Exploiting the building energy flexibility: demand response assessment and energy markets

By

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This thesis is submitted to University College Dublin in part fulfilment of the requirements for the degree:

ME in Mechanical Engineering

School of Mechanical and Materials Engineering

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February 2020

STATEMENT OF ORIGINAL AUTHORSHIP

I hereby certify that the submitted work is my own work, was completed while registered as a candidate for the degree stated on the Title Page, and I have not obtained a degree elsewhere on the basis of the research presented in this submitted work.

ACKNOWLEDGEMENTS

Firstly, I would like to thank Dr Donal Finn and Dr Mattia De Rosa for all their valuable help and time during this semester. I would also like to thank Francesco D'Ettorre in his help with the models used for the simulation. Finally, I would like to thank family and friends from Spain for their continued support throughout the project but especially to all the friends I have made during my time as an erasmus student, who have supported and accompanied me in my day to day life. Also, all those I have met in Dublin who in the last few weeks have helped me for the last push in my university career.

ABSTRACT

To help keep modern power grids stable, due to the strong incorporation of renewable sources, it is necessary to manage the demand side response. Demand response is an example of demand-side flexibility that adapts end-user profiles to better match network requirements. The ability to determine the energy flexibility and in turn the cost of a building makes it the subject of study from an economic and environmental point of view. This project is supported by a predictive controller model in MATLAB, which is used to simulate the optimal daily heating profile of an Irish home, minimizing the daily operating cost during the heating season from October to March. To meet the heating needs of the home, the system consists of a heat pump, thermal energy storage, and gas boiler. On the one hand, to determine the impact on the cost of the building's flexibility, the electricity tariff based on real-time hourly prices has been used. On the other hand, in order to determine the energy flexibility, two cases have been studied, the case base that corresponds to the simulation of an optimal system and the other one has exposed the same model but incorporating the demand response programs and it has been verified that the application of the demand response programs helps to improve the energy flexibility by increasing the use of thermal energy storage devices when the market and demand conditions are favourable for the system regardless of the restrictions that apply to the use of the equipment. It is also noted that for all prices considered, it is more cost efficient to reduce a given amount of electrical energy for a short duration but high intensity measure rather than a longer but lower intensity measure.

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NOMENCLATURE

Acronyms

CPP – Critical peak pricing
DR – Demand Response
DRP – Demand Response Programs
DSM – Demand side management
DSO – Distribution System Operations
DHW – Domestic Hot Water
EED – Energy Efficiency Directive
EF – Energy Flexibility
EMSA – Energy Management Systems Aggregators
EMS – Energy Management System
EPBD – Energy Performance of Building Directive
EU – European Union
IBP – Incentive Based Programs
IEA – International Energy Agency
PBP – Price based programs
PCR – Price Coupling of Regions
RES – Renewable Energy Sources
SO – System Operator
TES – Thermal Energy Storage
ToU – Time-Of-Use
TPER – Total primary energy requirement
TSO – Transmission System Operator
VPP – Virtual Power plant

Variables

α – Heat Pump Output Relative to Reference Case (-)
δ – Duration of Measure (Per 15 minutes)
σ – Standard Deviation of Daily Electricity Price (€/MWh)
η – Efficiency (-)
ρ – Density (kg/m^3)
A – Area (m^2)
c – Specific Heat Capacity (J/kgK)
C – Cost (€)
j – Index Variable (-)
p – Price (€/kWh)
P – Power (W)
Q – Thermal Energy (J)
t – Time (15 minutes)
$\Delta\mathrm{t}$ – Time Increment (Minutes)
T – Length of Day (Minutes)
$\mathbf{u}$ – Vector of Inputs (-)
U – U-value (W/m^{2}K)
V – Volume of Storage (m^3)
x – State Vector (℃)
η^{II} – Second Law Efficiency
η_B – Boiler Efficiency
$\psi_{HP,L}$ – Binary Variable, Heat Pump Operation to Load (-)
$\psi_{HP,TES}$ – Binary Variable, Heat Pump Operation to TES (-)
COP_L – Coefficient of Performance of Heat Pump to Load (-)
COP_{TES} – Coefficient of Performance of Heat Pump to TES (-)
ΔC_{Flex} – Daily Flexibility Cost (€)
p_{el} – Electricity Price (€/MWh)
$\hat{p}_{el}$ – Mean Daily Electricity Price (€/MWh)
p_{gas} – Gas Price (€/kWh)
$\dot{Q}_{HP,TES}$ – Thermal Input to TES (W)
$\dot{Q}_{TES,L}$ – Thermal Output from TES (W)
$\dot{Q}_{loss}$ – Thermal Loss from TES (W)
T_e – Ambient Air Temperature (℃)
T_{ground} – Ground Temperature (℃)
T_{sink} – Sink Temperature (℃)
T_{source} – Source Temperature (℃)
T_{TES} – Temperature of TES (℃)
t_{ON} – Time Room Temperature at Setpoint (-)

Q_B – Thermal Output of Boiler (W)

$Q_{HP,L}$ – Thermal Output from Heat Pump (W)

ϕ_{HP}^{L} – Binary Variable for Heat Pump Operation (-)

C_{op}^{Day} – Daily Operational Cost (€)

$C_{op\_DR}^{Day}$ – Daily Operational Cost with DR (€)

$C_{op\_ref}^{Day}$ – Daily Operational Cost in Reference (Base) Case (€)

p_{el}^{thld} – Daily Electricity Price Threshold (€/MWh)

P_{HP}^{DR} – Electrical Power Consumption of Heat Pump with DR Measure (W)

P_{HP}^{ref} – Reference Power Consumption of Heat Pump (W)

$\dot{Q}_{HP,L}^{min}$ – Minimum Thermal Output from Heat Pump (W)

$\dot{Q}_{HP,L}^{max}$ – Minimum Thermal Output from Heat Pump (W)

T_{room}^{SP} – Setpoint Temperature of Room (℃)

Z_{HP}^{L} – Semi-continuous Variable of Heat Pump Thermal Power (W)

1. Introduction

1.1 Context

Energy is an indispensable element in improving the progress and well-being of a society, but it is one of the great problems facing humanity currently.

The main causes of this problem are (Rafiee & Khalilpour, 2019):

- The exponential growth of energy demand in the world
- The existence of a finite number of reserves and their unequal location throughout the world
- And the excessive environmental impact of current technologies and energy uses.

Therefore, it is necessary to evolve energy generation towards a renewable model that ensures generation over long periods, while reducing environmental impact.

The European Union (EU) is already working on a long-term strategic vision for a clean planet for all by 2050. The aim is to create a prosperous, modern, competitive and climate-neutral economy. Following this line, Europe wants to lead the way towards climate neutrality by investing in realistic technological solutions and appropriate policies (commision, 2018). Among these, the Energy Performance of Building Directive (EPBD) and the Energy Efficiency Directive (EED) are the main legislative instruments established to promote long-term strategies for mobilising efforts aimed at implementing energy efficiency measures (D'Ettorre, Rosa, Conti, & Daniele Testi, 2019). An energy policy framework is needed to facilitate the transition from fossil fuels to cleaner energy and to meet the commitments made in the EU's Paris agreement to reduce greenhouse gas emissions (comission, 2017).

According to the International Energy Agency (IEA), global electricity demand will increase by 70% by 2040, raising its share of final energy use from 18% to 24% over the same period (IEA, 2018). Therefore, emphasis should be placed on the use of RES. Hence, it is necessary to carry out a decarbonization in the generation of electricity as an increase in electrification of the economy. In order for these factors to be met, our energy consumption must be reduced by means of greater efficiency (the least polluting consumption is that which is not produced) and fossil fuels must be replaced by renewable energies (española). However, its intermittent and unpredictable requires the system to have backup generation to assure supply reliability.

It is important that a change of model be made in the electricity sector, i.e. an energetic transition from a centralized model to a decentralized model (Fig. 1). The current model is the centralized one, which consists of the generation of electricity by means of a relatively small number of large thermal or hydroelectric plants, far from large consumption centres and which could vary their production levels at will in order to adapt to the fluctuation of a fairly rigid electricity demand. In contrast, the decentralised model advocates the coexistence of large units connected to very high and high voltage and a multitude of small installations located in the medium, low and very low voltage distribution networks at the same consumption points (española).

The aim is to combine variable generation with a flexible system in which demand and storage management contribute to the security and quality of supply, reducing dependence on fossil fuel thermal power plants as a backup mechanism (española).

Large-scale electrification of endues sectors such as buildings, industry and transport, as well as gradual decarbonisation of the power sector, are key for the energy transition. Flexibility has to be harnessed in all sectors of the energy system, from power generation to stronger transmission and distribution systems, storage (both electrical and thermal) and more flexible demand (DSM and sector coupling) (IRENA, 2018). This thesis will focus on the building sector, which is composed of residential and commercial buildings, the first being the cases to study.

An important factor for this energy transition occurs in the residential sector, where the end-users themselves make an important contribution to the paradigm shift (Peter Fitzpatrick, 2019). Buildings are responsible for approximately 40% of energy consumption and 36% of $CO2$ emissions in the EU, making them the single largest energy consumer in Europe (comission, 2017).

Therefore, the Energy Flexibility (EF) in buildings can help stabilize the future energy system and thereby facilitate large penetration of RES (Jensen, y otros, 2017). But in order to understand this concept it is necessary to define that it is the EF in buildings and according to the IEA it is (Jensen, y otros, 2017):

“The EF of a building is the ability to manage its demand and generation according to local climate conditions, user needs, and energy network requirements.

EF of buildings will thus allow for demand side management/load control and thereby Demand Response (DR) based on the requirements of the surrounding energy networks”

The potential for flexibility can be translated through great technological advances such as thermal energy storage (TES) or the use of batteries (Junker, y otros, 2018).

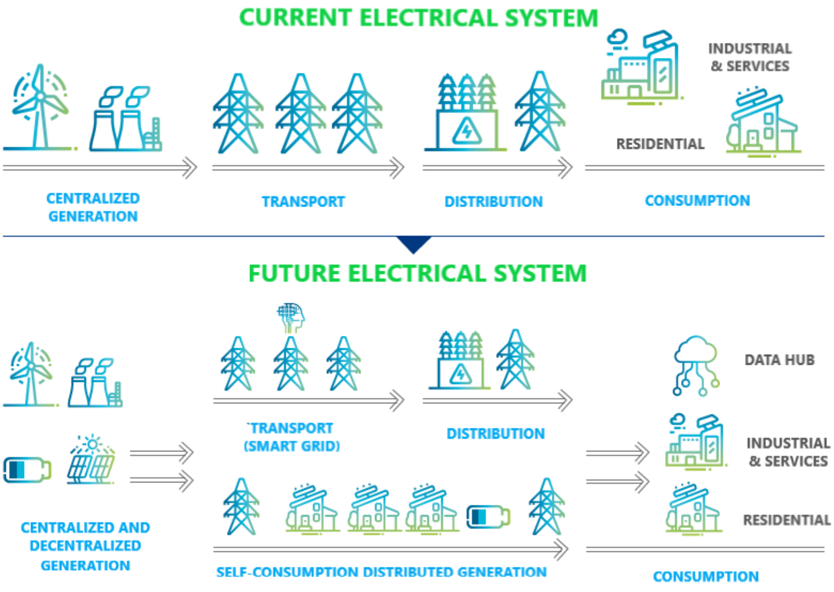


Fig. 1: Traditional electrical system vs. future electrical system (española)

This concept is strongly related to the design of the building, the installed energy service systems and the control of the energy demand in the building. In other words, the user's day-to-day behaviour, the climate to which the building is exposed, and the state of the surrounding energy networks are the factors that determine EF (IEA, 2018). Estimating the effect of each element requires an in-depth knowledge of the interactions between these factors and the related physics.

In this scenario, where end-users become very important, being the key to the paradigm shift, with the help of new intelligent technologies and advanced control systems, demand management can be carried out (Peter Fitzpatrick, 2019). Demand side management (DSM) consists of a series of actions, which allow for the modification of end-user demand through the implementation of strategies capable of reducing end-user energy consumption, taking advantage of demand efficiencies, improving control and optimization, as well as incorporating renewable energy sources (RES) safety measures (D'Ettorre, Rosa, Conti, & Daniele Testi, 2019).

Among the benefits that DSM can bring can be found:

- Economic and environmental benefits. Consumers will be able to receive the incentive to see that the consumption of electricity is lower, adapting their consumption curve.
- Shifting of the load curve, as this is achieved by creating a more flexible system with better response to signals.
- Reduction of price volatility, improving the efficiency of the operation of the electrical system.
- Savings in infrastructure, due to an expected decrease in peak demand. This implies the delay of the investment in reinforcing the transport and distribution networks for the peak generation.

In particular, Demand response programs (DRP) are being considered as a promising technique for the emerging smart grid, based on voluntary modulation of consumer load through direct external requests (D'Ettorre, Rosa, Conti, & Daniele Testi, 2019) (Peter Fitzpatrick, 2019).

DR is referred, hence, to modification of consumption pattern in end-users for responding to the electricity price variations or due to the technical or economic reasons (Mahsa Khorram & Vale, 2018)

There are two main types of DRP (Mahsa Khorram & Vale, 2018):

- **Incentive-based**: is related to a program in which the customers are paid with the fixed or time varying incentive, provided by the grid operator or other DR provider.
- **Price-based**: are referred to the changes in the consumption of the customers when facing electricity price variations. In this concept, the end-users tend to participate in such programs in order to reduce their electricity bills by shifting their high consumption appliances to the off-peak hours, or reduce their high consumption loads in peak hours.

Two great advantages can be reflected when it comes to carrying out a greater flexibility to modify the power consumed:

- In the short term, it may allow a more economical operation of the system, used as a secondary reserve or as a resource to manage detours and congestion.
- In the medium and long term, it will make it possible to flatten the demand curve of the system.

In order to increase the efficiency of the system, the consumer must be given economic incentives that reflect the real costs of energy and the conditions of the system at any given time, in such a way as to modify its consumption in relation to the usual patterns. This is when consumers come into play, i.e. they respond by reducing or shifting their consumption of hours of the day when the price of electricity is highest or when the reliability of the system is at risk. The use of DRP provides customers with savings on their electricity bills in a flexible way. One method consists of reducing electricity consumption during peak periods, or simply reducing consumption without exceeding the average of its class. However, it was also possible to increase the total final consumption of energy by operating outside peak hours. Not only do participants receive benefits, some influence the market. As a greater efficiency of the available infrastructure due to the reduction of costly electricity generating units or the reduction of the implementation of distribution and transmission infrastructure improvements (M.H.Albadi & El-Saadany, 2008).

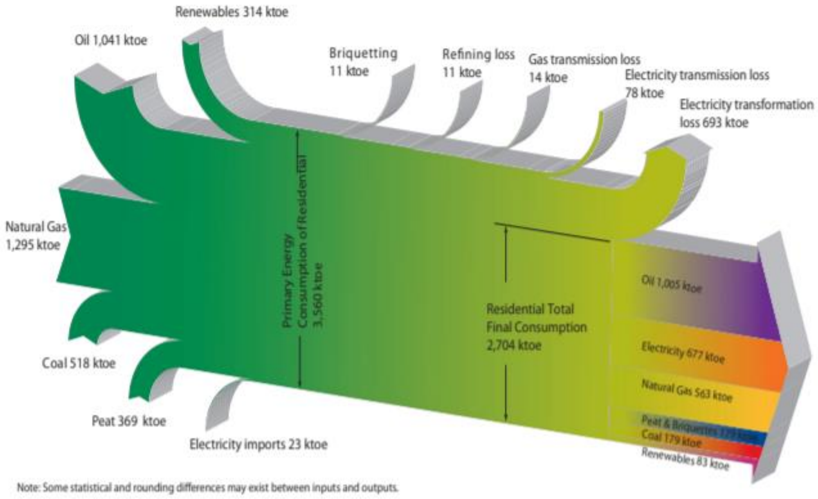
In order to participate in DRP, it is necessary to install some technologies such as intelligent thermostats, maximum load controls, power management systems and on-site generation units. (M.H.Albadi & El-Saadany, 2008). Similarly, a technical team provides technical assistance to carry out the response plan or strategy.

The idea of the new paradigm is to create a decentralised model where the users themselves can be part of the electricity grid, i.e. be able to generate their own energy from RES and pour it into the grid if they produce more than they need. This means that in order to be able to control demand in response to the requirements of the electricity grid, it will depend on its type and size. Normally it is the industries and large businesses that can adapt to the DR mainly due to two reasons, the first is that they are equipped with the systems and facilities necessary to enable DRP and the second reason is because they move large amounts of energy (Peter Fitzpatrick, 2019). For this reason, a single dwelling is not considered a fundamental part of the network, which is why the concept of the set of buildings is born. As its name well indicate, is a group of buildings physically connected or commercially aggregated, i.e. , that the buildings are not necessarily connected to the same distributed energy networks (IEA, 2018). As (Nolan & O'Malley, 2015) said, the aggregation of a few thousand households represents a stable resource of the system. In this way, the set of buildings, act as a single producer, that added to the industries and the great trades, is created the denominated Virtual power plants (VPP). A single cluster behaves as similar as possible to a conventional power station. The aim of this union is to achieve greater reliability in generation, since the deficiencies of one can be replaced by the other and the energy produced can be added.

Nowadays, the technology brings the consumer closer to exploit the resources to activate DRP, such as appliances (dishwashers, televisions, refrigerators ...), heating and cooling systems (heat pumps, solar thermal and photovoltaic panels, small windmills, batteries ...) (Peter Fitzpatrick, 2019). It should be borne in mind that 75% of existing buildings today will still be in 2050 (Jensen, y otros, 2017). This tells us that new homes must be designed according to the new paradigm. To this field must be added the rehabilitation of existing ones in order to carry out the objectives set.

A clear example is an Irish house built in the 70s, defined in the following study (Pallonetto, Simos Oxizidis, Neu, & Finn, 2013), which has been retrofitted from a conventional mixed fuel dwelling to a smart grid enabled all-electric dwelling. The dwelling consists of a kerosene boiler, wood fired stove and domestic hot water (DHW). In addition to this, they changed the gasoline car for an electric one, which means a structural change of the electrical system of the house assuming a new microgeneration equipment. Thus, TES was incorporated, photovoltaic system and improved ventilation by heat recovery, the change of the kerosene boiler for a heat pump and the afore mentioned electric car. All controlled by a system defined by DR. The results were satisfactory, reducing the carbon footprint, CO2 from 9000 kg (43.3 kg/m2 of CO2) to 6400 kg (30.8 kg/m2 of CO2). In particular, a saving of 800 kg of CO2 per year was achieved in the heating system, which represents a 34% economic saving between the HP and the kerosene boiler. The overall result is more than 50% lower cost of energy products compared to the old system (Pallonetto, Simos Oxizidis, Neu, & Finn, 2013).

The following diagram shows the energy balance in the Ireland residential sector in 2016. On the left side of the diagram are represented the fuel inputs, which are like the primary energy use. Being predominant the use of natural gas and oil for electricity generation, which corresponds to 36% and 29% respectively and a scarce 9% from renewable energy. It is also worth noting that 76% of all this primary energy consumption is used, as 24% corresponds to transformation or transmission losses (Ireland S. e., Energy in the residential sector, 2018).



