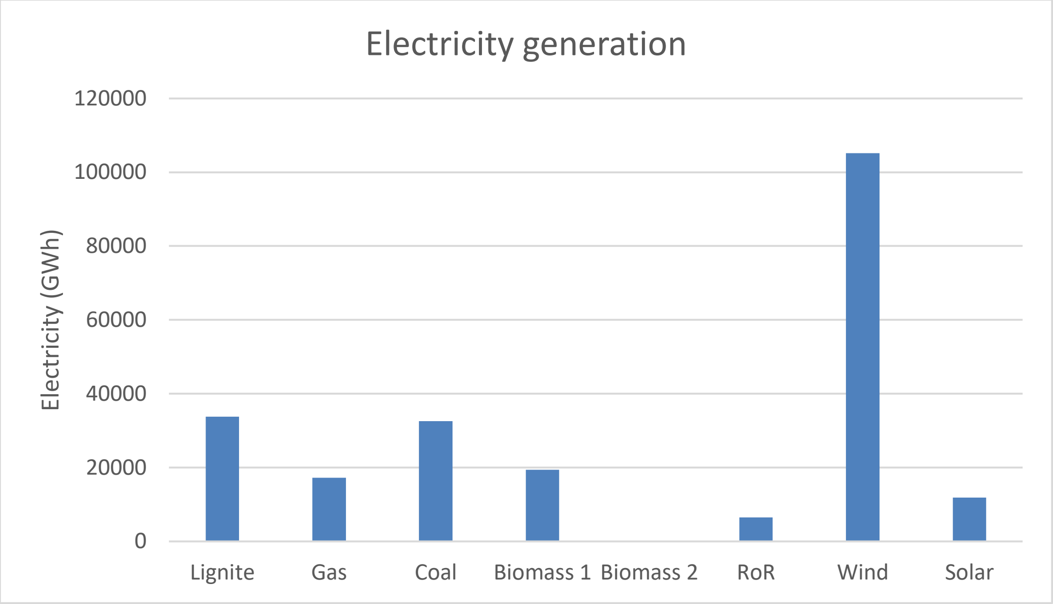


Figure 39. Electricity generation per source of generation. Case Study 3-Scenario 1

Hourly operation

Figure 40 shows the operation of the power system for the heating period. Wind is supplying a large portion of the demand, and there is a base demand covered by lignite. There are many periods where the wind availability is low. In these periods, gas and coal units are switched on to generate the remaining electricity.

Renewable energy curtailment is observed in some hours. Sometimes, this occurs due to high surplus of renewables. However, it can happen that renewable energy curtailment occurs because inflexible thermal generators cannot reduce the generation.

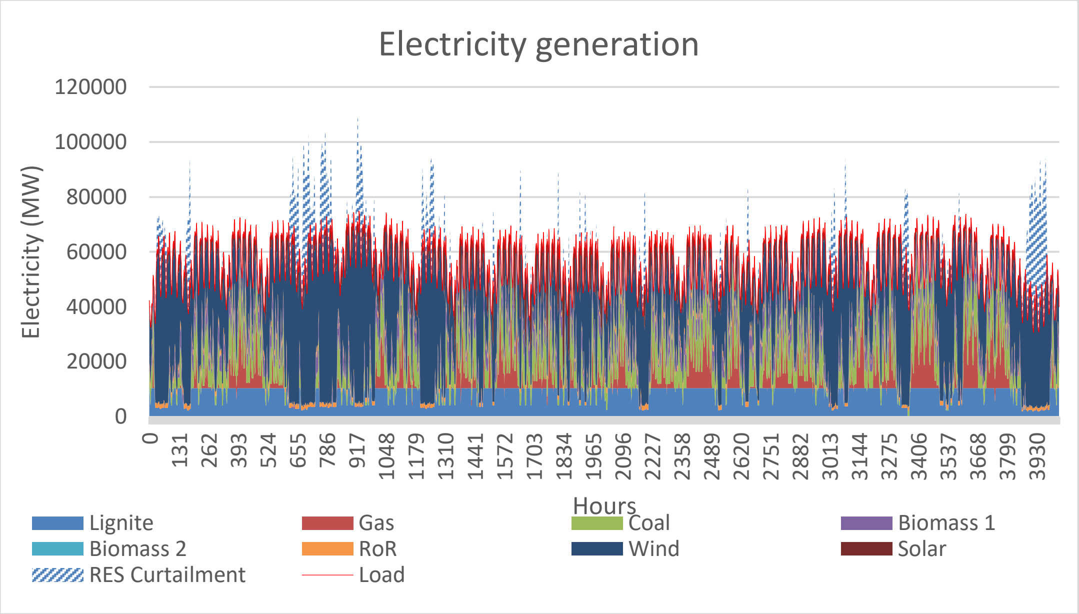


Figure 40. Electricity generated per source, load and RES Curtailment. Case Study 3-Scenario 1

4.5.3 Scenario 2. System with heating load, no smart case

In this scenario, loads for residential space heating are considered in addition to the previous loads. Heating load corresponds to the thermal demand of the different single and multi-family houses.

The operation mode for the thermal loads is a non-smart operation. As is described in section 4.3.3 the system tries to maintain the indoor air temperature to a fixed value. In this case, the value is set as 21.2°C.

Operation cost

When the heating load is included in the system, the operation cost is increased compared to the first scenario. The generation cost represents a 95.63% of the total cost.

Table 15. Operation cost. Case Study 3-Scenario 2

Scenario 2: System with heating load, no smart case	
Generation Cost	3,724,727,665.83 €
Start-up/Shut down Cost	170,324,000.00 €
Operation Cost	**3,895,051,665.83 €**

Electricity generation

Figure 41 shows the electricity generation per source of generation. The load is mainly supplied by wind, generating a 108,795.5 GWh, a 2.8% more than the wind generated in scenario 1. The rest of renewable electricity generated such as solar, biomass and hydro have a generation of 11,929.6 GWh, 11.85 GWh and 6,569.2 GWh, respectively. The generation with conventional sources has been increased with respect to scenario 1, accounting for 30,018.6 GWh for gas and 38,155.7 GWh for coal. The generation with lignite has increased a 5.4% respect the generation in scenario 1, summing up to 35,697.5 GWh.

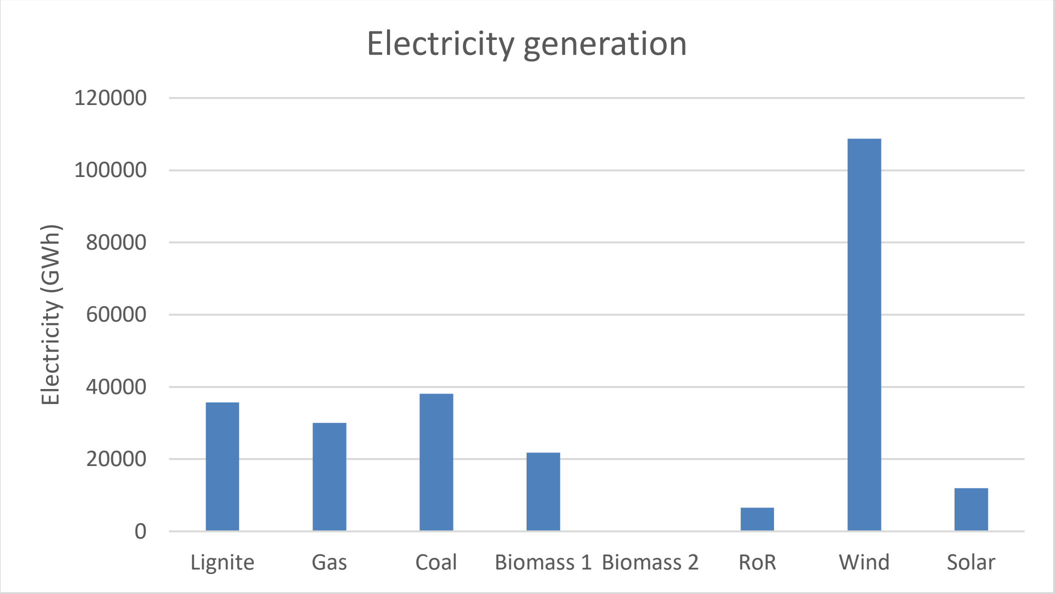


Figure 41. Electricity generation per source of generation. Case Study 3-Scenario 2

Hourly operation

Figure 42 shows the amount of electricity generated, and also the load and thermal load demanded. The major part of the demand is covered by wind. As in the scenario 1, lignite covers a base demand. The rest of the generating units are turned on when is not possible to cover the demand with wind and the lignite base. Comparing the hourly operation of the scenario 1, scenario 2 has more hours where the gas generation is required. The generation peaks are higher than the generation peaks of the scenario 1.

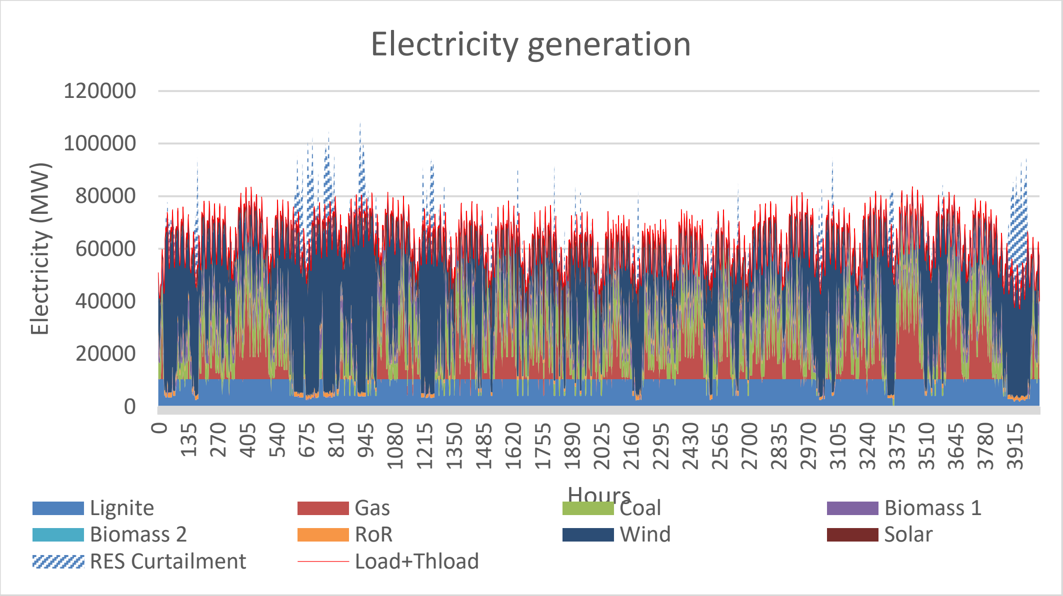


Figure 42. Electricity generated per source, load and RES Curtailment. Case Study 3-Scenario 2

4.5.4 Scenario 3. System with heating load, smart case

The third scenario of the case study 3 represents the behaviour of the power system with different generators, different loads and different heating loads for each zone. The input data is the same as described at the beginning of the section, yet the system responds to the heating demand smarter than in scenario 2. By contrast, the indoor air temperature can vary between a range of temperature that corresponds to 21.2°C and 24°C.

Operation cost

The operation cost in the scenario 3 is a 5.76% lower than scenario 2. Regarding the start-up and shut-down cost, the cost in scenario 3 has been reduced due to the smart operation that avoids the on and off of the generation units.

Table 16. Operation cost. Case Study 3-Scenario 3

Scenario 3: System with heating load and smart case	
Generation Cost	3,549,496,176.03 €
Start-up/Shut-down Cost	121,314,100.00 €
Operation Cost	**3,670,810,276.03 €**

Electricity generation

Figure 43 shows the electricity generation per source of generation. As in the rest of the case studies, the electricity generated is mainly by wind, summing up for a 111,063.2 GWh, 2% less than the wind generation in scenario 2. The solar and biomass generation have 12,045.26 GWh and 4.2 GWh of generation, respectively. The hydro generation has decreased 1% compared with scenario 2, having 6,502.04 GWh. The generation with coal and lignite have higher values than scenario 2, accounting for 39,189.36 GWh and 36,418.72 GWh, respectively. The generation with gas is 26,168.14 GWh, 12.8% less than in scenario 2.

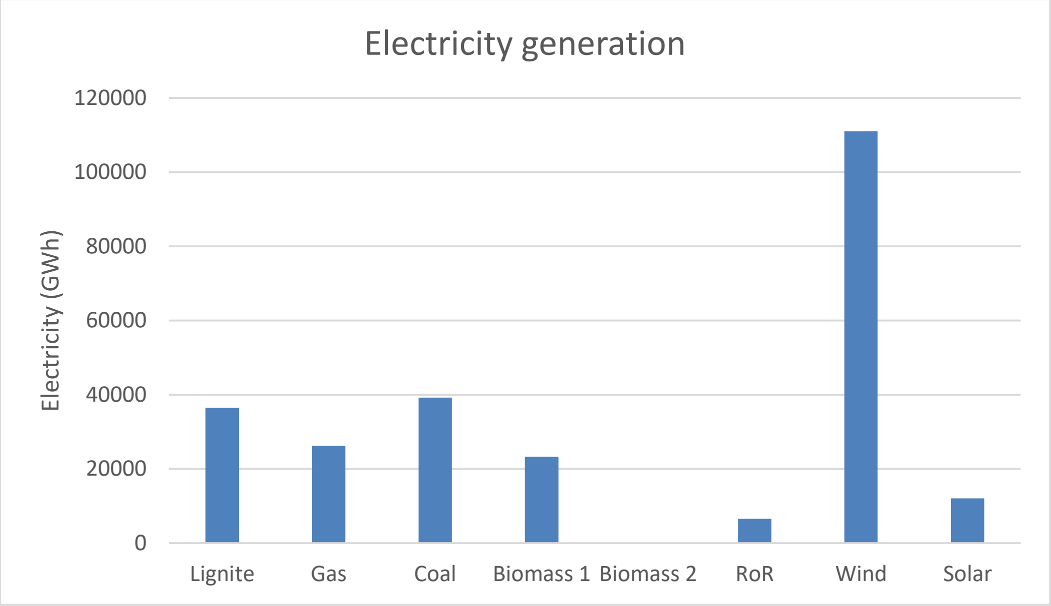


Figure 43. Electricity generation per source of generation. Case Study 3-Scenario 3

Hourly operation

Figure 44 expose the electricity generated with the load and thermal load demanded. The generation with gas is reduced in some hours of the generation compared with scenario 2. Due to the flexibility added by the smart case, the renewable energy curtailment is reduced comparing with non-smart case. Due to the start-up and shut-down restrictions there are some hours where the generation is supplied by conventional sources, although there is capacity for generating with renewable energies.

