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Optimum use of existing energy production assets in a dwelling

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In the course of writing this thesis, the ChatGPT AI tool was used primarily for text formulation, as well as for information retrieval, synthesis and organization assistance.

Abstract

Given the increasing importance of addressing rising environmental concerns and energy costs, optimizing energy consumption in households has become a crucial focus of research. This thesis explores the optimization of residential energy systems in Belgian households, focusing on the integration of photovoltaic systems with various production assets.

The study provides a comprehensive analysis of energy consumption patterns, residential photovoltaic potential, and energy pricing mechanisms in Belgium. A linear optimization model has been developed as a practical tool for users, guiding them to maximize the economic benefits of their solar panel installations.

The model is applied to two case studies, each demonstrating the value of combining different household energy assets in achieving optimal energy efficiency and cost savings. In the first case, the results indicate that the strategy to adopt is based on the annual balance between grid injection and consumption, without necessitating immediate self-consumption. When the household's photovoltaic production exceeds its consumption, it is beneficial to use an electric resistance heater, although the impact of this strategy is limited. If the household produces 1.5 times more energy than it consumes, installing a heat pump becomes an advantageous option, enhancing both efficiency and economic returns. In the second case, immediate self-consumption becomes essential, highlighting the need to adapt energy strategies to the specific solar production and consumption patterns of each household. When solar production surpasses consumption, it is beneficial to utilize the excess energy with an electric resistance heater, which is managed intelligently through a hot water tank. However, in this scenario, investing in a heat pump does not provide significant economic benefits.

These findings highlight the necessity of a customized approach to energy management, aligning strategies with the unique production and consumption dynamics of each household. This tailored approach enables households to maximize economic savings and environmental benefits, supporting a more sustainable and cost-efficient energy future.

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Nomenclature

Symbols

$\Delta \mathbf{T}$	Temperature difference between stored hot water and ambient air (K)
$\Delta \mathbf{t}$	Time period (hours)
$\eta_{\mathbf{BESS,ch}}$	Charging efficiency of the battery energy storage system (unitless)
$\eta_{\mathbf{BESS,dch}}$	Discharging efficiency of the battery energy storage system (unitless)
$\eta_{\mathbf{GB}}$	Efficiency of the gas boiler (unitless)
$\eta_{\mathbf{R}}$	Efficiency of the electric resistance heater (unitless)
$\gamma_{\mathbf{BESS}}$	Self-discharge rate of the battery energy storage system (unitless)
$\gamma_{\mathbf{WT}}$	Standby heat loss coefficient for the hot water tank (unitless)
$\rho_{\mathbf{water}}$	Density of water (kg/l)
$\mathbf{CF_{PV}}$	Photovoltaic capacity factor (unitless)
$\mathbf{Cons}_{\mathbf{elec}}^{\mathbf{abs}}$	Absolute electricity consumption (kWh)
$\mathbf{Cons_{elec,annual}}$	Annual electricity consumption (kWh)
$\mathbf{Cons_{elec}}$	Electricity consumption (kWh)
$\mathbf{Cons_{gas,annual}}$	Annual gas consumption (kWh)
$\mathbf{COP_{HP}}$	Coefficient of Performance of the heat pump (unitless)
$\mathbf{Cost_{elec,fixed}}$	Fixed annual cost for electricity supply (€/year)
$\mathbf{Cost_{elec}}$	Total cost of electricity (€)
$\mathbf{Cost_{energy}}$	Total energy cost (€)
$\mathbf{Cost_{gas,fixed}}$	Fixed annual cost for gas supply (€/year)

$\mathbf{Cost_{household}}$	Total annual household cost (€)
$\mathbf{Cost_{inj,fixed}}$	Fixed annual cost for electricity injection (€/year)
$\mathbf{Cost_{installation}}$	Installation cost (€)
$\mathbf{c_{p,water}}$	Specific heat capacity of water (kWh/kgK)
$\mathbf{DP^{elec}}$	Hourly demand profile for electricity (unitless)
$\mathbf{DP^{space}}$	Hourly demand profile for space heating (unitless)
$\mathbf{DP^{water}}$	Hourly demand profile for hot water heating (unitless)
$\mathbf{D^{elec}_{house}}$	Household hourly demand for electricity (kWh)
$\mathbf{D^{elec}_{ref,tot}}$	Total annual electricity demand (kWh)
$\mathbf{D^{space}_{house}}$	Household hourly demand for space heating (kWh)
$\mathbf{D^{space}_{ref,tot}}$	Total annual space heating demand (kWh)
$\mathbf{D^{tot}_{ref}}$	Total annual household energy demand (kWh)
$\mathbf{D^{water}_{house}}$	Household hourly demand for hot water (kWh)
$\mathbf{D^{water}_{ref,tot}}$	Total annual hot water demand (kWh)
$\mathbf{E^{elec}_{BESS,ch}}$	Electricity charged into the battery energy storage system (kWh)
$\mathbf{E^{elec}_{BESS,dch}}$	Electricity discharged from the battery energy storage system (kWh)
$\mathbf{E^{elec}_{BESS,max}}$	Maximum energy storage capacity of the battery energy storage system (kWh)
$\mathbf{E^{elec}_{cons}}$	Total electricity consumed by the household (kWh)
$\mathbf{E^{elec}_{grid,cons}}$	Electricity consumed from the grid (kWh)
$\mathbf{E^{elec}_{grid,inj}}$	Electricity injected into the grid (kWh)
$\mathbf{E^{elec}_{HP}}$	Electricity consumed by the heat pump (kWh)
$\mathbf{E^{elec}_{PV,max}}$	Maximum electricity capacity of the PV panels (kWh)
$\mathbf{E^{elec}_{PV}}$	Electricity produced by the PV panels (kWh)
$\mathbf{E^{elec}_{R}}$	Electricity consumed by the electric resistance heater (kWh)

E^{elec}_{supply}	Total electricity supplied to the household (kWh)
E^{gas}_{GB}	Energy content in natural gas consumed by the gas boiler (kWh)
$E^{heat,max}_{GB}$	Maximum heat capacity of the gas boiler (kWh)
$E^{heat,max}_{HP}$	Maximum heat capacity of the heat pump (kWh)
$E^{heat,max}_{R}$	Maximum heat capacity of the electric resistance heater (kWh)
E^{heat}_{GB}	Thermal energy produced by the gas boiler (kWh)
E^{heat}_{HP}	Thermal energy produced by the heat pump (kWh)
E^{heat}_{R}	Thermal energy produced by the electric resistance heater (kWh)
E^{space}_{GB}	Electricity used by the gas boiler for space heating (kWh)
E^{space}_{HP}	Electricity used by the heat pump for space heating (kWh)
E^{water}_{GB}	Electricity used by the gas boiler for water heating (kWh)
E^{water}_{HP}	Electricity used by the heat pump for water heating (kWh)
E^{water}_{R}	Electricity used by the electric resistance heater for water heating (kWh)
$E^{water}_{WT,L}$	Energy input from storage loading in the hot water tank (kWh)
$E^{water}_{WT,max}$	Maximum energy capacity of the hot water tank (kWh)
$E^{water}_{WT,U}$	Energy output from storage unloading in the hot water tank (kWh)
E^{water}_{WT}	Energy stored in the hot water tank (kWh)
$Inj_{elec,annual}$	Annual electricity injected into the grid (kWh)
Inj_{elec}	Electricity injection (kWh)
N^{max}	Maximum number of transitions between heating technologies (unitless)
$Price_{elec,fixed}$	Fixed price per kWh of electricity (€/kWh)
$Price_{elec,variable\ i}$	Fixed price per kWh of electricity during period i (€/kWh)
$Price_{gas,fixed}$	Fixed price per kWh of gas (€/kWh)
$Price_{gas,variable\ i}$	Fixed price per kWh of gas during period i (€/kWh)
$Price_{inj,fixed}$	Fixed price per kWh for electricity injected into the grid (€/kWh)

$\mathbf{Price_{inj,variable\ i}}$	Fixed price per kWh for electricity injected into the grid during period i (€/kWh)
$\mathbf{P^{elec}_{BESS,ch}}$	Electrical power charged into the battery energy storage system (kW)
$\mathbf{P^{elec}_{BESS,dch}}$	Electrical power discharged from the battery energy storage system (kW)
$\mathbf{P^{elec}_{PV,max}}$	Peak capacity of PV installation (kW or also kWp)
$\mathbf{Q_{gas}}$	Energy per unit volume of gas (kWh/m^3)
$\mathbf{SOC_{BESS,max}}$	Maximum SOC of the battery energy storage system (unitless)
$\mathbf{SOC_{BESS,min}}$	Minimum SOC of the battery energy storage system (unitless)
$\mathbf{SOC_{BESS}}$	SOC of the battery energy storage system (unitless)
$\mathbf{V^{gas}_{GB}}$	Volume of gas consumed by the gas boiler (m^3)
$\mathbf{V_{WT}}$	Volume of the hot water tank (l)
$x^{\mathbf{space}}_{\mathbf{GB}}$	Binary variable indicating if the gas boiler is producing space heating (unitless)
$x^{\mathbf{water}}_{\mathbf{GB}}$	Binary variable indicating if the gas boiler is producing hot water (unitless)
$x_{\mathbf{BESS,ch}}$	Binary variable indicating if the battery is charging (unitless)
$x_{\mathbf{BESS,dch}}$	Binary variable indicating if the battery is discharging (unitless)
$x_{\mathbf{GB}}$	Binary variable indicating whether the gas boiler is active (unitless)
$x_{\mathbf{HP}}$	Binary variable indicating whether the heat pump is active (unitless)
$x_{\mathbf{inst,BESS}}$	Binary variable indicating whether a battery energy storage system is installed (unitless)
$x_{\mathbf{inst,HP}}$	Binary variable indicating whether a heat pump is installed (unitless)
$x_{\mathbf{R}}$	Binary variable indicating whether the electric resistance heater is active (unitless)

Abbreviations

Abbreviation	Definition
BESS	Battery Energy Storage System
CF	Capacity factor
CO_2	Carbon Dioxide
COP	Coefficient Of Performance
CREG	Belgian Commission for Electricity and Gas Regulation
EU	European Union
FPS	Federal Public Service
GB	Gas Boiler
GEHHP	Gas-Electric Hybrid Heat Pump
GHG	Greenhouse Gas
HEMS	Home Energy Management System
HP	Heat Pump
OPSD	Open Power System Data
PNEC	Plan National Energie et Climat
PV	Photovoltaic
R	Resistance Heater
SLP	Synthetic Load Profile
SOC	State of Charge
UNFCCC	United Nations Framework Convention on Climate Change
VREG	Vlaamse Regulator van de Elektriciteits- en Gasmarkt
WT	Water Tank

Introduction

The imperative to address climate change is undeniably one of the most significant challenges facing humanity today. The scientific consensus attributes the primary cause to human activities, especially CO_2 emissions from fossil fuels [1]. In response, the Paris Agreement has prompted numerous countries to commit to reducing their carbon emissions in the upcoming years [2].

The European Union (EU) has proactively contributed to these efforts by setting an ambitious energy plan with the goal of reducing greenhouse gas emissions by 55% by 2030 from 1990 levels [3]. Central to this plan is a substantial shift towards lower energy consumption and a higher reliance on renewable energy sources. The European Renewable Energy Directive sets a target for the EU to achieve at least 42.5% of its energy from renewable sources by 2030 [4]. Achieving this target, alongside the United Nations' Sustainable Development Goals, particularly those concerning affordable and clean energy, requires substantial transformation of energy systems [5].

The residential sector is essential in this transition, contributing a substantial portion of final energy use—30% and 12% of CO_2 emissions in the European Union [6]. Similar trends are observed in Belgium, with the residential sector responsible for 26% of energy use and 20% of CO_2 emissions [6]. Consequently, enhancing energy efficiency and management in this sector is critical for lowering carbon footprints and optimizing energy consumption.

As part of the National Energy and Climate Plan 2021-2030, aiming to increase the share of renewable energy in Belgium's energy mix to 21.7% by 2030, Belgium plans to increase its photovoltaic (PV) production [7]. Belgium has turned towards national initiatives such as the widespread installation of solar panels to promote local green electricity production in residential settings. Indeed, the number of households equipped with solar panels has significantly risen in recent years, reflecting the strong growth in household solar panel installations across the country. For example, the residential sector played a major role in photovoltaic

solar installations, representing 65% in Flanders and 82% in Wallonia of the additional capacity added to the electric grid in 2023 [8]. To further encourage this trend, tax incentives and regional subsidies have been implemented to motivate individuals to invest in solar panels and other sustainable energy technologies.