Note: Some statistical and rounding differences may exist between inputs and outputs.

Fig 2: Residential sector energy balance 2016 (Ireland S. e., Energy in the residential sector, 2018).

1.2 Motivation

This project deals with the assessment of consumption from the residential sector focuses on the development of innovative DR heating system services for residential and commercial applications in Ireland. According to the data, 61% of the final consumption of residential energy corresponds to the heating system and 47% is responsible for oil for only 7% covered by renewable energy (Ireland S. e., Energy in the residential sector, 2018). There is a need to carry out studies for a regulation of the consumption of the heating system with the intention of creating an efficient and optimum model, that is, to design a strategy which allows the comfort inside the home to be maintained at all times, reducing generation costs and respecting the environment (Ireland S. e., Energy in the residential sector, 2018). To carry out this paradigm shift, this work bets on the potential of demand management to provide significant economic and environmental benefits among which stand out:

- Limit or reduce the approach to building new power plants, while reducing infrastructure costs.

- Increase demand in periods of lower demand, where electricity generation prices are lower, and reduce it in periods of higher demand, where prices are higher. A strategy for the use of the heating system will be necessary.
- Ability to shift the load in a relatively short period of time in response to changes in electricity generation.
- Demand side services will be increasingly valuable as thermal generation is squeezed from the merit order and the cost of provision of frequency response and similar ancillary services increases.

The combination of DR, load shifting and reduction, load balancing, the integration of electrical storage and the management of the import and export of electricity, the smart grid will enable large amounts of distributed generation and renewable wind electricity onto the system, thus improving security of supply. Therefore, renewable sources are asynchronous and variable, which will require the implementation of strategies and mechanisms to change, store or export excess generation in order to maximize the total amount of final energy that can be supplied by distributed generation sources (Ireland S. e., Smartgrid - roadmap).

Therefore, all these factors must be understood in order to quantify the capacity of DR measures to help the stability of the network in a cost-effective and environmentally beneficial manner.

1.3 Aim

The aim of the present project is to investigate the influence of energy market framework on building flexibility and associated energy and environmental cost. In the same way:

- The study of the flexibility of electrical energy in the heating system of a residential building will be carried out for the real time market will be carried out.
- The costs of electricity generation will be analysed in order to know the difference between the model based on the optimization of the system without the application of DRP and the same model but with the application of DRP.
- Explain the behaviour of the optimization system and how it affects the demand response programs in the heating system.

The heating system equipment consists of a heat pump, a gas boiler and TES. The combination of these devices will be analysed for different studies.

1.4 Objectives

This project has three areas of interest:

1. Assessment of EF that will determine the amount of EF available.
2. Economic assessment, which aims to identify financial costs.

Thus, it is intended to quantify the flexibility that the building can provide, and the cost associated with this flexibility. The field of study will be the heating system composed of a heat pump, a gas boiler and a TES of a residence in Ireland. The aim is always to find the most optimal solution or solutions within the energy market in order to obtain the lowest possible cost in the electricity bill but always maintaining comfort within the home and respecting the environment before each action is taken. Through DR measures, the intention is to give flexibility to the building in order to maintain comfort inside the home at the lowest possible cost, adapting to the needs of the consumer.

By conducting a study on a wide range of DR measures, it will allow for different indicators or trends to be developed which can be used to help the controller to select the optimum DR measure for a given day based on the electricity price. Furthermore, the effect of using the control algorithm with fixed and moving prediction horizons will be noted.

1.5 Methodology

In order to carry out the objectives proposed in this project, the methodology to be followed in this document will be as follows:

The first step is to carry out a study that consists of compiling information from different papers, reports, websites or projects that deal with the evolution of demand management in the residential sector, from a more general point of view to the more specific ones. From these, images, information and relevant data will be obtained for the development of this project with the aim of clarifying this study in the best possible way.

Once the study has been carried out and the information has been contrasted, the housing model is designed using various computer programs. With the help of Energy plus, it will be possible to obtain from its database the ambient temperature and solar radiation values to define the different surfaces of the building in Ireland. These variables are used as inputs for MATLAB's simplified construction model. From this program, the control of the gas boiler and heat pump can be optimized for each day according to the thermal load and the price of electricity during the day. Similarly, it is possible to predict the behaviour of the building's temperature and heating load so that they can be optimised for each day in terms of cost.

In order to analyse the effect of different electricity prices, different DR measures are defined in order to see the behaviour of the system. Different tariffs can be used:

- Typical two-level rate.
- Various time of use rates.
- Real-time electricity prices with different cost components are considered.

But this thesis only covers the real-time electricity prices. With the definition of RD measures and following the analysis, the technical, energy and economic implications following the implementation of RDs will be examined. This will identify if there are conflicts between the implementation of RD measures to provide greater stability to the grid and the reduction of emissions.

1.6 Layout of Thesis

The master thesis begins with a study of the literature on the subject that offers an overview of grid development and the growing need for flexibility on the demand side. Different studies similar to the present one is examined, but focusing on the electricity grid, electricity markets and DR in order to understand the fields that affect us in the face of the challenges posed previously.

The methodological section explains in detail the description of the building to be studied both for its architectural characteristics and the heating system to be studied, which were previously studied by (Pallonetto, Rosa, & Finn, Environmental and economic benefits of building retrofit measures for the residential sector by utilising sensor data and advanced calibrated models, 2019). The Matlab program has been used to model the thermal load of the building during the heating season and to simulate DR measurements. Section 4 describes the results of the simulation using RTP rates for two models, the base case without the application of RD and with the application of RD. Five studies are explained, organized in such a way as to go from the most general to the most specific. Finally, in section 5, conclusions, the main findings of the thesis are detailed.

2. Literature Review

This chapter develops a study of the literature on electricity markets and DR implementations. Specifically, section 2.1 presents a broad view of the electricity grid and its development to date, focusing on technical aspects of Ireland. It explores the challenges facing the grid in the coming years, the concept of Smart Grid is also defined and the potential opportunities and applications for the DR. The paper continues with section 2.2, which examines the various electricity markets around the world but with an emphasis on the emerald country. The emphasis of these markets falls particularly on Day Ahead and Real Time Markets. Access to markets is also analysed in a general way. Finally, in chapter 2.3, the DRP are explained detailing the different types and the importance of flexibility in these systems.

2.1 Electricity grid

2.1.1 Overview

Just as the world is trying to reduce its CO2 emissions, Ireland is also challenged to reduce its dependence on fossil fuels for transport, heating and electricity production. In 2017, more than 90% of all energy used in the emerald country comes from fossil fuels. Several plans are underway to improve this situation, such as the investment of 7600 million euros of public funds between now and 2027 to carry out cutting-edge projects and be able to reduce CO2 emissions. (Ireland S. E., 2018). Similarly, as citizens, we have an obligation in our homes and businesses to be more sustainable with the use of energy.

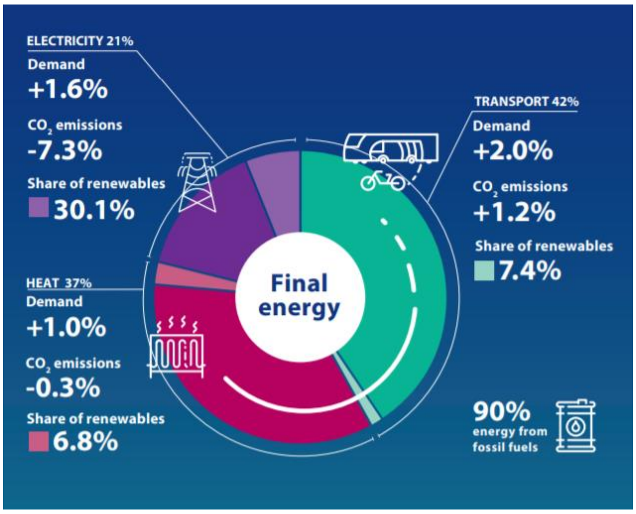


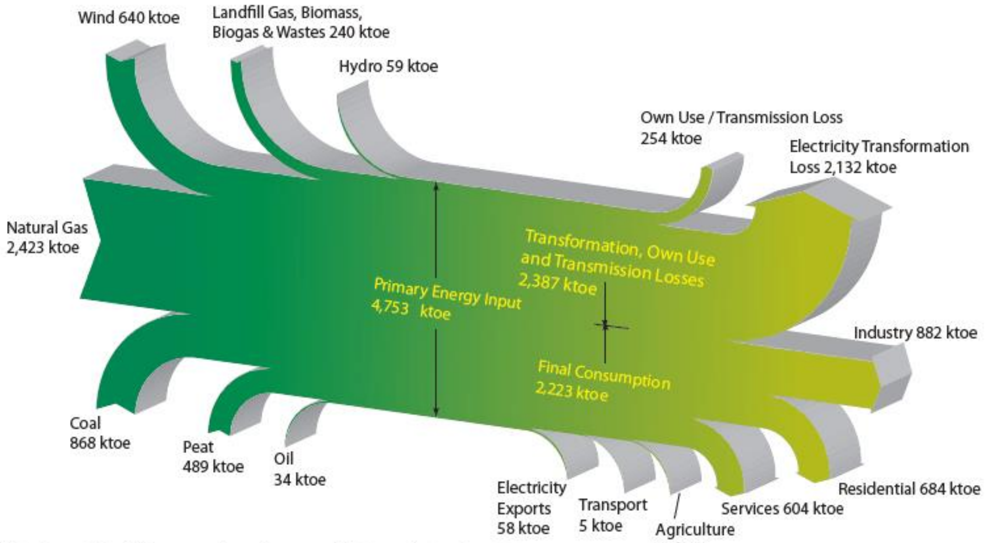
Fig 3: Final energy consupmtion per sector (Ireland S. E., 2018)

We can observe that heating accounts for 37% of the total final energy consumed, and that only 6.8% is covered by renewable energy. This indicates that there is much room for improvement in this aspect and that this work echoes. In addition, the average household emitted 5.1 tonnes of CO2 of which 63% came from direct fuel use in the home and the remainder from electricity use.

2.1.2 Evolution of electricity generation

Total primary energy requirement (TPER): This is the total requirement for all uses of energy, including energy used to transform one energy form to another (e.g. burning fossil fuel to generate electricity) and energy used by the final consumer.

Modern economies and societies are dependent on reliable and secure supplies of electricity. In Ireland, electricity generation accounts for a third of all annual energy use. The following figure shows the energy flow in electricity generation.



Note: Some statistical differences and rounding errors exist between inputs and outputs

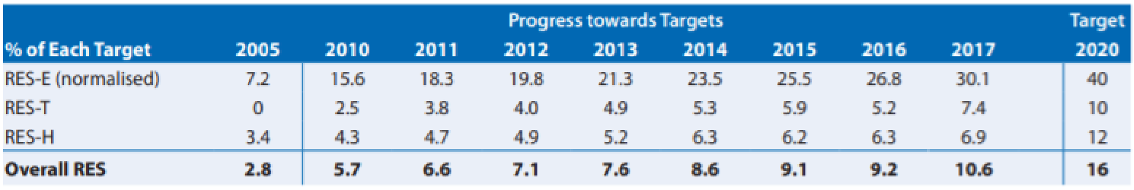
Fig 4: Flow of energy in electricity generation (Ireland S. E., 2018)

It can be seen that total energy inputs are 4,753 ktoe for electricity generation and that 50% represent losses in energy inputs, due to poor transformation and transmission of energy. It should be noted that 51% of electricity generation corresponds to natural gas and almost 20% to renewable energies (8,877 GWh in 2017), with wind energy being the main source of generation. (Ireland S. E., 2018).

In the future, the use of heat pumps, thus electrifying domestic heating systems, is expected to substantially alter energy demand patterns. (Pallonetto, Oxizidis, Milano, & Finn, 2016).

2.1.3 Challenges

By 2020, the Irish target in the EU Renewable Energy Directive is to provide a 16% share of renewable energy in gross final consumption (Ireland S. E., 2018). The directive states that a national renewable energy action plan must be adopted to reach the 2020 targets. This plan is divided into three sectors, RES-E (electricity), RES-T (transport) and RES-H (heat).



	Progress towards Targets									Target
% of Each Target	**2005**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2020**
RES-E (normalised)	7.2	15.6	18.3	19.8	21.3	23.5	25.5	26.8	30.1	40
RES-T	0	2.5	3.8	4.0	4.9	5.3	5.9	5.2	7.4	10
RES-H	3.4	4.3	4.7	4.9	5.2	6.3	6.2	6.3	6.9	12
Overall RES	**2.8**	**5.7**	**6.6**	**7.1**	**7.6**	**8.6**	**9.1**	**9.2**	**10.6**	**16**

Fig 5: Renewable energy progress to tarjets

As can be seen, the objective for 2020 is to cover 40% of electricity consumption from renewable energies, with 30.1% in 2017, with wind energy being the most important source (Ireland S. E., 2018).

For heat production the target is 12% from renewable sources. Due to the growing activity of industrial sectors, some incentives and regulations for renewable systems in residential housing, has contributed to the increase in renewable sources, increasing by 67% from 2005 to 2017. Every year the tendency to use renewable thermal energy is increasing, from 2016 to 2017, increased by 9.8% in absolute terms. In the following figure shows the contribution from renewable energy to heat or thermal energy uses.

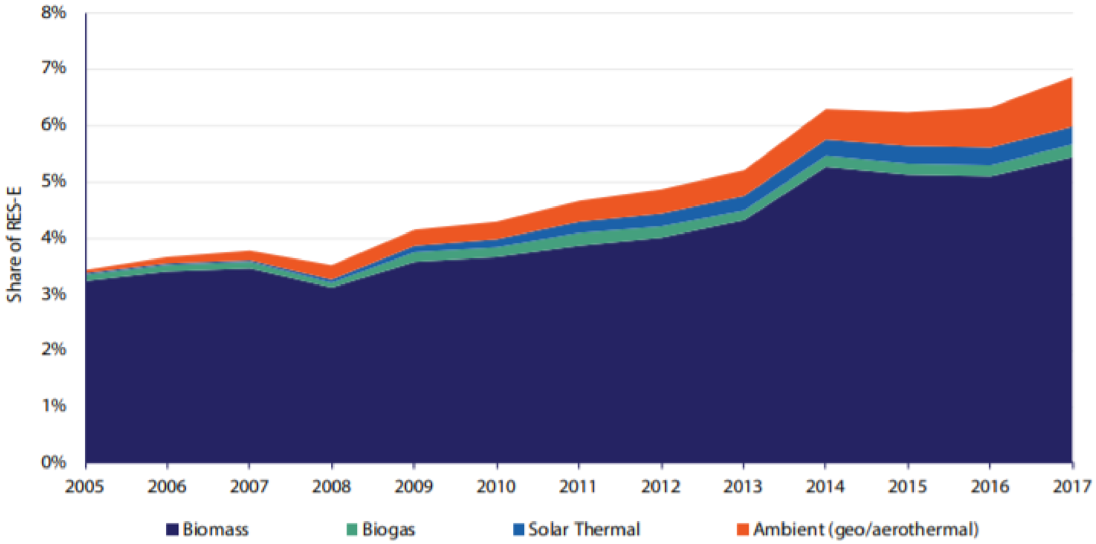


Fig 6: Renewable energy contribution to thermal energy (RES-H)

The element that contributes most to this energy contribution is the use of biomass. The state of Ireland, aware of the situation, has provided support with subsidies and greater control in the revisions of building regulations that require that a part of the energy demand of new housing comes from renewable sources.

2.1.4 Smart grid

First of all it is necessary to define this concept: "A Smart Grid is an electricity network that can cost efficiently integrate the behaviour and actions of all users connected to it – generators, consumers and those that do both – in order to ensure an economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety." (Ireland S. e., Smartgrid - roadmap)

The smart grid is an electricity network which has advanced monitoring systems and two-way communication between generators and suppliers, and can intelligently balance the varying electricity demands of end users with the transport of electricity from all generation sources (Ireland S. e., Smartgrid - roadmap). Alam y col. (Pallonetto, Oxizidis, Milano, & Finn, 2016) defines an intelligent home as the end node of the intelligent network that provides services in the form of ambient intelligence, remote home control or home automation. In Ireland, wind energy will dominate the integration of electricity, as the wind element is the most abundant natural resource on the emerald island. The variability of wind requires the establishment of a system to match availability of supply with load so that the maximum amount of renewable electricity is utilised on the system at all times (Ireland S. e., Smartgrid - roadmap).

The combination of DR, load shifting and reduction, load balancing, the integration of electrical storage and the management of the import and export of electricity, the smart grid will enable large amounts of distributed generation and renewable wind electricity onto the system, thus improving security of supply. Therefore, renewable sources are asynchronous and variable, which will require the implementation of strategies and mechanisms to change, store or export excess generation in order to maximize the total amount of final energy that can be supplied by distributed generation sources.

2.2 Electricity markets

2.2.1 Overview

In recent years, electricity has been traded under uncompetitive rules because energy markets have been deregulated. Producers, traders and large consumers were often able to buy or sell energy in organised markets due to the creation of energy exchanges or consortia. In the 1990s, the United Kingdom and Scandinavia were the first countries to carry out energy exchanges. Soon after, more competitive markets were established in Europe, Australia and North America. (Mayer & StefanTrüc, Electricity markets around the world, 2018).

The economic rationale for the deregulation of energy markets was necessary to bring greater efficiency to markets, as well as to stimulate and facilitate competition between market participants in monopolised market structures. According to (Morales & Hanly, 2018) the meaning of market efficiency is defined as that efficient market in which prices always reflect available information.

Generally, the way to achieve greater competition was to divide vertically integrated energy producers and privatize utilities. Nevertheless, as the power grid is a perfect example of a natural monopoly, regulation is still needed. Transmission networks have been dissolved from generation and distribution, or are still part of the utilities, but are separate from the other parts of the business and are strongly regulated. The market structure needs to take into account the grid connection and the need to constantly balance generation and demand (Mayer & StefanTrüc, Electricity markets around the world, 2018)

According to (Mayer & StefanTrüc, Electricity markets around the world, 2018), there are two models for energy markets:

1. One where the trading, dispatch, and transmission takes place at the system operators side, the so called power pools. The pool model can be seen more related to the technical issues.
2. The other, where trading and an initial dispatch takes place at power exchanges that are independent from the transmission. The exchange model as being more related to markets in a classical economic school of thought.

The participation of the generators involved in the pool model is generally mandatory, as the network operator manages the entire demand for electricity in this area. Moreover, no real consumer is involved in the trade. All generator bids are assembled using a system operator optimisation procedure to comply with technical constraints, such as transmission capacities, or start-up time and costs. Often a separate price is calculated for each node in the network, the so-called location price since the pool model takes the transmission into account. In theory, this model leads to an optimal dispatch cost for each power plant.

In the exchange model, participation is voluntary in many countries, and generators and retailers can conduct additional bilateral transactions off-exchange. It should be noted that this model involves high-demand consumers such as industries, other generators or energy resellers. The disadvantage of an exchange model is that the location of supply and demand is not considered in the process. As the market is balanced only in terms of price, technical limitations can make it sometimes impossible to physically fulfil operations.