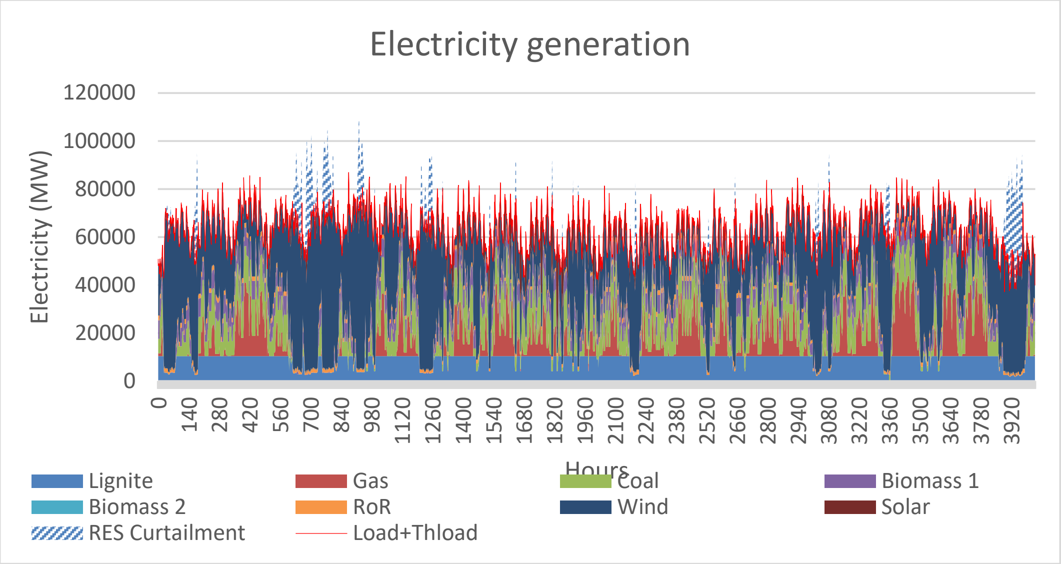


Figure 44. Electricity generated per source, load and RES Curtailment. Case Study 3-Scenario 3

4.5.5 Results analysis

With the comparison of the three scenarios, the impact of the operation of thermal loads in the power system is noticed. The analysis is made in terms of system costs, electricity generation, CO_2 emissions, and the impact on the net load.

System costs

Table 17 shows the costs generated by the three scenarios. As the first scenario does not have thermal load, the generation cost is lower than scenarios 2 and 3. In scenario 2, the inclusion of the thermal load to the power system increases the operation cost by 34.11% with respect of the first scenario.

The smart case is able to reduce the operation cost a 5.76% regarding to the second scenario. The cost reduction of start-up and shut-down costs allow an increment of the lifespan of thermal generation units and reduces the maintenance requirements.

Table 17. System costs Case Study 3

	Operation Cost	Generation Cost	Start-up/Shut-down Cost
Scenario 1: System without heating load	2,904,354,172.18 €	2,759,872,772.18 €	144,481,400.00 €
Scenario 2: System with heating load, no smart case	3,895,051,665.83 €	3,724,727,665.83 €	170,324,000.00 €
Scenario 3: System with heating load and smart case	3,670,810,276.03 €	3,549,496,176.03 €	121,314,100.00 €

Electricity generation

In Figure 45 shows the electricity generation by source in each scenario. It is possible to differentiate the electricity generated in each scenario. When adding the thermal load to the power system, the electricity generation is increased by a 10.5% in scenario 2 and 11% in scenario 3. The difference is due to the heat losses that are as a result of the smart operation. The most significant change is on the generation with gas. Adding the thermal load causes the share of gas generation increases by 4%, accounting for 8% for scenario 1 and 12% for scenario 2. When the smart case takes place, the share of gas generation is reduced by 2% respect the scenario 2. The scenario 3 has a share of 10% of the total generation with gas.

Lignite has the same share on the three scenarios and renewable energies have small variations in terms of generation. The wind generation experiments variations, in scenario 1 has a share of 46%, adding the thermal load in scenario 2 the share of wind is 43%, and in scenario 3 the share is 44%.

With the addition of the thermal load the RES Curtailment is reduced a 23.86% for scenario 2 and 38.6% for scenario 3.

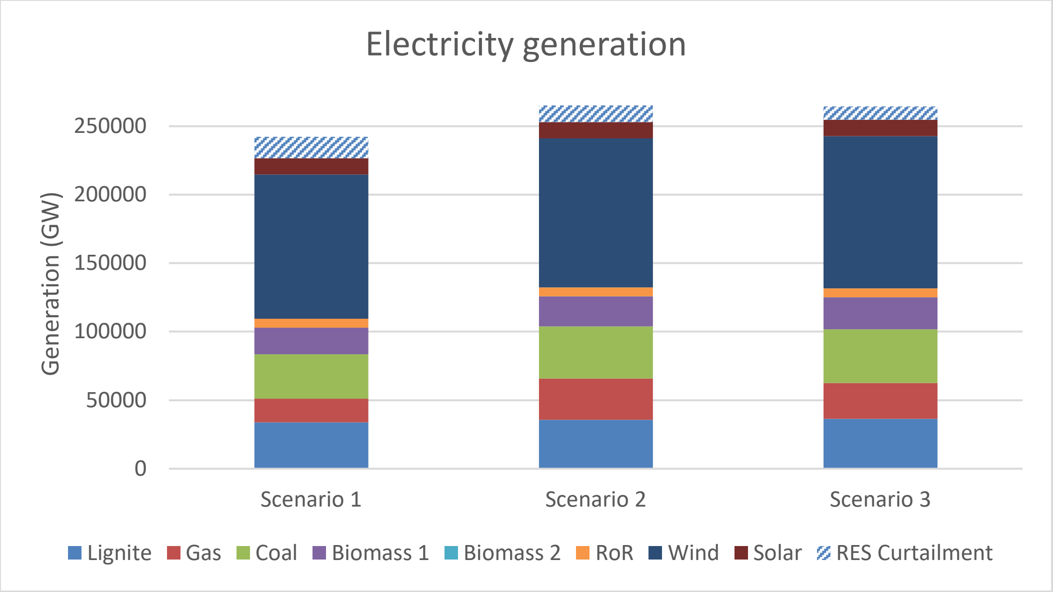


Figure 45. Electricity generation comparison per source. Case Study 3

CO_2 emissions

As it is explained in section 4.3.5, the first scenario only takes into account the electricity generated to cover the load demand, but also the emissions produced by thermal demand have to be quantified too.

Table 18 shows the CO_2 emissions per scenario. Regarding the first scenario, the CO_2 emissions are almost 90 million tonnes. When thermal loads are supplied by electricity generation, the emissions are reduced by 19.5% for the second scenario and 19.6% for the third scenario. This large reduction is achieved because a significant part of the thermal load would be supplied by renewable energy. The quantity of CO_2 emissions per KWh are lower in scenario 3. The small reduction is thanks to the flexibility added by smart case. The system capable of increase the generation with renewable units.

Table 18. CO_2 emissions. Case Study 3

CO_2 emissions (tn)	
Scenario 1: System without heating load	89,832,103.8
Scenario 2: System with heating load, no smart case	72,316,090.5
Scenario 3: System with heating load and smart case	72,188,321

Net load

Figure 46 shows the net load of the three scenarios. As happen in the previous case studies, the base scenario has a load demand lower than other scenarios, there is more renewable capacity available to supply it. When there is thermal demand, the net load curve moves up and has higher load in almost all hours. Also, the peak demand is increased.

The difference is noticed in the smart case, where the demand peak is almost the same as the first scenario, 66667.7 MW for the first scenario and a 68294.6 MW for the third scenario. In comparison with the second scenario, the peak load is reduced by 10.73% with a smart operation. The curve of net demand flattens slightly, reducing the consumption in hours of high demand and increasing it in hours of less demand.

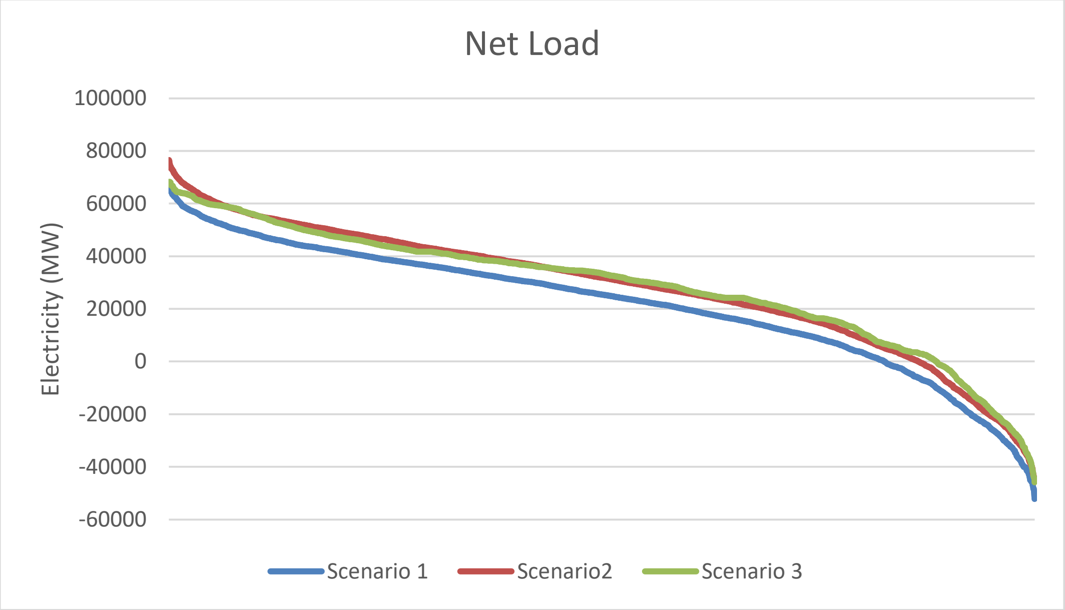


Figure 46. Net load. Case Study 3

5 Conclusions

Considering the future electrification of residential space heating loads, a tool for studying the impact of thermal loads operation on the power system is developed. A unit commitment model is developed including the modelling of the thermal behaviour of the residential buildings and the space heating requirements. The unit commitment problem aims to minimize the operation cost considering the generation with renewable energies and flexibility provided by thermal loads. The different tools used to solve the problem are implemented in the java language. The operation planning problem is modelled and solved through ILOG libraries and the optimizer CPLEX.

5.1 Thermal load

The thermal properties of the building are modelled in order to represent the behaviour of the dwelling as accurate as possible and the gains and losses that are able to change the state of the indoor air temperature are considered too. The heat gains due to solar radiation, internal heat gains, heat loss by transmission, ventilation losses and the heat recovery for the ventilation system were modelled.

Furthermore, the thermal loads are added to the power system, since their behaviour will impact the operation of the power system.

5.2 Case studies

The case studies are based on a future projection of the German power system by the year 2030. The study consists of the power system connected to thermal loads that are supplied by electric heating devices.

The three case studies follow the same structure to be able to compare between them. They have a base scenario, without thermal load, a scenario with thermal load but working in a non-smart case, and the third scenario with the thermal load and with a smart operation.

In the first case study the operation of an efficient single-family dwelling is studied for one week. The operation cost is increased when the thermal load is added to the system since there are an increment of electricity generated. Regarding the addition of the smart operation in scenario 3, the flexibility added is working as a battery. The dwelling storages energy and releases it in hours where there is less wind availability. The indoor temperature is able to increase and decrease between a range of 21.2°C and 24°C. As a result, the heating consumption is adapted to renewable energies availability and the total operation cost can be reduced by 16.07% compared with non-smart operation. Concerning the net load, when the thermal load with a non-smart operation is considered the curve moves up and also the peak demand is increased. When considering the smart operation, the peak demand is reduced and the curve flattens.

The second case study refers to an inefficient single-family dwelling. Comparing the two case studies the operation cost is higher for the case study 2 because the losses of the house are higher than in case study 1. The dwelling needs more heating consumption to be able to maintain the temperature inside the comfort limits. In the smart case operation, the flexibility is limited because of the high losses in the building. In consequence, the impact of the smart operation on the net load is reduced, and the operation cost reduction is only a 6.38% compared with the non-smart operation.

Finally, the third case study studies the whole heating period for the year 2030. The building stock is modelled with two representative single-family and multi-family units. In this case study, the availability of renewable generation is lower compared to the previous case studies. Therefore, the smart operation benefits are lower.

The smart operation reduces the start-up and shut-down costs and reduces the operation cost by 5.76% compared to the non-smart operation. Regarding the net load, the curve is flattened and the peak demand is reduced to almost the same level as the scenario without thermal load.

Regarding the CO_2 emissions, the emissions produced by the residential space heating have a great impact on the environment, for that reason it is important to reduce the emissions for the next years.

When the thermal load supplied by fossil fuels, as today, there is a very high level of CO_2 emissions. With the electrification of the residential space heating a reduction of 18.6%, 26.7% and 19.5% of CO_2 emissions is reached in scenario 2 of case study 1, case study 2 and case study 3, respectively.

The emissions are reduced when the smart operation is added to the system. The flexibility added to the system allows the modification of the energy demand to hours where there are more renewable energy sources available.

With the smart case a reduction of CO_2 emissions by 8.1%, 2% and 0.2% are reached for the three different case studies comparing non-smart and smart operation. The difference in reduction between the three case studies is that the smart operation in case study 1 is able to add more flexibility than in case study 2. As a result, the CO_2 emissions reduced are higher than in case study 1. In case study 3, the reduction is lower than in the other case studies since the availability of renewable generation is lower and the benefits when a smart operation is added are lower too.

In summary, when a smart operation of the space heating demand is considered, the flexibility in the power system is increased. The system takes advantage of the demand response ability of the smart operation and reduces the operation costs. The case studies show that the level of benefits obtained from a smart operation of the thermal loads depends on the thermal efficiency of the studied buildings and the availability of renewable generation.

5.3 Future work

The following aspects can be analysed to further study the operation of thermal loads in power systems:

- Study the system when the number of dwellings that use electricity for the residential space heating has increased.
- Keep improving the capacity of renewable energies until the demand is covered with renewable units.
- Increase the efficiency of the buildings in order to increase the thermal inertia of the house and lower the heating demand.

6 Bibliography

[1] United Nations, “Paris Agreement,” 2015. [Online]. Available: http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf. [Accessed 25 April 2019].

[2] European Commission, “Overview of support activities and projects of the European Union on energy efficiency and renewable energy in the heating and cooling sector,” Luxembourg, 2016.

[3] Agora Energiewende, “The EU power sector in 2017,” 2017. [Online]. Available: https://www.agora-energiewende.de/en/. [Accessed 2 06 2019].

[4] K. Hedegaard, B. Mathiesen , H. Lund and P. Heiselberg, “Wind power integration using individual heat pumps - Analysis of different heat storage options,” *Energy,* vol. 47, pp. 284-293, 2012.

[5] A. Bloess, “Power-to-heat for renewable energy integration: A review of technologies, modeling approaches, and flexibility potentials,” *Applied Energy,* vol. 212, pp. 1611-1626, 2017.

[6] Umwelt undesamt, “Energie Daten,” [Online]. Available: https://www.umweltbundesamt.de/daten/energie/. [Accessed 08 05 2019].

[7] A. J. Conejo and L. Baringo, Power System Operations, New York: Springer, 2017.

[8] Y. Huang, P. M. Pardalos and Q. P. Zheng, Electrical Power Unit Commitment, Orlando: Springer, 2016.

[9] G. Energy, Western wind and solar integration study, New York: NREL, 2010.

[10] E. Nyholm, S. Puranik, É. Mata, M. Odenberger and F. Johnsson, “Demand response potential of electrical space heating in Swedish single-family dwellings,” *Building and Environment,* vol. 96, pp. 270-282, 2016.

[11] A. Sancho, “Integrated modelling of electrical energy systems for the study of residential demand response strategies,” in *University of Nottingham,* Nottingham, 2017.

[12] I. Energy, “Technology Roadmap: Solar Photovoltaic,” Paris, 2014.

[13] H. C. Gils, “Balancing of Intermitent Renewable Power Generation by Demand Response and Thermal Energy Storage,” in *University of Stuttgart,* Stuttgart, 2015.

[14] U. Persson and S. Werner, *Stratego. Quantifying the Heating and Cooling Demand in Europe,* Halmstad: Public Document, 2015.

[15] A. Honoré, “Decarbonisation of heat in Europe: implications for natural gas demand,” 2018.