Today, a substantial percentage of households have installed solar panels, which they aim to make profitable. Beyond achieving electricity self-sufficiency, many households are considering investing in additional technologies that would consume the electricity produced by their solar panels but not currently self-consumed. This shift not only promotes the efficient use of generated electricity but also contributes to a more resilient and decentralized energy system. As such, the adoption of these complementary technologies is critical for maximizing the benefits of residential photovoltaic systems and advancing towards a sustainable energy system.

Among these complementary technologies, one particularly noteworthy option is the use of electric heating systems, in addition to energy storage solutions. Currently, most of the annual energy consumption of a Belgian household is dedicated to heat production, with space heating accounting for a 74.4% percentage and hot water production comprising 10.9% [9]. Moreover, residential heating is responsible for 12.6% of Belgium's total CO_2 emissions, predominantly due to the reliance on gas and oil, which are not renewable and pollutant energy sources [10]. However, there exist heating solutions that use electricity, such as electric resistances and heat pumps. When these solutions are powered by renewable energy from solar panels, they not only reduce household energy costs and carbon emissions but also enhance the full potential of residential photovoltaic systems. By maximizing the consumption of self-generated electricity, households can significantly decrease their dependence on fossil fuels, further amplifying the economic and environmental benefits of solar panel installations.

However, to fully realize these benefits, there is a need for intelligent energy management systems that can seamlessly integrate these new technologies with existing ones, along with the PV production. Despite advancements in technology, the majority of Belgian residences are still not equipped with such systems, leaving many households to operate their various energy production modes manually. This manual operation poses a significant challenge in optimizing the use of solar panels and different heating technologies throughout the year. In addition, there remains a common and relevant question about when it is worthwhile to invest in more expensive technologies, such as heat pumps or energy storage systems, which entail high investment costs.

Addressing these challenges requires a clear roadmap to guide consumers in optimizing their solar energy production. This thesis specifically explores these questions within the Belgian context, equipping users with comprehensive tools to effectively manage their diverse energy production systems and maximize the economic benefits of their solar panels. By examining the optimal integration of these technologies, this case study will serve as the foundation for developing practical solutions and recommendations for the broader residential sector in order to enhance the overall efficiency and sustainability of residential energy consumption in Belgium.

This thesis is organized into several sections, each building upon the previous to provide a comprehensive analysis of residential energy management in Belgium.

Chapter 1, *Literature review*, provides a thorough review of the existing research on home energy management systems. It focuses on the integration of photovoltaic systems with household energy assets and examines various optimization strategies for enhancing energy efficiency and reducing costs in residential settings.

Chapter 2, *Belgian residential energy analysis*, analyzes the energy consumption patterns of Belgian households, the potential for photovoltaic energy production, and the existing energy pricing mechanisms. The insights gained from this analysis form the basis for optimizing energy management strategies in the residential sector.

Chapter 3, *Case study description*, introduces the specific case studies used in the thesis. It details the household energy assets considered, including heating production assets, photovoltaic panels, and energy storage solutions. The configuration and operation of these assets are discussed to set the stage for the optimization model.

Chapter 4, *Optimization model description*, outlines the linear optimization model developed to optimize the economic benefits of solar panel installations. The model considers various constraints and aims to identify the optimal configuration of energy assets in a residential setting.

Chapters 5 and 6, *Case studies*, present and analyze two different case studies. Both case studies focus on the integration of photovoltaic systems with household energy assets, discussing the results of the optimization model, including the economic and environmental impacts of different energy strategies.

Chapter 7, *Model limitations and future research directions*, discusses the limitations of the developed optimization model and proposes areas for future research. The aim is to provide a roadmap for further improving residential energy management systems in Belgium.

The thesis concludes with a *Conclusion* that summarizes the key findings and their implications for residential energy management in Belgium.

Chapter 1

Litterature review

In response to the growing need to optimize household energy consumption, research has increasingly focused on the strategic management of residential energy systems, commonly referred to as Home Energy Management Systems (HEMS). These systems have emerged as essential tools for optimizing energy distribution and integrating renewable energy sources into residential environments. The energy management strategies developed through scientific research have the potential to reduce energy costs by effectively coordinating and controlling various energy-consuming and energy-producing devices, such as solar photovoltaic panels, heating systems, and energy storage units. By maximizing efficiency, HEMS not only lead to significant cost savings but also contribute to the sustainability of residential energy consumption.

This chapter presents a comprehensive literature review, highlighting key findings from various scientific studies on HEMS, with a specific focus on their capacity to integrate multiple heating systems and other household assets with solar energy production. The range of HEMS methodologies that have produced these results is then explored, with the aim of identifying the most suitable approach for application in the Belgian context of this research.

1.1 Research results on Home Energy Management Systems

1.1.1 Potential of HEMS in coordinating heating systems

Heating represents a significant portion of energy consumption in residential buildings. The optimization of multiple heating systems within a home can result

in substantial energy savings and a reduction in emissions.

A study conducted in Ireland demonstrated that hybrid heating systems, which combine heat pumps, electric resistance water heaters, and gas boilers, can reduce operational costs, improve efficiency, and prevent the over-dimensioning of heat pumps [11]. Furthermore, another study revealed that these hybrid systems offer a more cost-effective heating solution for homes, reducing operational energy costs by approximately 20% compared to systems relying solely on electricity or gas [12]. Additionally, scientific research has examined the integration of hybrid components, such as gas-electric hybrid heat pumps (GEHHPs), which leverage the strengths of both technologies. A study carried out in Denmark showed that optimal operation of these technologies enabled the heat pump to be used 76% of the time and the gas boiler 24% of the time [13]. These findings also indicated that, compared to technologies used independently, GEHHPs are more efficient and cost-effective for households [13].

1.1.2 Optimization of HEMS for the integration of photovoltaic systems with household assets

The integration of solar panels with electric heating systems, such as electric water heaters and heat pumps, along with energy storage solutions like batteries or hot water tanks, presents significant opportunities for optimizing energy use and achieving cost savings in residential settings.

PV and Electric Resistance Domestic electric water heaters are widely used globally due to their affordability and potential to significantly support the integration of photovoltaic systems [14]. Numerous studies have therefore investigated the potential of integrating electric resistive heaters in homes equipped with solar panels. One study demonstrated that integrating an electric water heater could improve the self-consumption rate of PV systems by 52% [15]. Another European study indicated that using a 3.2 kWp PV system in combination with domestic electric water heating technology could result in cost savings of up to 1.500 euros for Belgian households in 2022 [14].

PV and Heat Pumps Energy systems combining solar PV with heat pumps have shown significant potential in enhancing energy efficiency and achieving cost savings. For example, a German study found that households using solar PV in combination with heat pumps and thermal storage could achieve PV self-consumption rates of up to 65% [16]. Further research supports these findings, demonstrating that such hybrid systems can significantly reduce greenhouse gas

emissions, mitigate over-voltage issues induced by PV systems, and improve energy autonomy for households by up to 10% when adding a heat pump to a single-family home with PV [17].

PV and Energy Storage Systems Energy storage systems are crucial in enhancing the management and self-consumption of electricity by storing the variable output from solar panels, effectively aligning solar energy production with household demand over time [18]. In Sweden, a study examined a PV system integrated with two distinct energy storage methods: batteries and a hot water storage tank. The system utilizing batteries achieved an annual PV self-consumption rate of 89%, while the system with a hot water storage tank achieved a self-consumption rate of 88% [19].

These studies collectively underscore the potential of combining PV panels with other energy systems to achieve cost reductions and improve self-consumption. By integrating insights from various studies on energy management methods and PV panels integration, this thesis aims to draw meaningful conclusions that are particularly relevant to the Belgian context.

1.2 Overview of Home Energy Management Systems methods

Numerous literature reviews have explored the diverse approaches and potential applications within Home Energy Management Systems. These comprehensive analyses delve into a variety of methodologies and categorize HEMS across several dimensions, highlighting the complexity and adaptability of these systems in different residential settings [20] & [21] :

- **Techniques:** Mathematical optimization, model predictive control, game theory, (meta)heuristic approaches, etc.
- **Criteria:** Electricity bill reduction, distribution system losses, peak load reduction, carbon emissions, customer comfort, etc.
- **Constraints:** Constraint types (appliance constraints, comfort constraints, etc.) and constraint-handling techniques (penalty functions, special operators, constrained objective optimization, etc.)
- **Household Appliance Models:** Uncontrollable, curtailable, (un)interruptible, regulating energy storage, etc.

- **Energy Billing Schemes:** All-in-rate, time of use, critical peak pricing, real-time pricing, etc.

Given the diversity of HEMS, it is essential to tailor these systems to specific contexts. This thesis aims to select the most appropriate HEMS configurations for the Belgian residential sector, leveraging the demonstrated potential of PV panels with combined heating systems as shown in previous studies.

1.3 Application to the Belgian residential sector

The primary objective of this thesis is to provide a tool that is accessible to Belgian households, as outlined in the introduction. This involves creating an HEMS that is easy to use, adaptable, and reflective of the reality of Belgian households. Consequently, a linear optimization code will be developed, focusing on the economic optimization of household energy costs based on Belgian energy pricing mechanisms, particularly regarding the billing of electricity consumption and injection.

Unlike most studies that concentrate on smart homes capable of continuously monitoring household and market parameters to adjust energy flows, this model will constraint the number of transitions between different technologies. This approach reflects the current limitations faced by Belgian users, who are not yet equipped with fully automated systems capable of continuous switching between energy production methods. Moreover, this model will only consider uncontrollable electrical loads, assuming that users cannot dynamically alter the electrical components of their homes.

Finally, this research emphasizes the importance of understanding the specific needs and conditions of individual households in Belgium. The differences in climate, energy pricing, and consumer behavior in Belgium necessitate tailored solutions for effective implementation.

Conclusion

Numerous studies have examined the extensive possibilities offered by HEMS, each developed using different tools, scenarios, criteria, and configurations. Given the context of this thesis, the focus is on energy management systems that integrate solar panels, particularly by optimizing multiple heating and storage systems within a home.

This thesis provides a comprehensive analysis of long-term energy management, ensuring that households can optimize their energy system throughout the year, balancing heating production assets and solar energy production without constant adjustments. Moreover, the approach developed provides practical insights and solutions that cater to the unique energy needs of Belgian households. By focusing on household-level energy management, this research aims to deliver tailored solutions that are directly applicable to Belgian homes.

Chapter 2

Belgian residential energy analysis

In the global shift towards more sustainable energy practices, understanding and optimizing household energy consumption is essential. This is particularly relevant in Belgium, where ambitious targets for reducing fossil fuel use and increasing the share of renewable energy are in place. This chapter delves into three critical areas that are key to understanding and enhancing residential energy management.

The first section, Household Energy Consumption Analysis, provides an in-depth examination of household energy needs, covering electricity, space heating, and water heating. By analyzing consumption patterns throughout the year, this section highlights opportunities for better aligning energy supply with demand, particularly in the context of integrating renewable energy sources.

The second section, Residential Photovoltaic Potential, explores the potential for solar energy generation on residential rooftops in Belgium. It considers the geographic and climatic factors that influence photovoltaic (PV) efficiency, as well as the specific characteristics of homes that impact solar panel installations. This section sheds light on the opportunities and challenges of maximizing solar energy production in residential settings.

Finally, the third section, Household Energy Pricing, investigates the energy pricing mechanisms in Belgium and their impact on consumer behavior. This section discusses the economic incentives for adopting residential PV systems and how these pricing models can influence self-consumption and electricity injection into the grid.

Together, these sections provide a comprehensive overview of the key factors influencing household energy management in Belgium, offering insights into how to optimize energy use and contribute to a more sustainable future.

2.1 Household energy consumption analysis

Household energy requirements encompass electricity, space heating and cooling, hot water and cooking. Electricity is essential for operating various electrical appliances, including lighting, refrigeration, and electronic devices. Space heating and cooling are necessary to maintain a comfortable indoor environment. Hot water is required for domestic activities such as cooking, cleaning, and sanitary hygiene. Finally, cooking requires energy too. Determining the precise energy demands of a household is fundamental for ensuring that these needs are met efficiently.

Accurate assessment of household energy demand patterns involves analyzing the dynamics of energy use over time. This includes identifying peak demand periods, understanding seasonal variations, and recognizing the impact of different habits on overall energy consumption. By examining these patterns, it is possible to develop strategies for optimizing energy use, such as shifting certain activities to periods of high PV output or implementing energy storage solutions.