The electricity markets are a complex field, which represent a high volatility of them, which makes electricity prices an interesting field for research and of which several studies have been carried out on the modelling and forecasting of electricity prices, as well as on hedging and risk management in energy markets, see (Mayer & Trück, Electricity markets around the world, 2018) where they explain several studies by different authors, analysing the markets between different countries and their points of view. Their results suggest that electricity markets organised by day-ahead tend to show significantly lower overall price variation compared to markets with real-time trading. Differences occur both in cross-market observation and in markets with both trading systems. Especially in real-time electricity markets, retailers and large customers with direct access to these exchanges will have to better cover their risks, as they face the difficult task of managing highly volatile input prices.

Thus, a fundamental difference between energy markets are their different market designs, which appear in various forms and characteristics, one of which is market trading, which can take place one day in advance, usually at auctions, or continuously and in real time, which we will explain and develop in the following chapters.

2.2.2 Day ahead markets

In order to understand this market, it is necessary to make reference to Price Coupling of Regions (PCR), which is the project of European Power Exchanges to develop a single price coupling solution to be used to calculate electricity prices across Europe respecting the capacity of the relevant network elements on a day-ahead basis. It is composed by eight Power Exchanges and is used to couple 25 countries currently. In Ireland and Northern Ireland, SEMO (single electricity market operator), is the market operator for SEM (single electricity market), which is the wholesale electricity market operating in these countries. The main objective of the European Union is to create a harmonised European electricity market in order to increase liquidity, efficiency and social welfare. One of the key elements of PCR project is the development of a single price coupling algorithm, which adopts the name of EUPHEMIA (acronym of Pan-European Hybrid Electricity Market Integration Algorithm). It is used to calculate energy allocation, net positions and electricity prices across Europe, maximising the overall welfare and increasing the transparency of the computation of prices and power flows resulting in net positions (EpexSpot, 2019).

In the day-ahead market customers can sell or buy energy for the next 24 hours in a closed auction. Orders are matched to maximize social welfare while taking network constraints provided by transmission system operators (SO) into consideration. So, the day-ahead market aims to provide sufficient generation capacity and ancillary services to meet the forecasted demand for the next day (Fitzpatrick, 2018).

These markets are based on the matching procedure for price determination, which is determined by means of a marginalist mechanism. This mechanism works in the following way, the demand is first covered by cheaper generation sources (nuclear power plants and non-pumped hydraulic power plants) and then the more expensive ones are incorporated until supply and demand are crossed as shown in Figure X. The resulting price for all electrical energy is therefore that of the most expensive kWh sold at any given time. (valencia, 2016).

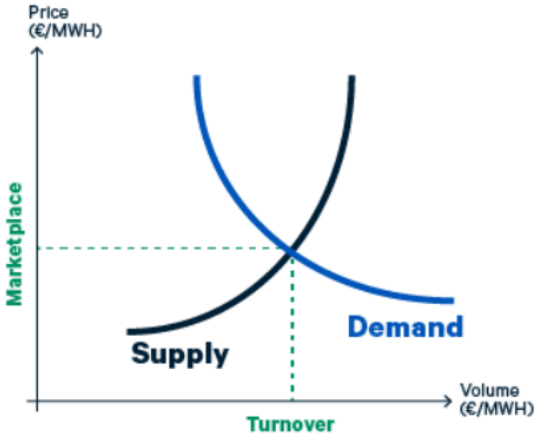


Fig. 7: Price matching chart (Pool, 2019)

In contrast to day-ahead trading are the real time or intraday markets with continuous trading until about 5-15 minutes before delivery. Both trading mechanisms exist in some markets, but in these cases the real time trading is generally used as a sort of balancing market to adjust the predetermined quantities of the day ahead market (Mayer & Trück, Electricity markets around the world, 2018).

2.2.3 Real time market

After the day-ahead market session, there are several intraday market sessions, where traders can negotiate electric power for different times of the day covered by that market. The real time electricity market aims to establish an efficient and effective mechanism for small distributed energy sources and DR to participate in balancing market transactions, while handling their meteorological or intermittent characteristics (Fitzpatrick, 2018)

Real-time markets are used to mitigate discrepancies between forecasted and actual demand by adjusting energy and ancillary service schedules and procuring additional capacity (Fitzpatrick, 2018). It involves agents with a natural position (producers), who can buy energy, as well as agents with a natural purchasing position (marketers) can sell it (valencia, 2016).

Currently, in Ireland, it carried out three auctions and a continuous trading market which runs up to an hour before real-time, de la mano de SEMOpx (operator). All the agents participating in the day-ahead market or those who could not participate due to being unavailable may submit bids for the sale of electric power. These agents may only participate in the intraday market for the hourly scheduling periods corresponding to those included in the daily market session in which they participated or did not participate because they were unavailable. (valencia, 2016).

The use of this market consists of 4 situations:

1. When a producer generates less than the day-ahead contract, in order to make up the difference, he has to buy more energy from the market in real time.
2. If more energy is generated, the excess energy is sold to the market in real time at a spot price.
3. If a consumer uses less than the previous day's contract, it is equivalent to generating electricity and the rest of the energy is liquidated for the price in real time.
4. If a consumer uses more energy, he needs to buy additional energy at a real time price.

2.2.4 Market access

Since 1996, measures have been taken to address market access, consumer protection, transparency and regulation, adequate levels of supply and supporting interconnection to harmonise and liberalise the EU's internal energy market. The objective of these measures is to build a more competitive, flexible, customer-focused and non-discriminatory European market with market-based supply prices. In so doing, they strengthen and expand the rights of individual customers and energy communities, address energy poverty, clarify the roles and responsibilities of market participants and regulators and address the security of the supply of electricity, gas and oil, as well as the development of trans-European networks for transporting electricity and gas (Gouardères, 2019).

In order to achieve a flexible, decarbonised electricity market and to provide undistorted market signals, the EU is governed by Regulation EC 714/2009, which aims to aims to deliver real choice for all consumers in the Community, be they citizens or businesses, new business opportunities and more cross-border trade, so as to achieve efficiency gains, competitive prices and higher standards of service, and to contribute to security of supply and sustainability (Gouardères, 2019).

2.3 DEMAND RESPONSE

2.3.1 Overview

In the history of energy systems, the concept of DR is not new. During the 1980s, the need arose to reduce peak demand, as well as the operation of diesel generators due to the increase in oil and gas. Some important developments followed. In 1980, Schweppe introduced the concept of homeostasis control. He applied DR measures based on load displacement as a function of frequency deviation in the grid and price in real time with the intention of maintaining the state of equilibrium in the electrical system. And in 1986, Rosenfeld explored the effect of dynamic pricing on maximum load reduction (Ghaemi & Schrnider, 2013)

At present, the DSM concept can be considered mature, particularly for industrial consumers. In addition, with many efforts to reduce or shift the consumption of end-users in order to reduce the stress on power system assets, especially in critical peak demand periods. DSM comprises four actions: energy efficiency, savings, self-production and load management. Among DSM solutions, load management techniques and especially DR strategies are gaining more attention in power system operations recently. The Smart Grid concept facilitates the incorporation of new techniques and new studies in this regard. In the study of (G.Paterakis, Erdinç, & P.S.Catalão, 2016) According to the current literature regarding DSM and DR, they can be classified into three main categories:

1. A general DSM/DR overview followed by recommendations for future developments, where he mentions different authors explaining from their points of view the benefits, characteristics, and evolution of DR in the consumption of final consumers in a global way.
2. The second classification refers to those authors who particularize the subject of DSM and DR, for a specific country or region. On the one hand, the studies focus on the United Kingdom, the most prominent country because it was a pioneer in this system and therefore there are more studies on the benefits, the importance of the penetration of this electrical system and the political vision that this implies. On the other hand, China is booming with relevant pilot projects and betting strongly on this paradigm although still with regulatory problems.
3. And the last category corresponds to a specific implementation of DSM/DR, such as end-user behaviour especially in the residential sector (Shahryari, Shayeghi, Mohammadi-ivatloo, & Moradzadeh, 2018). As has been the development of this project, since between 30-40% of the total energy consumed in developed countries is found in the buildings (Fitzpatrick, 2018). This energy is used for space heating, heating of DHW, cooling ventilation, pumps, control and lighting of rooms as well as appliances used by occupants. A large part of this energy use can be shifted in time. This includes the thermal part of energy demand, DHW as well as energy for washing machines, dishwashers and heat for tumble dryers. As all buildings have thermal mass associated with them, it makes it possible to store a certain amount of heat (Fitzpatrick, 2018)

The daily economic benefit of peak reduction may be of little financial incentive to the customer. Customer behaviour is unlikely to change as a result, which is why the majority of DRP use information technology to develop automated systems for managing end-use participation (Fitzpatrick, 2018). Due to the fact that DR represents an intentional change in electricity usage due to price fluctuations or incentive payments, consumers who exhibit more-variable load patterns on normal days may be capable of altering their loads more significantly in response to dynamic pricing plans (Fitzpatrick, 2018)

In Ireland, the residential sector accounts for more than 27% of total end-use electricity consumption. In winter, there is an increase in demand for lighting and heating which translates into peaks in electricity demand, and therefore high wholesale electricity prices and reduced reliability due to tight generation reserve margins. Advance planning on the generation side is necessary, as high penetration levels of renewable generation and high demand peaks can lead to system contingencies, or in an extreme case, system outages. DR is one of the DSM measures that have been promoted since the 1970s, in order to reduce high winter peaks and avoid the costs of upgrading the system infrastructure. (Pallonetto, Oxizidis, Milano, & Finn, 2016).

Exploiting residential flexible electricity demand, facilitated by clear and appropriate regulation to promote the operation of DRP, can be part of the solution for the power system balancing challenges.

The penetration of Renewable Energy Systems (RES) at the building level and the electrification of thermal loads have shifted the attention of SO from generation to load controls via DRP. DR has been defined as ‘‘changes in electricity use by demand-side resources from their normal consumption patterns in response to changes in the price of electricity or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardised’’ (Pallonetto, Mangina, Milano, & P.Finn, 2019).

The intention is to provide EF to the power system by intentionally remodelling electricity demand in response to a signal sent by an aggregator or transmission system operator (TSO).

There are three factors that directly influence DR's actions (D'Ettorre, Rosa, Conti, & Daniele Testi, 2019):

- Thermal characteristics of the building.
- User behaviour.
- Presence of storage or RES at building level.

These factors must therefore be considered when carrying out DR actions. These can dynamically alter the electricity demand curve, providing measurements of peak shaving, load displacement and load forcing (Pallonetto, Mangina, Milano, & P.Finn, 2019). Electric charges are gaining importance as a controllable resource in the residential sector. To carry out this action, it is necessary to integrate a series of intelligent devices that can respond to a communication signal from the SO (Pallonetto, Mangina, Milano, & P.Finn, 2019). Actions can be performed manually or automatically (Ghaemi & Schrnider, 2013). On the one hand, the former is those that predominate in large loads such as the industrial and commercial sectors. While, on the other hand, to achieve reliable results by aggregating many households and small businesses, automated execution actions are likely to be the best option (Ghaemi & Schrnider, 2013).

Price signals are in charge of sending the signal, as it includes information on the availability of the generation and the demand requested and can support the stability of the energy system (Ghaemi & Schrnider, 2013). These signals are received by the controllers, which can reconfigure the thermostat setpoints or directly turn the appliances on or off as required. Two types can be given (Ghaemi & Schrnider, 2013):

- The "passive controller" is like the one currently being implemented. Customers use their appliances without the information being sent or received by the utility. The function of the appliances using the passive controller is price inelastic.
- The "active controller" is similar to the passive controller, which is additionally provided by information such as the dynamic price, so that the configuration of the controllers can be adjusted accordingly. The active controller controls the end-use devices to react automatically to price information. End-use devices alter their consumption schedule based on the price signal but are not able to re-bid the market and influence the market price.

DRP fall into two basic categories, incentive-based programs and Price based programs (PBP), each of which consists of several programs. The following figure shows a summary of what will be explained in the following chapters (Moghaddam, Abdollahi, & Rashidinejad, 2011).

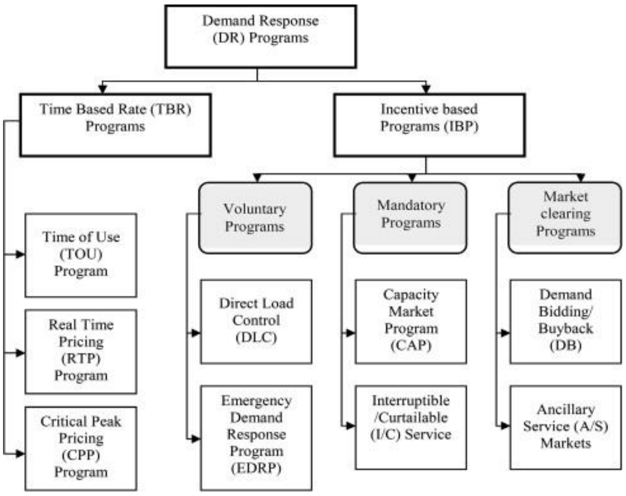


Fig 8: Categories of DRP (Moghaddam, Abdollahi, & Rashidinejad, 2011).

Each DR category has its own benefits and exploits different aspects of the potential of flexible demand. While the common goal is to reduce costs, improve system reliability, and mitigate price volatility. (Asadinejad & Tomsovic, 2017)

2.3.2 Incentive based programs

In Incentive Based Programs (IBP), a fixed or time-varying incentive payment is offered to the consumers to diminish their load. These programs include schemes such as: direct load control, interruptible/curtailable service, demand bidding/buy back, emergency DRP, capacity market program, and ancillary service markets (Shahryari, Shayeghi, Mohammadi-ivatloo, & Moradzadeh, 2018). These programs offer customers incentives in addition to their retail electricity rate, which may be fixed or time-varying for their load reduction (Fitzpatrick, 2018). The programs mentioned are explained below (M.H.Albadi & El-Saadany, 2008):

- In direct load control programs, utilities can turn off utility equipment at short notice. Typically, these appliances are remotely controlled water heaters and air conditioners, which are of interest to residential customers and small residential customers. Participants in classical IBP are entitled to receive incentive payments for their participation.
- Customers who participate in interruptible/curtailable service receive a rate of incentive payment in advance or discounts on fees. Participants may suffer penalties if they do not reduce their burden to predefined values, although it will always depend on the terms and conditions of the program.
- Demand bidding or buy-back programmes are those in which consumers bid for specific load reductions in the wholesale electricity market. The participant would be penalized if once the offer has been accepted, i.e. a lower offer than the market price and the customer does not reduce his load by the specified amount.
- It should also be noted that during emergency DRP, if customers reduce their load during emergency conditions, they are rewarded with incentives.
- Capacity market programs are offered to those customers who can commit to providing pre-specified load reductions when system contingencies arise. These customers usually receive a day ahead notice of events and are penalised if they do not respond to calls for reduction.
- Auxiliary Services Market programs allow customers to bid for the reduction of load in the spot market as an operating reserve. In this program, when an offer is accepted, participants are paid the spot market price for committing to be on standby and are paid spot market energy price if load curtailment is required. Customers in market-based IBP receive payments according to their performance.

In percentage terms, IBP programs provide about 93% of the reduction in the maximum load of existing DR resources in the United States. The authors of (Shahryari, Shayeghi, Mohammadi-ivatloo, & Moradzadeh, 2018) used as a case study, on the one hand, the peak hour peak load of the Spanish electricity market, in which the IBP program increased customer profits by 1.6 and 1.95 million dollars in the day-ahead and real time markets. On the other hand, the second case study was with a residential complex of 200 units in Iran simulating a small customer, and the increases were 1,956 and 2,384 dollars, respectively. Using control relays, they demonstrated the reduction of maximum load in the day-ahead and real-time markets and the improvement of economic indices (Shahryari, Shayeghi, Mohammadi-ivatloo, & Moradzadeh, 2018).

2.3.3 Price based programs

In PBP, the consumers are directly informed of the changes in the electricity market price so that they pay the electricity cost at various times of day. The main idea of PBP programs is based on existence of a significant difference between electricity prices of various hours. This difference encourages consumers to modify their load pattern in such a way that they can take advantage of cheaper hours (Shahryari, Shayeghi, Mohammadi-ivatloo, & Moradzadeh, 2018). In other words, the objective is to flatten the demand curve, offering a high price during periods of higher demand and lower prices during periods of lower demand. (Fitzpatrick, 2018). PBP are classified into three categories namely: time-of-use pricing, critical peak pricing and real-time pricing (Shahryari, Shayeghi, Mohammadi-ivatloo, & Moradzadeh, 2018)

- The time-of-use (ToU) is the most basic example in which two-time blocks can be differentiated: peak and off-peak. The tariff design attempts to reflect the average cost of electricity during that time period.
- Critical peak pricing (CPP) rates include a higher pre-specified electricity usage price superimposed on ToU rates or flat rates. For a limited number of hours or days per year, CPP prices are used in contingency periods or high wholesale prices.
- Real time pricing is a program in which customers pay fluctuating hourly rates that reflect the real cost of electricity in the wholesale market. These customers receive price information by the day or by the hour. These tariffs are considered by economists to be the most direct and efficient DRP in competitive electricity markets and should be the focus of attention for policy formulation (M.H.Albadi & El-Saadany, 2008).

These programs are focused on residential customers. To carry out the actions of these programs, smart meters and display units must be installed to transmit the appropriate price and load adjustment signals. The application of this program handles overload problems and voltage problems and ensures that both customers and utilities benefit from this scheme (Asadinejad & Tomsovic, 2017). Thus, PBP will be the protagonists in the modelling of this project.

2.3.4 Flexibility of residential buildings

In this thesis, demand flexibility is considered the ability to force (activate) or change (defer) the electrical energy consumption of the building. In a residential building, flexible loads correspond to appliances, electric vehicles or water and space heating systems. Flexibility is generally enabled by means of energy storage systems, which can be electric, such as batteries, electric vehicle or thermal storage, in which two types can be differentiated: (Pallonetto, Oxizidis, Milano, & Finn, 2016):

- Active thermal storage such as water tanks.
- Passive thermal storage, such as construction fabric.

In particular, this project focuses on active thermal storage, which the building's heating system manages to heat the home spaces.

These functions will be carried out through the use of an Energy management system (EMS), capable of comprehensively controlling general domestic electricity demand, providing dynamic signals of supply response according to demand, providing short-term reserves for the energy system without affecting thermal comfort. Therefore, a large-scale communication and data infrastructure, such as real-time prices, weather forecasts, energy mix generation and end-use consumption, is required to use residential buildings as a flexible resource for electricity demand. By putting these elements into practice, they will be able to allow end users to configure their electricity consumption according to price signals, achieving a real-time balance between renewable energy generation and energy system demand (Pallonetto, Oxizidis, Milano, & Finn, 2016).

A key element in this system is the use of heat pumps, which provide flexibility and meet the thermal comfort expectations of the end user. In addition, it is easily combined with TES systems, either active as thermal storage, or passive, as the construction of more thermal. The combination that carries out this work is that of a heat pump, TES and a gas boiler in case it is necessary to cover the demand, and that together with sophisticated algorithms of control, can provide capacities of response to the flexible demand to the electrical network (Pallonetto, Oxizidis, Milano, & Finn, 2016).