[16] Heat Roadmap Europe 2050, “Heating and Cooling. The transformation towards a low-carbon Heating & Cooling sector,” 2017.

[17] M. Ram, D. Bogdanov, A. Aghahosseini, A. Gulagi, A. Oyewo, M. Child, U. Caldera, K. Sadovskaia, J. Farfan, L. Barbosa, M. Fasihi, S. Khalili and H.-J. Fell, “Global Energy System based on 100% Renewable Energy – Energy Transition in Europe Across Power, Heat, Transport and Desalination Sectors,” Berlin, 2018.

[18] E. Mata and A. Kalagasidis, Calculation of energy use in Swedish housing, Göteborg: Chalmers, 2009.

[19] Intelligent Energy Europe Programme of the EU, “Tabula Web Tool,” [Online]. Available: http://webtool.building-typology.eu/?c=de#bm. [Accessed 27 05 2019].

[20] T. Taylor, V. Mendon and M. Zhao, *Cost-Effectiveness of Heat Recovery Ventilation,* 2015.

[21] G. Sanchis, B. Betraoui, T. Anderski, E. Peirano, R. Pestana, B. De Clercq, G. Migliavacca, M. Czernie and M. Paun, “The Corridors of Power: A Pan-European Electricity Highway System for 2050,” *IEEE Power and Energy Magazine,* vol. 13, no. 1, pp. 38-51, 2014.

[22] European Commission, “PVGIS European Communities,” [Online]. Available: http://re.jrc.ec.europa.eu/pvg_download/data_download.html.

[23] Agora Energiewende, “Energiewende 2030: The Big Picture. Megatrends, Targets, Strategies ans a 10-Point Agenda for the Second Phase of Germany's Energy Transition,” 2018.

[24] European Commission, “Renewable Energy Progress,” 2017.

[25] R. Kemna and J. M. Acedo, Average EU building heat load for HVAC equipment, Brussels, 2014.

[26] Heat Roadmap Europe, “Heat Roadmap Europe 4 (HRE4): Building the knowledge, skills, and capacity required to enable new policies and encourage new investments in the heating and cooling sector,” 2017.

[27] United Nations, 2005. [Online]. Available: https://unfccc.int/resource/docs/convkp/kpspan.pdf.

[28] Federal Ministry for Economic Affairs and Technolo, “BMWi,” 2010. [Online]. Available: http://www.bmwi.de/BMWi/Redaktion/PDF/E/energiekonzept-. [Accessed 06 06 2019].

[29] “European Environment Agency,” 17 01 2019. [Online]. Available: https://www.eea.europa.eu/data-and-maps/daviz/final-energy-intensity-by-sector-3#tab-chart_1. [Accessed 25 5 2019].

[30] C. Zhao, J. Wang, J.-P. Watson and Y. Guan, “Multi-stage robust unit commitment considering Wind and Demand Response,” in *2013 FERC Technical Conference,* 2013.

[31] I. Fraunhofer, “Net public electricity generation in Germany in 2018,” Fraunhofer ISE, 13 3 109. [Online]. Available: https://www.energy-charts.de/energy_pie.htm?year=2018. [Accessed 06 06 2019].

[32] M. Xue, J. Xie, F. Chen, X. Ke, T. Xu and H. Hou, “Review on Multi-objective Joint Economic Dispatching of Microgrid in Power System,” *Procedia Computer Science,* vol. 130, p. 6, 2018.

[33] D. Fischer and H. Madani, “On heat pumps in smart grids: A review,” *Renewable and Sustainable Energy Reviews,* vol. 70, pp. 342-357, 2016.

[34] K. Bauermann, “German energiewende and the heating market - impact and limits of policy,” *Energy Policy,* vol. 94, pp. 235-246, 2016.

[35] A. Bloess, “Impacts of heat sector transformation on Germany’s power system through increased use of power-to-heat,” *Applied Energy,* vol. 239, pp. 560-580, 2019.

[36] H. Johra, K. Filonenko, P. Heiselberg and C. Veje, “Integration of a magnetocaloric heat pump in an energy flexible residential building,” *Renewable Energy,* vol. 136, pp. 115-126, 2019.

[37] F. Yang, J. Yiliu and L. Zhenkum, “Optimal economic dispatch for microgrid considering shiftable loads,” in *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, Beijing, 2017.

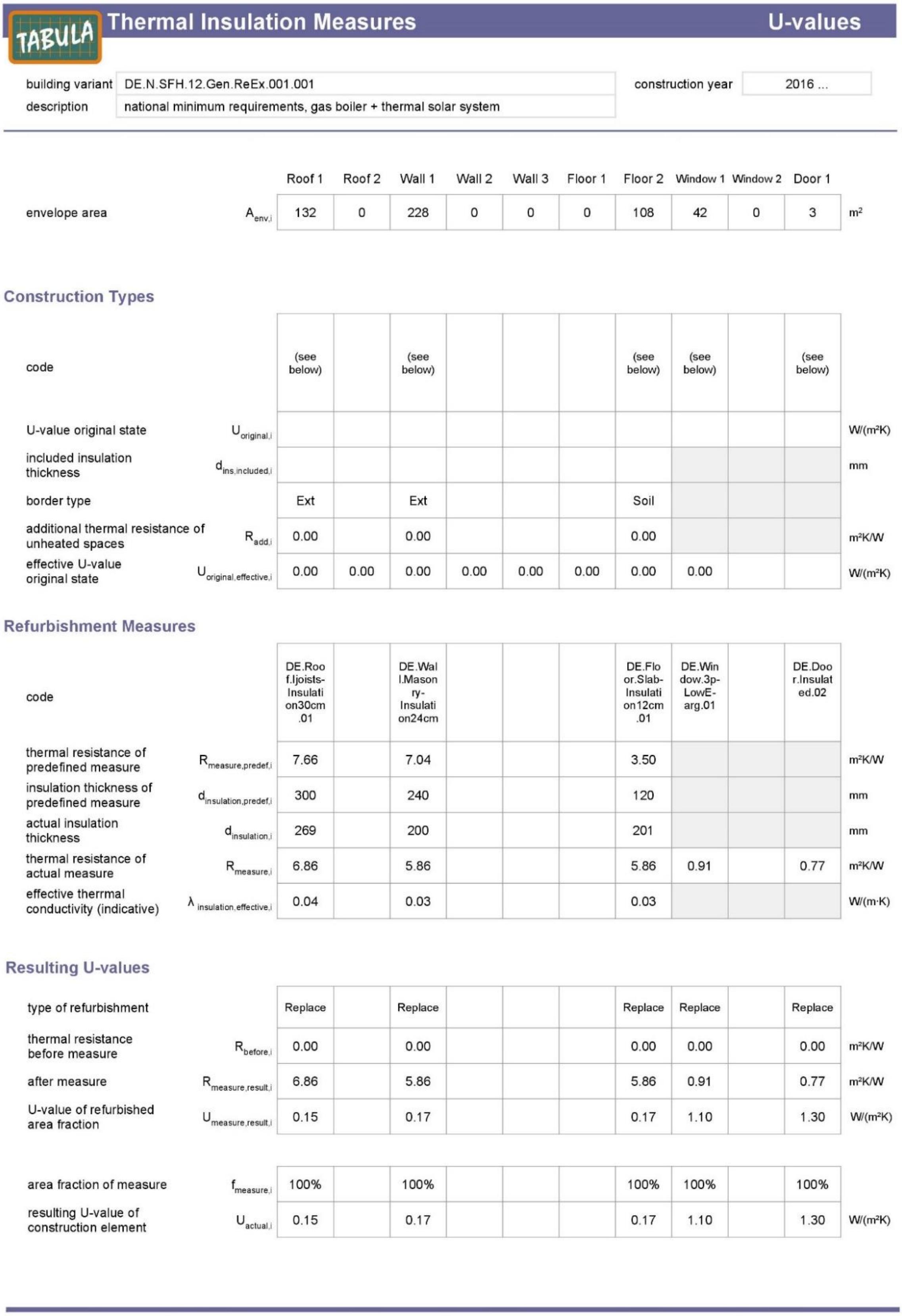
[38] Z. Zhang, J. Wang and X. Cao, “Economic dispatch model considering battery lifetime for microgrid,” in *2014 International Conference on Power System Technology,* Chengdu, 2015.

[39] U. A. Ozturk, M. Mazumdar and B. Norman, “A solution to the stochastic unit commitment problem using chance constrained programming,” *IEEE Transactions on Power Systems,* vol. 19, no. 3, pp. 1589-1598, 2004.

[40] Y. Simmhan, V. Prasanna and S. Aman, Toward data-driven demand-response optimization in a campus microgrid, vol. 10, New York: ACM New York, 2011, pp. 1125-2434.

7 Appendixes

7.1 Appendix 1. Tabula Data Case Study 1



Thermal Insulation Measures **U-values**

building variant: DE.N.SFH.12.Gen.ReEx.001.001
construction year: 2016 ...
description: national minimum requirements, gas boiler + thermal solar system

		Roof 1	Roof 2	Wall 1	Wall 2	Wall 3	Floor 1	Floor 2	Window 1	Window 2	Door 1	
envelope area	$A_{env,i}$	132	0	228	0	0	0	108	42	0	3	m²

Construction Types

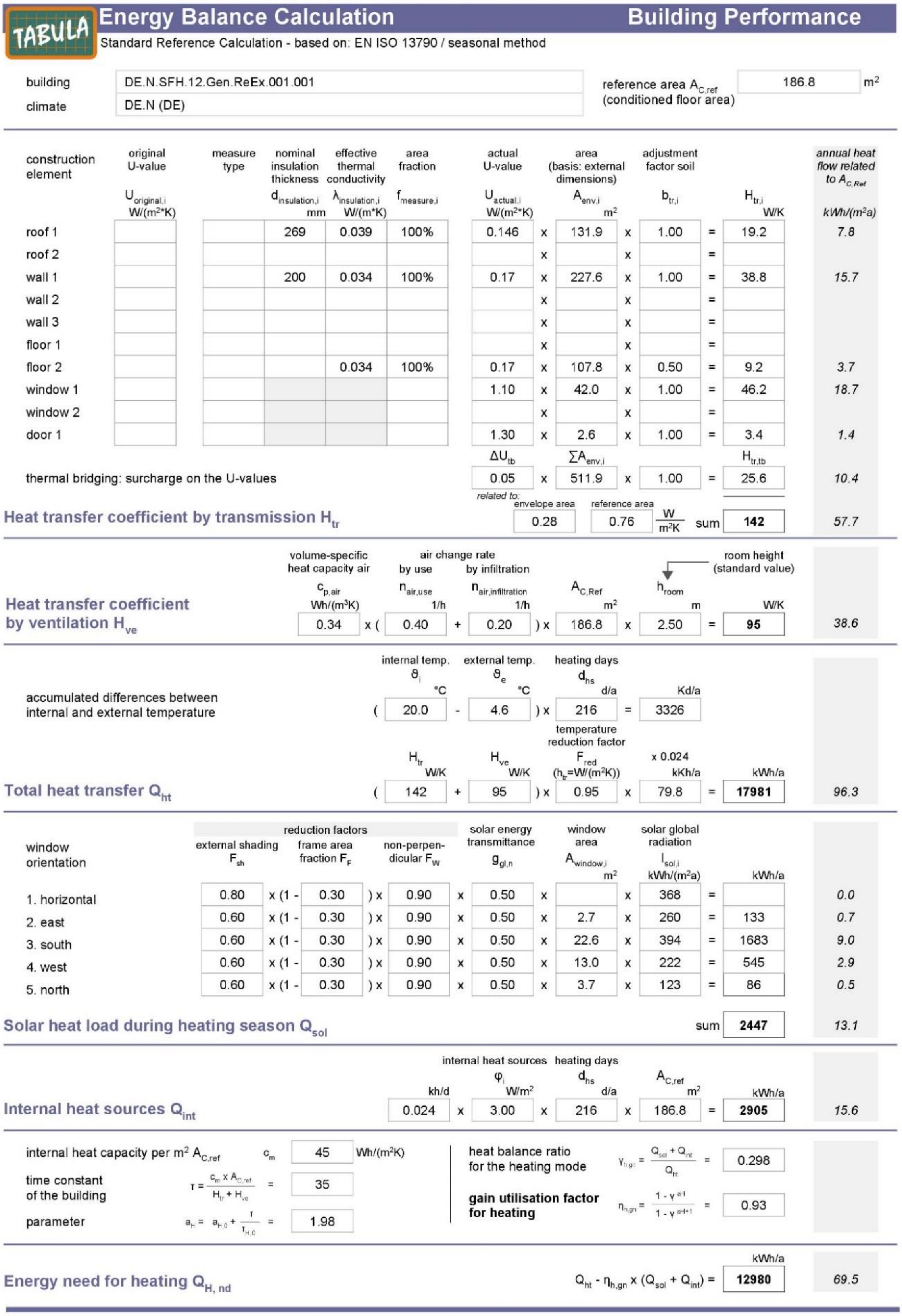
		Roof 1	Roof 2	Wall 1	Wall 2	Wall 3	Floor 1	Floor 2	Window 1	Window 2	Door 1	
code		(see below)		(see below)				(see below)	(see below)		(see below)	
U-value original state	$U_{original,i}$											W/(m²K)
included insulation thickness	$d_{ins,included,i}$											mm
border type		Ext		Ext				Soil				
additional thermal resistance of unheated spaces	$R_{add,i}$	0.00		0.00				0.00				m²K/W
effective U-value original state	$U_{original,effective,i}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			W/(m²K)

Refurbishment Measures

		Roof 1	Roof 2	Wall 1	Wall 2	Wall 3	Floor 1	Floor 2	Window 1	Window 2	Door 1	
code		DE.Roof.Ijoists-Insulation30cm.01		DE.Wall.Masonry-Insulation24cm				DE.Floor.Slab-Insulation12cm.01	DE.Window.3p-LowE-arg.01		DE.Door.Insulated.02	
thermal resistance of predefined measure	$R_{measure,predef,i}$	7.66		7.04				3.50				m²K/W
insulation thickness of predefined measure	$d_{insulation,predef,i}$	300		240				120				mm
actual insulation thickness	$d_{insulation,i}$	269		200				201				mm
thermal resistance of actual measure	$R_{measure,i}$	6.86		5.86				5.86	0.91		0.77	m²K/W
effective therrmal conductivity (indicative)	$\lambda_{insulation,effective,i}$	0.04		0.03				0.03				W/(m·K)

Resulting U-values

		Roof 1	Roof 2	Wall 1	Wall 2	Wall 3	Floor 1	Floor 2	Window 1	Window 2	Door 1	
type of refurbishment		Replace		Replace				Replace	Replace		Replace	
thermal resistance before measure	$R_{before,i}$	0.00		0.00				0.00	0.00		0.00	m²K/W
after measure	$R_{measure,result,i}$	6.86		5.86				5.86	0.91		0.77	m²K/W
U-value of refurbished area fraction	$U_{measure,result,i}$	0.15		0.17				0.17	1.10		1.30	W/(m²K)
area fraction of measure	$f_{measure,i}$	100%		100%				100%	100%		100%	
resulting U-value of construction element	$U_{actual,i}$	0.15		0.17				0.17	1.10		1.30	W/(m²K)