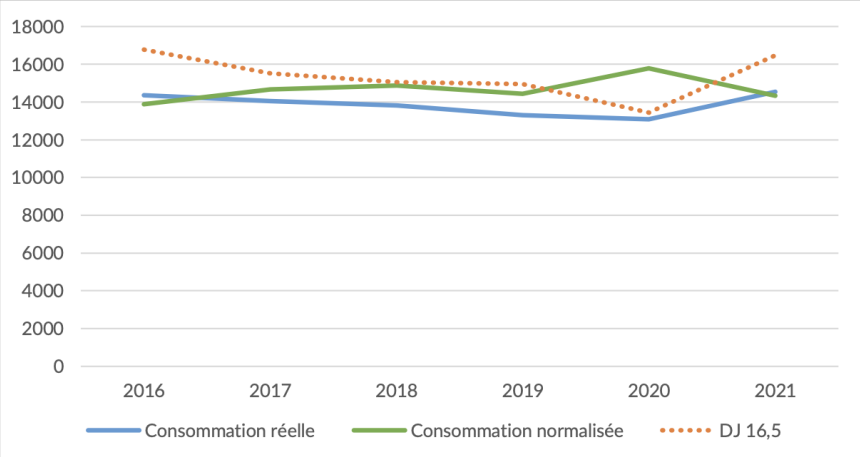
The section presents a detailed analysis of actual household energy demand and its patterns, focusing on the dynamics of energy use. In this section, the household annual energy demand by end-use is presented, i.e. what the house needs as final demands.

2.1.1 Annual household energy demands

In Belgium, the residential sector accounted for 21% of the total energy consumption in 2021 [22]. Detailed metrics on annual energy consumption, particularly for the residential sector, are provided in several Belgian reports [22], [23] & [24]. According to the Belgian Federal Commission for Electricity and Gas Regulation (CREG)[1], the average annual household consumes 3.500 kWh of electricity and 17.000 kWh of gas [26].

The electricity and hot water demands remain relatively constant throughout the year, maintaining a steady level. In contrast, the demand for space heating is highly dependent on climate conditions, as it is crucial for maintaining thermal

[1]The Belgian Federal Commission for Electricity and Gas Regulation is the federal regulatory authority overseeing Belgium's electricity and natural gas markets. As an independent entity with its own legal personality, the CREG carries out two primary missions: promoting transparency and competition within these markets and ensuring that market conditions align with the public interest and the broader energy policy, while consistently considering the fundamental interests of consumers [25]



Source : Bilan annuel concernant la désagrégation de la consommation énergétique des ménages (2021), Perspectives de la population (2022).

Figure 2.1: Evolution of household space heating energy consumption in Belgium from 2016 to 2021, measured in kWh [22]. Space heating demand is strongly influenced by climate conditions. The climate-adjusted intensity metric is used to isolate the impact of annual climate variations, providing a clearer picture of energy consumption trends under consistent climate conditions.

comfort. Consequently, space heating demand can vary significantly based on the specific climatic conditions of each year. To account for this variability, it is more accurate to use climate-adjusted intensity, which isolates the influence of annual climate fluctuations to provide a clearer view of energy consumption trends under a constant climate, as illustrated in Figure 2.1 [22]. According to the Economy (FPS Economy)[2], the household demand for space heating is approximately 15.000 kWh [22].

The total annual energy demand for a typical household is approximately 20.500 kWh, which can be broken down into 3.500 kWh for electricity, 15.000 kWh for space heating, and 2.000 kWh for water heating. This estimate provides a general understanding of a household's energy consumption and serves as a useful benchmark, though it can vary considerably depending on factors such as usage habits, the number of occupants, and climatic conditions. Table 2.1 provides a detailed breakdown of energy demand by end-use, offering a comprehensive overview of a household's annual energy requirements. The dynamic distribution

[2]Belgium's Federal Public Service Economy is in charge of making sure the country's products and services market runs smoothly, sustainably, and in a balanced manner by offering the resources necessary for a competitive and sustainable economy, especially with regard to household budgeting and energy-related issues like consumer protection [27] & [28].

of these demands will be further explored in the following section.

End-use energy demand	Symbol	Annual demand [kWh]
Hot water demand	$D^{water}_{ref,tot}$	2000
Heating demand	$D^{space}_{ref,tot}$	15000
Electricity demand	$D^{elec}_{ref,tot}$	3500
Total demand	D^{tot}_{ref}	20500

Table 2.1: End-use energy demands for an average Belgian household with an annual energy demand of 20.500 kWh [22]

2.1.2 Household demands distribution

Understanding the distribution of household energy needs is crucial for optimizing the integration of solar panel-generated electricity, which varies by time of day and season, as well as household's energy demands. Indeed, electricity produced by PV panels must be used, stored, or injected to the grid depending of the household demands at that time. Therefore, this section presents the hourly demand profiles.

A preliminary approximation that provides insight into the distribution of these energy demands is the monthly distribution provided by the Synergrid[3], as shown in Figure 2.2 [30]. As illustrated, the demand for gas varies significantly throughout the year, primarily in response to climatic conditions, while electricity demand remains relatively constant.

Heating demand profiles The Open Power System Data (OPSD) platform[4] provides an open-source for power system modeling, supplying data necessary for energy system analyses [34]. The OPSD platform offers hourly time series up to 2022 for households' heat profile demands for space and water heating in European countries, including Belgium [35]. The patterns are derived from gas

[3]Synergrid is the federation representing the Belgian electricity and gas network operators. It serves as the primary liaison between these network operators and the Belgian and European authorities, advocating on their behalf and addressing sector-related matters [29]

[4]The Open Power System Data platform was established in 2014 by energy researchers advocating for open-source and open data, leading to the formation of the Open Energy Modelling Initiative. For Belgium-specific data, primary sources include VREG (Flemish regulator for electricity and gas markets) and ELIA (operator of the electricity transmission network) [31], [32] & [33]. These organizations play key roles in providing essential data that supports the analysis of energy conditions and management within Belgium.

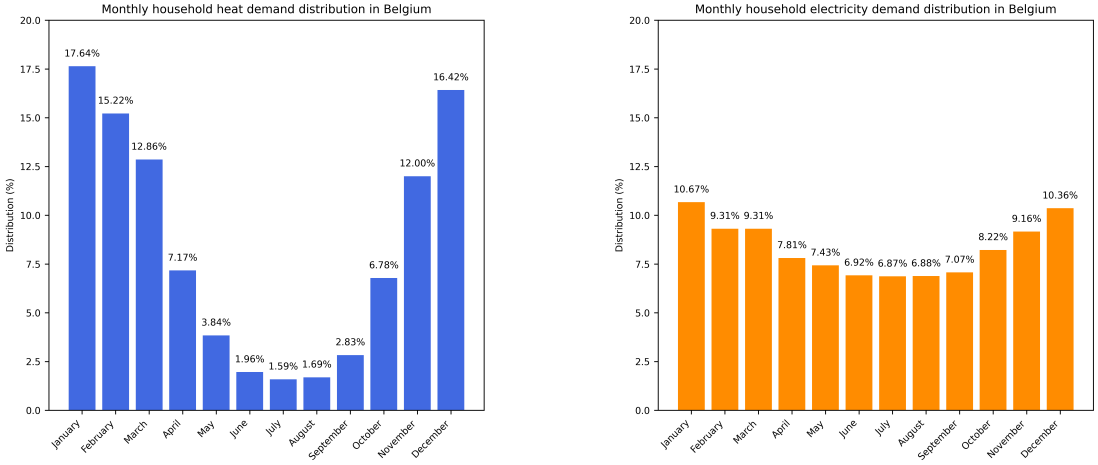


Figure 2.2: Monthly distribution of household energy demands as reported by Synergrid [30]. Household energy demand exhibits significant seasonal fluctuations, particularly in heating needs, which are heavily influenced by climatic changes. In contrast, electricity usage tends to stay consistent throughout the year.

standard load profiles, spatial temperature, wind speed reanalysis, and population geodata [35].

The time series demand profiles for hot water heating $DP^{water}(t)$ and space heating $DP^{space}(t)$ are standardized annually to 1 TWh and illustrated on Figure 2.3. Space heating demands, linked to outdoor temperature, vary significantly throughout the year. Indeed, as explained, the space heating is highly linked to the outdoor temperature for thermal comfort. In winter, due to colder weather conditions, the space heating demand is higher than during summer periods. In contrast, hot water demand remains relatively constant year-round. Both habits exhibit two peaks, in the morning and evening.

In this study, it is assumed that the heating demand is negligible from May 15 to September 15. The data presented are functions of both the outdoor temperature and the desired indoor temperature, reflecting in part the household's requirements [35]. In Belgium, it is common practice not to heat during the summer months rather than maintaining a slight heating demand during certain summer days. Therefore, this assumption will be applied throughout this thesis[5].

[5]Furthermore, this assumption allows the use of an electric resistance to heat domestic hot water during the summer without simultaneously operating a boiler for space heating. This will be further explained later in this thesis.

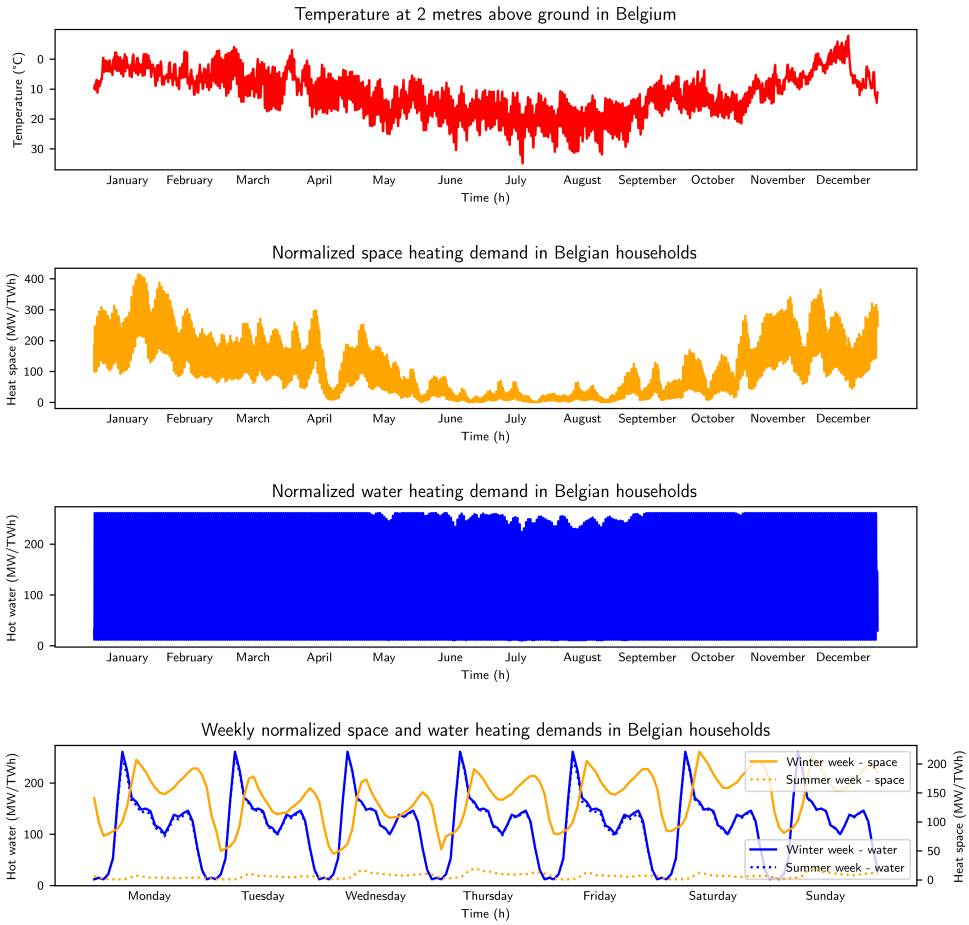


Figure 2.3: Normalized heat demand in Belgium in MW/TWh for space and water heating in households in 2022 [35]. Due to thermal comfort, the need for space heating is correlated with the outside temperature and consequently varies year-round. On the other hand, the need for hot water stays mostly consistent throughout the year. There are two peaks to both habits: one in the morning and one at night.

Electricity demand profile Although electricity consumption varies over the course of the year and throughout the day, these variations are much less pronounced compared to heating, which is heavily influenced by outdoor temperatures, as suggested by Figure 2.2. Nonetheless, annual electricity consumption does show some variation based on climatic conditions. During the winter, for example, people tend to spend more time indoors, leading to higher electricity consumption. Additionally, shorter daylight hours during winter months result in increased electricity use for lighting. Beyond climatic variations, the electricity demand depends heavily on household consumption habits.

No specific scientific dataset on the hourly distribution of electricity demand in Belgium has been found. However, Synergrid provides standard electricity consumption profiles. To develop these annual load curve models, Synergrid utilizes historical consumption data from a statistically selected group of grid users equipped with automated metering systems [30]. These models also consider key factors influencing energy consumption, including meteorological conditions (e.g., temperature, wind speed, and cloud cover) as well as the annual calendar (e.g., sunrise and sunset times, weekdays versus weekends, public holidays, and school breaks) [36].

These standard electricity consumption profiles $DP^{elec}(t)$ are depicted in Figure 2.4. The annual distribution shows that electricity demand is higher in winter, with daily peaks occurring in the morning and evening.