2.3.5 Demand response costs

The response to demand is still a service, that is to say, a set of activities that seek to satisfy the needs of a client. Therefore, there are a number of costs to be covered, both participants and owners of the programmes must carry a number of upfront and current payments, which can be divided into three categories:

1. Tools and equipment. On the one hand, participants must install a number of electronic devices, such as on-site generation units, smart thermostats, power management systems, and peak load

controls in order to participate in DRP. On the other hand, owners must bear the initial and overall costs of the system, in addition to obtaining a benefit from carrying out technical assistance to establish the response plan or strategy (M.H.Albadi & El-Saadany, 2008).

2. Administration and operation. Participants' operating costs are those associated with events. There are measurements that are more difficult to evaluate such as when a customer decides to restart the thermostat or there are measurements that are easier to quantify such as reprogramming of processes or industrial activities. Other added costs include measurement, as advanced measurement systems will be required to measure, store and transmit energy usage at the required intervals, such as hourly readings for real-time pricing. Also the costs of administration and operation of the program to keep the system up to date due to the variable costs of electricity over time (M.H.Albadi & El-Saadany, 2008).
3. Education: The change towards a better world is in the hands of each one of the citizens who compose the planet Earth. It is therefore necessary to re-educate in the paradigm shift, that is, before the implementation of DRP, it is necessary to educate clients about the potential benefits of the program. It is an obligation of the owners to make them understand to the clients or participants of the global problem, of the necessity of the decarbonization process to promote this type of measures. Carry out explanations of the different options of RD programs so that they learn the possible strategies to respond to the demand and the benefits that it entails. Ongoing marketing is important to attract new participants and to develop a better approach to achieve the final objectives of the programmes (M.H.Albadi & El-Saadany, 2008).

All of these issues should be seriously considered and heavily researched before implementing a DRP. If the program will not ultimately change participants' behaviour or reduce costs to them, the program will not be implemented successfully.

2.3.6 Demand response measurement

The mean goal about DRP is to reduce peak demand. In order to measure peak demand reduction, several appropriate statistical and load investigation techniques are used to measure and verify the impact of load reduction resulting from the use of a DRP. In short, demand response measures is a process for quantifying with statistical confidence, the value of a reduction in the DR load over the duration of a DR event (Companies, 2009).

A percentage peak demand reduction is used to normalize this indicator. Both percentage and actual peak demand reduction are used to evaluate IBP. The performance of dynamic pricing programs is measured using demand price elasticity which represents the sensitivity of customer demand to the price of electricity (M.H.Albadi & El-Saadany, 2008).

Generally, the price demand curve of any commodity is non-linear. Elasticity can however be linearized around the initial price-demand balance (p_o, q_o) as shown in Fig 9. The elasticity of a substitution is a measure of the rate a customer substitutes off-peak electricity consumption for peak usage in response to a change in the ratio of peak to off-peak prices. This elasticity is important in ToU and CPP pricing programs (M.H.Albadi & El-Saadany, 2008)

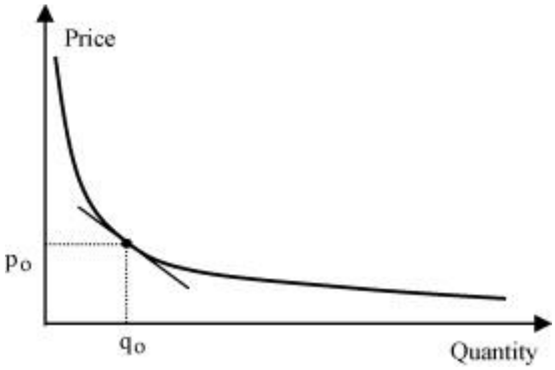


Fig 9: Price elasticity around (p_o, q_o).

2.3.7 Aggregators

According to the DR definition, DRP attempt to incentivize consumers so that they themselves, along with the power grid, can benefit from managing their energy use. These programmes play an important role in reducing prices and improving the reliability of the electricity supply. (Shahryari, Shayeghi, Mohammadi-ivatloo, & Moradzadeh, 2018).

DR can be provided to residential, commercial and industrial customers, however, the first two cannot resolve the system imbalances caused by uncertain RES generation individually. They must be aggregated and coordinated to have a substantial effect on RES generation. To carry out this action, it is necessary to install aggregators, which are mediators between electricity customers, who offer DR, and electricity market participants who wish to exploit this DR (Okur, Voulis, Heijnen, & Lukszo, 2019). To achieve this, aggregators participate in various electricity markets and offer consumers DR in these markets to cope with uncertain RES generation.

DR aggregators are placed between the independent system operator (ISO) and retail consumers to specify the best offer for retail consumer participation in DR (Shahryari, Shayeghi, Mohammadi-ivatloo, & Moradzadeh, 2018). The aggregator participates in the day-ahead market in order to purchase the net energy for their customers. A probabilistic optimization problem is solved, resulting in the optimal quantity of energy to be purchased (or sold) in each period of time. When the day ahead market is cleared, the scheduled energy for each period of time is known (Fitzpatrick, 2018)

The adjustment of the end-user's electric usage is realized as a response to change in electricity prices over time or when system reliability is threatened. La estructura de este ajuste está compuesta por tres los participantes (Carreiro, Jorge, & Antunes, 2017) que se explican a continuación y resumida en la Fig 10:

1. End-user loads that participate in the DRP, whether residential, commercial or industrial.
2. The Energy Management Systems Aggregators (EMSA), which are connected to the end-user's EMS, ready to run the DRP.
3. A SO, which manages the system.

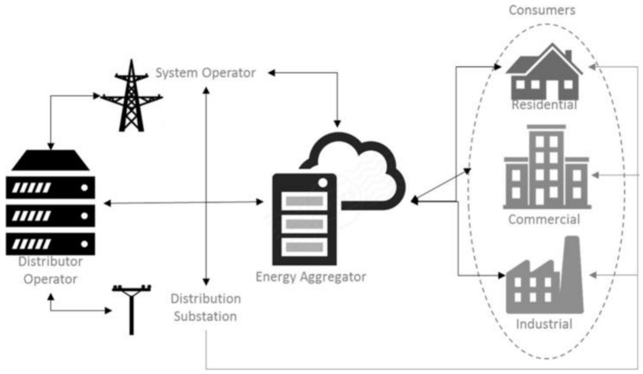


Fig 10: Main participants in DRP.

Its operation is as follows, the SO determines the volume of demand to be reduced or increased in each period of time. This information is sent to EMSA, which selects participating end-users based on their availability. Taking into account the number of end-users who agree with the proposed DR scheme, EMSA calculates the total load flexibility that can be offered in response to the OS request, the amount of flexibility that will be used from each participating end-user and reports back to the OS. (Carreiro, Jorge, & Antunes, 2017).

In order to implement this system, it is necessary to have efficient Information and Communication Technologies infrastructures, so that end users can have greater control to manage loads. This is achieved thanks to the EMS that have the function of monitoring and controlling devices in the house through infrastructures and robust communication protocols. There is also a need for secure and reliable communication infrastructures between EMSA and local EMS and OS, thus offering secure routing, interoperability, and scalability. Special attention should also be paid to privacy issues arising from the management of metering data, which contains private information and end-user activities or options, in relation to security vulnerabilities and unauthorized access to data. (Carreiro, Jorge, & Antunes, 2017).

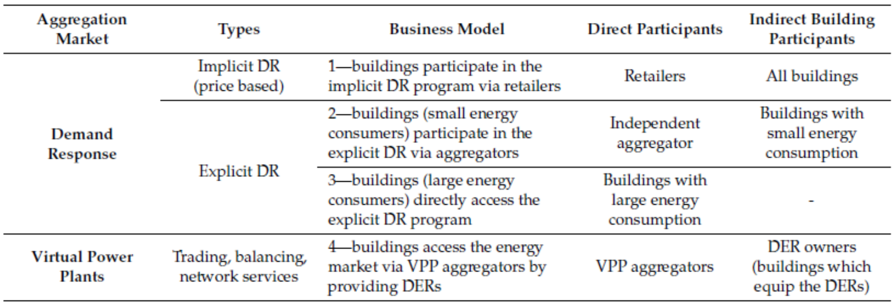
Similarly, attention should be paid to the contracts underlying the relationships between end-users, EMSA and SO. In the first instance, EMSA should establish bilateral contracts with end-users and the SO, with the obligation to deliver to the SO the requested load flexibility according to the availability expressed by end-users involving a certain amount of energy at specific time intervals. A comprehensive definition of the remuneration scheme is needed as a way of attracting and achieving end-user loyalty to EMSA, ensuring the implementation of the required changes in the load diagram through specific devices or the change of energy behaviour. Therefore, end-users should receive rewards for load availability, load changes effectively provided and also penalties for not meeting load change commitments. (Carreiro, Jorge, & Antunes, 2017).

2.3.8 Building applications

Buildings play an important role in the energy aggregation market due to their potential for flexible consumption of energy and distributed energy resources (DER). However, it is often a complex operation, the EF that buildings provide. Currently, the contribution of buildings in the aggregation markets is a challenge, due to a weak development in the market structure, few clear incentives and restrictions in national regulations.

According to (Ma, Billanes, & Jørgensen, 2017), it proposes four business models to contribute to the aggregation market share by providing flexible loads and DER. In addition, a summary scheme is shown in Fig 11.

1. Buildings participate in the implicit DRP via retailers. The author refers to implicit DR as the PBP. In this model all buildings can participate. It consists of the electricity retailer and the customer agreeing on the electricity supply contract in the form of DRP packages. In this way, the goal is to get a lower bill. The activities that stand out most in this model are reducing electricity use during peak periods or shifting use to off-peak periods.
2. Buildings with small energy consumption participate in the explicit DR via aggregators. This model is aimed at energy-efficient buildings to obtain direct payment by participating in explicit DRP (Incentive based programs). On this occasion the aggregators maintain good relationships with customers through a wide range of services. As a control system, an efficient and customer-friendly payment system; custom DR contracts to provide capitation and consulting service; provide discounts or free control systems and maintenance services to customers with the installation of direct load control system; increase overall reliability and reduce risk to individual consumers by providing support for individual loads as part of grouping activities. In this modelling, aggregators generate revenue by providing DR services to the market and may receive incentives from TSO and DSO (Distribution System Operations) regulators.
3. Buildings directly access the explicit DRP. Energy-intensive buildings are ideal for this type of model. In order to participate in wholesale and balancing markets, large energy consumers must comply with market rules. Buildings can receive direct payment by providing flexibility via direct participation in explicit DRP, and may get incentives from regulators, DSO and TSO.
4. Buildings access energy market via VPP aggregators by providing DER. In this business model, buildings that have DER can obtain direct payment from VPP aggregators by providing EF. The idea is that VPP aggregators add DER and flexible loads as a single entity in the wholesale market. This entity consists of the DER owners, who collectively participate as a single cluster.



Aggregation Market	Types	Business Model	Direct Participants	Indirect Building Participants
Demand Response	Implicit DR (price based)	1—buildings participate in the implicit DR program via retailers	Retailers	All buildings
	Explicit DR	2—buildings (small energy consumers) participate in the explicit DR via aggregators	Independent aggregator	Buildings with small energy consumption
		3—buildings (large energy consumers) directly access the explicit DR program	Buildings with large energy consumption	-
Virtual Power Plants	Trading, balancing, network services	4—buildings access the energy market via VPP aggregators by providing DERs	VPP aggregators	DER owners (buildings which equip the DERs)

Fig 11: Summary, four business models of building's participation in the aggregation market.

The author places emphasis on studying the needs, amenities and behaviours of building owners in order to develop viable market access strategies for different types of buildings.

A similar course of action is proposed (Auba, 2016), where consumers keep pre-established bilateral contracts. Each of these contracts has specific characteristics that allow each user to participate in special DRP, which traditionally would not be available to each user individually due to the low volume of energy. It proposes three resources that define its aggregate demand and deliver the flexibility associated with consumers. Among them are:

- <u>Fixed loads</u>, which refers to the expected consumption of its consumers that represent the base demand of the aggregator.
- <u>Reduction of load</u>, which consists of the consumer being willing to participate in DRP that disconnect part of their electricity consumption in exchange for incentives according to the requirements of the aggregator. Some examples are the disconnection of the air conditioning or heating home or lighting of buildings.
- <u>Charges of differentiated duration</u>, this type of contract refers to certain types of loads that require a fixed consumption of a given duration within a period of operation, not necessarily continuous. In other words, it is usually used to increase demand at a certain time. An example results in appliances such as washing machines that require a fixed consumption for 1 hour in any of the following 8 hours.

On the other hand, other studies, such as the SABINA project, consider that the exhaustive knowledge of the functional reality and costs of each and every one of the consumers seems to be computationally complex to develop, so it proposes a simple system that requires relatively few data, is fast and able to take into account other parameters of the strictly economic ones. Put simply, it tries to use the minimum information from the EMS to make the aggregation, thus trying to get closer to the commercial reality (Casals, Barbero, Barbero, Corchero, & Igualada, 2018).

According to the literature, the reaction time of aggregators to DR is important to evaluate. The faster the evaluation, the greater the accumulation of energy reduction. In the future it is expected that aggregators will collect energy reductions from many widely distributed building installations as quickly as possible, e.g. 1 minute. However, conventional installations have not been designed to match these rapid actions. In the study bank (Suzuki, y otros, 2013), on average it took 5.8 minutes to add 5MW power reduction reports from the 100-building HVAC installation emulator. The authors are trying to drastically reduce the delay by our idea of "Real-time Web Service Pulling" allowing current on-the-market firewall policy and conventional facility communication systems (Suzuki, y otros, 2013)

3. Methodology

3.1 Overview

The building under study in this paper is located in eastern Ireland. In order to simulate this building, firstly it is used the EnergyPlus program, which is used to define the characteristics of the building, and then we obtained results that help MATLAB interpret the data in order to carry out the appropriate simulations. Through the EnergyPlus program, average weather data for the year can be provided and the structural characteristics of the house can be defined. With this information, the Matlab model uses the input values such as ambient temperature, radiation affecting each of the building surfaces and roof. Since, during the year, the angle of the sun that affects the surface is different, the fraction of solar radiation on each surface varies. Another aspect to take into account is two inputs consisting of the DR measures which are triggered by the spot market price and vary in intensity and length. The electricity prices being considered are the final input and vary with the pricing scheme assumed for each case.

This is a parallel heating system in which both the heat pump and the boiler gas can work together or separately depending on the strategy to be followed. There is also a TES, which will only be charged by the heat pump and the latter will not be able to cover the demand load while this action is taking place. The heating season to be considered extends from October to March.

3.2 Building description

The building selected for this study is a detached house built in 1973 and is situated in a rural location in eastern Ireland. This house has been the object of numerous studies, which serve as a precedent to this one and from which the initial items have been obtained. On the one hand, it is possible to discard the investigation of (Pallonetto, Rosa, & Finn, Environmental and economic benefits of building retrofit measures for the residential sector by utilising sensor data and advanced calibrated models, 2019) which consists in the potential energy savings associated with the implementation of retrofitting measures on Irish residential buildings and on the other hand there is the development and evaluation of control algorithms for the implementation of demand response strategies in a smart-grid enabled all-electric residential building performed by (Pallonetto, Oxizidis, Milano, & Finn, 2016).

It is a single storey building, constructed using a two leaf concrete wall with cavity insulation, so the inner walls display significant passive energy storage capacity (Pallonetto, Rosa, & Finn, Environmental and economic benefits of building retrofit measures for the residential sector by utilising sensor data and advanced calibrated models, 2019). The total exterior area is 187 m², not including windows and doors. The windows occupy 33 m² and the doors 5.4 m². The roof is covered with slate and it has a surface area of 279 m² (Pallonetto, Rosa, & Finn, Environmental and economic benefits of building retrofit measures for the residential sector by utilising sensor data and advanced calibrated models, 2019). The roof does not have insulation, while the ceiling is covered with tiles to ensure both acoustic and thermal insulation. On top of the tiles, a 200 mm layer of fibreglass ensures high thermal resistance due to its low thermal conductivity (0.04 W/mK). The floor area is 208 m², and the overall window to wall ratio is 15%, with a 22% and 10% ratio on the south and north facades, respectively. Two temperature sensors were installed, one in the main living area and one in the corridor.

The following table shows a summary of the house dimensions entered the EnergyPlus program.

Table 1. Dimensions of the study dwelling

Total surface area (exterior walls)	187 m²
Doors (exterior walls)	5.4 m²
Windows	33 m²
Roof	279 m²
Floor area	208 m²

The data in Table 1 was entered by (Pallonetto, Rosa, & Finn, Environmental and economic benefits of building retrofit measures for the residential sector by utilising sensor data and advanced calibrated models, 2019) and simulated in the Energyplus program, obtaining a summary of the house in 3D as shown in the following Figure.

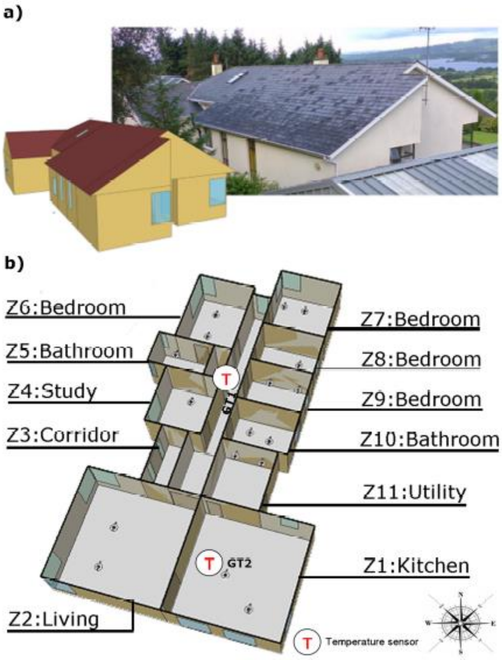


Fig 12.: a) Aerial view and Energy Plus model of the test bed house (Pallonetto, Rosa, & Finn, Environmental and economic benefits of building retrofit measures for the residential sector by utilising sensor data and advanced calibrated models, 2019). b) Internal sketch of the building with orientation and temperature sensors installed.

Although its architectural characteristics are those of a typical rural Irish bungalow dwelling of the 1970s, its fabric specifications are very close to the current Irish building regulation values as outlined in Table 2. The difference between the conventional and all-electric configurations in the building architecture and thermal envelope was the replacement of the aluminium double-glazed windows with triple glazed windows with an air cavity of 13 mm and PVC frame. Moreover, an additional insulation layer was added to the ceiling to reach a lower U-value of 0.21 W/ m²K (Pallonetto, Rosa, & Finn, Environmental and economic benefits of building retrofit measures for the residential sector by utilising sensor data and advanced calibrated models, 2019).