Energy Balance Calculation — Building Performance

Standard Reference Calculation - based on: EN ISO 13790 / seasonal method

building	DE.N.SFH.12.Gen.ReEx.001.001	reference area $A_{C,ref}$ (conditioned floor area)	186.8 m^2
climate	DE.N (DE)		

construction element	original U-value $U_{original,i}$ W/(m²*K)	measure type	nominal insulation thickness $d_{insulation,i}$ mm	effective thermal conductivity $\lambda_{insulation,i}$ W/(m*K)	area fraction $f_{measure,i}$	actual U-value $U_{actual,i}$ W/(m²*K)		area (basis: external dimensions) $A_{env,i}$ m²		adjustment factor soil $b_{tr,i}$		$H_{tr,i}$ W/K	*annual heat flow related to $A_{C,Ref}$* *kWh/(m²a)*
roof 1			269	0.039	100%	0.146	x	131.9	x	1.00	=	19.2	*7.8*
roof 2							x		x		=		
wall 1			200	0.034	100%	0.17	x	227.6	x	1.00	=	38.8	*15.7*
wall 2							x		x		=		
wall 3							x		x		=		
floor 1							x		x		=		
floor 2				0.034	100%	0.17	x	107.8	x	0.50	=	9.2	*3.7*
window 1						1.10	x	42.0	x	1.00	=	46.2	*18.7*
window 2							x		x		=		
door 1						1.30	x	2.6	x	1.00	=	3.4	*1.4*
						ΔU_{tb}		$\sum A_{env,i}$				$H_{tr,tb}$	
thermal bridging: surcharge on the U-values						0.05	x	511.9	x	1.00	=	25.6	*10.4*

related to: envelope area 0.28 — reference area 0.76 $\frac{W}{m^2K}$

Heat transfer coefficient by transmission H_{tr} sum **142** *57.7*

	volume-specific heat capacity air $c_{p,air}$ Wh/(m³K)		air change rate by use $n_{air,use}$ 1/h		air change rate by infiltration $n_{air,infiltration}$ 1/h		$A_{C,Ref}$ m²		h_{room} m (room height (standard value))		W/K	
Heat transfer coefficient by ventilation H_{ve}	0.34	x (	0.40	+	0.20	) x	186.8	x	2.50	=	**95**	*38.6*

		internal temp. ϑ_i °C		external temp. ϑ_e °C		heating days d_{hs} d/a		Kd/a			
accumulated differences between internal and external temperature	(	20.0	-	4.6	) x	216	=	3326			
		H_{tr} W/K		H_{ve} W/K		temperature reduction factor F_{red} (h_c=W/(m²K))		x 0.024 kKh/a		kWh/a	
Total heat transfer Q_{ht}	(	142	+	95	) x	0.95	x	79.8	=	**17981**	*96.3*

window orientation	reduction factors: external shading F_{sh}		frame area fraction F_F		non-perpendicular F_W		solar energy transmittance $g_{gl,n}$		window area $A_{window,i}$ m²		solar global radiation $I_{sol,i}$ kWh/(m²a)		kWh/a	
1. horizontal	0.80	x (1 -	0.30	) x	0.90	x	0.50	x		x	368	=		*0.0*
2. east	0.60	x (1 -	0.30	) x	0.90	x	0.50	x	2.7	x	260	=	133	*0.7*
3. south	0.60	x (1 -	0.30	) x	0.90	x	0.50	x	22.6	x	394	=	1683	*9.0*
4. west	0.60	x (1 -	0.30	) x	0.90	x	0.50	x	13.0	x	222	=	545	*2.9*
5. north	0.60	x (1 -	0.30	) x	0.90	x	0.50	x	3.7	x	123	=	86	*0.5*

Solar heat load during heating season Q_{sol} sum **2447** *13.1*

	kh/d		internal heat sources φ_i W/m²		heating days d_{hs} d/a		$A_{C,ref}$ m²		kWh/a	
Internal heat sources Q_{int}	0.024	x	3.00	x	216	x	186.8	=	**2905**	*15.6*

internal heat capacity per m² $A_{C,ref}$ c_m = 45 Wh/(m²K)

time constant of the building $\tau = \frac{c_m \times A_{C,ref}}{H_{tr} + H_{ve}}$ = 35

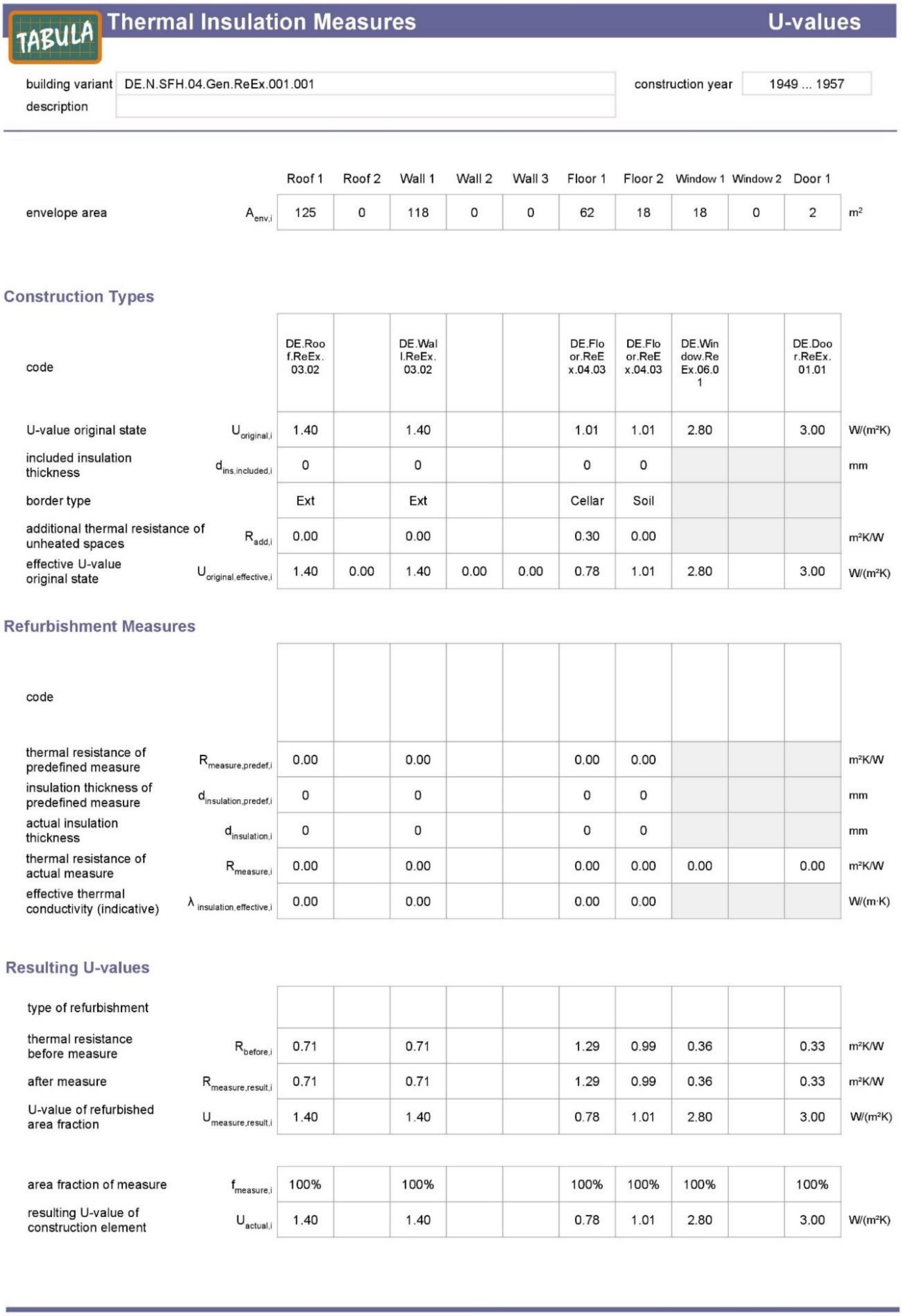
parameter $a_H = a_{H,0} + \frac{\tau}{\tau_{H,0}}$ = 1.98

heat balance ratio for the heating mode $\gamma_{h,gn} = \frac{Q_{sol} + Q_{int}}{Q_{ht}}$ = 0.298

gain utilisation factor for heating $\eta_{h,gn} = \frac{1 - \gamma^{aH}}{1 - \gamma^{aH+1}}$ = 0.93

Energy need for heating $Q_{H, nd}$ $Q_{ht} - \eta_{h,gn} \times (Q_{sol} + Q_{int})$ = **12980** kWh/a *69.5*

7.2 Appendix 2. Tabula Data Case Study 2



Thermal Insulation Measures — U-values

building variant	DE.N.SFH.04.Gen.ReEx.001.001	construction year	1949 ... 1957
description			

		Roof 1	Roof 2	Wall 1	Wall 2	Wall 3	Floor 1	Floor 2	Window 1	Window 2	Door 1	
envelope area	$A_{env,i}$	125	0	118	0	0	62	18	18	0	2	m²

Construction Types

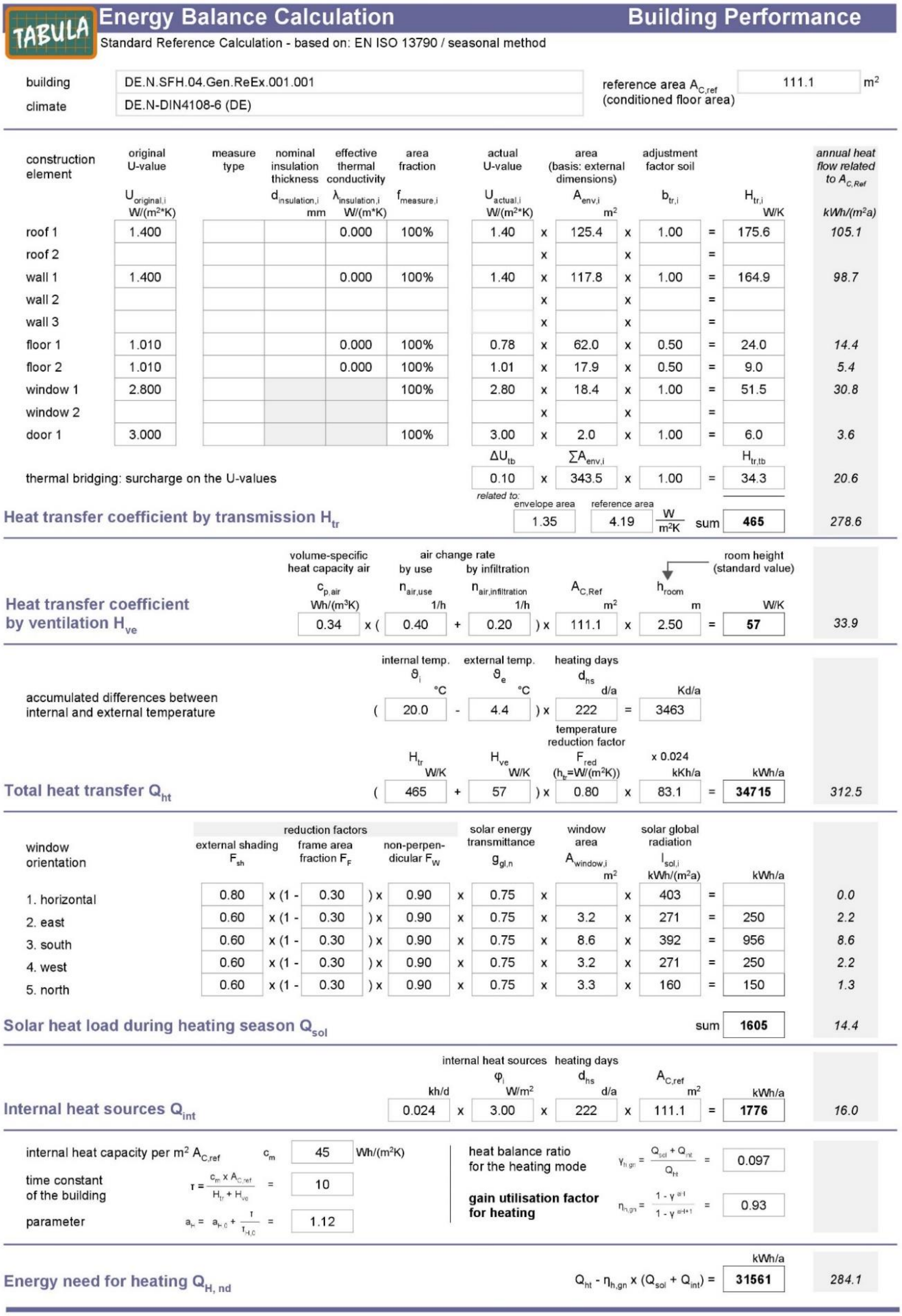
		Roof 1	Roof 2	Wall 1	Wall 2	Wall 3	Floor 1	Floor 2	Window 1	Window 2	Door 1	
code		DE.Roof.ReEx.03.02		DE.Wall.ReEx.03.02			DE.Floor.ReEx.04.03	DE.Floor.ReEx.04.03	DE.Window.ReEx.06.01		DE.Door.ReEx.01.01	
U-value original state	$U_{original,i}$	1.40		1.40			1.01	1.01	2.80		3.00	W/(m²K)
included insulation thickness	$d_{ins,included,i}$	0		0			0	0				mm
border type		Ext		Ext			Cellar	Soil				
additional thermal resistance of unheated spaces	$R_{add,i}$	0.00		0.00			0.30	0.00				m²K/W
effective U-value original state	$U_{original,effective,i}$	1.40	0.00	1.40	0.00	0.00	0.78	1.01	2.80		3.00	W/(m²K)

Refurbishment Measures

		Roof 1	Roof 2	Wall 1	Wall 2	Wall 3	Floor 1	Floor 2	Window 1	Window 2	Door 1	
code												
thermal resistance of predefined measure	$R_{measure,predef,i}$	0.00		0.00			0.00	0.00				m²K/W
insulation thickness of predefined measure	$d_{insulation,predef,i}$	0		0			0	0				mm
actual insulation thickness	$d_{insulation,i}$	0		0			0	0				mm
thermal resistance of actual measure	$R_{measure,i}$	0.00		0.00			0.00	0.00	0.00		0.00	m²K/W
effective therrmal conductivity (indicative)	$\lambda_{insulation,effective,i}$	0.00		0.00			0.00	0.00				W/(m·K)

Resulting U-values

		Roof 1	Roof 2	Wall 1	Wall 2	Wall 3	Floor 1	Floor 2	Window 1	Window 2	Door 1	
type of refurbishment												
thermal resistance before measure	$R_{before,i}$	0.71		0.71			1.29	0.99	0.36		0.33	m²K/W
after measure	$R_{measure,result,i}$	0.71		0.71			1.29	0.99	0.36		0.33	m²K/W
U-value of refurbished area fraction	$U_{measure,result,i}$	1.40		1.40			0.78	1.01	2.80		3.00	W/(m²K)
area fraction of measure	$f_{measure,i}$	100%		100%			100%	100%	100%		100%	
resulting U-value of construction element	$U_{actual,i}$	1.40		1.40			0.78	1.01	2.80		3.00	W/(m²K)