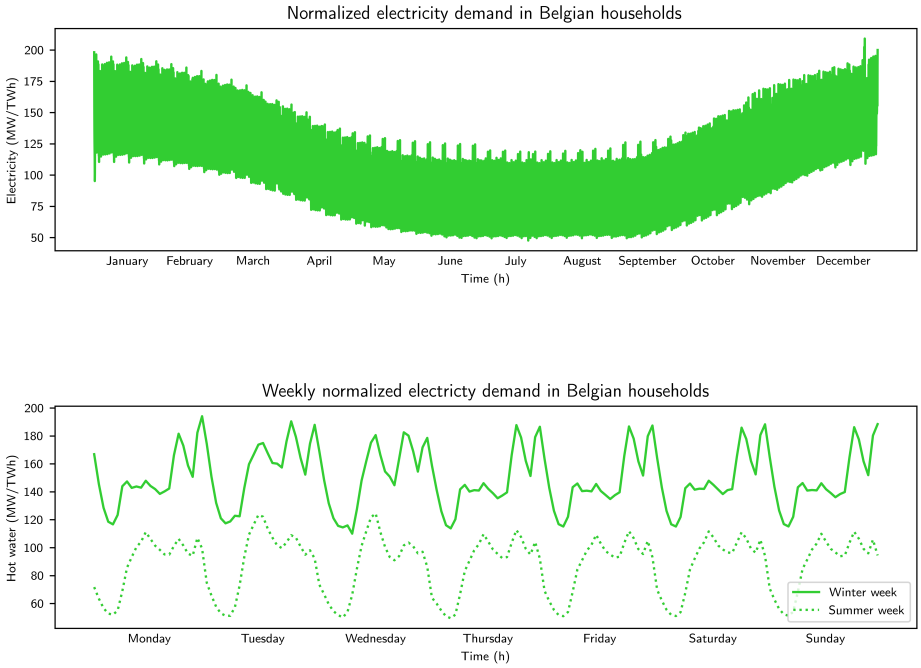


Figure 2.4: Synthetic electricity load profiles for Belgian households, demonstrating seasonal variations and daily peaks in electricity demand [30].

This analysis provides an initial understanding of electricity demand distribution, although it should be noted that actual demand can vary significantly depending on individual household habits. While the annual profile is a reasonable approximation, hourly profiles are highly influenced by the specific behaviors and routines of each household.

2.1.3 Annual household demands

The final hourly energy demand profiles, $D^{\text{end use}}_{\text{house}}(t)$, for an average household in Belgium are estimated by applying the previous presented hourly demand profiles, $DP^{\text{end use}}(t)$, to the yearly demand, $D^{\text{water}}_{\text{ref,tot}}$ as computed in Equation 2.1, 2.2 and 2.3 and presented in Figure 2.5. This method enables a dynamic representation of household energy specific needs throughout the day and year.

$$D^{\text{space}}_{\text{house}}(t) = DP^{\text{space}}(t) \cdot D^{\text{space}}_{\text{ref,tot}} \tag{2.1}$$

$$D^{\text{water}}_{\text{house}}(t) = DP^{\text{water}}(t) \cdot D^{\text{water}}_{\text{ref,tot}} \tag{2.2}$$

$$D^{\text{elec}}_{\text{house}}(t) = DP^{\text{elec}}(t) \cdot D^{\text{elec}}_{\text{ref,tot}} \tag{2.3}$$

This chapter has explored the key aspects of household energy consumption in Belgium, with a focus on electricity, space heating, and hot water. Analyzing the energy demand profiles and consumption patterns provides valuable insights into how households utilize energy throughout the day and across different seasons. Such an understanding is crucial for developing effective energy management strategies that enhance PV integration and improve overall household energy usage.

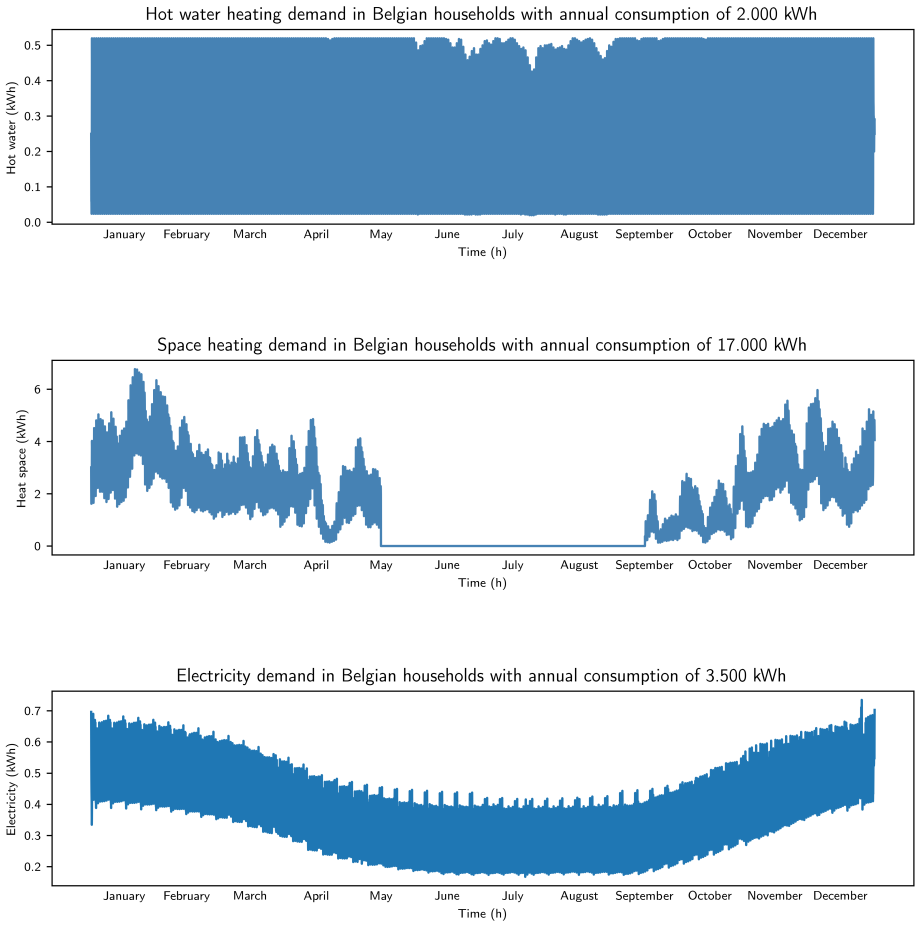


Figure 2.5: Final hourly energy demand profiles for an average household in Belgium, derived from annual consumption data and corresponding hourly profiles. These profiles provide a detailed representation of the household's dynamic energy demands throughout the day and across the year, accounting for variations due to climatic conditions and daily household routines.

2.2 Residential Photovoltaic Potential

As part of the National Energy and Climate Plan for 2021-2030, Belgium is targeting an increase in the proportion of renewable energy within its overall energy mix, with a goal of reaching 21.7% by 2030 [7]. Due to its high urban density, Belgium, particularly the Brussels-Capital Region, has a relatively limited potential for generating renewable energy compared to other areas. This makes it critical to investigate the possibilities offered by solar energy, particularly photovoltaic solar panels on Brussels rooftops.

The Region's overall photovoltaic potential is evaluated at 2,500,000 kW, while the combined output of current installations reached around 210 000 kW in 2021, representing 8% of the potential [37]. Therefore, there is a specific opportunity for PV panels on residential rooftops which represented 21% of the installed solar electricity in Brussels in 2021 [37].

The photovoltaic potential presented refers to what can be realistically installed in Brussels, considering aspects such as the city's layout and the current solar panel technology. However, to achieve the goal set by the Air-Climate-Energy Plan for 2030, where the Brussels-Capital Region aims to generate 334 GWh from solar panels [37], this will inevitably depend on both the installations and the solar energy potential available in Belgium. Specifically, it will depend on the amount of solar energy that can be harnessed within the country.

Photovoltaic potential in Belgium The solar potential in Belgium is quantified by the photovoltaic capacity factor, denoted CF_{PV}. The PV capacity factor is a metric that represents the ratio of the actual energy produced by a PV installation over a specific period E_{PV}^{elec}, to the energy that could have been produced if the installation had operated at its full rated/peak capacity continuously over the same period $E_{PV,max}^{elec}$, as described in Equation 2.4 [38]. In other words, the PV capacity factor quantifies how efficiently the solar panels are expected to operate under given conditions. It is common to express the rated or peak capacity in kilowatt-peak (kWp), which represents the maximum energy output under optimal conditions.

$$CF_{PV} = \frac{E_{PV}^{elec}}{E_{PV,max}^{elec}} = \frac{E_{PV}^{elec}}{P_{PV,max}^{elec} \cdot \Delta t} \text{(unitless)} \tag{2.4}$$

Solar photovoltaic systems inherently face limitations in their capacity factor due to their reliance on daylight, which ideally should be free from obstructions such as clouds, smoke, smog, or shading from trees and buildings. Key determinants of sunlight availability include the latitude of the installation and local cloud cover. Moreover, local environmental factors such as dust and ambient temperature, which ideally should be low, also play a significant role in influencing actual energy production. Figure 2.6 shows the average capacity factor across different regions of Belgium, highlighting the influence of geographical location on solar energy production. For instance, Brussels experiences a lower capacity factor, particularly due to its high urban density.

1) Average annual capacity factor
As sunlight availability varies with time of day and across different seasons, the capacity factor is generally calculated on an annual basis. For example, the average PV capacity factor in Brussels is around 2.8-2.9 kWh/kWp daily and approximately 1022 to 1058.5 kWh/kWp annually, as illustrated in the Figure 2.6 [39]. These data indicate that a 1 kWp PV system in Brussels can produce approximately 2.8 to 2.9 kWh per day and between 1022 to 1058.5 kWh annually.

2) Hourly annual capacity
The hourly capacity factor over the year provides insight into how seasonal and daily variations impact the performance of PV systems in Belgium. As illustrated in Figure 2.8, the hourly capacity factor [6] for solar energy in Belgium exhibits significant intermittency. This variability is largely influenced by the time of year, the time of day, and prevailing weather conditions. The load curve indicates that approximately half of the hours throughout the year will experience a capacity factor of zero, meaning no solar energy production occurs during those times. The maximum observed capacity factor reaches 0,75. The data provided is specific to the year 2023. However, the load curves, represented on Figure 2.7, suggest that the overall distribution of the capacity factor remains relatively stable throughout the years in Belgium.

[6]The hourly Belgian capacity factor data presented is sourced from the Renewables.ninja website, which employs satellite observations and advanced modeling techniques to analyze historical climate data [40]. This analysis is supported by various scientific studies [41], [42], and [40]. Data obtained from Renewables.ninja and licensed under the Creative Commons Attribution - Non Commercial 4.0 International License. The dataset is aggregated using the second version of the Modern-Era Retrospective analysis for Research and Applications (MERRA-2 reanalysis) [40]. Additionally, the platform allows for the integration of other data sources, such as PV simulations based on the SARAH dataset [40].

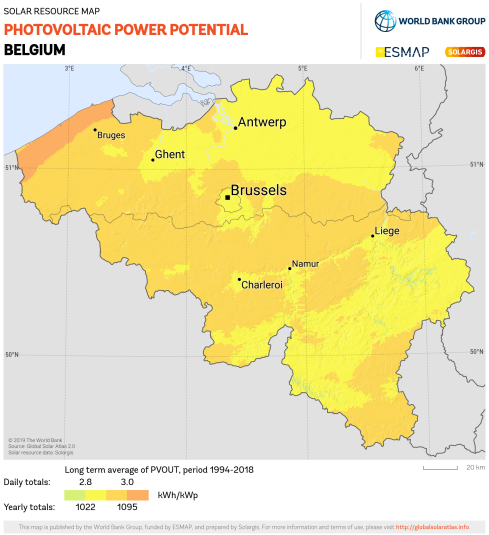


Figure 2.6: Geographical variation in average capacity factors for solar PV systems across different regions of Belgium, illustrating the impact of location on solar energy potential [39].

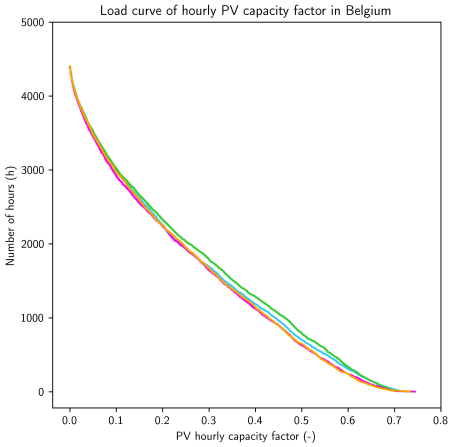


Figure 2.7: Load curve of hourly PV capacity factor in Belgium over multiple years, indicating that the overall distribution of capacity factors has remained relatively stable over time [40].