Table 2. U-Value of different building elements for the conventional and all-electric models compared to Irish building regulation standards (IBRS) (regulation, 2011)

U-Values in (W/m²K)			
Building element	**Pre-retrofitting**	**All-electric**	**IBRS**
Walls	0.21	0.21	0.21
Roof	0.25	0.21	0.21
Windows	2.6	1.7	1.6
Floor	0.21	0.21	0.21

The climatic conditions of the area are important to study in order to configure and calibrate the heating system. The meteorological file used comes from the study conducted by (Pallonetto, Oxizidis, Milano, & Finn, 2016) and was obtained from the EnergyPlus website. Fig 13 shows the outdoor dry bulb air temperature for the year 2014. The graph represents the period from January 1st to December 31st and can be seen in the middle zone of the graph, which corresponds to the summer months, when the highest temperatures are reached, around 20°C. On the other hand, at both extremes, which represent the winter months, they are the coldest, averaging around 6.4°C.

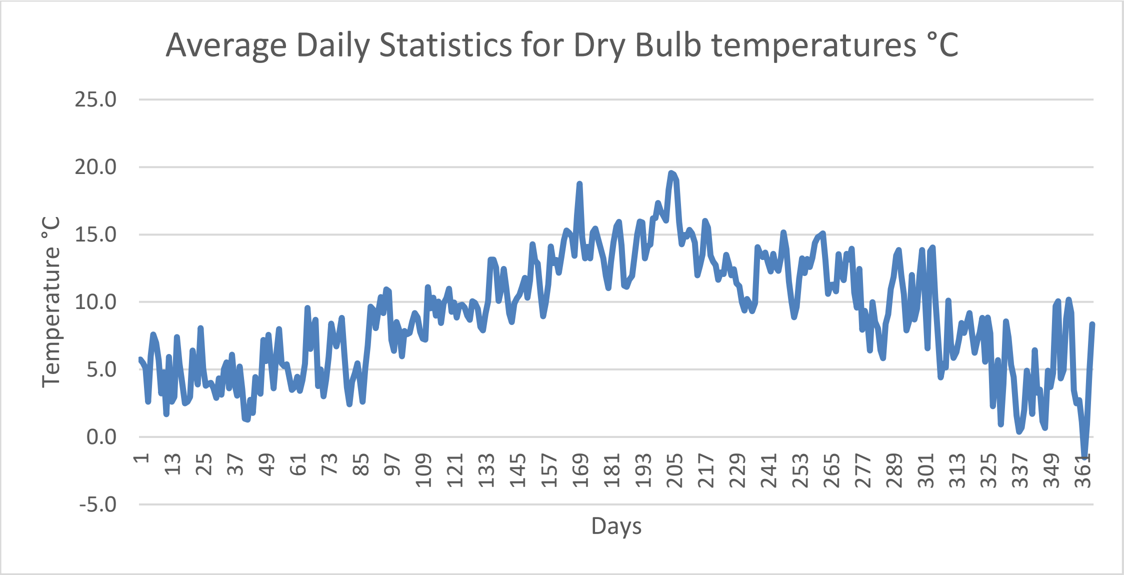


Fig 13: Average daily for dry bulb temperature for a year

In the following table you can see the average monthly external temperature, to have a clearer perception of the climate that affects the house.

Table 3. The average monthly external temperature

Month	Temperature °C
January	4,6
February	4,5
March	5,8
April	8,8
May	10,4
June	13,5
July	15,3
August	12,4
September	12,6
October	10,0
November	6,7
December	4,1

Once the temperature has been analysed in general terms, the next step is to focus the study on the heating period, which corresponds to October to April. Another factor to take into account will be the hourly regime, since for 24 hours a day the temperature is changing, so a period of comfort can be predicted according to the needs. The following figure shows the average hourly external temperature.

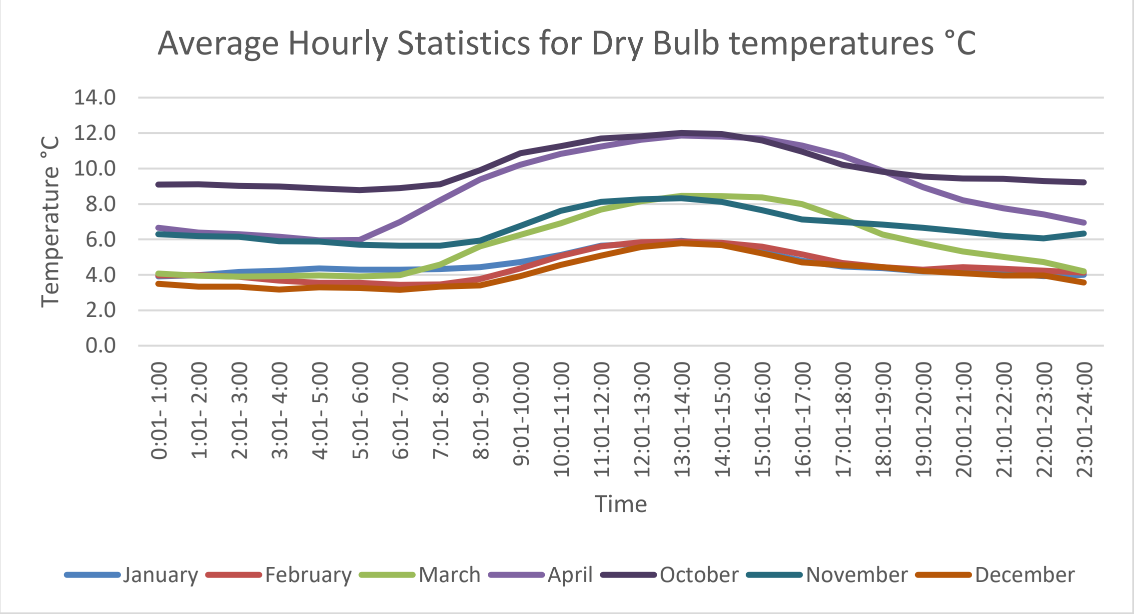


Fig 14: Average Hourly Statistics for dry bulb temperatures

It can be seen within the heating period that the months with the highest temperatures correspond to the months of April and October, but it is only during the hours of half a day that it exceeds 10°C, the rest of the day being lower, which denotes a clear factor for the lack of comfort inside the house. The coldest months are December, January and February, and the temperature does not exceed 6°C during the midday hours. It is therefore important to take into account this time schedule in order to carry out the strategy for maintaining comfort inside the home.

3.3 Heating system

The heating system of the house is emitted by radiators except for the rooms, where the heat is produced by electric fan convectors. Additionally, there is a 5kW wood fired stove in the kitchen, which is used by the occupants daily from 6pm to 10pm during the whole heating period. The heat demand of the kitchen and living room is compensated by the stove, as this has an impact on energy efficiency and thermal conditions. The heating period is set between 1st October and 31st March according to the occupants' heating pattern.

At each time step, the zone temperature is maintained at set point as illustrate in Table X with an associated 2ºC bandwidth (Pallonetto, Oxizidis, Milano, & Finn, 2016).

Table 4. Building thermostatic set points for each case (Pallonetto, Oxizidis, Milano, & Finn, 2016).

Time of the day	Weekdays	Weekends
00:00 to 06:30	19°C	20°C
06:30 to 09:00	18°C	
09:00 to 16:00	16°C	
16:00 to 19:00	18°C	
19:00 to 00:00	18°C	

The study apartment in this project, which is fully electric, has a 15kW (thermal output) GSHP heating system. Water to water heat pump uses water from a nearby open well as cold heat source. This system is equipped with a thermal energy storage supply, i.e, a hot water storage tank of 0.1 m³. In addition, there is a gas boiler, which will support the system. In the following table you can see a summary of the characteristics of the heating system.

Table 5: Heating system datasheet

Heating system	Data sheet
Heat pump	15 kw
Gas boiler	Performance 88%
Thermal energy storage	Volume 0.1 m³

The system would then consist of three elements, the HP, the TES and the gas boiler. This system is connected in parallel, which means that the heat pump and the gas boiler can work separately or together. Only the heat pump can charge the thermal storage and the heat pump will not be able to meet the demand load of the house when carrying out this operation. Therefore, a strategy will be designed through the combination of the three equipments achieving a triple objective:

1. Increased energy efficiency.
2. Lower cost in the electricity bill.
3. Always maintain comfort inside the house.

3.4 MATLAB

The MATLAB program helps to model the housing explained above, using a simplified model and a predictive model control (MPC) algorithm. The model was developed by Francesco D'Ettorre and Carlos Andrade-Cabrera and is used to model different DR measures. In order to solve the optimization problem YALMIP and CPLEX solvers are used. The configuration of the heating system to be studied consists of a water to water heat pump and a gas boiler. Besides, a TES which works as a hot water tank, which can only be charged by the heat pump. The idea is to be able to charge the TES during low tariff hours and to discharge it at peak times of the day. The objective of the system is to design a strategy to minimize the energy bill, maintaining the temperature of the comfort inside the house. The gas boiler and the heat pump can work independently or together. To do this, fuel switching strategies are implemented to minimise costs and/or CO2 emissions.

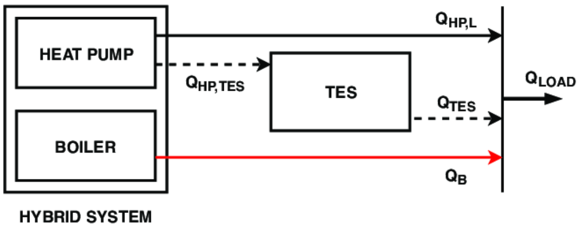


Fig 15: Schematic of the hybrid system configuration (D'Ettorre, y otros, 2019).

The HP is modelled by the second-law efficiency, T_{sink} is the sink temperature which is to the external temperature and T_{source} is the source temperature which is the heat supply temperature. If the HP directly covers the load, the supply temperature is considered equal to that required by the emission system. In the case of the HP being used to charge the TES, the supply temperature will be considered equal to the maximum storage temperature. The gas boiler is modelled with a constant efficiency over its operational range (D'Ettorre, y otros, 2019).

$$COP = \eta^{II} \cdot \frac{T_{sink}}{T_{sink} - T_{source}} \tag{1}$$

With the following energy balance, the water tank is modelled as a perfectly-mixed tank:

$$\rho V c \frac{dT_{TES}}{dt} = \dot{Q}_{HP,TES} \ - \dot{Q}_{TES,L} - \dot{Q}_{loss}(t) \tag{2}$$

The meaning of the variables is as follows:

- *ρ:* water density;
- *V:* storage volume
- *c:* specific heat of water
- T_{TES}: storage temperature
- UA_{TES}: overall heat transfer coefficient of the tank

The TES is modelled in MATLAB using Equation *(2)*. To get to this form of the equation, the vector of inputs first needs to be defined. The vector **u** is defined as follows:

$$\boldsymbol{u} = [T_e \; EAST \; WEST \; NORTH \; SOUTH \; T_{ground} \; ROOF_E \; ROOF_W \; ROOF_N \; ROOF_S$$
$$\underbrace{\mathrm{u1}}_{Q_{TES,L}} \; \underbrace{\mathrm{u2}}_{Q_{B,L}} \; \underbrace{\mathrm{u3}}_{Q_{HP,TES}} \; \underbrace{\mathrm{u4}}_{z_{HP}^{TES}} \; \underbrace{\mathrm{u5}}_{\delta_{HP}^{TES}} \; \underbrace{\mathrm{u6}}_{\delta_{TES}} \; \underbrace{\mathrm{u7}}_{Q_{HP,L}} \; \underbrace{\mathrm{u8}}_{z_{HP}^{L}} \; \underbrace{\mathrm{u9}}_{\delta_{HP}^{L}}]$$

Starting from the energy balance on the storage tank and substituting for $\dot{Q}_{loss}$, the following can be written:

$$\dot{Q}_{loss}(t) = \underbrace{\boldsymbol{UA}}_{\substack{\boldsymbol{Storage}\\ \boldsymbol{UA}}} \cdot [T_{TES}(t) - T_e(t)] \quad \textbf{(3)}$$

$$\rho c V \cdot \frac{dT_{TES}(t)}{dt} = \dot{Q}_{HP,TES}(t) - \dot{Q}_{TES,L}(t) + UA \cdot [T_e(t) - T_{TES}(t)] \quad \textbf{(4)}$$

The building dynamic is described by a linear state-space model developed on the basis of experimental data collected from the residential building located in near Stuttgart, Germany. This leads to a similar expression (Fitzpatrick, 2018).

$$\mathrm{x_{k+1} = Ax_k + Bu_k} \quad \textbf{(5)}$$

The state and input matrices are represented by the variables *A* and *B*. The state vector *x* consists of the node temperatures, with *u* being the input vector containing the input signals, thermal power delivered to the building by the generation system and weather conditions, as described earlier in equation **¡Error! No se encuentra el origen de la referencia.**. The matrix *B* was extended to include the last eight components of ***u*** (D'Ettorre, et al., 2019).

In order to examine some initial DR measures, the following parameters are defined:

$$\alpha = P_{HP}^{DR} / P_{HP}^{ref} \quad \textbf{(7)}$$

$$\Delta t_{DR} = l \cdot \Delta t_{DR}^{min} \quad \textbf{(8)}$$

The variable P_{HP}^{ref} is the baseline power consumption while P_{HP}^{DR} is the power consumption of the HP after the DR measure has been implemented. Hence, α can be a value between 0 and 1, with (1 - α) being the amount of electric power reduced or equivalently the intensity of the DR measure. On one hand, the value of 1 represents no power reduction of the heat pump, on the other hand, of 0 meaning that the heat pump has been turned off entirely. The parameter l represents the duration of the DR measure. It can go from a minimum of 15 minutes, l equal to 1, to a maximum of 4 hours, l equal to 16. By changing the values of these two measures, a map can be created comparing all of the different DR scenarios with the cost of each.

The thermal power becomes a semi-continuous variable because it is not desired that the heat pump should operate if its load factor drops below a minimum percentage of its nominal value.

$$Z_{HP}^{L} = \phi_{HP}^{L} Q_{HP,L} \quad \textbf{(9)}$$

$$Z_{HP}^{L} = \phi_{HP}^{L} Q_{HP,L} = Q_{HP,L} \; if \; \phi_{HP}^{L} = 1 \quad \textbf{(10)}$$

$$Z_{HP}^{L} = \phi_{HP}^{L} Q_{HP,L} = 0 \; if \; \phi_{HP}^{L} = 0 \quad \textbf{(11)}$$

As the optimisation problem is to be solved by means of linear programming, Equation **¡Error! No se encuentra el origen de la referencia.** has to be linearized. This can be done by introducing the following inequalities constraints:

$$\phi_{HP}^{L} \cdot Q_{HP,L}^{min} \leq Q_{HP,L} \leq \phi_{HP}^{L} \cdot Q_{HP,L}^{max} \quad \textbf{(12)}$$

$$Q_{HP,L}^{min}(1 - \phi_{HP}^{L}) \leq z_{HP}^{L} - Q_{HP,L} \leq Q_{HP,L}^{max}(1 - \phi_{HP}^{L}) \quad \textbf{(13)}$$

This represents the following 4 inequalities:

$$-Q_{HP,L} + \phi_{HP}^{L} \cdot Q_{HP,L}^{min} \leq 0 \tag{14}$$

$$+Q_{HP,L} - \phi_{HP}^{L} \cdot Q_{HP,L}^{max} \leq 0 \tag{15}$$

$$-Z_{HP}^{L} + Q_{HP,L} - \phi_{HP}^{L} \cdot Q_{HP,L}^{min} \leq -Q_{HP,L}^{min} \tag{16}$$

$$Z_{HP}^{L} - Q_{HP,L} + \phi_{HP}^{L} \cdot Q_{HP,L}^{max} \leq +Q_{HP,L}^{max} \tag{17}$$

The hourly electricity price is used as an external signal to simulate the request of DR actions from the grid. When the electricity price is higher than an upper threshold value, the reference heat pump consumption is reduced to a fraction specified by α. The upper threshold value is calculated for each day by obtaining the standard deviation of electricity prices for that day. A lower threshold is also calculated which can be used for charging the TES during times of low electricity price (Fitzpatrick, 2018). For each scenario an optimum control strategy is defined by solving a new OCP in which the objective function is the same adopted in the baseline case, with new constraints added to account for the DR actions (D'Ettorre, y otros, 2019).

The goal of the controller is to minimise the daily operational cost of the system while preserving the comfort condition of the building. The objective function is defined as the sum of hourly operational costs over the whole day. This is shown in Equation **¡Error! No se encuentra el origen de la referencia.**.

$$C_{op}^{Day} = \int_{0}^{\mathrm{T}} \left[p_{el} \cdot \left(\psi_{HP,TES} \cdot \frac{\dot{Q}_{HP,TES}}{COP_{TES}} + \psi_{HP,L} \cdot \frac{\dot{Q}_{HP,L}}{COP_{L}} \right) + \ p_{gas} \cdot \frac{\dot{Q}_{B}}{\eta_{B}} \right] \cdot dt \tag{18}$$

Two binary variables are used to identify the HP operation. The system works as follows, when the heat pump is charging the storage tank ($\psi_{HP,TES} = 1$), then it is not used to meet the load demand. On the other hand, when ($\psi_{HP,L} = 1$), the HP is only used to meet the load demand.

$$0 \leq \psi_{HP,TES} + \ \psi_{HP,L} \leq 1 \tag{19}$$

Constraints on the operative limits of the two generators is given by the following equations. The two generators can only produce power between zero and their specified maximum power output.

$$0 \leq \dot{Q}_{HP} \leq \dot{Q}_{HP}^{max} \tag{20}$$

$$0 \leq \dot{Q}_{B} \leq \dot{Q}_{B}^{max} \tag{21}$$

The TES has the following constraints, as shown in Equations **¡Error! No se encuentra el origen de la referencia.** and **¡Error! No se encuentra el origen de la referencia.**.

- The first constraint considers that the TES can deliver energy to the load only if its temperature is greater than that required of the emissions system.
- The second constraint specifies the minimum and maximum temperature of the TES.

$$0 \leq \dot{Q}_{TES} \leq \begin{cases} \rho V c (T_{TES} - T_{em}) & if \quad T_{TES} > T_{em} \\ 0 & \quad otherwise \end{cases} \tag{22}$$

$$T_{TES}^{min} \leq T_{TES} \leq T_{TES}^{max} \tag{23}$$

Through the following formula, which depends on the ambient air temperature, the electrical and thermal performance of the heat pump can be obtained. The DR measure reduces the output of the heat pump to a fraction, α, of the output corresponding to the base case heating load which minimises the cost of the heating system for the day.

$$P_{HP} = \frac{\dot{Q}_{HP,L}}{COP_{L}} = \alpha \cdot P_{HP\_ref} \tag{64}$$

The threshold values for each day are evaluated as follows based on the hourly day ahead electricity price. The standard deviation for the day, σ, is based on the daily distribution of the electricity price, and $\hat{p}_{el}$ is the mean daily price.

$$p_{el}^{thld} = \hat{p}_{el} + \sigma$$ **(75)**

The cost associated with implementing the DR action is based on the difference in operational cost between no DR measure applied, the base or reference case, and the specified DR measure.

$$\Delta C_{Flex} = C_{op\_DR}^{Day} - C_{op\_ref}^{Day}$$ **(86)**

3.5 Electricity prices

In this document the analysis will be performed with the RTP model. The price of electricity is stored in a row vector at 15 minute intervals. These prices correspond to the Irish electricity market and were used in the simulations carried out in the study de (Pallonetto, Rosa, & Finn, Environmental and economic benefits of building retrofit measures for the residential sector by utilising sensor data and advanced calibrated models, 2019). The curve of these prices can be seen in the following figure

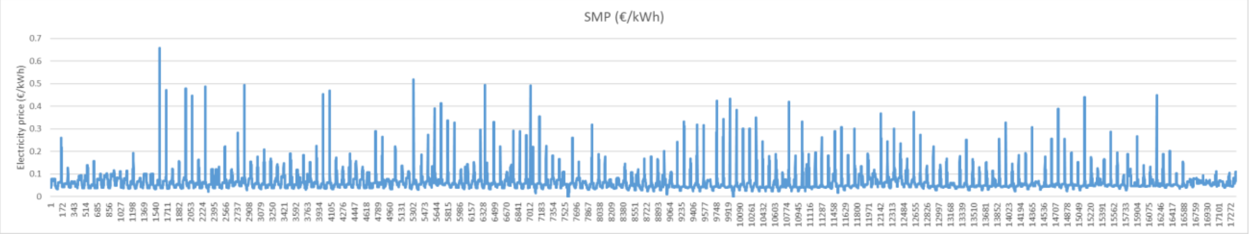


Fig 16: Real Time price of the heating period

In Fig 16, the RTP used in the simulations of this project is represented. The prices are obtained every 15 min for the heating period from 1st October to 31st March. It can be seen that the market peaks take place from the end of October to mid-March. This may be due to the high demands from users and the low contribution of renewable energies during this period. The highest peak of this price vector is 0.65708 €/kWh and occurs on October 18 at 8:15 pm. The market average during these 6 months is 0.064025 €/kWh.