TABULA **Energy Balance Calculation** **Building Performance**

Standard Reference Calculation - based on: EN ISO 13790 / seasonal method

building	DE.N.SFH.04.Gen.ReEx.001.001	reference area $A_{C,ref}$ (conditioned floor area)	111.1	m^2
climate	DE.N-DIN4108-6 (DE)			

construction element	original U-value $U_{original,i}$ W/(m²*K)	measure type	nominal insulation thickness $d_{insulation,i}$ mm	effective thermal conductivity $\lambda_{insulation,i}$ W/(m*K)	area fraction $f_{measure,i}$	actual U-value $U_{actual,i}$ W/(m²*K)		area (basis: external dimensions) $A_{env,i}$ m²		adjustment factor soil $b_{tr,i}$		$H_{tr,i}$ W/K	annual heat flow related to $A_{C,Ref}$ kWh/(m²a)
roof 1	1.400			0.000	100%	1.40	x	125.4	x	1.00	=	175.6	105.1
roof 2							x		x		=		
wall 1	1.400			0.000	100%	1.40	x	117.8	x	1.00	=	164.9	98.7
wall 2							x		x		=		
wall 3							x		x		=		
floor 1	1.010			0.000	100%	0.78	x	62.0	x	0.50	=	24.0	14.4
floor 2	1.010			0.000	100%	1.01	x	17.9	x	0.50	=	9.0	5.4
window 1	2.800				100%	2.80	x	18.4	x	1.00	=	51.5	30.8
window 2							x		x		=		
door 1	3.000				100%	3.00	x	2.0	x	1.00	=	6.0	3.6
						ΔU_{tb}		$\Sigma A_{env,i}$				$H_{tr,tb}$	
thermal bridging: surcharge on the U-values						0.10	x	343.5	x	1.00	=	34.3	20.6

related to:

	envelope area	reference area			
Heat transfer coefficient by transmission H_{tr}	1.35	4.19	$\frac{W}{m^2K}$ sum	**465**	278.6

	volume-specific heat capacity air $c_{p,air}$ Wh/(m³K)		air change rate by use $n_{air,use}$ 1/h		air change rate by infiltration $n_{air,infiltration}$ 1/h		$A_{C,Ref}$ m²		h_{room} m (room height (standard value))		W/K	
Heat transfer coefficient by ventilation H_{ve}	0.34	x (	0.40	+	0.20	) x	111.1	x	2.50	=	**57**	33.9

		internal temp. ϑ_i °C		external temp. ϑ_e °C		heating days d_{hs} d/a		Kd/a			
accumulated differences between internal and external temperature	(	20.0	-	4.4	) x	222	=	3463			
		H_{tr} W/K		H_{ve} W/K		temperature reduction factor F_{red} (h_{tr}=W/(m²K))		x 0.024 kKh/a		kWh/a	
Total heat transfer Q_{ht}	(	465	+	57	) x	0.80	x	83.1	=	**34715**	312.5

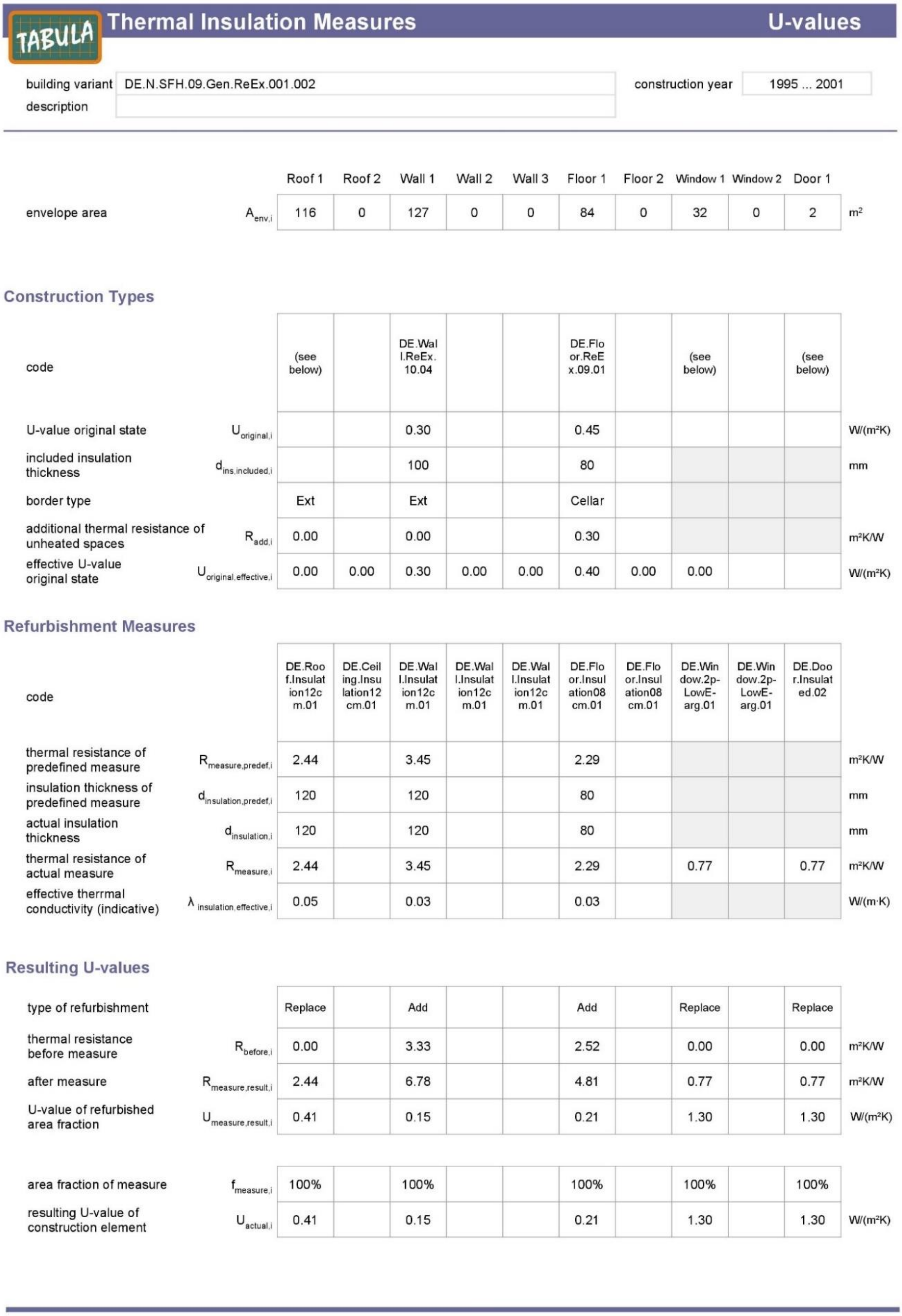
window orientation	reduction factors: external shading F_{sh}		frame area fraction F_F		non-perpendicular F_W		solar energy transmittance $g_{gl,n}$		window area $A_{window,i}$ m²		solar global radiation $I_{sol,i}$ kWh/(m²a)		kWh/a	
1. horizontal	0.80	x (1 -	0.30	) x	0.90	x	0.75	x		x	403	=		0.0
2. east	0.60	x (1 -	0.30	) x	0.90	x	0.75	x	3.2	x	271	=	250	2.2
3. south	0.60	x (1 -	0.30	) x	0.90	x	0.75	x	8.6	x	392	=	956	8.6
4. west	0.60	x (1 -	0.30	) x	0.90	x	0.75	x	3.2	x	271	=	250	2.2
5. north	0.60	x (1 -	0.30	) x	0.90	x	0.75	x	3.3	x	160	=	150	1.3
Solar heat load during heating season Q_{sol}												sum	**1605**	14.4

	kh/d		internal heat sources φ_i W/m²		heating days d_{hs} d/a		$A_{C,ref}$ m²		kWh/a	
Internal heat sources Q_{int}	0.024	x	3.00	x	222	x	111.1	=	**1776**	16.0

internal heat capacity per m² $A_{C,ref}$	c_m	45	Wh/(m²K)	heat balance ratio for the heating mode	$\gamma_{h,gn} = \frac{Q_{sol} + Q_{int}}{Q_{ht}}$ =	0.097	
time constant of the building	$\tau = \frac{c_m \times A_{C,ref}}{H_{tr} + H_{ve}}$ =	10		**gain utilisation factor for heating**	$\eta_{h,gn} = \frac{1 - \gamma^{aH}}{1 - \gamma^{aH+1}}$ =	0.93	
parameter	$a_H = a_{H,0} + \frac{\tau}{\tau_{H,0}}$ =	1.12					

		kWh/a	
Energy need for heating $Q_{H,nd}$	$Q_{ht} - \eta_{h,gn} \times (Q_{sol} + Q_{int})$ =	**31561**	284.1

7.3 Appendix 3. Tabula Data Case Study 3 SFH



Thermal Insulation Measures **U-values**

building variant	DE.N.SFH.09.Gen.ReEx.001.002	construction year	1995 ... 2001
description			

		Roof 1	Roof 2	Wall 1	Wall 2	Wall 3	Floor 1	Floor 2	Window 1	Window 2	Door 1	
envelope area	$A_{env,i}$	116	0	127	0	0	84	0	32	0	2	m²

Construction Types

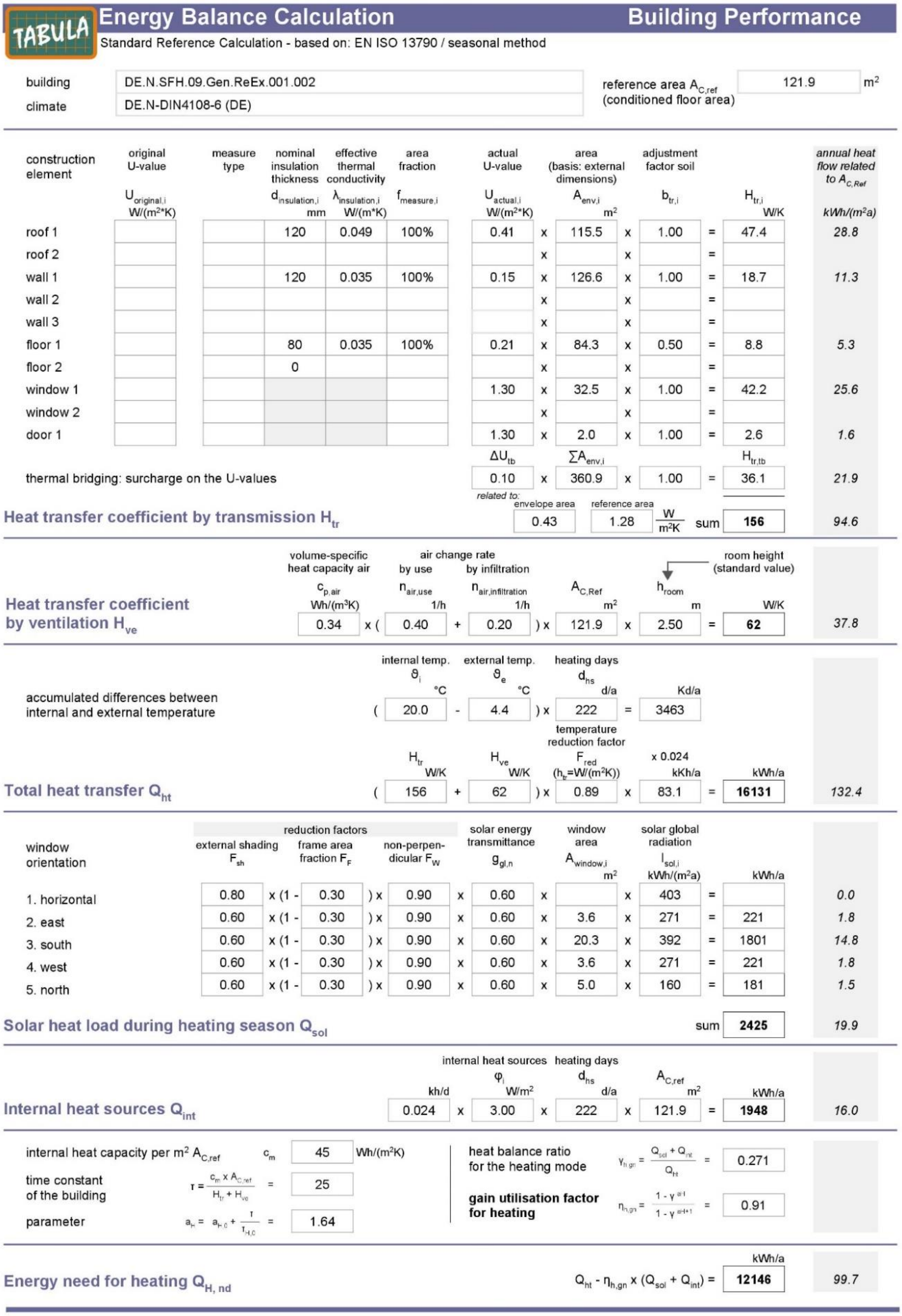
		Roof 1	Roof 2	Wall 1	Wall 2	Wall 3	Floor 1	Floor 2	Window 1	Window 2	Door 1	
code		(see below)		DE.Wall.ReEx.10.04			DE.Floor.ReEx.09.01		(see below)		(see below)	
U-value original state	$U_{original,i}$			0.30			0.45					W/(m²K)
included insulation thickness	$d_{ins,included,i}$			100			80					mm
border type		Ext		Ext			Cellar					
additional thermal resistance of unheated spaces	$R_{add,i}$	0.00		0.00			0.30					m²K/W
effective U-value original state	$U_{original,effective,i}$	0.00	0.00	0.30	0.00	0.00	0.40	0.00	0.00			W/(m²K)

Refurbishment Measures

		Roof 1	Roof 2	Wall 1	Wall 2	Wall 3	Floor 1	Floor 2	Window 1	Window 2	Door 1	
code		DE.Roof.Insulation12cm.01	DE.Ceiling.Insulation12cm.01	DE.Wall.Insulation12cm.01	DE.Wall.Insulation12cm.01	DE.Wall.Insulation12cm.01	DE.Floor.Insulation08cm.01	DE.Floor.Insulation08cm.01	DE.Window.2p-LowE-arg.01	DE.Window.2p-LowE-arg.01	DE.Door.Insulated.02	
thermal resistance of predefined measure	$R_{measure,predef,i}$	2.44		3.45			2.29					m²K/W
insulation thickness of predefined measure	$d_{insulation,predef,i}$	120		120			80					mm
actual insulation thickness	$d_{insulation,i}$	120		120			80					mm
thermal resistance of actual measure	$R_{measure,i}$	2.44		3.45			2.29		0.77		0.77	m²K/W
effective therrmal conductivity (indicative)	$\lambda_{insulation,effective,i}$	0.05		0.03			0.03					W/(m·K)

Resulting U-values

		Roof 1	Roof 2	Wall 1	Wall 2	Wall 3	Floor 1	Floor 2	Window 1	Window 2	Door 1	
type of refurbishment		Replace		Add			Add		Replace		Replace	
thermal resistance before measure	$R_{before,i}$	0.00		3.33			2.52		0.00		0.00	m²K/W
after measure	$R_{measure,result,i}$	2.44		6.78			4.81		0.77		0.77	m²K/W
U-value of refurbished area fraction	$U_{measure,result,i}$	0.41		0.15			0.21		1.30		1.30	W/(m²K)
area fraction of measure	$f_{measure,i}$	100%		100%			100%		100%		100%	
resulting U-value of construction element	$U_{actual,i}$	0.41		0.15			0.21		1.30		1.30	W/(m²K)



TABULA Energy Balance Calculation — Building Performance

Standard Reference Calculation - based on: EN ISO 13790 / seasonal method

building	DE.N.SFH.09.Gen.ReEx.001.002	reference area $A_{C,ref}$ (conditioned floor area)	121.9 m^2
climate	DE.N-DIN4108-6 (DE)		

construction element	original U-value $U_{original,i}$ W/(m²*K)	measure type	nominal insulation thickness $d_{insulation,i}$ mm	effective thermal conductivity $\lambda_{insulation,i}$ W/(m*K)	area fraction $f_{measure,i}$	actual U-value $U_{actual,i}$ W/(m²*K)		area (basis: external dimensions) $A_{env,i}$ m²		adjustment factor soil $b_{tr,i}$		$H_{tr,i}$ W/K	annual heat flow related to $A_{C,Ref}$ kWh/(m²a)
roof 1			120	0.049	100%	0.41	x	115.5	x	1.00	=	47.4	28.8
roof 2							x		x		=		
wall 1			120	0.035	100%	0.15	x	126.6	x	1.00	=	18.7	11.3
wall 2							x		x		=		
wall 3							x		x		=		
floor 1			80	0.035	100%	0.21	x	84.3	x	0.50	=	8.8	5.3
floor 2			0				x		x		=		
window 1						1.30	x	32.5	x	1.00	=	42.2	25.6
window 2							x		x		=		
door 1						1.30	x	2.0	x	1.00	=	2.6	1.6
						ΔU_{tb}		$\sum A_{env,i}$				$H_{tr,tb}$	
thermal bridging: surcharge on the U-values						0.10	x	360.9	x	1.00	=	36.1	21.9