Photovoltaic potential of Belgian residential rooftops The previously discussed photovoltaic power potential in Belgium represents the total amount of solar energy that can be captured across the country. Beside this general context, this potential depends on various household PV system parameters, including the tilt angle, azimuth angle, tracking systems, and the specific characteristics of PV panels that relate to the geometry of rooftops and installation setups [40].

In this context, the *Cartesolaire.brussels* tool has been developed to assist residents in identifying the solar potential of their rooftops and understanding the associated economic benefits [43]. By entering their address, residents can view a visual representation of their roof's solar potential, determine the optimal number of solar panels needed, estimate installation costs, and project future economic returns. The goal of this solar map is to demonstrate to Brussels residents that investing in solar panels is both financially viable and environmentally beneficial. This study aligns with that objective and aims to provide consumers with guidelines for integrating PV panels to reduce household energy costs.

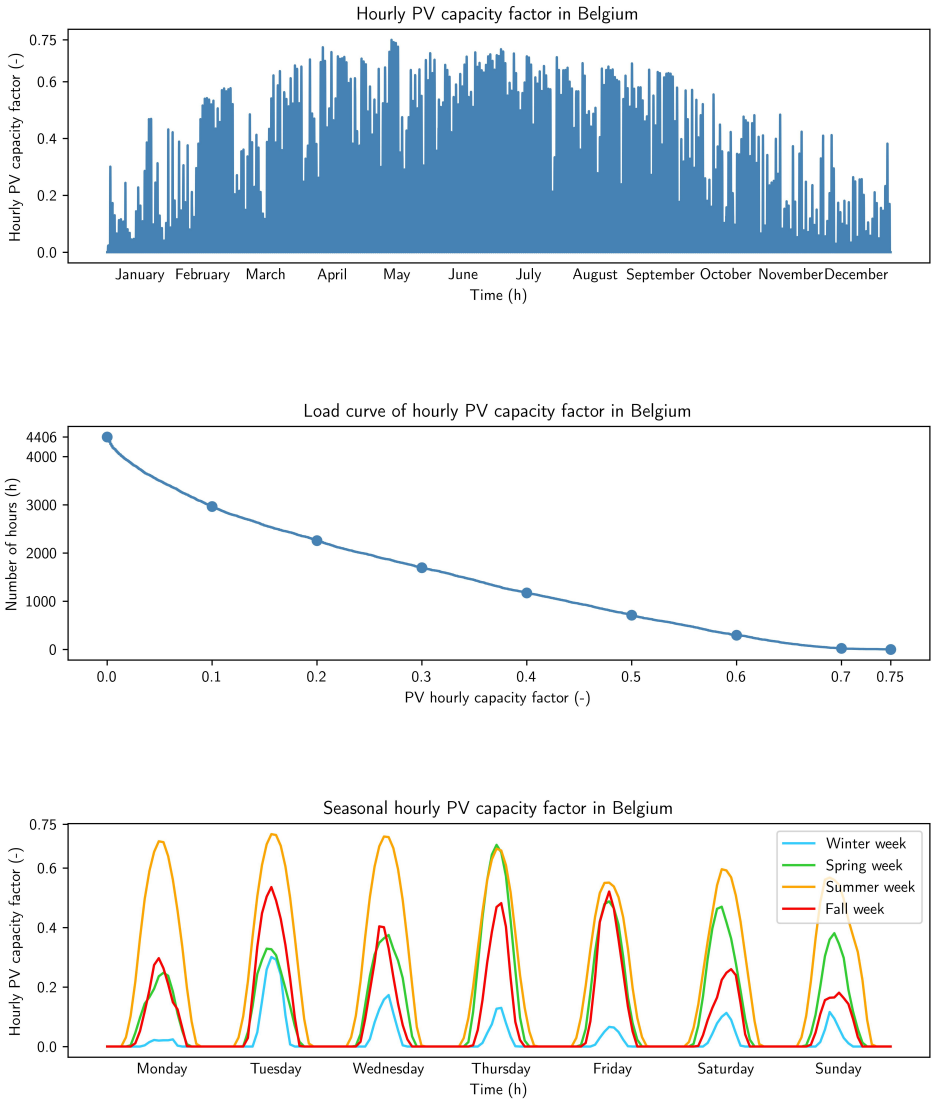


Figure 2.8: Annual hourly PV capacity factor in Belgium, including load curves and seasonal variability [40]. This variability is significantly impacted by the time of year, time of day, and prevailing weather conditions. The load curve shows that approximately half of the hours in a year have a capacity factor of zero, indicating no solar energy production during those periods, with a maximum observed capacity factor of 0,75 .

2.3 Household Energy Pricing

An in-depth examination of the energy pricing scheme in Belgium is essential for identifying the most efficient methods for integrating photovoltaic panels into residential settings. This chapter focuses on the definition of pricing mechanisms and their influence on consumption patterns, as well as how these mechanisms can either facilitate or hinder the adoption of PV technology in homes.

2.3.1 Analysis of Belgian energy pricing models

This section provides an overview of the energy pricing mechanisms in Belgium, with further and deeper details elaborated in Appendix A.

In Belgium, households are billed for the gas and electricity they consume from the grid, based on a specific tariff that is determined by energy prices and consumption levels. This tariff structure is contractually agreed upon and reflects the prevailing energy costs. The actual consumption is accurately recorded by meters, which measure the precise amount of gas and electricity used by the household.

Household pricing tariff In addition to an annual fixed cost, charges are incurred based on consumption, calculated either through a fixed price per kilowatt-hour (kWh) or a variable price per kWh depending on specific periods. Variable energy prices can be adjusted on an annual, quarterly or monthly basis for gas and electricity, and hourly rates are also available for electricity.

Residential energy price Residential electricity and gas prices exhibit significant variability, driven by various external factors. This fluctuation is observable both on an annual and monthly basis, as illustrated in Figures 2.9 and 2.10. These figures display the average prices of gas and electricity for the months of 2023, as well as over the years. In 2023, the average gas price was approximately 10.75 ct/kWh, while electricity was around 40.5 ct/kWh.



Figure 2.10: Monthly trends in the energy component of gas (left) and electricity (right) prices for a typical residential customer in 2023 show significant fluctuations. Gas prices varied between 4 and 16 ct/kWh, while electricity prices ranged from 10 to 45 ct/kWh, reflecting considerable month-to-month volatility. The sharp variations in recent years have been largely driven by the impacts of the COVID-19 pandemic and the war in Ukraine. Under more stable conditions, the price trends were relatively flat. Source: Annual Report 2023, CREG [44]

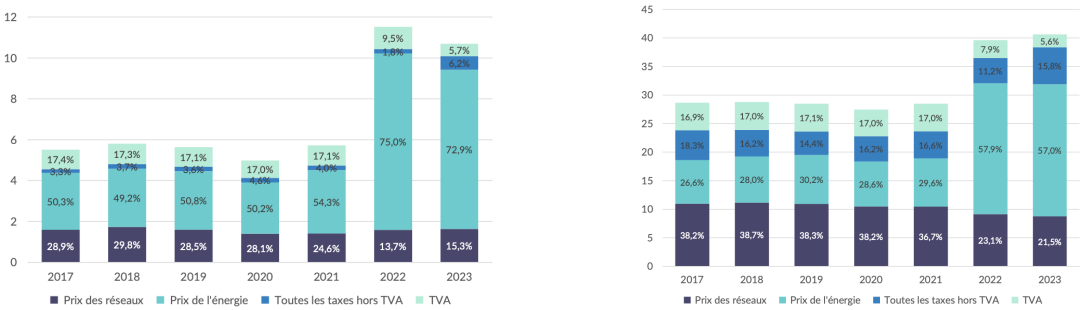


Figure 2.9: Trends in the average residential gas and electricity prices in Belgium from 2017 to 2023, expressed in euro cents per kWh, show significant year-to-year fluctuations. In 2023, the average gas price was around 10.75 ct/kWh, and electricity was approximately 40.5 ct/kWh. The energy cost component accounted for 72.9% of the total gas expense and 57% of the total electricity expense. Source: Belgian Energy Data Overview 2024, FPS Economy [7] [9].

Household energy meters The energy supplier uses data from the household's meter to accurately calculate the annual bill. There are two primary types of meters used in Belgium: classic (traditionnal) meters and smart meters.

1. **Classic meters**: Classic meters accumulate energy consumption data without providing specific timestamps. The total consumption is calculated after

two human readings. For households with conventional meters, billing is by default at a fixed price throughout the year, regardless of whether the contract is fixed-rate or variable-rate. This fixed price is either stipulated in the contract or calculated by default by the energy provider using consumption profiles (see Appendix A). As a result, classic meters offer no incentive for households to adjust their consumption based on time-of-use, as the price remains constant.

The energy cost $\text{Cost}_{\text{energy}}$ for households with classic meters is calculated as follows:

$$\begin{aligned}\text{Cost}_{\text{energy}} = & \underbrace{\text{Price}_{\text{elec,fixed}} \cdot \text{Cons}_{\text{elec,annual}} + \text{Cost}_{\text{elec,fixed}}}_{\text{Cost}_{\text{elec}}} \\ & + \text{Price}_{\text{gas,fixed}} \cdot \text{Cons}_{\text{gas,annual}} + \text{Cost}_{\text{gas,fixed}}\end{aligned} \tag{2.5}$$

where:

- $\text{Price}_{\text{elec,fixed}}$ is the fixed price per kWh of electricity consumed.
- $\text{Cons}_{\text{elec,annual}}$ is the annual electricity consumption in kWh.
- $\text{Cost}_{\text{elec,fixed}}$ is the fixed annual cost associated with electricity supply.
- $\text{Price}_{\text{gas,fixed}}$ is the fixed price per kWh of gas consumed.
- $\text{Cons}_{\text{gas,annual}}$ is the annual gas consumption in kWh.
- $\text{Cost}_{\text{gas,fixed}}$ is the fixed annual cost associated with gas supply.

2. **Smart meters**: Smart meters record the precise time of energy consumption and share this information with the energy supplier. Households equipped with smart meters can choose between fixed and variable rate contracts. Under a variable rate contract, the actual consumption during specific periods is billed according to the rates applicable at those times. Therefore, smart meters with variable rate contracts offer a significant incentive to shift consumption to periods when energy prices are lower.

   The energy cost $\text{Cost}_{\text{energy}}$ for households with smart meters is calculated as follows:

$$\text{Cost}_{\text{energy}} = \underbrace{\sum_{i \in \text{periods}} \text{Price}_{\text{elec,variable i}} \cdot \text{Cons}_{\text{elec}}(i) + \text{Cost}_{\text{elec,fixed}}}_{\text{Cost}_{\text{elec}}} + \sum_{i \in \text{periods}} \text{Price}_{\text{gas,variable i}} \cdot \text{Cons}_{\text{gas}}(i) + \text{Cost}_{\text{gas,fixed}} \tag{2.6}$$

where:

- $\text{Price}_{\text{elec,variable i}}$ is the price per kWh of electricity consumed during period i. It remains constant if the price is fixed, but varies across periods if the price is variable.
- $\text{Cons}_{\text{elec}}(i)$ is the electricity consumption in kWh during period i.
- $\text{Cost}_{\text{elec,fixed}}$ is the fixed annual cost associated with electricity supply.
- $\text{Price}_{\text{gas,variable i}}$ is the variable price per kWh of gas consumed during period i.
- $\text{Cons}_{\text{gas}}(i)$ is the gas consumption in kWh during period i.
- $\text{Cost}_{\text{gas,fixed}}$ is the fixed annual cost associated with gas supply.

To reduce energy costs, households may consider installing photovoltaic panels to decrease their reliance on grid electricity. The following section discusses how PV panels affect household energy bills and influence self-consumption behavior.

2.3.2 Compensation mechanisms for PV panels electricity injection in Belgium

Installing PV panels enables homeowners to use solar energy to produce electricity for powering household appliances, charging electric vehicles, or storing energy in batteries. When PV panels generate electricity, the household can directly use this energy to power its electrical appliances. This practice is known as self-consumption, as the household consumes the electricity it produces. Consequently, it reduces dependency on grid electricity and lowers the billed consumption from the energy provider.

Moreover, if at any given time, PV panels generate more electricity than the household consumes, surplus electricity can be injected back into the grid. About 30% of the energy produced by the average Belgian household is consumed; the remaining energy is fed into the grid [**pvperc**]. The homeowner receives an economic return from the energy provider for this injected electricity. In Belgium,

there are two methods of compensation: the reduction in billed electricity consumption or the financial compensation based on injection quantity and price.