After a general analysis of the heating period, the behaviour of this market is studied month by month.

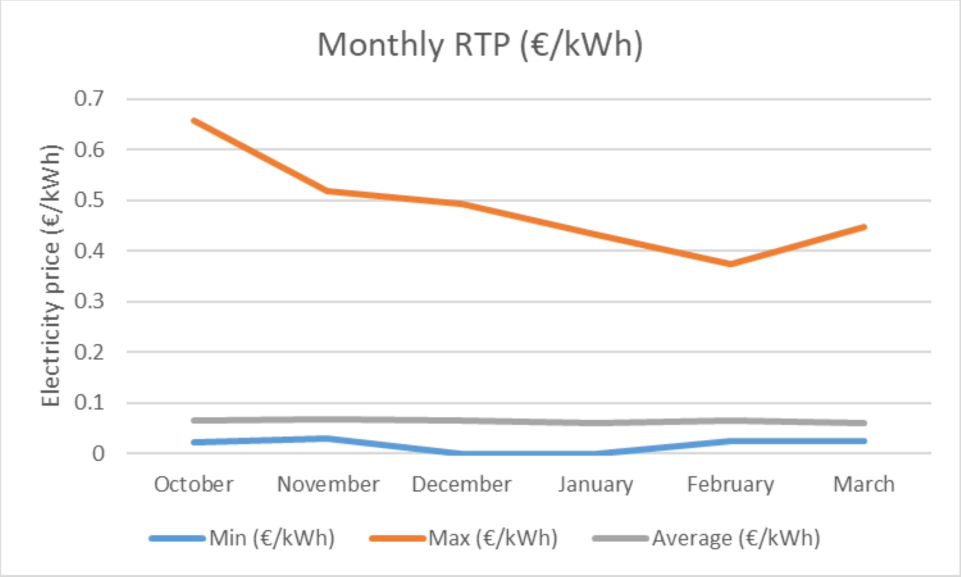


Fig 17: Monthly real time price.

It is noted that as winter progresses, market prices drop due to weather conditions that favour the country's renewable resources, such as increased wind for wind energy production, the main renewable source in Ireland, and low temperatures that favour the use of heat pumps, improving the COP.

On the other hand, the gas price is assumed constant at 0.08 euros/kWh, as considered by (D'Ettorre, Rosa, Conti, & Daniele Testi, 2019).

4. Simulation

This chapter explains the studies carried out for each model, making an analysis and the appropriate comments to explain the operation of the heating system. The analysis strategy consists of a more general study, starting with the whole heating period, which can be seen in chapter 4.2. The following analyses refer to two weeks, which, due to their different system behaviour, have been the object of study in chapter 4.3. Finally, the coldest day of the year is analyzed to know the behaviour of the equipment before a typical day, chapter 4.4. together with a typical day when the TES and the boiler gas are more used.

4.1 Overview

The analysis covered by this work carries out a series of studies in which two models are differentiated. One consists of optimising the heating system of the home without applying demand response programmes, i.e. obtaining the lowest possible cost of electricity and gas. On the other hand, the remaining model does carry out the application of demand response programmes. In this way, it will be possible to see how demand response programmes affect the heating system. Within each model, five studies will be carried out, all based on the RTP. Two, are the objectives to be covered:

1. Explain the behaviour of the optimization system and how it affects the demand response programs in the heating system.
2. Compare both models and observe the energy and cost in each of the studies and for each of the models.

Thus, the studies to be carried out can be seen represented in the following table:

Table 6. The studies of the simulation

	Base case (without DRP)	**With DRP**
Study 1	October - March	October - March
Study 2	9th-15th January	9th-15th January
Study 3	27th February – 5th March	27th February – 5th March
Study 4	28th December	28th December
Study 5	3th March	3th March

4.2 October-March (Study 1)

This study covers the entire heating period of the dwelling, which corresponds from 1 October to 31 March. The intention of this study is to know the energy value and cost during this period. In addition, in order to know the behaviour of the heating equipment, it begins with a more general analysis and then goes on to specify it.

In the study of the model without the application of the demand response programs, the optimization of the system concludes with a cost of 251.17 € and an energy consumption of 3659.74 kWh while with the application of the PRA at 100% the cost was 276.05 € and the energy consumption was 3963.41 kWh. This price difference is due to an increase in the use of boiler gas in the DRP, consuming almost twice as much as in the base case, 1001.14 kW as opposed to 559.39kW in the model without the application of DRP. And the increase in energy is due to the heating system working more hours, but with less power in the DRP model than without it. It has also been studied when DRP acts at 75% and 50% and denotes a higher consumption and cost. These values are shown in the following figure.

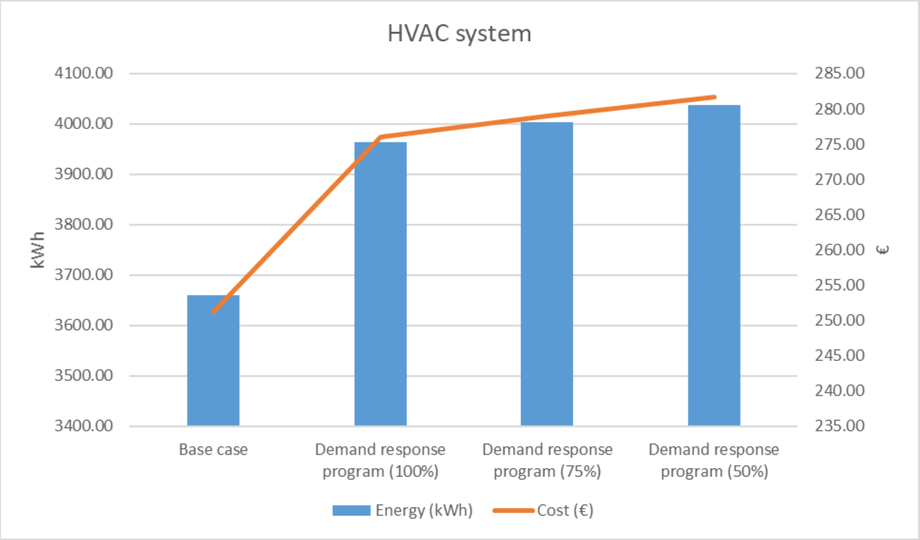


Fig 18: Energy and cost of heating period

After an analysis in general terms, we proceed to study more in depth how the heating system behaves during the 6 months of this activity.

In the base case has been verified that the most expensive month was February with 46.43 € but it was not the one that consumed more, since it was January with 709.22 kWh against 690.57kWh of the successor month. This is due to a greater use of boiler gas since 11% of all the energy consumed by boiler gas in the heating period was in the month of February as opposed to 4% in January and especially because of the increased use of HP in the TES load..

It has been proven that the highest use of HP was during the months of December, January and February, with a little more than 20% of the total. On the other hand, October and March were the months when boiler gas was most used, 34% of the total use, and December and January were the months when it was least used, with 5% and 4% respectively. This is due to the fact that during the months of October and March the thermal energy coming from HP came from TES, which meant an energy saving since HP did not produce heat directly to the house but charged the TES. This can be seen in the following figure.

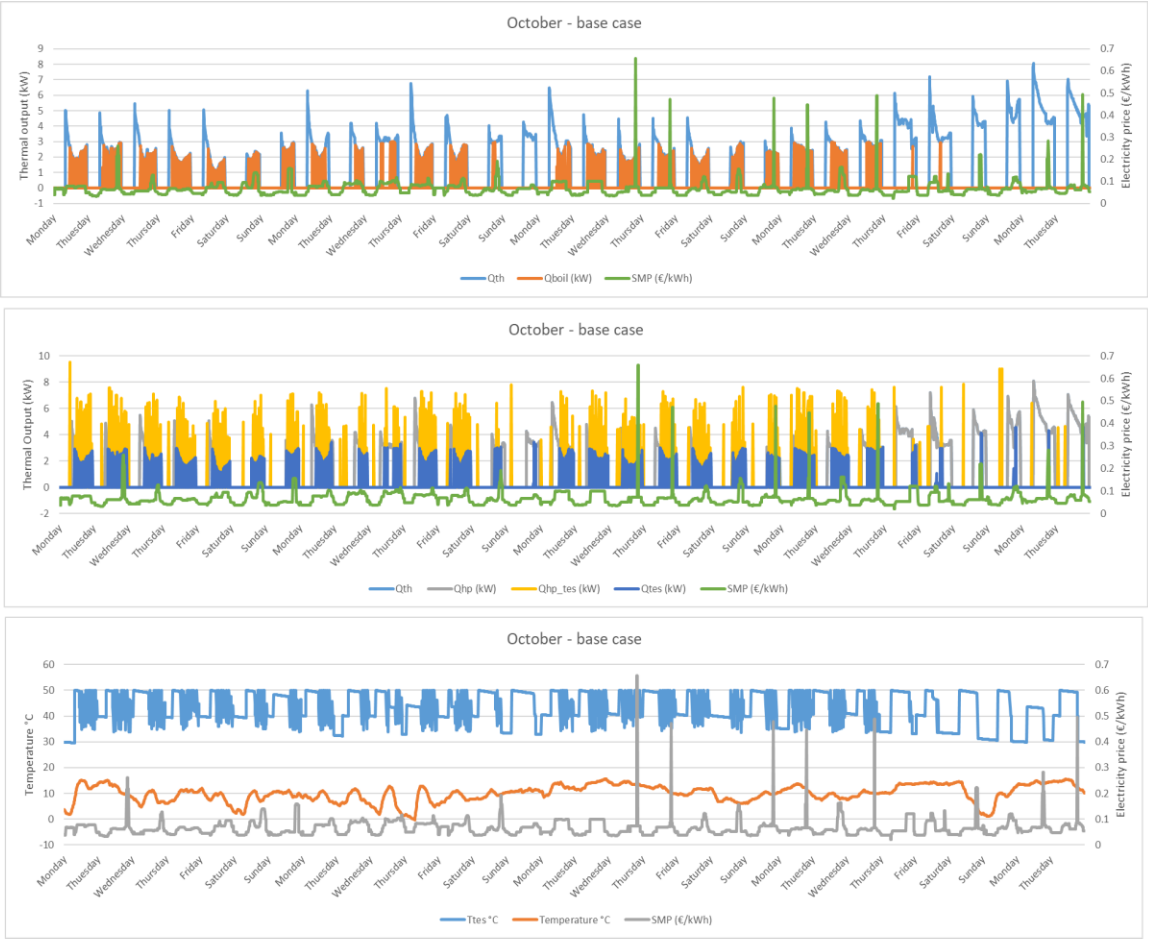


Fig 19: a) Gas boiler system on October – Base case; b) HP system on October – Base case; c) TES system on October – Base case.

On the one hand, fig 19.a) shows how much of the demand is covered by the boiler gas. While, on the other hand, in fig 19.b) you can see how the HP loads the TES, while the boiler gas is in operation and once it is loaded the boiler gas is turned off and the demand is covered by the TES. In fig 19.c) you can see how the tank is continuously unloaded and loaded. This is due to the configuration imposed on the system that consists of the HP not going to cover the demand directly if the power is less than 3 kW, that is, it will not work until it exceeds 20% of the power of the HP, which is 15 kW. That is why in the range of 0 to 3 kW, the demand is covered between the boiler gas and the TES alternately. Except in the early hours of the morning, where the heat pump works directly covering the demand of the house since the necessary power is higher than 3 kW

In the following chapters the behaviour of the equipment on this model is analysed in more detail. As a summary of the above, the data is presented in the following table.

Table 7. Heating system period in the base case

Studio 1 - October-March - base case							
Month	Units	Heat pump	%	Gas boiler	%	Total	%
October	Kwh	305.30	10%	187.80	34%	493.10	13%
	€	22.58	11%	15.02	34%	37.60	15%
November	Kwh	480.69	16%	66.11	12%	546.80	15%
	€	35.72	17%	5.29	12%	41.01	16%
December	Kwh	662.50	21%	28.38	5%	690.89	19%
	€	45.88	22%	2.27	5%	48.15	19%
January	Kwh	686.63	22%	22.59	4%	709.22	19%
	€	40.61	20%	1.81	4%	42.42	17%
February	Kwh	627.01	20%	63.57	11%	690.57	19%
	€	41.34	20%	5.09	11%	46.43	18%
March	Kwh	338.22	11%	190.94	34%	529.16	14%
	€	20.29	10%	15.28	34%	35.56	14%

On the other hand, when DRP works at 100%, it has been proven that the most expensive month was December with 55.18€, and it is also the month with the highest consumption, 780.17kWh. If we compare the two most expensive months of each model, being February of the base case and December with DRP at 100%, we can see that the use of boiler gas in December represents 16% of the total against 11% in February, substantially increasing the bill in the model of DRP-100%. As for the higher energy consumption, it is due, as mentioned before in the introduction of the chapter, to a higher use of the heating system, since the DRP can activate the equipment for a longer time but with less power and/or independently of the fact that the demand power to be covered is less than 3 kW as it happens with the base case, in this way it provides flexibility to the system. It has also been verified that the highest use of HP was during the months of December, January and February as it happened with the base case, with a little more than 20% over the total.

On the other hand, it is worth noting that October and March are the months when boiler gas was most used, representing 23% and 21% respectively of the total consumed during the heating period. If the two models are compared, fig 19 and fig 20, it can be seen that in the DRP-100% model, the use of boiler gas is more spread out during the months of the heating period, unlike the base case where October and March account for 68% of total consumption, this is because the DRP acts according to the price and the characteristics of the system at that time.

In order to continue analyzing the DRP-100% model, we will analyze the month of October as before. Thus, the month of October carries out the same behavior of the heating system as the previous model where the boiler gas and the TES act intercalated when the demand power is less than 3kW but this time, if we look at the last week of October, we can see that the use of boiler gas and TES is interspersed in contrast to the base case. This is because the DRP comes into play (fig. 20.d)), without the need for demand power below 3kW, as it takes advantage of market opportunities.

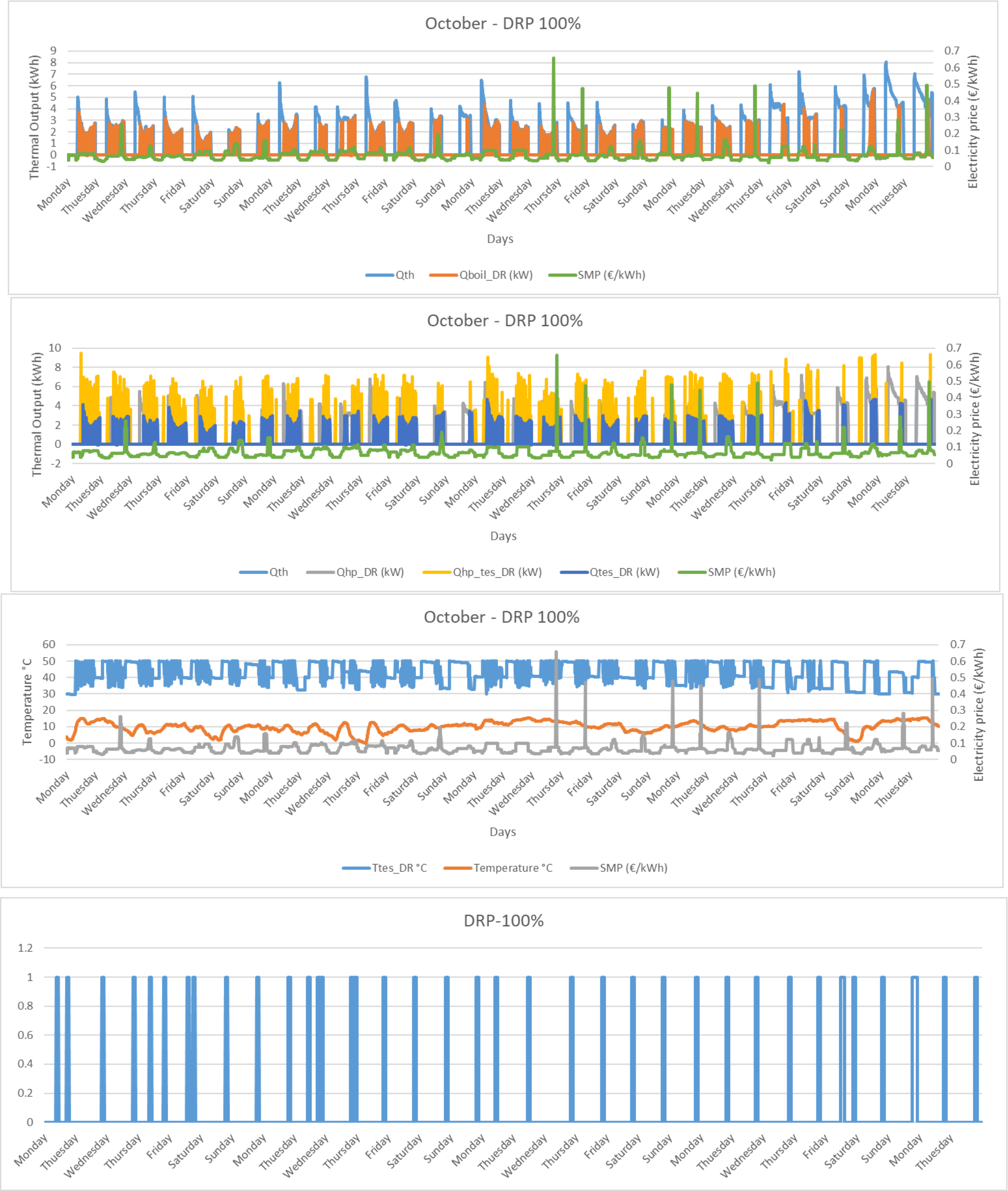


Fig 20: a) Gas boiler system on October – DRP-100%; b) HP system - DRP-100%; c) TES system DRP-100%; d) DRP – 100%

The behavior during this system is the same as the previous one, the only difference is found in figure X.d), where it can be seen when the DRP takes action to carry out the appropriate orders in the heating system. The DRP comes into play at least once a day and that this occurs during the afternoon and also occasionally on some mornings taking advantage of market opportunities. The behavior of DRP is specified below by analyzing weekly and daily studies. As a summary of the above, the data is presented in the following table.