Heat transfer coefficient by transmission H_{tr}

related to: envelope area	reference area			
0.43	1.28	$\frac{W}{m^2K}$	sum	**156**

annual: 94.6

Heat transfer coefficient by ventilation H_{ve}

volume-specific heat capacity air $c_{p,air}$ Wh/(m³K)		air change rate by use $n_{air,use}$ 1/h		air change rate by infiltration $n_{air,infiltration}$ 1/h		$A_{C,Ref}$ m²		room height (standard value) h_{room} m		W/K	
0.34	x (	0.40	+	0.20	) x	121.9	x	2.50	=	**62**	37.8

accumulated differences between internal and external temperature

	internal temp. ϑ_i °C		external temp. ϑ_e °C		heating days d_{hs} d/a		Kd/a
(	20.0	-	4.4	) x	222	=	3463

Total heat transfer Q_{ht}

	H_{tr} W/K		H_{ve} W/K		temperature reduction factor F_{red} (h_{tr}=W/(m²K))		x 0.024 kKh/a		kWh/a	
(	156	+	62	) x	0.89	x	83.1	=	**16131**	132.4

window orientation	reduction factors: external shading F_{sh}		frame area fraction F_F		non-perpendicular F_W		solar energy transmittance $g_{gl,n}$		window area $A_{window,i}$ m²		solar global radiation $I_{sol,i}$ kWh/(m²a)		kWh/a	
1. horizontal	0.80	x (1 -	0.30	) x	0.90	x	0.60	x		x	403	=		0.0
2. east	0.60	x (1 -	0.30	) x	0.90	x	0.60	x	3.6	x	271	=	221	1.8
3. south	0.60	x (1 -	0.30	) x	0.90	x	0.60	x	20.3	x	392	=	1801	14.8
4. west	0.60	x (1 -	0.30	) x	0.90	x	0.60	x	3.6	x	271	=	221	1.8
5. north	0.60	x (1 -	0.30	) x	0.90	x	0.60	x	5.0	x	160	=	181	1.5

Solar heat load during heating season Q_{sol} sum **2425** 19.9

Internal heat sources Q_{int}

kh/d		internal heat sources φ_i W/m²		heating days d_{hs} d/a		$A_{C,ref}$ m²		kWh/a	
0.024	x	3.00	x	222	x	121.9	=	**1948**	16.0

internal heat capacity per m² $A_{C,ref}$ c_m 45 Wh/(m²K)

time constant of the building $\tau = \frac{c_m \times A_{C,ref}}{H_{tr} + H_{ve}}$ = 25

parameter $a_H = a_{H,0} + \frac{\tau}{\tau_{H,0}}$ = 1.64

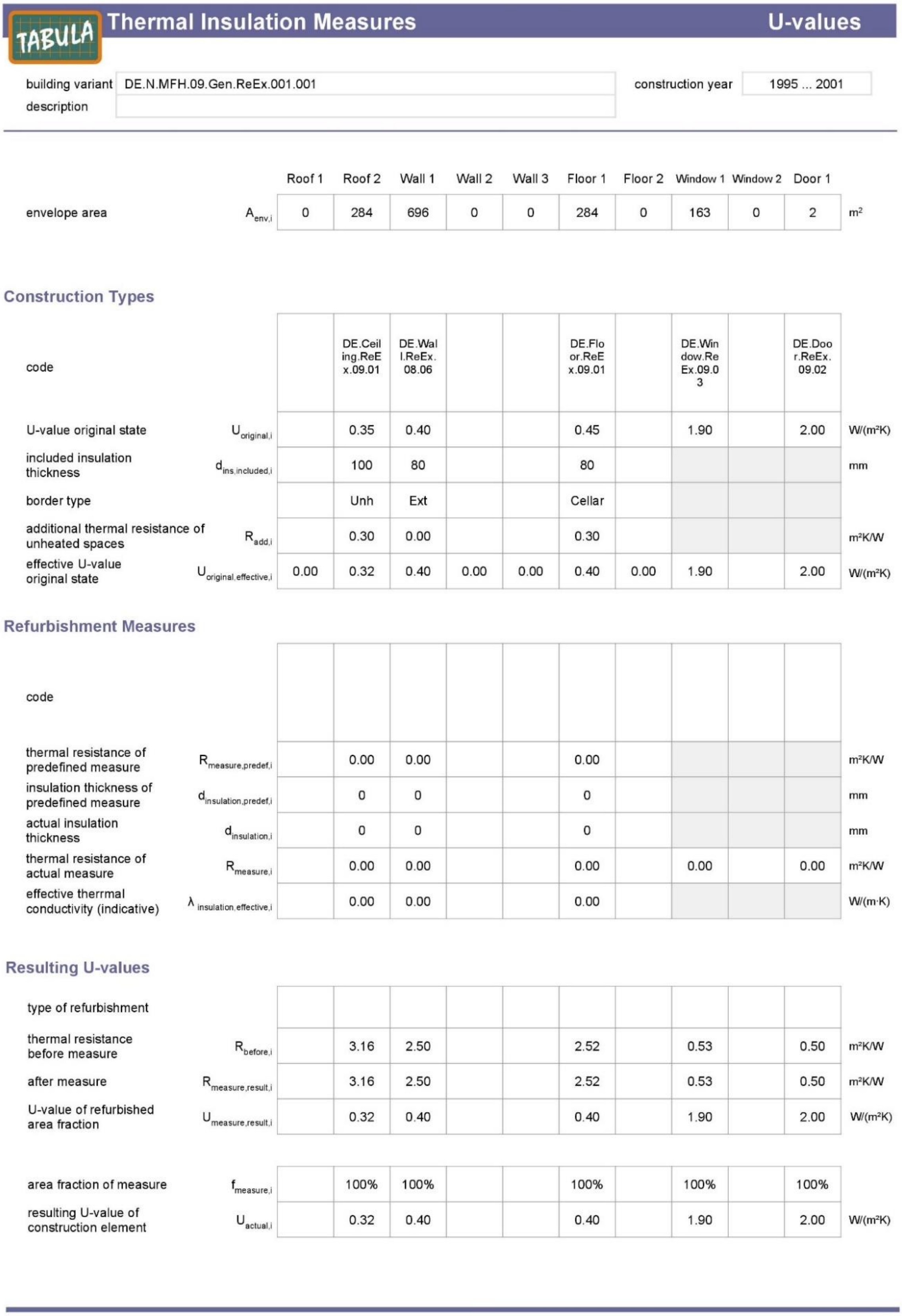
heat balance ratio for the heating mode $\gamma_{h,gn} = \frac{Q_{sol} + Q_{int}}{Q_{ht}}$ = 0.271

gain utilisation factor for heating $\eta_{h,gn} = \frac{1 - \gamma^{aH}}{1 - \gamma^{aH+1}}$ = 0.91

Energy need for heating $Q_{H,nd}$

$Q_{ht} - \eta_{h,gn} \times (Q_{sol} + Q_{int})$ = **12146** kWh/a 99.7

7.4 Appendix 4. Tabula Data Case Study 3 MFH



TABULA Thermal Insulation Measures U-values

building variant	DE.N.MFH.09.Gen.ReEx.001.001	construction year	1995 ... 2001
description			

		Roof 1	Roof 2	Wall 1	Wall 2	Wall 3	Floor 1	Floor 2	Window 1	Window 2	Door 1	
envelope area	$A_{env,i}$	0	284	696	0	0	284	0	163	0	2	m^2

Construction Types

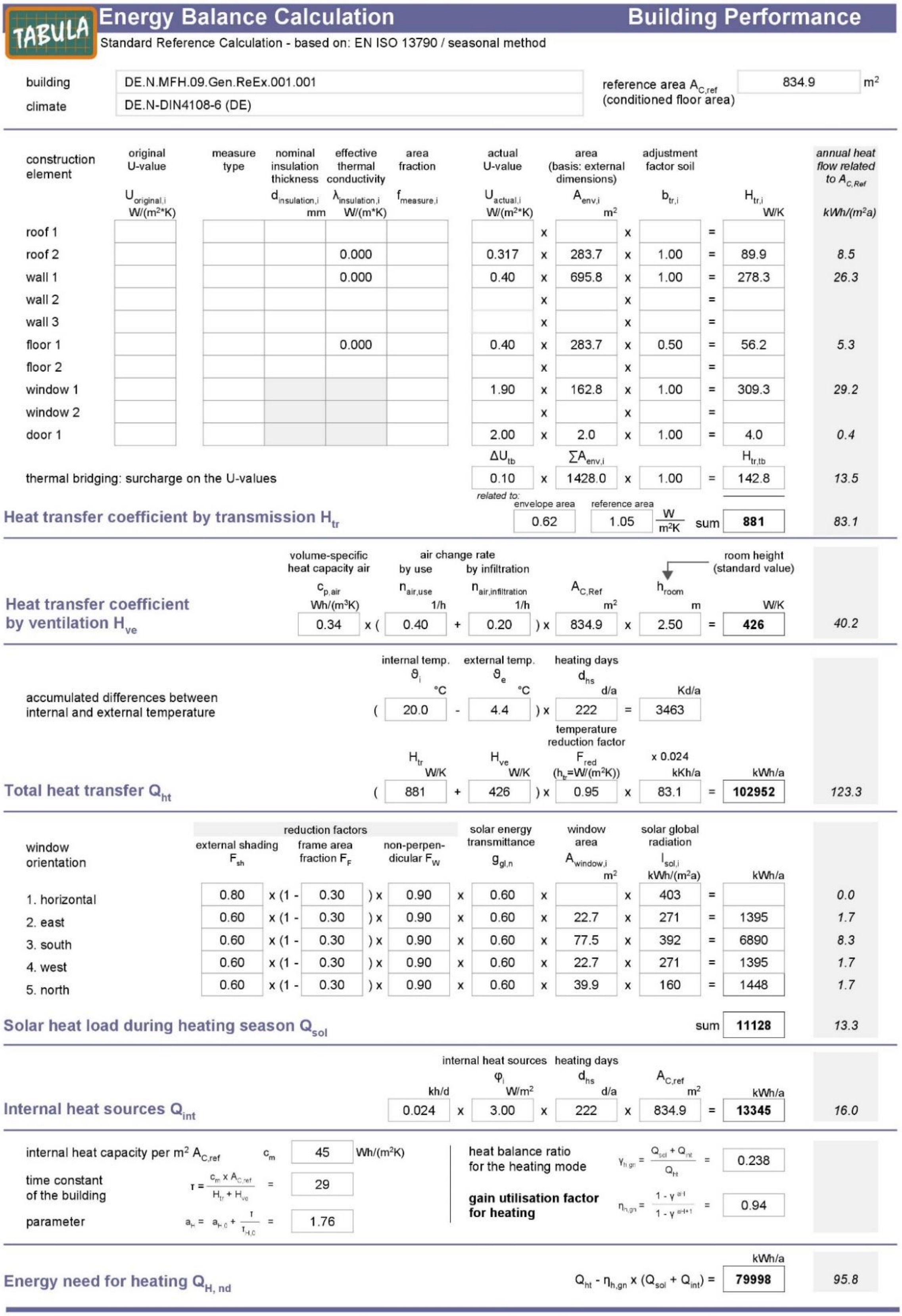
		Roof 1	Roof 2	Wall 1	Wall 2	Wall 3	Floor 1	Floor 2	Window 1	Window 2	Door 1	
code			DE.Ceiling.ReEx.09.01	DE.Wall.ReEx.08.06			DE.Floor.ReEx.09.01		DE.Window.ReEx.09.03		DE.Door.ReEx.09.02	
U-value original state	$U_{original,i}$		0.35	0.40			0.45		1.90		2.00	W/(m²K)
included insulation thickness	$d_{ins,included,i}$		100	80			80					mm
border type			Unh	Ext			Cellar					
additional thermal resistance of unheated spaces	$R_{add,i}$		0.30	0.00			0.30					m²K/W
effective U-value original state	$U_{original,effective,i}$	0.00	0.32	0.40	0.00	0.00	0.40	0.00	1.90		2.00	W/(m²K)

Refurbishment Measures

		Roof 1	Roof 2	Wall 1	Wall 2	Wall 3	Floor 1	Floor 2	Window 1	Window 2	Door 1	
code												
thermal resistance of predefined measure	$R_{measure,predef,i}$		0.00	0.00			0.00					m²K/W
insulation thickness of predefined measure	$d_{insulation,predef,i}$		0	0			0					mm
actual insulation thickness	$d_{insulation,i}$		0	0			0					mm
thermal resistance of actual measure	$R_{measure,i}$		0.00	0.00			0.00		0.00		0.00	m²K/W
effective therrmal conductivity (indicative)	$\lambda_{insulation,effective,i}$		0.00	0.00			0.00					W/(m·K)

Resulting U-values

		Roof 1	Roof 2	Wall 1	Wall 2	Wall 3	Floor 1	Floor 2	Window 1	Window 2	Door 1	
type of refurbishment												
thermal resistance before measure	$R_{before,i}$		3.16	2.50			2.52		0.53		0.50	m²K/W
after measure	$R_{measure,result,i}$		3.16	2.50			2.52		0.53		0.50	m²K/W
U-value of refurbished area fraction	$U_{measure,result,i}$		0.32	0.40			0.40		1.90		2.00	W/(m²K)
area fraction of measure	$f_{measure,i}$		100%	100%			100%		100%		100%	
resulting U-value of construction element	$U_{actual,i}$		0.32	0.40			0.40		1.90		2.00	W/(m²K)



TABULA **Energy Balance Calculation** **Building Performance**

Standard Reference Calculation - based on: EN ISO 13790 / seasonal method

building	DE.N.MFH.09.Gen.ReEx.001.001	reference area $A_{C,ref}$ (conditioned floor area)	834.9	m^2
climate	DE.N-DIN4108-6 (DE)			

construction element	original U-value $U_{original,i}$ W/(m²*K)	measure type	nominal insulation thickness $d_{insulation,i}$ mm	effective thermal conductivity $\lambda_{insulation,i}$ W/(m*K)	area fraction $f_{measure,i}$	actual U-value $U_{actual,i}$ W/(m²*K)		area (basis: external dimensions) $A_{env,i}$ m²		adjustment factor soil $b_{tr,i}$		$H_{tr,i}$ W/K	*annual heat flow related to $A_{C,Ref}$* *kWh/(m²a)*
roof 1							x		x		=		
roof 2				0.000		0.317	x	283.7	x	1.00	=	89.9	*8.5*
wall 1				0.000		0.40	x	695.8	x	1.00	=	278.3	*26.3*
wall 2							x		x		=		
wall 3							x		x		=		
floor 1				0.000		0.40	x	283.7	x	0.50	=	56.2	*5.3*
floor 2							x		x		=		
window 1						1.90	x	162.8	x	1.00	=	309.3	*29.2*
window 2							x		x		=		
door 1						2.00	x	2.0	x	1.00	=	4.0	*0.4*
						ΔU_{tb}		$\sum A_{env,i}$				$H_{tr,tb}$	
thermal bridging: surcharge on the U-values						0.10	x	1428.0	x	1.00	=	142.8	*13.5*

related to: envelope area 0.62 reference area 1.05 $\frac{W}{m^2K}$ sum **881** *83.1*