2.3.2.1 Reduction in billed electricity consumption

In this compensation method, financial remuneration is provided indirectly by deducting the injected electricity from the total electricity consumption billed at the end of the year. In other words, the billed electricity amount is calculated as the grid electricity consumption reduced by the electricity injected back into the grid.

This method of remuneration is available to users with a classic meter, often referred to as a 'meter that runs in reverse' in Belgium. The meter's disk rotates counterclockwise (when viewed from above) when it measures positive consumption, i.e., when the household is drawing electricity from the grid. Conversely, it rotates clockwise when electricity is being injected into the grid. As a result, both consumption and injection are recorded as a single cumulative value. This value increases when electricity is imported from the grid and decreases when it is exported back to the grid.

However, while a household can reduce its electricity bill, it cannot receive any payment for surplus electricity beyond its consumption. Put another way, even if the household produces more electricity than it consumes, the energy provider will not compensate for the extra electricity injected into the grid. The maximum financial benefit is reducing the consumption bill to zero, leaving only the fixed charges to be paid [8].
In other words, at the end of the billing period, the net cumulative value recorded by the meter determines the energy provider's charge. This net value, also referred to as the consumption balance, cannot be negative. It is either positive, indicating that the household consumes more electricity than it produced, or it is zero, meaning that the household's production exactly matched its consumption. Any negative balance is automatically set to zero and does not result in any further benefit.

Consequently, this remuneration is limited, creating an interesting situation where households inject more electricity than they consume, leading to lost injections. This, in turn, encourages them to increase their electricity consumption,

[8] Fixed charges cannot be reduced and must be paid regardless of the amount of electricity consumed or injected

such as by using electric heating systems, leading to the interest of this study.

Therefore, the electricity cost determined in Equation (2.5) becomes the Equation 2.7, indicating that the electricity provider bills the absolute consumption and imposes an additional fixed cost due to injection. The absolute consumption corresponds to the amount of electricity consumed from the grid minus the quantity of electricity injected into the grid.

$$\text{Cost}_{\text{elec}} = \text{Price}_{\text{elec,fixed}} \left(\max \left(0, \underbrace{\text{Cons}_{\text{elec}} - \text{Inj}_{\text{elec}}}_{\text{Cons}^{\text{abs}}_{\text{elec}}} \right) \right) + \text{Cost}_{\text{elec,fixed}} + \text{Cost}_{\text{inj,fixed}} \tag{2.7}$$

where:

- $\text{Price}_{\text{elec,fixed}}$ is the fixed price per kWh of electricity consumed.
- $\text{Cons}_{\text{elec}}$ is the total electricity consumed from the grid in kWh.
- Inj_{elec} is the total quantity of electricity injected back into the grid in kWh.
- $\text{Cons}^{\text{abs}}_{\text{elec}}$ is the absolute electricity consumption in kWh, calculated as the difference between the electricity consumed from the grid and the electricity injected back into the grid.
- $\text{Cost}_{\text{elec,fixed}}$ is the fixed annual cost associated with the electricity supply.
- $\text{Cost}_{\text{inj,fixed}}$ is the additional fixed cost imposed by the provider due to the injection of electricity into the grid.
- $\max\left(0, \text{Cons}^{\text{abs}}_{\text{elec}}\right)$ ensures that the annual balance cannot be negative. If the amount of electricity injected into the grid exceeds the amount consumed, this term becomes zero, meaning the household only needs to pay the fixed costs. However, if the consumption exceeds the injected amount, the household must pay the remaining consumption costs after accounting for the injected electricity.

  Note: the household cannot simultaneously consume and inject electricity; it must operate in either one mode or the other.

Consequently, if the household's photovoltaic system annually produces more electricity than the household consumes, this excess energy is economically wasted, as it does not contribute to further reducing costs. This scenario presents a significant economic inefficiency. To address this, households are encouraged to increase their electricity consumption to align with the total annual production of their PV panels. By utilizing the surplus electricity—rather than allowing it to go uncompensated—the household can maximize the economic returns from their PV system. This can be achieved by integrating electric heating systems that utilize the surplus electricity generated by the PV panels. By converting this excess electricity into heat, households can reduce their reliance on gas for heating. In some cases, particularly when using a heat pump, it may even be possible to eliminate gas costs entirely. This thesis examines these strategies in detail, focusing on how to optimize household electricity consumption to fully capitalize on the economic benefits of surplus solar energy production.

This remuneration mechanism does not necessitate specific adjustments to self-consumption, which refers to the immediate use of electricity generated by PV panels as it is produced. Instead, the focus is on increasing total annual electricity consumption, regardless of when the electricity is used throughout the year. This approach contrasts with the following compensation mechanism where immediate self-consumption is crucial.

2.3.2.2 Financial compensation based on injection quantity

In this remuneration structure, homeowners receive direct financial compensation, termed as injection costs, based on an agreed price per unit of injected electricity and the amount of electricity injected. The homeowner acts as an electricity seller to the grid, with the grid acting as the buyer at a contracted price settled by the energy provider.

This compensation method is applicable to users with bidirectional meters that can separately measure electricity injection and consumption. Classic bidirectional meters apply a fixed price to both, while smart bidirectional meters may apply either a fixed or variable price depending on the contract.

The supplier applies the same tariff structure for electricity injection as it does for consumption. This means that injection costs are determined in the same way as consumption costs, as described in the previous section. The supplier may offer either a fixed or variable injection price, which is the rate at which the grid purchases the electricity injected by the user. Therefore, Equation (2.5) and Equation (2.6) establishing the electricity cost are transformed into Equation 2.8

and Equation 2.9 respectively.

1. *For classic meters :*

$$\begin{aligned} \text{Cost}_{\text{elec}} = \text{Price}_{\text{elec,fixed}} \cdot \text{Cons}_{\text{elec,annual}} + \text{Cost}_{\text{elec,fixed}} \\ - \text{Price}_{\text{inj,fixed}} \cdot \text{Inj}_{\text{elec,annual}} + \text{Cost}_{\text{inj,fixed}} \end{aligned} \tag{2.8}$$

   where:

   - $\text{Price}_{\text{elec,fixed}}$ is the fixed price per kWh of electricity consumed.
   - $\text{Cons}_{\text{elec,annual}}$ is the annual electricity consumption in kWh.
   - $\text{Cost}_{\text{elec,fixed}}$ is the fixed annual cost associated with the electricity supply.
   - $\text{Price}_{\text{inj,fixed}}$ is the fixed price per kWh for the electricity injected into the grid.
   - $\text{Inj}_{\text{elec,annual}}$ is the annual quantity of electricity injected into the grid in kWh.
   - $\text{Cost}_{\text{inj,fixed}}$ is the fixed annual cost associated with the injection of electricity into the grid.

     Note: the household cannot simultaneously consume and inject electricity; it must operate in either one mode or the other.

2. *For smart meters :*

$$\begin{aligned} \text{Cost}_{\text{elec}} = & \sum_{i \in \text{periods}} \text{Price}_{\text{elec,variable i}} \cdot \text{Cons}_{\text{elec}}(i) + \text{Cost}_{\text{elec,fixed}} \\ & - \sum_{i \in \text{periods}} \text{Price}_{\text{inj,variable i}} \cdot \text{Inj}_{\text{elec}}(i) + \text{Cost}_{\text{inj,fixed}} \end{aligned} \tag{2.9}$$

   where:

   - $\text{Price}_{\text{elec,variable i}}$ is the price per kWh of electricity consumed during period i.
   - $\text{Cons}_{\text{elec}}(i)$ is the electricity consumption in kWh during period i.
   - $\text{Cost}_{\text{elec,fixed}}$ is the fixed annual cost associated with the electricity supply.
   - $\text{Price}_{\text{inj,variable i}}$ is the price per kWh for the electricity injected into the grid during period i.

- $\text{Inj}_{\text{elec}}(i)$ is the quantity of electricity injected into the grid in kWh during period i.
- $\text{Cost}_{\text{inj,fixed}}$ is the fixed annual cost associated with the injection of electricity into the grid.

  Note: the household cannot simultaneously consume and inject electricity; it must operate in either one mode or the other.

In Belgium, the price for electricity injected into the grid is currently approximately 10% of the consumption price [45]. This significant difference creates a strong economic incentive for households to prioritize self-consumption of electricity generated by photovoltaic systems rather than injecting the excess into the grid. Indeed, for every kilowatt-hour self-consumed, a household avoids paying the full electricity tariff. This represents a savings of up to 90% more than what would be earned if that energy were instead injected into the grid. Consequently, maximizing self-consumption is a financially advantageous strategy.

This remuneration mechanism, where electricity injection is compensated at a lower rate than consumption, highlights the importance of determining how households should manage their electricity usage in relation to their solar production. This includes direct self-consumption of the energy, such as through electric heating systems, or the potential storage of excess energy, either in batteries or as hot water. This study explores the optimal management of self-consumption to identify the most economically beneficial strategy.

In both scenarios, there is a clear incentive to align household electricity consumption with PV electricity production. In the first scenario, the focus is on increasing annual electricity consumption to match annual production, thereby avoiding the loss of excess solar energy that is not consumed and remunerated. In the second scenario, the emphasis is on immediate self-consumption of energy as it is produced, to avoid injecting electricity into the grid at a low compensation rate. Both scenarios highlight the need to optimize consumption patterns and consider the potential investment in additional electrical consumption methods, strategies that this study will explore in depth.

2.4 Conclusion

This chapter has provided a comprehensive analysis of residential energy management in Belgium, focusing on energy consumption patterns, residential photovoltaic potential, and energy pricing mechanisms. Understanding household energy demand profiles, seasonal variations, and consumption habits is essential for optimizing the integration of photovoltaic systems. Additionally, the climatic factors affecting PV potential were examined, highlighting both opportunities and challenges in maximizing solar energy production. Lastly, the impact of energy pricing on consumer behavior was discussed, particularly in terms of self-consumption of electricity and grid injection.

The next chapter will delve into the case study, detailing how household energy assets are configured and interconnected to meet the identified energy demands while minimizing costs, as discussed in this chapter.

Chapter 3

Case study description

A house requires energy for heating water, heating space, and powering electrical devices. To meet these needs, various energy production assets, storage technologies, and connections to the public grid are employed. This section explores the technologies available for heating and electrical production, focusing on the specific technologies studied in this thesis: gas boilers, heat pumps, electric resistance water heaters, PV panels, water tanks, and battery energy storage systems. Additionally, the energy management system under study is discussed, detailing how all the previously presented assets are interconnected to meet the household's needs.

3.1 Household Assets

3.1.1 Heating Production Assets

In Belgium, most households rely on natural gas (49%) for space heating, followed by heating oil (33%), biomass (10%), and electricity (3%) [22]. For water heating, the primary sources are natural gas (52%), electricity (30%), and heating oil (13%) [22].

Given the prevalence of natural gas boilers over boilers using heating oil or biomass, this thesis will focus on natural gas boilers. Additionally, common residential electrical heating methods, such as electric resistance heaters and heat pumps, will be discussed. Among the various types of heat pumps, the air-source heat pump is chosen for its common usage, ease of installation, and affordability in Belgium. Other methods, though less common, include ambient heat, solar thermal, coal, and propane butane [22].

This study evaluates three household heating technologies, each with distinct capacities and efficiencies: the natural gas boiler, the electric resistance water heater and the heat pump.

- Gas Boiler: A gas boiler with an efficiency of 90% and a maximum capacity of 25 kW is examined.
- Electric Resistance Heater: An electric resistance heater with an efficiency of 98% and a maximum capacity of 3 kW is considered.
- Heat Pump: A heat pump with a Coefficient Of Performance (COP) ranging from 2.6 to 4 and a maximum capacity of 12 kW is analyzed.

Each of these assets is characterized by its distinct efficiency, capacity, cost, and environmental impact, as presented in more detail in this section.

3.1.1.1 Natural gas boilers

Operation & Efficiency Natural gas boilers (denoted as GB) burn natural gas to heat water, which can be used for both domestic hot water and space heating. When gas is burned in the boiler's combustion chamber, it generates heat that is then transferred to the water circulating through the boiler's pipes.

The efficiency of natural gas boilers can vary significantly depending on the technology and age of the unit. Generally, the efficiency of these boilers ranges from 80% to 110% [46]. Traditional non-condensing boilers typically operate at the lower end of this spectrum, achieving efficiencies around 80-90% [46]. These boilers lose a significant amount of heat through their exhaust gases. In contrast, modern condensing boilers can achieve efficiencies above 100% [46]. The boiler considered in this study is a traditional and commonly used residential boiler with an efficiency of 90% [12].