Table 8. Monthly heating period with DRP-100%

Studio 1 - October-March - DRP 100%							
Month	Units	Heat pump	%	Gas boiler	%	Total	%
October	Kwh	296.30	10%	227.05	23%	523.34	13%
	€	21.83	11%	18.16	23%	39.99	14%
November	Kwh	456.79	15%	139.16	14%	595.95	15%
	€	33.89	17%	11.13	14%	45.02	16%
December	Kwh	618.74	21%	161.43	16%	780.17	20%
	€	42.27	22%	12.91	16%	55.18	20%
January	Kwh	655.51	22%	113.33	11%	768.83	19%
	€	38.57	20%	9.07	11%	47.64	17%
February	Kwh	602.08	20%	147.74	15%	749.82	19%
	€	39.44	20%	11.82	15%	51.26	19%
March	Kwh	332.85	11%	212.43	21%	545.28	14%
	€	19.97	10%	16.99	21%	36.96	13%

4.3 Weekly simulation (Studies 2 & 3)

After analyzing the entire heating period and month by month, this chapter aims to go deeper to better understand the behavior of the heating system in the base case and when DRP is applied.

Two typical weeks will be analyzed, one of which is notable for the use of the heat pump (on 9th-15th January), and the other for the notable use of boiler gas and TES (on 27th February - 5th March). Thus, specifying a week can be seen graphically better and therefore make the relevant analysis to ensure the quality of the study.

9th – 15th January (Study 2) – Base case

In the simulation of the base case, it can be seen that, during this week, the thermal demand was 147.47 kWh and that 96% corresponds to the use of the HP, and with a total cost of 8.10 €. The following values can be seen in the following table.

Table 9. Energy and cost from heating system on 9th – 15th January – Base case

		Base case				
		Heat pump	%	Gas boiler	%	Total
Studio 5 - 3st March	Kwh	11.34	48%	12.08	52%	23.42
	€	0.58	37%	0.97	63%	1.54

In the following figure, you can see the behavior of the equipment during this period.

Fig 21: a) Gas boiler system on 9th-15th January – Base case; b) HP system on 9th-15th January – Base case; c) TES system on 9th-15th January – Base case.

It can be seen in Figure 21.b), the demand is covered directly by the HP. The behavior that can be seen is more or less constant throughout the week and is as follows. During the early morning (2-6 am approx.), taking advantage of the lower market prices, the HP loads the TES. The demand starts around 7 am until 12 am and it is the HP that directly covers the heating needs of the house in an almost interrupted way. When prices are higher, that is, when the system detects the market peak, which occurs between 6pm-8pm, the HP is turned off and the TES, which was previously loaded during the early morning, acts. When the TES runs out or the market price drops, the HP is activated again. As seen in the previous chapter, during the months of November, December, January and February, the boiler gas is barely activated, although it can be seen (Fig 21.a) that on Wednesday and Thursday during peak hours the boiler was in operation although the TES was previously downloaded. This is due to the combination of two factors one, prices were high and two, demand power was close to 3 kW.

The isolated case is represented on Saturday night (11pm-12pm) which did run for a short period of time, due to a demand power of less than 3kW. However, before using the gas boiler, the TES is always pre-discharged and is able to almost completely cover the demand during the peak period of the prices. Looking at figure 21.c), it can be seen that it is loaded during the night in two stages on some occasions and then between 6pm-8pm, where the market peak coincides, is when it is unloaded.

9th – 15th January (Study 2) – DRP-100%

In the simulation of the DRP-100%, it can be seen that, during this week, the thermal demand was 161.89 kWh and that 84% corresponds to the use of the HP, and with a total cost of 9.38€. This increase of energy is due to a greater prolonged use of the heating system, because the DRP acts on the system to carry out the intercalation function between the boiler gas and TES. The above values are shown in the following table.

Table 10. Energy and cost from heating system on 9th – 15th January – DRP-100%

		Demand response program (100%)				
Studio 5 - 3st March		Heat pump	%	Gas boiler	%	Total
	Kwh	11.54	48%	12.30	52%	23.84
	€	0.59	37%	0.98	63%	1.57

In the following figure, you can see the behavior of the equipment during this period.

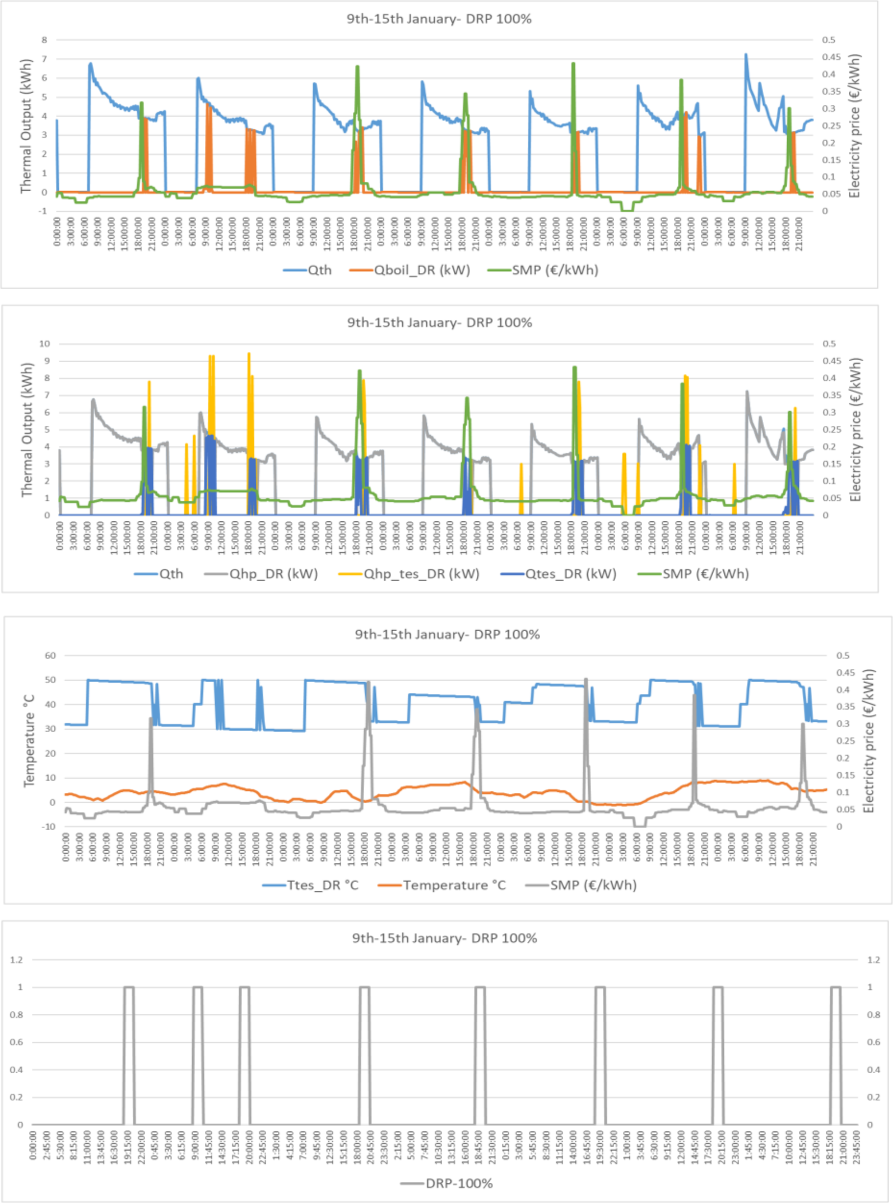


Fig 22: a) Gas boiler system on 9th-15th January – DRP-100%; b) HP system on 9th-15th January – DRP-100%; c) TES system on 9th-15th January – DRP-100%; d) DRP-100%

It can be seen in Fig 22.b) that the demand is directly covered by the HP almost all day long. The behaviour that can be seen is more or less constant throughout the week and is the same as in the previous model. In this case, it can be seen in Figure X.d) when the DRP acts, which, enters into operation once a day coinciding with the market peaks, that is, between 6pm-8pm. During this process, the system combines TES and boiler gas, regardless of whether the demand is less than 3 kW, thus achieving greater energy flexibility.

A case in point is the performance of the heating system during Tuesday. On this occasion the DRP acts twice, in the morning because the system interprets the ideal conditions for the TES to act, which was recharged between 3 am and 6 am and in the afternoon, that on this occasion there is not a market peak, perhaps due to a strong use of renewable energies at that time. So, taking advantage of low prices and low power demand, there is the combined operation of boiler gas and TES, and as with the previous model, primarily discharges before the TES and once this is being loaded by the heat pump, is when the boiler gas is put into operation. Once the TES is loaded again, it is discharged. This behaviour can be seen in figure X.c), where it can be seen when loading and unloading the TES.

27th February-5th March (Study 3) – Base case

In this week's simulation, referring to the base case, the thermal demand was 157.31 kWh and there is an increase in the use of boiler gas, compared to studio 2, which represents 39% of all demand during this week, compared to 61% of HP. But if we realize (Table 11) in the price, even though the HP has produced more energy, 52% of the cost of thermal production of that week comes from this equipment, against 48% of the boiler gas. This is because, during this week, the HP has been dedicated to load the TES and this to cover the demand.

Table 11. Energy and cost from heating system on 27th February-5th March – Base case

		Base case				
		Heat pump	%	Gas boiler	%	Total
Studio 5 - 3st March	Kwh	11.34	48%	12.08	52%	23.42
	€	0.58	37%	0.97	63%	1.54

In the following figure, you can see the behavior of the equipment during this period.

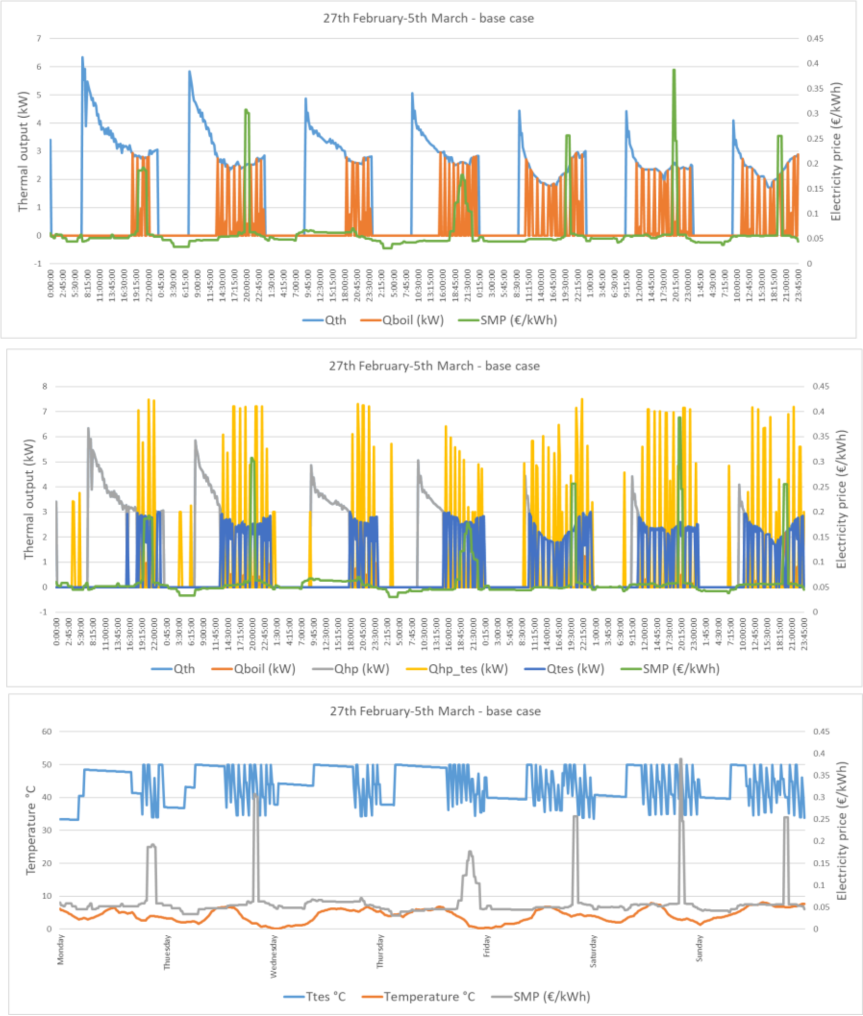


Fig 23: a) Gas boiler system on 27th February-5th March – Base case; b) HP system on 27th February-5th March – Base case; c) TES behaviour on 27th February-5th March – Base case

In this figure you can see how the use of TES and boiler gas is alternated. As mentioned above, during the early morning hours (4am-6am), the system takes advantage of the off-peak hours to charge the TES. It is also observed that during the first 4 days, between 7am to 4pm, the one in charge of covering the demand is the HP directly, then Friday, Saturday and Sunday, being the demand to cover less, that is to say a power of less than 3 kW, the combination between the TESand gas boiler takes place. This means that while the HP charges the TES, the boiler gas covers the demand and once the TES is charged, it is discharged (Figure X.c)).

27th February-5th March (Study 3) – DRP-100%

On the other hand, for this week's simulation, when DRP-100% is applied, the thermal demand was 158.28 kWh and there is an increase in the use of boiler gas, which accounts for 41% of all demand during this week, compared to 59% of HP. But if we look at the price (Table 12), despite the fact that the HP has produced more energy, 51% of the cost of thermal production that week comes from this equipment, compared to 49% of boiler gas. This is because, during this week, the HP has been dedicated to load the TES and this to cover the demand.

Table 12. Energy and cost from heating system on 27th February-5th March – DRP-100%

		Demand response program (100%)				
		Heat pump	%	Gas boiler	%	Total
Studio 5 - 3st March	Kwh	11.54	48%	12.30	52%	23.84
	€	0.59	37%	0.98	63%	1.57

In the following figure, you can see the behavior of the equipment during this period.

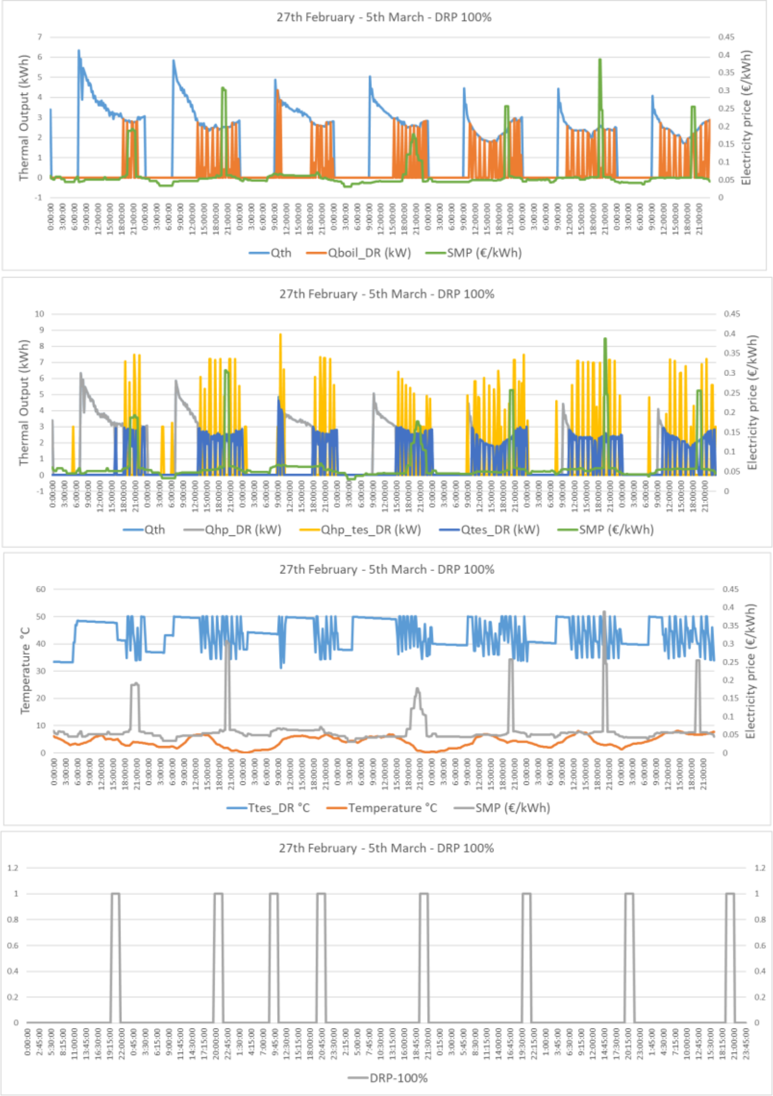


Fig 24: a) Gas boiler system on 27th February-5th March – DRP-100%; b) HP system on 27th February-5th March – DRP-100%; c) TES behaviour on 27th February-5th March – DRP-100%; d) DRP-100%

In this case, it can be seen in fig 24.d) when the DRP acts, which, enters into operation once a day coinciding with the market peaks, that is, between 6pm-8pm. During this process the system carries out the combination of TES and gas boiler.

It is also observed that, during the first 4 days, between 7am and 4pm, the one in charge of covering the demand is the HP directly, then Friday, Saturday and Sunday, being the demand to cover less, that is to say a power of less than 3 kW, the combination between the TES and gas boiler previously commented takes place. This means that while the HP charges the TES, the boiler gas covers the demand and once the TES is charged, it is discharged (Fig. 24.c)). The case where the use of DRP stands out is on Wednesday morning where the combination of low prices and low power demand makes the combination of boiler gas and TES take place.

It can be concluded by comparing this week's base case and the DRP-100% that work in a similar way when the demand power to be covered is less than 3kW, in that case it influences the prices for the activation of the DRP.

4.4 Daily simulation (Studies 4 & 5)

Once the weekly heating period has been analyzed, this chapter intends to go even deeper to better understand the behavior of the heating system in the base case and at the time DRP is applied.

It will analyze two typical days, this time the days chosen have been the coldest day of the year corresponding to December 28th, which stands out for the use of the heat pump, and the other for the outstanding use of boiler gas and TES, on 3rd march. In this way, it is possible to see the course of the heating equipment for a particular day, guaranteeing the quality of the analysis in the study.

28th December (Study 4) – Base case

For the study of the base case on the coldest day of the year, 23.97 kWh were consumed, 83% of which came from HP and had a cost share of 81% compared to 19% from boiler gas. Therefore, both systems were present during that day, as shown in the following table.

Table 13. Energy and cost from heating system on 28th December – Base case

		Base case				
		Heat pump	%	Gas boiler	%	Total
Studio 5 - 3st March	Kwh	11.34	48%	12.08	52%	23.42
	€	0.58	37%	0.97	63%	1.54

In the following figure, you can see the behavior of the equipment during this period.