Heat transfer coefficient by transmission H_{tr}

Heat transfer coefficient by ventilation H_{ve}

volume-specific heat capacity air $c_{p,air}$ Wh/(m³K)		air change rate by use $n_{air,use}$ 1/h		air change rate by infiltration $n_{air,infiltration}$ 1/h		$A_{C,Ref}$ m²		room height (standard value) h_{room} m		W/K	
0.34	x (	0.40	+	0.20	) x	834.9	x	2.50	=	**426**	*40.2*

accumulated differences between internal and external temperature

	internal temp. ϑ_i °C		external temp. ϑ_e °C		heating days d_{hs} d/a		Kd/a
(	20.0	-	4.4	) x	222	=	3463

Total heat transfer Q_{ht}

	H_{tr} W/K		H_{ve} W/K		temperature reduction factor F_{red} (h_{tr}=W/(m²K))		x 0.024 kKh/a		kWh/a	
(	881	+	426	) x	0.95	x	83.1	=	**102952**	*123.3*

window orientation	reduction factors: external shading F_{sh}		reduction factors: frame area fraction F_F		reduction factors: non-perpendicular F_W		solar energy transmittance $g_{gl,n}$		window area $A_{window,i}$ m²		solar global radiation $I_{sol,i}$ kWh/(m²a)		kWh/a	
1. horizontal	0.80	x (1 -	0.30	) x	0.90	x	0.60	x		x	403	=		*0.0*
2. east	0.60	x (1 -	0.30	) x	0.90	x	0.60	x	22.7	x	271	=	1395	*1.7*
3. south	0.60	x (1 -	0.30	) x	0.90	x	0.60	x	77.5	x	392	=	6890	*8.3*
4. west	0.60	x (1 -	0.30	) x	0.90	x	0.60	x	22.7	x	271	=	1395	*1.7*
5. north	0.60	x (1 -	0.30	) x	0.90	x	0.60	x	39.9	x	160	=	1448	*1.7*

Solar heat load during heating season Q_{sol} sum **11128** *13.3*

Internal heat sources Q_{int}

kh/d		internal heat sources φ_i W/m²		heating days d_{hs} d/a		$A_{C,ref}$ m²		kWh/a	
0.024	x	3.00	x	222	x	834.9	=	**13345**	*16.0*

internal heat capacity per m² $A_{C,ref}$ c_m = 45 Wh/(m²K)

time constant of the building $\tau = \frac{c_m \times A_{C,ref}}{H_{tr} + H_{ve}}$ = 29

parameter $a_H = a_{H,0} + \frac{\tau}{\tau_{H,0}}$ = 1.76

heat balance ratio for the heating mode $\gamma_{h,gn} = \frac{Q_{sol} + Q_{int}}{Q_{ht}}$ = 0.238

gain utilisation factor for heating $\eta_{h,gn} = \frac{1 - \gamma^{aH}}{1 - \gamma^{aH+1}}$ = 0.94

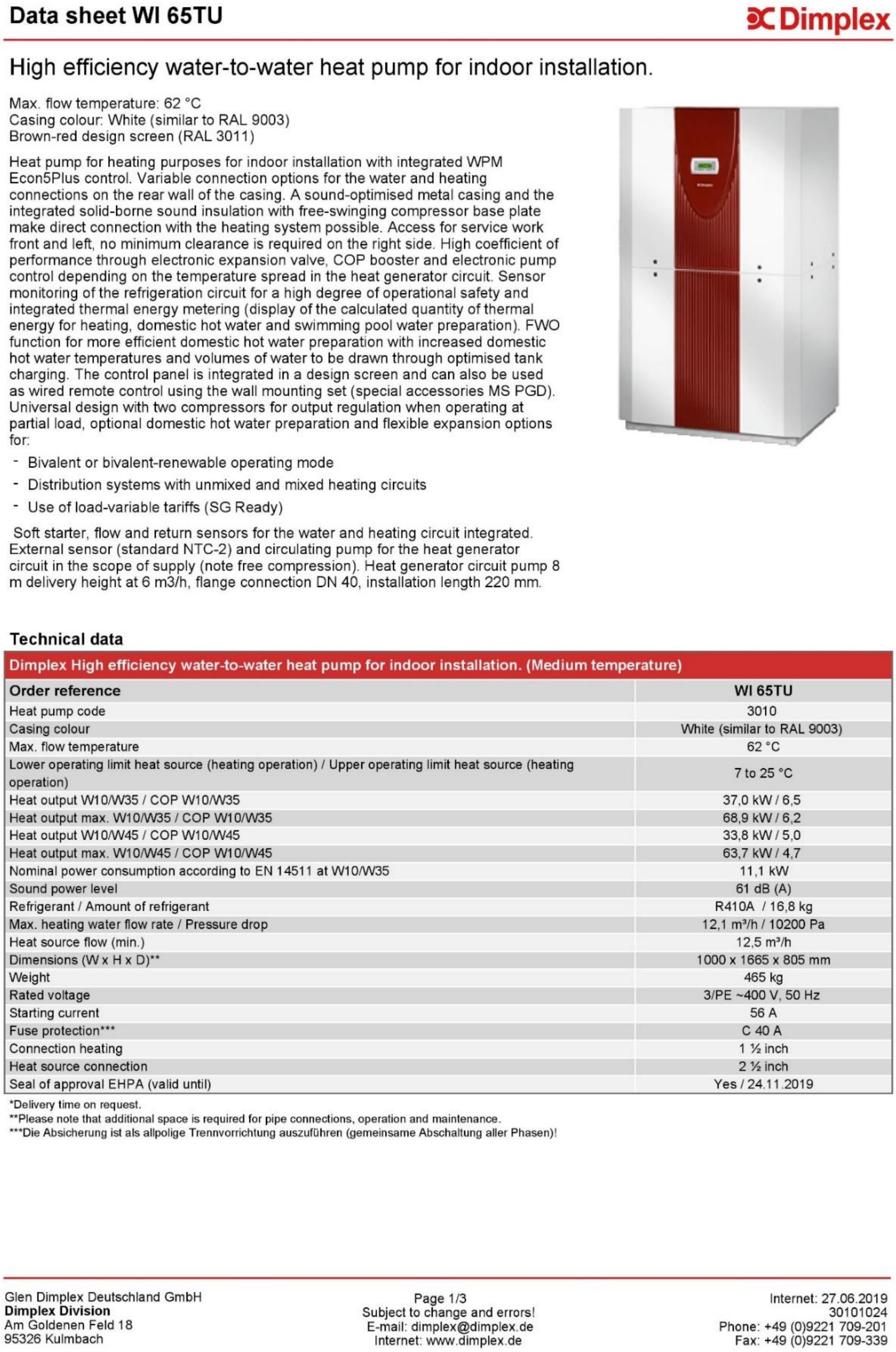
Energy need for heating $Q_{H,nd}$ $Q_{ht} - \eta_{h,gn} \times (Q_{sol} + Q_{int})$ = **79998** kWh/a *95.8*

7.5 Appendix 5. Heat pump for single dwelling

Table 19. Heat pump data sheet

ORIONAIR Therma V Air Heat Pump	
Model:	AHUW126A0 + H12SNE
Nominal heating:	12 kW
COP Heating:	4.46
Voltage:	240Volt 1 phase
Refrigerant:	R410A
Option of solar collector connection	
Rated to -20DegC Heating	
Dimensions Outdoor:	L1760, W600, D650
Dimensions Indoor:	L850, W390, D315
Heating for DHW and heating	
Weight:	204 Kg (Indoor and outdoor)

7.1 Appendix 6. Heat pump for multi-family dwelling



Data sheet WI 65TU

Dimplex

High efficiency water-to-water heat pump for indoor installation.

Max. flow temperature: 62 °C
Casing colour: White (similar to RAL 9003)
Brown-red design screen (RAL 3011)

Heat pump for heating purposes for indoor installation with integrated WPM Econ5Plus control. Variable connection options for the water and heating connections on the rear wall of the casing. A sound-optimised metal casing and the integrated solid-borne sound insulation with free-swinging compressor base plate make direct connection with the heating system possible. Access for service work front and left, no minimum clearance is required on the right side. High coefficient of performance through electronic expansion valve, COP booster and electronic pump control depending on the temperature spread in the heat generator circuit. Sensor monitoring of the refrigeration circuit for a high degree of operational safety and integrated thermal energy metering (display of the calculated quantity of thermal energy for heating, domestic hot water and swimming pool water preparation). FWO function for more efficient domestic hot water preparation with increased domestic hot water temperatures and volumes of water to be drawn through optimised tank charging. The control panel is integrated in a design screen and can also be used as wired remote control using the wall mounting set (special accessories MS PGD). Universal design with two compressors for output regulation when operating at partial load, optional domestic hot water preparation and flexible expansion options for:

- Bivalent or bivalent-renewable operating mode
- Distribution systems with unmixed and mixed heating circuits
- Use of load-variable tariffs (SG Ready)

Soft starter, flow and return sensors for the water and heating circuit integrated. External sensor (standard NTC-2) and circulating pump for the heat generator circuit in the scope of supply (note free compression). Heat generator circuit pump 8 m delivery height at 6 m3/h, flange connection DN 40, installation length 220 mm.

Technical data

Dimplex High efficiency water-to-water heat pump for indoor installation. (Medium temperature)

Order reference	**WI 65TU**
Heat pump code	3010
Casing colour	White (similar to RAL 9003)
Max. flow temperature	62 °C
Lower operating limit heat source (heating operation) / Upper operating limit heat source (heating operation)	7 to 25 °C
Heat output W10/W35 / COP W10/W35	37,0 kW / 6,5
Heat output max. W10/W35 / COP W10/W35	68,9 kW / 6,2
Heat output W10/W45 / COP W10/W45	33,8 kW / 5,0
Heat output max. W10/W45 / COP W10/W45	63,7 kW / 4,7
Nominal power consumption according to EN 14511 at W10/W35	11,1 kW
Sound power level	61 dB (A)
Refrigerant / Amount of refrigerant	R410A / 16,8 kg
Max. heating water flow rate / Pressure drop	12,1 m³/h / 10200 Pa
Heat source flow (min.)	12,5 m³/h
Dimensions (W x H x D)**	1000 x 1665 x 805 mm
Weight	465 kg
Rated voltage	3/PE ~400 V, 50 Hz
Starting current	56 A
Fuse protection***	C 40 A
Connection heating	1 ½ inch
Heat source connection	2 ½ inch
Seal of approval EHPA (valid until)	Yes / 24.11.2019

*Delivery time on request.
**Please note that additional space is required for pipe connections, operation and maintenance.
***Die Absicherung ist als allpolige Trennvorrichtung auszuführen (gemeinsame Abschaltung aller Phasen)!

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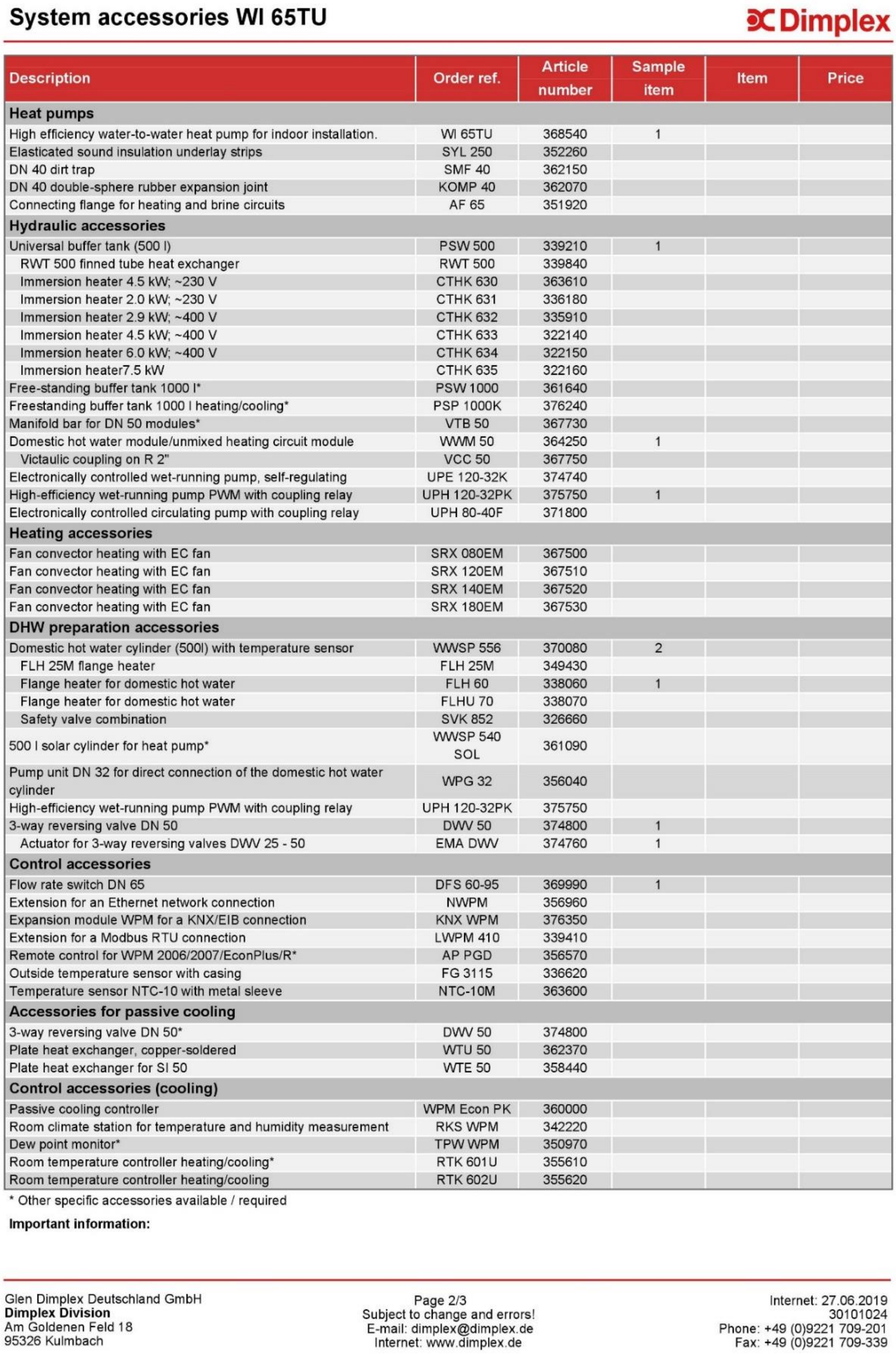