The amount of thermal energy produced, denoted E_{GB}^{heat} in kWh, is defined by the efficiency of the gas boiler, represented by η_{GB} dimensionless, and the energy content in the natural gas, denoted E_{GB}^{gas} in kWh. Moreover, the output heat is limited by the gas boiler's maximum heat capacity $E_{GB}^{heat,max}$.

$$\eta_{GB} \cdot E_{GB}^{gas} = E_{GB}^{heat} \leq E_{GB}^{heat,max} \tag{3.1}$$

The energy content in natural gas is determined by the volume of gas consumed, V_{GB}^{gas}, and the energy per unit volume of gas, Q_{gas} = 9.8 kWh/m^3 [12]. This relationship is expressed as $E_{GB}^{gas} = V_{GB}^{gas} \cdot Q_{gas}$.

Characteristics Gas-fired boilers are known for their low initial investment cost and lower fuel costs compared to electricity. They are suitable for both hot water and space heating. However, they depend on gas supply and fluctuating prices, and require regular maintenance. In addition, the combustion process releases greenhouse gas emissions and other pollutants that contribute to air pollution and climate change.

3.1.1.2 Electric resistance water heaters

Operation & Efficiency Electric resistance water heaters (denoted as R) function by submerging a heating element, typically a resistor, into the water tank. When the water heater is turned on, an electric current flows through the resistor, converting electrical energy into heat energy.

The conversion efficiency from electricity to heat of the electric resistance water heaters is approaching 100%, around 98% [12] . However, system effectiveness is reduced by transmission losses and heat dissipation from the tank [11].

The delivered thermal energy, denoted E_R^{heat} in kWh, is determined by the electrical water heater's efficiency, denoted η_R without unit, and the electricity consumed by the electrical water heater, denoted E_R^{elec} in kWh.

$$\eta_R \cdot E_R^{elec} = E_R^{heat} \leq E_R^{heat,max} \tag{3.2}$$

Characteristics The main advantages of electric resistance water heaters are their low initial cost, simple installation, and minimal maintenance. However, they have significant drawbacks, such as heat loss from storage tanks, inadequacy for space heating, and inefficiency leading to higher operational costs compared to other technologies.

3.1.1.3 Air-source heat pumps

Operation & Efficiency Air-source heat pumps (denoted as HP) extract ambient heat from the air, intensify it by a compressor, and transfer it via a refrigerant to the source that needs to be heated for space heating or domestic hot water needs. The primary energy source for these devices is electricity, which powers the compressor, pumps, and fans essential for their operation.

Air-source heat pumps generally have a COP between 2.6 and 4 [11]. The COP of a heat pump is influenced by the temperature of the heat source, which

in the case of an air-source heat pump, is the outside air. In colder climates, as the outside temperature drops, the COP also decreases. Conversely, in warmer conditions, such as in summer, the COP increases, as illustrated in Figure 3.1.

The COP of the heat pump, denoted as COP_{HP} (unitless), and the electricity consumed by the heat pump, denoted as E_{HP}^{elec} in kWh, determine the delivered thermal energy, denoted as E_{HP}^{heat} in kWh.

$$COP_{HP} \cdot E_{HP}^{elec} = E_{HP}^{heat} \leq E_{HP}^{heat,max} \tag{3.3}$$

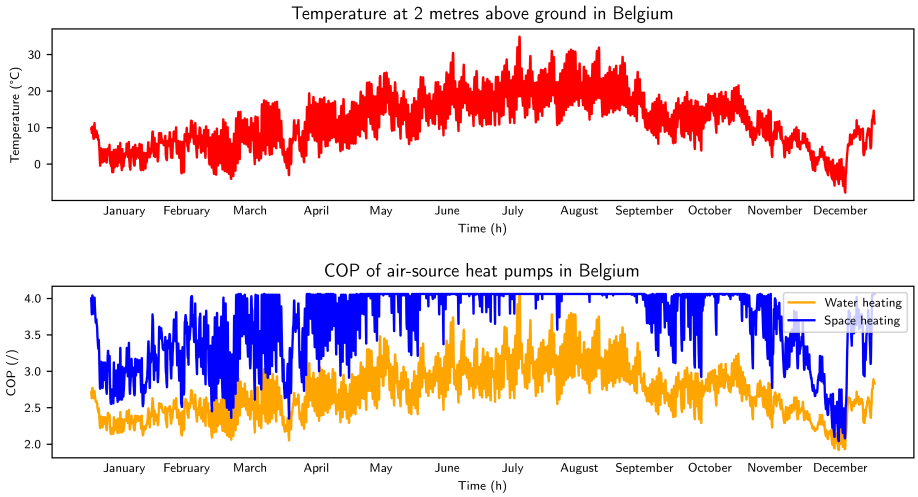


Figure 3.1: Hourly COP of an air-source heat pump throughout the year in Belgium [35]. The COP ranges between 2.6 and 4 and is affected by the ambient outdoor temperature: it decreases in colder conditions as the temperature drops, and increases in warmer conditions, such as during summer.

Investment price The cost of an air-source heat pump typically ranges between €7,500 and €12,500, including installation [47] & [48]. This estimate is subject to significant variability depending on several factors, including the specific model of the heat pump, installation expenses, and potential government subsidies available to the homeowner. In addition, the lifespan of a heat pump is generally estimated to be between 15 and 20 years [49].

Characteristics Heat pumps are highly efficient and can be used for both space heating and water heating. Additionally, they are reversible for space heating,

allowing them to provide cooling as well. Nevertheless, they have high initial costs and their efficiency decreases in cold climates.

Environmentally, heat pumps and electric resistance water heaters do not release greenhouse gas emissions during operation and can significantly reduce carbon emissions when powered by renewable electricity, especially when paired with PV panels.

3.1.2 Photovoltaic Panels

Operation & Efficiency Photovoltaic panels (denoted as PV panels) convert sunlight into electricity using semiconducting materials, typically silicon. When sunlight hits the PV cells, it excites electrons, creating an electric current through the photovoltaic effect. These panels can be installed on rooftops or ground-mounted and connected, beyond the household electricity system to the grid or battery storage systems. As explained in the Section 2.2, the electricity production from PV panels is determined by the PV capacity factor and the PV installed capacity.

The delivered electricity from PV panels, denoted as E_{PV}^{elec} in kWh, is determined by the capacity factor of the PV panels, represented as CF_{PV} (unitless), and the PV peak capacity, represented as $E_{PV,max}^{elec}$ in kWh.

$$CF_{PV} \cdot E_{PV,max}^{elec} = E_{PV}^{elec} \tag{3.4}$$

Characteristics PV panels offer a renewable energy source without directly producing greenhouse gases, reduce electricity bills, and can be paired with batteries for energy independence. However, they have high installation costs, their efficiency depends on sunlight availability, and they require installation space.

3.1.3 Storage Assets

Unlike energy production systems, storage assets are designed to retain energy over time rather than producing it instantaneously. As a result, a temporal dimension must be incorporated into the equations that describe these assets. This introduces additional complexity beyond just efficiency and capacity, requiring consideration of factors such as charging, discharging, and storage losses.

3.1.3.1 Hot Water Storage Tanks

Hot water storage tanks (denoted WT) store heated water for domestic hot water use, ensuring a consistent supply. They can be supplied with hot water by gas boilers or heat pumps, and they can integrate electric heaters directly inside them.

Operation & Efficiency Hot water storage tanks typically have insulation to reduce heat loss, but some heat loss is inevitable. The effectiveness of a hot water storage tank is often described by its standby loss, which can range around 1-2% per hour depending on the quality of insulation [11].

The energy stored in a water tank, denoted E_{WT}^{water} in kWh, varies between time steps (t and t+1) based on the net effect of energy inputs from storage loading $E_{WT,L}^{water}$ and energy outputs from unloading $E_{WT,U}^{water}$, along with standby heat loss between these time steps represented by γ_{WT}. The mathematical model describing the energy variation in the storage tank at each time step t is provided by Equation (3.5).

$$E_{WT}^{water}(t+1) = (1 - \gamma_{WT}) \cdot E_{WT}^{water}(t) + E_{WT,L}^{water}(t) - E_{WT,U}^{water}(t) \tag{3.5}$$

The stored hot water energy in the tank is constrained by the tank's volumetric capacity. Therefore, the maximum energy capacity, $E_{WT,max}^{water}$, is defined by the tank volume V_{WT} in liters, the specific heat capacity of water $c_{p,water}$ = 4.2 [kJ/kgK] = 1.163 [kWh/kgK], the density of water ρ_{water} = 1 [kg/L], and the temperature difference between the stored hot water and the ambient air outside the storage tank ΔT in [K] [12].

$$E_{WT}^{water}(t) \leq E_{WT,max}^{water} = c_{p,water} \cdot \rho_{water} \cdot \Delta T \cdot V_{WT}$$

The appropriate volume of the hot water tank is dependent on the number of occupants in the household and their specific hot water usage habits. For this study, a tank volume of 200 liters is selected, which is sufficient for an average household, with an estimated heat loss of 1% [11] & [14]. The temperature difference is assumed to be around 30 K, with an ambient temperature of approximately 20°C and hot water temperatures typically ranging from 40°C to 60°C for domestic hot water use [12]. Consequently, the maximum energy content of the storage tank is approximately $E_{WT,max}^{water}$ = 7 kWh.

It is assumed that the water storage tank is capable of both charging and discharging simultaneously. Additionally, the boiler is expected to be able to fully charge and discharge the tank within a one-hour period.

Finally, the purpose of Equation (3.6) is to ensure that the energy stored in the hot water tank at the end of the scheduling period equals the energy stored at the beginning, thereby ensuring the system's readiness for subsequent scheduling periods.

$$E_{WT}^{water}(N+1) = E_{WT}^{water}(1) \tag{3.6}$$

Characteristics Hot water tanks provide a reliable hot water supply, can be integrated with various heating technologies, and manage peak heating demand. Additionally, they can be used to store hot water when energy prices are low and utilize it when prices are high, optimizing energy costs. However, they suffer from heat loss, require space for installation, and need regular maintenance.

3.1.3.2 Battery Energy Storage Systems

Battery Energy Storage Systems (denoted BESS) work by storing electrical energy as chemical energy within batteries during charging. When energy is needed, the process is reversed, converting the stored chemical energy back into electrical energy for use. Typically connected to residential solar power systems, BESS allow homeowners to capture and store excess solar energy generated during the day. Additionally, they can store electricity from the grid when prices are low, enabling homeowners to use this stored energy during peak periods when electricity prices are higher.

Operation & Efficiency The operation of battery energy storage systems is fundamentally ruled by the concept of the State of Charge (SOC), which represents the proportion of the battery's total energy capacity that is currently available. The SOC fluctuates as energy is either stored in or drawn from the battery. It is crucial to manage the SOC within specific boundaries to avoid overcharging or deep discharging, as these conditions can significantly reduce the battery's lifespan.

The SOC can be described by the energy balance within the battery, which is subject to two primary energy flows: charging, where energy is accumulated, and discharging, where energy is utilized. A SOC value of 0 indicates a fully depleted battery, with no stored energy, while a SOC of 1 signifies a fully charged state. The progression of the SOC over time is captured by Equation (3.7), which shows that the SOC at the subsequent time step (1) depends on the SOC at the current time step (2), adjusted by the energy charged (3) or discharged (4) during the interval Δt. This equation also accounts for energy losses due to inefficiencies in the storage process, characterized by the self-discharge coefficient γ_{BESS}, as

well as losses during the charging and discharging processes, represented by the efficiency coefficients $\eta_{\text{BESS,ch}}$ and $\eta_{\text{BESS,dch}}$, respectively.

$$\underbrace{\text{SOC}(t+1)_{\text{BESS}}}_{(1)} = \underbrace{\text{SOC}(t)_{\text{BESS}} - (\gamma_{\text{BESS}} \cdot \Delta t)}_{(2)} + \underbrace{\left(\frac{\eta_{\text{BESS,ch}} \cdot \text{E}^{\text{elec}}_{\text{BESS,ch}}(t)}{\text{E}^{\text{elec}}_{\text{BESS,max}}} \right)}_{(3)} - \underbrace{\left(\frac{\text{E}^{\text{elec}}_{\text{BESS,dch}}(t)}{\eta_{\text{BESS,dch}} \cdot \text{E}^{\text{elec}}_{\text{BESS,max}}} \right)}_{(4)} \tag{3.7}$$

where $\text{SOC}(t+1)_{\text{BESS}}$ is the state of charge of the battery energy storage system at time t+1, $\text{SOC}(t)_{\text{BESS}}$ is the state of charge at time t, γ_{BESS} is the self-discharge rate, $\eta_{\text{BESS,ch}}$ and $\eta_{\text{BESS,dch}}$ are the charging and discharging efficiencies, $\text{E}^{\text{elec}}_{\text{BESS,ch}}$ and $\text{E}^{\text{elec}}_{\text{BESS,dch}}$ are the electrical energies charged and discharged, and $\text{E}^{\text{elec}}_{\text{BESS,max}}$ is the maximum energy storage capacity.