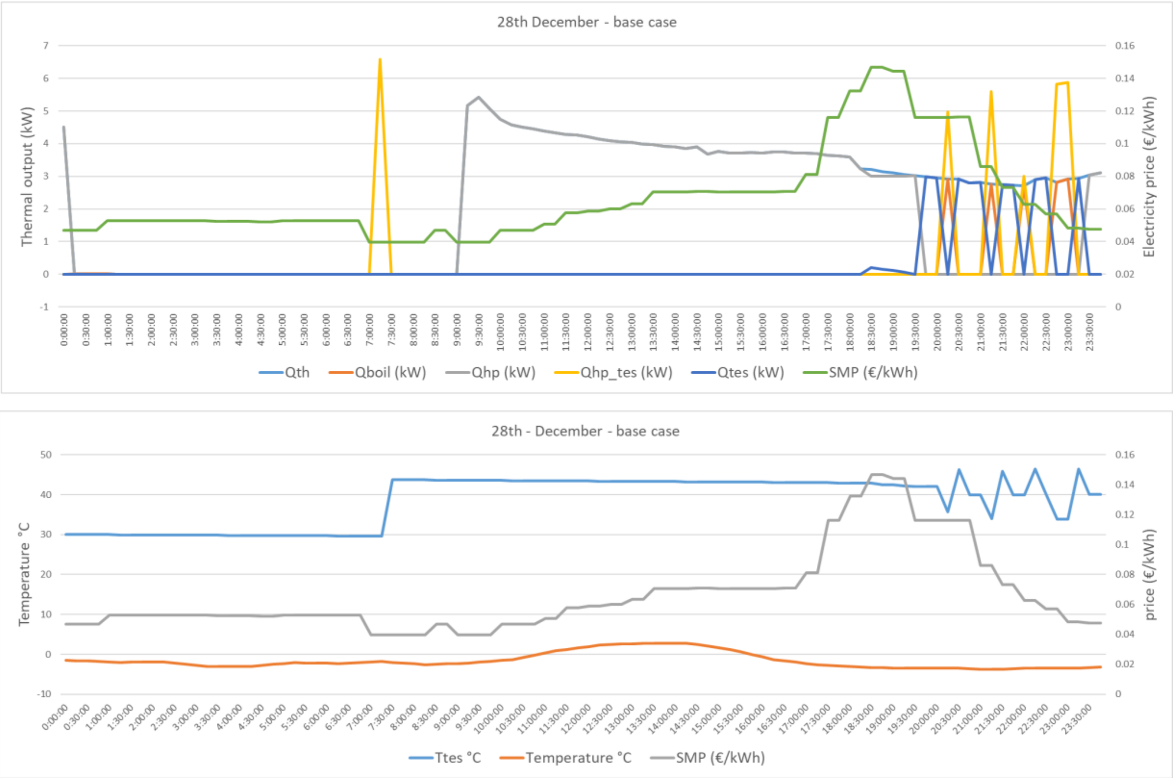


Fig 25: a) Heating system on 28th December – Base case; b) TES behaviour on 28th December – Base case

It can be seen in Figure 25.a that the demand is largely covered directly by the HP. The behaviour of the system is such that this is the case: During off-peak hours, the HP charges the TES, around 7 am. Demand begins at 9 am with a power of over 3 kW, so HP is responsible for covering demand. It can be seen that during the peak market the HP continues to work directly, this is because the system recognizes that the price is not excessively high as it was on the days of the week of the 9th-15th on January, where the peak market was more than twice as high as this occasion. It is then at 7pm that the first discharge from the TES occurs because the power demand is less than 3 kW. On up to four occasions, before the day is out, the TES is discharged and loaded.

28th December (Study 4) – DRP-100%

In this day's simulation, referring to DRP-100%, the thermal demand was 24.72 kWh (Table 14), where 77% corresponds to HP and 23% to boiler gas. It can be seen by comparing the table 13 and the table 14, that 0.75 kWh more energy is consumed with the DRP than on a base case and still the price is the same, 1.74€. This is because the DRP acts in such a way that it brings flexibility to the system and takes more advantage of the system's needs with the intention of not waiting for the demand power to drop below 3kW for the TES and gas boiler to act as if it happens on base case.

Table 14. Energy and cost from heating system on 28th December – DRP-100%

		Demand response program (100%)				
		Heat pump	%	Gas boiler	%	Total
Studio 5 - 3st March	Kwh	11.54	48%	12.30	52%	23.84
	€	0.59	37%	0.98	63%	1.57

In the following figure, you can see the behavior of the equipment during this period.

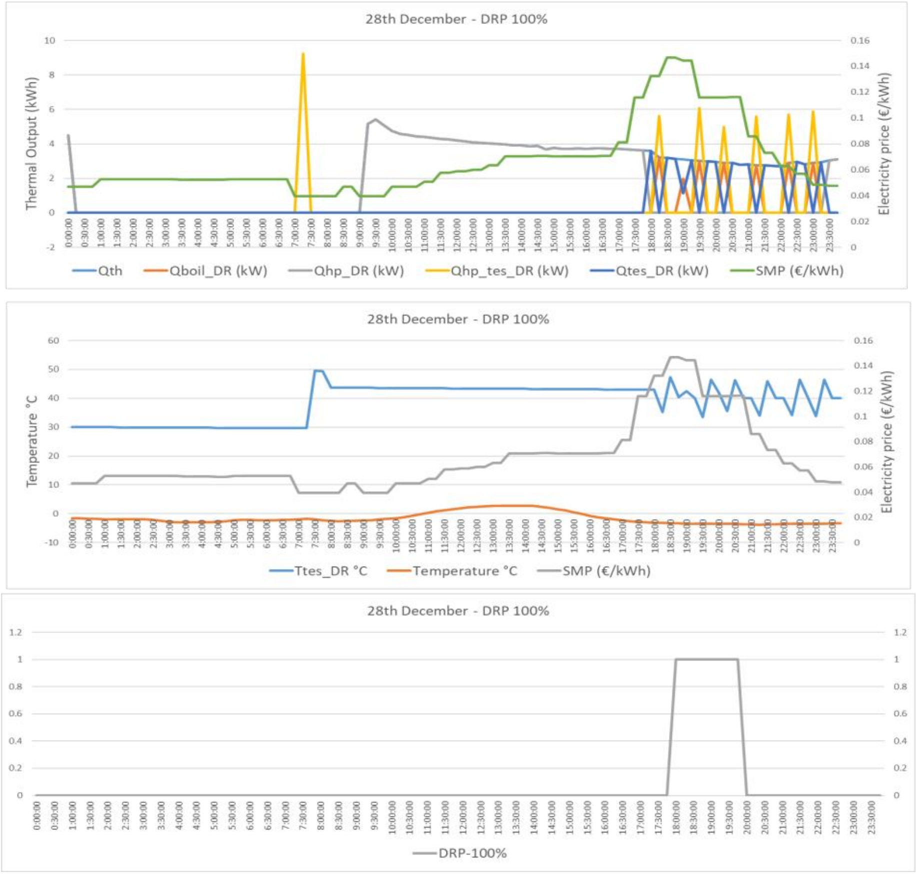


Fig 26: a) Heating system on 28th December – DRP-100%; b) TES behaviour on 28th December – DRP-100%; c) DRP-100%.

As you can see in figure 26.a), and comparing it with figure 25.a), the behavior is the same, the only difference is that the programs come into action from 5:30pm-8pm, which is just when the market peak occurs. In this way the interleaving between the boiler gas and the TES is started earlier without waiting for the demand power to go below 3 kW. Hence, this model consumes more energy than the base case and without the need to increase the price.

3th March (Study 5) – Base case

In the case of the base case, the consumption of the day was 23.42 kWh where the use is distributed between the heat pump and the boiler gas, 48% and 52% respectively, but being indicative that 63% of 1.54 € that cost the day, is from the boiler gas. In the following table you can check the energy cost of the 3rd march.

Table 15. Energy and cost from heating system on 3th March – Base case

		Base case				
		Heat pump	%	Gas boiler	%	Total
Studio 5 - 3st March	Kwh	11.34	48%	12.08	52%	23.42
	€	0.58	37%	0.97	63%	1.54

In the following figure, you can see the behavior of the equipment during this period.

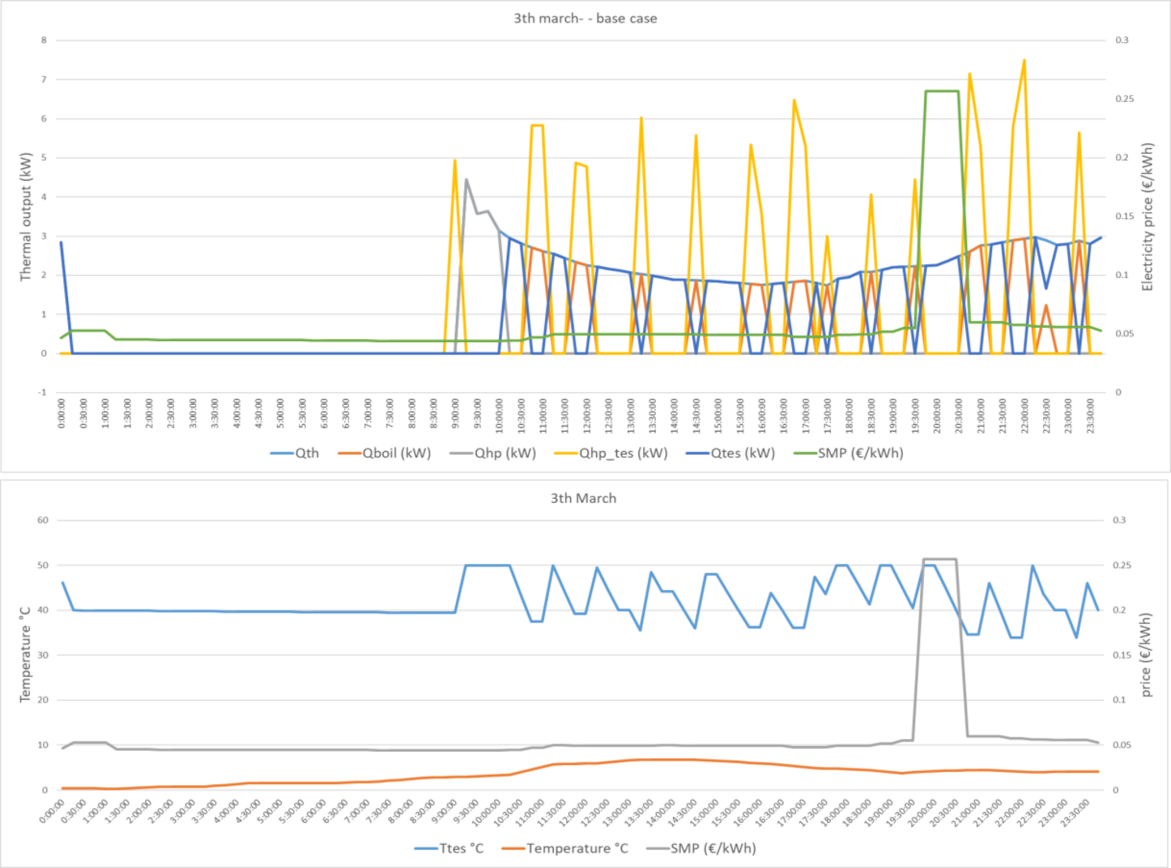


Fig 27: a) Heating system on 3th March – base case; b) TES on 3th March – Base case

As can be seen in figure 27.a) and figure 27.b), during demand, the exchange of equipment between the boiler gas and the TES can be seen, where practically from 10 am to 12 am, they alternate continuously, up to a total of 12 charges and discharges by the TES. The system takes advantage of the moment in which the energy price is low to load the TES as well as the power demand is less than 3kW. Hence, only 37% corresponded to the energy expenditure from the HP, as it was only used directly in the house during the first hour of demand (from 9am to 10 am).

3th March (Study 5) – DRP-100%

In the case of the DRP, the consumption of the day was 23.84 kWh where the used is divided between the heat pump and boiler gas, 48% and 52% respectively, but it is indicative that 63% of 1.57 € that cost the day, is from boiler gas. In the following table you can check the energy cost of the 3rd march.

Table 16. Energy and cost from heating system on 3th March -DRP-100%

		Demand response program (100%)				
		Heat pump	%	Gas boiler	%	Total
Studio 5 - 3st March	Kwh	11.54	48%	12.30	52%	23.84
	€	0.59	37%	0.98	63%	1.57

In the following figure, you can see the behavior of the equipment during this period.

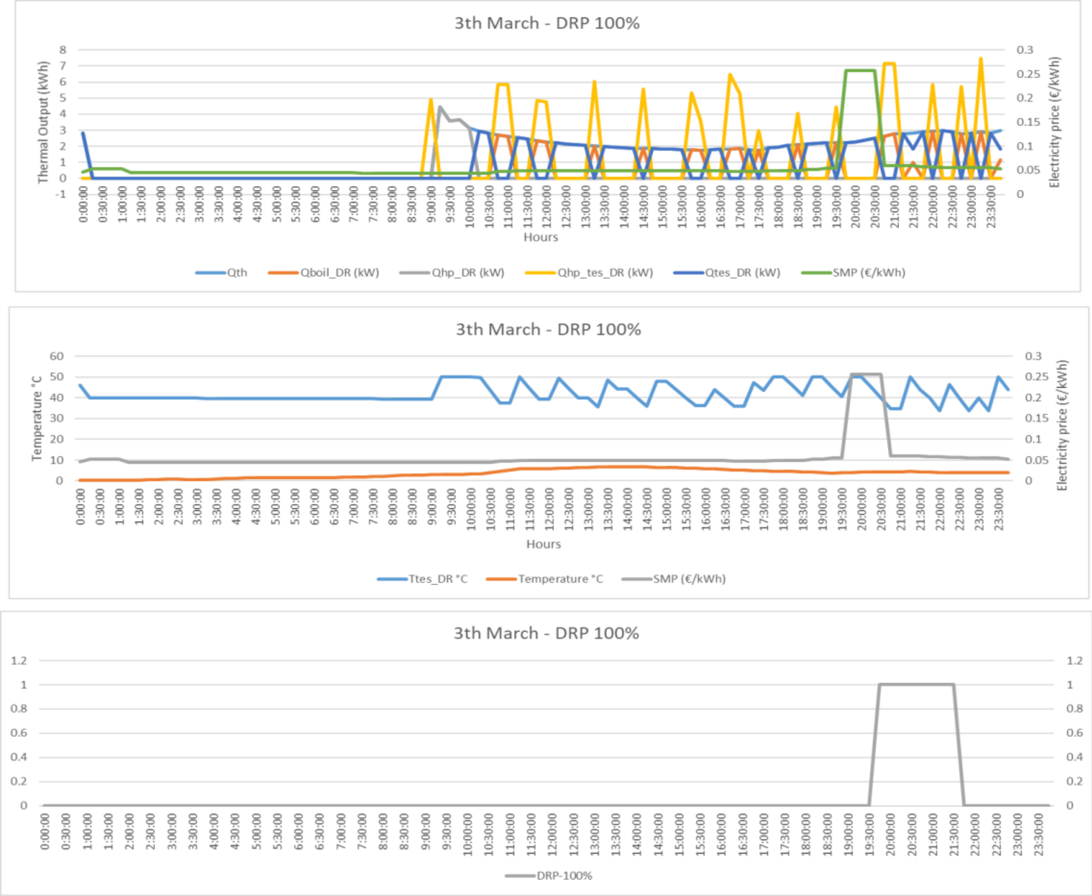


Fig 28: a) Heating system on 3th March – DRP-100%; b) TES behaviour on 3th March – DRP-100%; c) DRP-100%

With the application of DRP, in this case, as in study 3, when the demand power is less than 3 kW, the behavior of the heating system is very similar in both models. The only difference that can be seen is that when the market peak occurs (7:30pm-10pm), the DRP acts to manage the power of the TES and gas boiler, which makes it apply an additional load and unloading compared to the base case.

5. Conclusions

This thesis studied the behaviour of the heating system of an Irish residential house, composed of a heat pump, TES and boiler gas, when DR measures are added. The result has been an energy and economic analysis on two models, one of them, the base case, which consisted in obtaining the most economic action strategy of the heating system and the other one adding to that model the DRP. The electricity price structure used was RTP tariffs. The building characteristics used, the price vector and the temperature data were extracted from (Pallonetto, Rosa, & Finn, Environmental and economic benefits of building retrofit measures for the residential sector by utilising sensor data and advanced calibrated models, 2019). Once this data was obtained, it was the inputs needed for the MATLAB controller.

The study is carried out for the period from October 1st to March 31th, which is the heating period, using the hourly prices in real time mentioned above. Based on these prices, the times of DR's actions over the period were established. On the one hand, the events occurred mainly during the afternoon, as this was when market prices were highest, and on the other hand, occasionally also during the mornings, taking advantage of the system according to the needs of the house. So, with the help of the MATLAB controller I optimize the heating of the building for each day based on both the price of electricity and the demand of each day. The main conclusions drawn from the 5 studies carried out are the following:

It must be understood that in the case base, it is about the optimization of the heating system, that is, it always looks for the cheapest operation option. To this we must add the restriction on the minimum power at which the HP acts. This will directly cover the demand of the house if the required power demand is higher than 20% of its nominal power, that is, a minimum power of 3kW, since the nominal power is 15kW. This explains, as seen in study 1 - base case, that during the first three weeks of October and the last two weeks of March, the gas boiler and the TES cover most of the demand, which was less than 3kW. In addition, since the average temperature in October and March is low, but demand is not high, this indicates that the insulation characteristics of the house are of good quality.

One of the benefits of DRP is the energy flexibility it gives the system. One of the reasons to think this is that in the Study 1-DRP-100%, it was found that the energy consumption of the boiler gas and the TES is more spread out during the whole heating season and not in two months as it happens in the base case, where it depends on the condition of the minimum HP activation power. It is therefore that the system recognizes the price drop before it occurs by adapting the needs of the demand to the market prices. This could be seen in studio 2, when after a combination of price and demand, the DRP were activated on Tuesday morning to cover the demand with the TES without the need for the demand power to go below 3 kW.

The minimum power operating condition of the HP makes the base match and DRP-100% have a similar working behavior, as seen in study 3 or 5, but the DRPs act even when the demand power is less than 3 kW, which makes the use of the TES to be prolonged to less power.

DRP seeks to maximize power flexibility by increasing TES usage, either when the market peak occurs, as seen in the afternoons of Study 2, or when market conditions and high demand occur, as seen in the Tuesday morning of Study 2.

5.1 Future Work

A partir de este trabajo se encuentra una amplia gama de escenarios que pueden ser objetos de estudio:

- It would be interesting to study the contribution of the DRP at 75% and 50%, in addition to eliminating the restriction of the minimum power of the HP for its operation and to be able to observe when and how the DRP are applied. It would also be interesting to apply other types of tariffs such as ToU
- Study the environmental impact of using PRA versus not applying it. Measure the CO2 for each of the models.
- Instead of the parallel operation of the heat pump and gas boiler, an “in series” connection could be adopted. This would allow a higher COP thanks to the lower upper temperature of the heat pump and a more flexible application due to different supply temperatures achievable with the gas boiler.

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