System accessories WI 65TU

Dimplex

Description	Order ref.	Article number	Sample item	Item	Price
Heat pumps					
High efficiency water-to-water heat pump for indoor installation.	WI 65TU	368540	1		
Elasticated sound insulation underlay strips	SYL 250	352260			
DN 40 dirt trap	SMF 40	362150			
DN 40 double-sphere rubber expansion joint	KOMP 40	362070			
Connecting flange for heating and brine circuits	AF 65	351920			
Hydraulic accessories					
Universal buffer tank (500 l)	PSW 500	339210	1		
RWT 500 finned tube heat exchanger	RWT 500	339840			
Immersion heater 4.5 kW; ~230 V	CTHK 630	363610			
Immersion heater 2.0 kW; ~230 V	CTHK 631	336180			
Immersion heater 2.9 kW; ~400 V	CTHK 632	335910			
Immersion heater 4.5 kW; ~400 V	CTHK 633	322140			
Immersion heater 6.0 kW; ~400 V	CTHK 634	322150			
Immersion heater7.5 kW	CTHK 635	322160			
Free-standing buffer tank 1000 l*	PSW 1000	361640			
Freestanding buffer tank 1000 l heating/cooling*	PSP 1000K	376240			
Manifold bar for DN 50 modules*	VTB 50	367730			
Domestic hot water module/unmixed heating circuit module	WWM 50	364250	1		
Victaulic coupling on R 2"	VCC 50	367750			
Electronically controlled wet-running pump, self-regulating	UPE 120-32K	374740			
High-efficiency wet-running pump PWM with coupling relay	UPH 120-32PK	375750	1		
Electronically controlled circulating pump with coupling relay	UPH 80-40F	371800			
Heating accessories					
Fan convector heating with EC fan	SRX 080EM	367500			
Fan convector heating with EC fan	SRX 120EM	367510			
Fan convector heating with EC fan	SRX 140EM	367520			
Fan convector heating with EC fan	SRX 180EM	367530			
DHW preparation accessories					
Domestic hot water cylinder (500l) with temperature sensor	WWSP 556	370080	2		
FLH 25M flange heater	FLH 25M	349430			
Flange heater for domestic hot water	FLH 60	338060	1		
Flange heater for domestic hot water	FLHU 70	338070			
Safety valve combination	SVK 852	326660			
500 l solar cylinder for heat pump*	WWSP 540 SOL	361090			
Pump unit DN 32 for direct connection of the domestic hot water cylinder	WPG 32	356040			
High-efficiency wet-running pump PWM with coupling relay	UPH 120-32PK	375750			
3-way reversing valve DN 50	DWV 50	374800	1		
Actuator for 3-way reversing valves DWV 25 - 50	EMA DWV	374760	1		
Control accessories					
Flow rate switch DN 65	DFS 60-95	369990	1		
Extension for an Ethernet network connection	NWPM	356960			
Expansion module WPM for a KNX/EIB connection	KNX WPM	376350			
Extension for a Modbus RTU connection	LWPM 410	339410			
Remote control for WPM 2006/2007/EconPlus/R*	AP PGD	356570			
Outside temperature sensor with casing	FG 3115	336620			
Temperature sensor NTC-10 with metal sleeve	NTC-10M	363600			
Accessories for passive cooling					
3-way reversing valve DN 50*	DWV 50	374800			
Plate heat exchanger, copper-soldered	WTU 50	362370			
Plate heat exchanger for SI 50	WTE 50	358440			
Control accessories (cooling)					
Passive cooling controller	WPM Econ PK	360000			
Room climate station for temperature and humidity measurement	RKS WPM	342220			
Dew point monitor*	TPW WPM	350970			
Room temperature controller heating/cooling*	RTK 601U	355610			
Room temperature controller heating/cooling	RTK 602U	355620			

* Other specific accessories available / required

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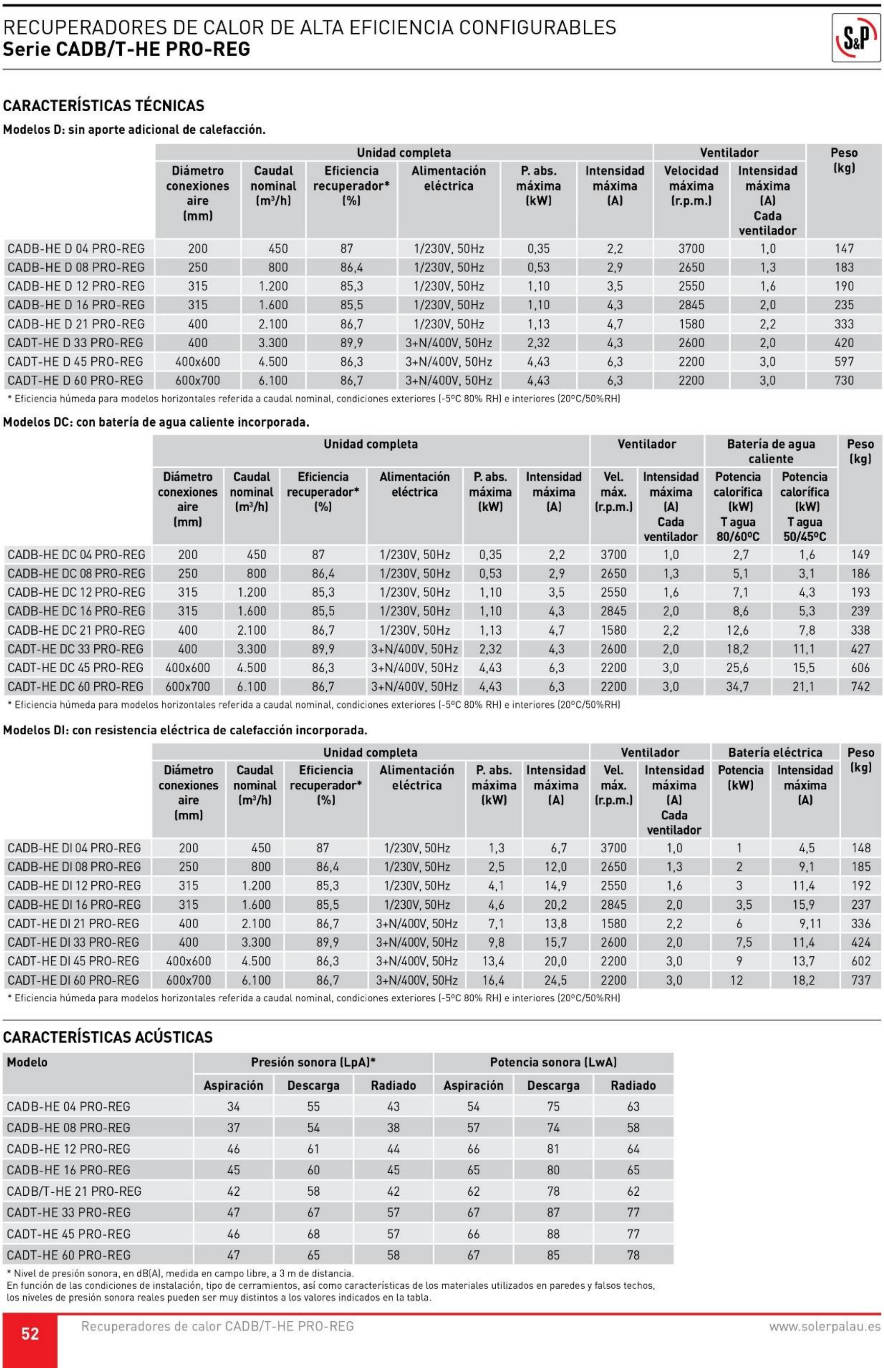
7.2 Appendix 7. Heat recovery



RECUPERADORES DE CALOR DE ALTA EFICIENCIA CONFIGURABLES
Serie CADB/T-HE PRO-REG

CARACTERÍSTICAS TÉCNICAS

Modelos D: sin aporte adicional de calefacción.

	Unidad completa						Ventilador		Peso (kg)
	Diámetro conexiones aire (mm)	Caudal nominal (m^3/h)	Eficiencia recuperador* (%)	Alimentación eléctrica	P. abs. máxima (kW)	Intensidad máxima (A)	Velocidad máxima (r.p.m.)	Intensidad máxima (A) Cada ventilador	
CADB-HE D 04 PRO-REG	200	450	87	1/230V, 50Hz	0,35	2,2	3700	1,0	147
CADB-HE D 08 PRO-REG	250	800	86,4	1/230V, 50Hz	0,53	2,9	2650	1,3	183
CADB-HE D 12 PRO-REG	315	1.200	85,3	1/230V, 50Hz	1,10	3,5	2550	1,6	190
CADB-HE D 16 PRO-REG	315	1.600	85,5	1/230V, 50Hz	1,10	4,3	2845	2,0	235
CADB-HE D 21 PRO-REG	400	2.100	86,7	1/230V, 50Hz	1,13	4,7	1580	2,2	333
CADT-HE D 33 PRO-REG	400	3.300	89,9	3+N/400V, 50Hz	2,32	4,3	2600	2,0	420
CADT-HE D 45 PRO-REG	400x600	4.500	86,3	3+N/400V, 50Hz	4,43	6,3	2200	3,0	597
CADT-HE D 60 PRO-REG	600x700	6.100	86,7	3+N/400V, 50Hz	4,43	6,3	2200	3,0	730

* Eficiencia húmeda para modelos horizontales referida a caudal nominal, condiciones exteriores (-5ºC 80% RH) e interiores (20ºC/50%RH)

Modelos DC: con batería de agua caliente incorporada.

	Unidad completa						Ventilador		Batería de agua caliente		Peso (kg)
	Diámetro conexiones aire (mm)	Caudal nominal (m^3/h)	Eficiencia recuperador* (%)	Alimentación eléctrica	P. abs. máxima (kW)	Intensidad máxima (A)	Vel. máx. (r.p.m.)	Intensidad máxima (A) Cada ventilador	Potencia calorífica (kW) T agua 80/60ºC	Potencia calorífica (kW) T agua 50/45ºC	
CADB-HE DC 04 PRO-REG	200	450	87	1/230V, 50Hz	0,35	2,2	3700	1,0	2,7	1,6	149
CADB-HE DC 08 PRO-REG	250	800	86,4	1/230V, 50Hz	0,53	2,9	2650	1,3	5,1	3,1	186
CADB-HE DC 12 PRO-REG	315	1.200	85,3	1/230V, 50Hz	1,10	3,5	2550	1,6	7,1	4,3	193
CADB-HE DC 16 PRO-REG	315	1.600	85,5	1/230V, 50Hz	1,10	4,3	2845	2,0	8,6	5,3	239
CADB-HE DC 21 PRO-REG	400	2.100	86,7	1/230V, 50Hz	1,13	4,7	1580	2,2	12,6	7,8	338
CADT-HE DC 33 PRO-REG	400	3.300	89,9	3+N/400V, 50Hz	2,32	4,3	2600	2,0	18,2	11,1	427
CADT-HE DC 45 PRO-REG	400x600	4.500	86,3	3+N/400V, 50Hz	4,43	6,3	2200	3,0	25,6	15,5	606
CADT-HE DC 60 PRO-REG	600x700	6.100	86,7	3+N/400V, 50Hz	4,43	6,3	2200	3,0	34,7	21,1	742

* Eficiencia húmeda para modelos horizontales referida a caudal nominal, condiciones exteriores (-5ºC 80% RH) e interiores (20ºC/50%RH)

Modelos DI: con resistencia eléctrica de calefacción incorporada.

	Unidad completa						Ventilador		Batería eléctrica		Peso (kg)
	Diámetro conexiones aire (mm)	Caudal nominal (m^3/h)	Eficiencia recuperador* (%)	Alimentación eléctrica	P. abs. máxima (kW)	Intensidad máxima (A)	Vel. máx. (r.p.m.)	Intensidad máxima (A) Cada ventilador	Potencia (kW)	Intensidad máxima (A)	
CADB-HE DI 04 PRO-REG	200	450	87	1/230V, 50Hz	1,3	6,7	3700	1,0	1	4,5	148
CADB-HE DI 08 PRO-REG	250	800	86,4	1/230V, 50Hz	2,5	12,0	2650	1,3	2	9,1	185
CADB-HE DI 12 PRO-REG	315	1.200	85,3	1/230V, 50Hz	4,1	14,9	2550	1,6	3	11,4	192
CADB-HE DI 16 PRO-REG	315	1.600	85,5	1/230V, 50Hz	4,6	20,2	2845	2,0	3,5	15,9	237
CADT-HE DI 21 PRO-REG	400	2.100	86,7	3+N/400V, 50Hz	7,1	13,8	1580	2,2	6	9,11	336
CADT-HE DI 33 PRO-REG	400	3.300	89,9	3+N/400V, 50Hz	9,8	15,7	2600	2,0	7,5	11,4	424
CADT-HE DI 45 PRO-REG	400x600	4.500	86,3	3+N/400V, 50Hz	13,4	20,0	2200	3,0	9	13,7	602
CADT-HE DI 60 PRO-REG	600x700	6.100	86,7	3+N/400V, 50Hz	16,4	24,5	2200	3,0	12	18,2	737

* Eficiencia húmeda para modelos horizontales referida a caudal nominal, condiciones exteriores (-5ºC 80% RH) e interiores (20ºC/50%RH)

CARACTERÍSTICAS ACÚSTICAS

Modelo	Presión sonora (LpA)*			Potencia sonora (LwA)		
	Aspiración	Descarga	Radiado	Aspiración	Descarga	Radiado
CADB-HE 04 PRO-REG	34	55	43	54	75	63
CADB-HE 08 PRO-REG	37	54	38	57	74	58
CADB-HE 12 PRO-REG	46	61	44	66	81	64
CADB-HE 16 PRO-REG	45	60	45	65	80	65
CADB/T-HE 21 PRO-REG	42	58	42	62	78	62
CADT-HE 33 PRO-REG	47	67	57	67	87	77
CADT-HE 45 PRO-REG	46	68	57	66	88	77
CADT-HE 60 PRO-REG	47	65	58	67	85	78

* Nivel de presión sonora, en dB(A), medida en campo libre, a 3 m de distancia.
En función de las condiciones de instalación, tipo de cerramientos, así como características de los materiales utilizados en paredes y falsos techos, los niveles de presión sonora reales pueden ser muy distintos a los valores indicados en la tabla.

52 Recuperadores de calor CADB/T-HE PRO-REG www.solerpalau.es

7.3 Appendix 8. Radiation factor

7.3.1 Case study 1

Table 20. Radiation Factor Case Study 1

Efficient	**Irad (kWh/m^{2}year)**	**Area window (m^2)**	**Irad / Iradhorizontal**	**Irad/Iradhorizontal* Area/Atotal**
Horizontal	368	0	1	0
East	260	2.7	0.706521739	0.04541925
South	394	22.6	1.070652174	0.57611284
west	222	13	0.60326087	0.1867236
north	123	3.7	0.33423913	0.02944488
	Total area	42	**Reduction factor**	**0.83770057**

7.3.2 Case Study 2

Table 21. Radiation Factor Case Study 2

Inefficient	**Irad (kWh/m^{2}year)**	**Area window (m^2)**	**Irad / Iradhorizontal**	**Irad/Iradhorizontal* Area/Atotal**
Horizontal	403	0	1	0
East	271	3.2	0.672456576	0.11758804
South	392	8.6	0.972704715	0.45711806
west	271	3.2	0.672456576	0.11758804
north	160	3.3	0.397022333	0.07159419
	Total area	18.3	**Reduction factor**	**0.76388832**

7.3.3 Case Study 3

Table 22. Radiation Factor Single Dwelling Case Study 3

Single Dwelling	**Irad (kWh/m²year)**	**Area window (m²)**	**Irad / Iradhorizontal**	**Irad/Iradhorizontal* Area/Atotal**
Horizontal	403	0	1	0
East	271	3.6	0.672456576	0.0744875
South	392	20.3	0.972704715	0.60756633
west	271	3.6	0.672456576	0.0744875
north	160	5	0.397022333	0.06108036
	Total area	32.5	**Reduction factor**	**0.81762168**

Table 23. Radiation Factor Multi-family house Case Study 3

Multi-family House	**Irad (kWh/m²year)**	**Area window (m²)**	**Irad / Iradhorizontal**	**Irad/Iradhorizontal* Area/Atotal**
Horizontal	403	0	1	0
East	271	22.7	0.672456576	0.09376391
South	392	77.5	0.972704715	0.46305046
west	271	22.7	0.672456576	0.09376391
north	160	39.9	0.397022333	0.09730461
	Total area	162.8	**Reduction factor**	**0.74788289**