The SOC is inherently limited by the BESS maximum energy storage capacity and consequently cannot exceed the upper limit of 1. To preserve battery health, the SOC is often kept below this maximum denoted $\text{SOC}_{\text{BESS,max}}$. Similarly, the SOC should not fall below a certain minimum level, $\text{SOC}_{\text{BESS,min}}$, to avoid deep discharging, which also shortens battery life. These constraints are expressed in Equation (3.8), ensuring the SOC remains within safe operating boundaries.

$$\text{SOC}_{\text{BESS,min}} \leq \text{SOC}(t)_{\text{BESS}} \leq \text{SOC}_{\text{BESS,max}} \tag{3.8}$$

Furthermore, BESS cannot be charged and discharged simultaneously. This operational constraint is captured in Equation (3.9), where $x_{\text{BESS,ch}}(t)$ and $x_{\text{BESS,dch}}(t)$ are binary variables, indicating whether the system is in a charging or discharging state, respectively.

$$x_{\text{BESS,ch}}(t) + x_{\text{BESS,dch}}(t) \leq 1 \tag{3.9}$$

To reflect the practical limitations of BESS, the charging and discharging power levels are also bounded by maximum values, as described by Equations (3.10) and (3.11). These constraints ensure that the power exchanged during each time interval is kept within the system's capabilities.

$$0 \leq \underbrace{\frac{\text{E}^{\text{elec}}_{\text{BESS,dch}}(t)}{\Delta t}}_{\text{P}^{\text{elec}}_{\text{BESS,dch}}(t)} \leq \underbrace{\frac{\text{E}^{\text{elec}}_{\text{BESS,dch,max}}}{\Delta t}}_{\text{P}^{\text{elec}}_{\text{BESS,dch,max}}} \cdot x_{\text{BESS,dch}}(t) \tag{3.10}$$

$$0 \leq \underbrace{\frac{E^{elec}_{BESS,ch}(t)}{\Delta t}}_{P^{elec}_{BESS,ch}(t)} \leq \underbrace{\frac{E^{elec}_{BESS,ch,max}}{\Delta t}}_{P^{elec}_{BESS,ch,max}} \cdot x_{BESS,ch}(t) \tag{3.11}$$

where:

- $P^{elec}_{BESS,dch}(t)$ represents the electrical power discharged by the battery energy storage system, calculated from the energy discharged $E^{elec}_{BESS,dch}(t)$ over the time interval Δt.
- $P^{elec}_{BESS,ch}(t)$ represents the electrical power charged into the battery energy storage system, derived from the energy charged $E^{elec}_{BESS,ch}(t)$ over the time interval Δt.
- $x_{BESS,dch}(t)$ and $x_{BESS,ch}(t)$ are binary variables indicating discharging and charging respectively, ensuring that the maximum power constraints are respected and preventing simultaneous charging and discharging.

Equation (3.12) serves to maintain the SOC consistency from the start to the end of the scheduling period, ensuring the system is well-prepared for the next cycle.

$$SOC(N+1)_{BESS} = SOC(1)_{BESS} \tag{3.12}$$

Typical values for residential BESS are summarized in Table 3.1, which includes parameters such as maximum capacity, charging and discharging power, and efficiency rates [12].

Table 3.1: Characteristics of residential battery energy storage systems [12].

Parameters	Symbols	Values	Units
Maximum capacity	$E^{elec}_{BESS,max}$	8	kWh
Maximum charging power	$P^{elec}_{BESS,ch,max}$	3.0	kW
Maximum discharging power	$P^{elec}_{BESS,dch,max}$	3.0	kW
Maximum SOC	$SOC_{BESS,max}$	0.9	–
Minimum SOC	$SOC_{BESS,min}$	0.1	–
SOC self-discharge rate	ε_{BESS}	0.004	–
Charging efficiency	$\eta_{BESS,ch}$	95	%
Discharging efficiency	$\eta_{BESS,dch}$	95	%

Investment price The cost of a battery is approximately €600 per kWh [50]. Given that currently available batteries on the market can store between 3 and 20.5 kWh, the total investment ranges from €1.800 to €12.000, excluding installation costs [50]. For a 3 kWh battery, the estimated cost is around €4.000. For an 8 kWh model, the cost is approximately €8.000, while a 14 kWh battery is priced at around €10.000. Moreover, the expected lifespan of these batteries is typically between 10 and 15 years [50].

Characteristics Battery energy storage systems are characterized by their high energy density, efficiency, and versatility. BESS can store excess electricity generated from renewable sources like photovoltaic panels, enhance the overall efficiency of energy systems, and reduce dependence on the grid by shifting energy consumption to off-peak periods. This is particularly beneficial when electricity prices are variable, allowing for the storage of energy when prices are low and its utilization during peak demand periods when prices are high. However, BESS come with challenges, including high initial costs, and the need for meticulous management and maintenance to optimize performance and longevity.

In summary, this chapter has provided a comprehensive overview of the various household energy assets, highlighting their characteristics, benefits, and limitations. Natural gas boilers, electric resistance heaters, heat pumps, and photovoltaic panels represent a diverse array of energy production, each playing a unique role in a household's energy management strategy. While natural gas boilers offer a cost-effective solution, they rely on fossil fuels. On the other hand, electric heaters and heat pumps stand out for their ability to operate on potentially renewable electricity, especially when integrated with photovoltaic panels and energy storage systems.

The following chapter will explore how these components can be integrated into a consistent household energy management system. This system, which will be detailed in the next section, aims to optimize the use of these assets by managing demand, storing energy, and minimizing energy costs for the household. This integrated approach tends to enhance energy efficiency while reducing the household's overall carbon footprint.

3.2 Household energy management system

This section delves into the practical integration of the various components discussed in Section 3.1 into a unified household energy management system, chosen specifically for this case study, which represents the most common energy system setup in Belgian households. The system is designed to manage the household's energy needs efficiently by balancing the production, consumption and storage of electricity and heat, reflecting typical Belgian energy practices.

To meet its electricity needs, the household can source power from solar panels, the grid, or battery storage. The system also enables excess electricity to be either fed back into the grid or stored in the battery for later use. For heating, the household can rely on a combination of the gas boiler and the heat pump, both of which are widely used in Belgium. Hot water needs are addressed by drawing from a hot water tank, which can be heated either by an electric resistance heater integrated within the tank or by hot water supplied by the gas boiler or heat pump—methods commonly employed in Belgian homes. All of these energy flows and their interactions are visually represented in Figure 3.2, providing a comprehensive overview of how the household's energy needs are managed within the system.

This energy management system was selected because it accurately reflects the energy configuration of most Belgian households. The system allows the utilization of multiple energy sources to meet household demands, while also providing the capability to store energy. However, to ensure maximum efficiency and cost reduction, it is essential to optimize the flow of energy between these various sources and needs. Before optimization can take place, a thorough definition of the system is necessary, which is the focus of this chapter. Given that a linear system will be employed, it is crucial to derive and demonstrate the governing equations, which are illustrated in Figure 3.2.

The chapter begins by detailing the equations that ensure a balance between the different energy flows—electricity, hot water, and heating. Following this, the interactions between energy generation and storage components within the system are described. This comprehensive framework will facilitate the efficient management of household energy in a manner that aligns with current Belgian practices.

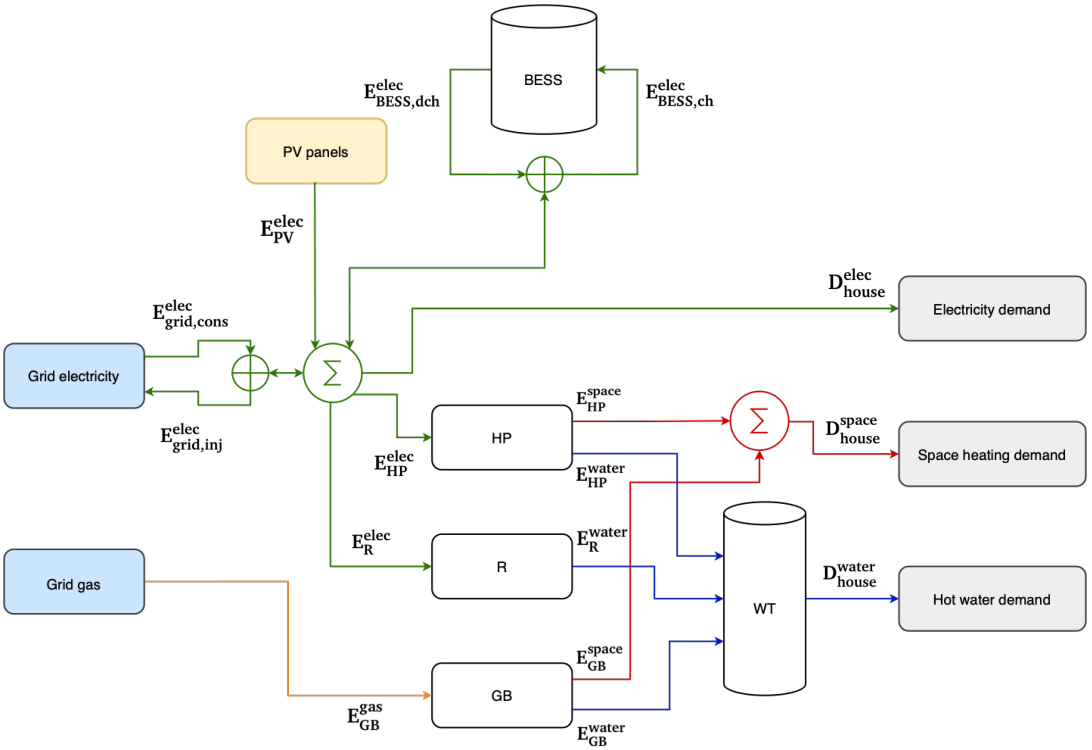


Figure 3.2: Illustration of the household energy management system. The energy flows are depicted as follows: electricity is represented by green lines, space heating by red lines, and hot water by blue lines. The household energy demands are enclosed in grey boxes, the connection to the grid is illustrated with a blue box, and the storage systems are represented by cylinders. Heating production assets are shown as black rectangles, and solar panels are indicated by a yellow box. The summation symbol signifies the addition of components, and the circular plus symbol indicates that the energy flow can be in one direction or the other, depending on the conditions.

3.2.1 Electrical balance

The electrical balance of the house is viewed as a system where certain components consume energy while others supply it.

- The energy-consuming components include the direct electrical demand of household appliances and lighting, as well as the indirect demand for operating electric assets such as the heat pump and electric resistance, and for charging the battery. Another energy-consuming component is the electricity injected into the grid as $E^{elec}_{grid,inj}(t)$.
- The energy-supplying components include the solar panels, electricity consumption from the grid as $E^{elec}_{grid,cons}(t)$, and battery discharge.

At any given time, the relationship between energy production $E^{elec}_{supply}(t)$ and consumption in the house $E^{elec}_{cons}(t)$ is ruled by Equation 3.13.

In addition, the house can either consume electricity from the grid or inject it, as described by Equations 3.14 to 3.16, and the battery energy storage system can either charge or discharge, as shown by Equation 3.17 to 3.19.

Box 1: Electrical balance equations

$$\underbrace{E^{elec}_{grid}(t) + E^{elec}_{PV}(t) + E^{elec}_{BESS,dch}(t)}_{E^{elec}_{supply}(t)} = \underbrace{E^{elec}_{HP}(t) + E^{elec}_{R}(t) + D^{elec}_{house}(t) + E^{elec}_{BESS,ch}(t)}_{E^{elec}_{cons}(t)} \quad \forall t \tag{3.13}$$

Grid usage equations :

$$x^{elec}_{grid,cons}(t) + x^{elec}_{grid,inj}(t) = 1 \quad \forall t \tag{3.14}$$

$$0 \leq E^{elec}_{grid,cons}(t) \leq E^{elec}_{grid,cons,max} \cdot x^{elec}_{grid,cons}(t) \quad \forall t \tag{3.15}$$

$$0 \leq E^{elec}_{grid,inj}(t) \leq E^{elec}_{grid,inj,max} \cdot x^{elec}_{grid,inj}(t) \quad \forall t \tag{3.16}$$

Battery charging/discharging equations :

$$x^{elec}_{BESS,ch}(t) + x^{elec}_{BESS,dch}(t) = 1 \quad \forall t \tag{3.17}$$

$$0 \leq E^{elec}_{BESS,dch}(t) \leq E^{elec}_{BESS,dch,max} \cdot x^{elec}_{BESS,dch}(t) \quad \forall t \tag{3.18}$$

$$0 \leq E^{elec}_{BESS,ch}(t) \leq E^{elec}_{BESS,ch,max} \cdot x^{elec}_{BESS,ch}(t) \quad \forall t \tag{3.19}$$

3.2.2 Space heating balance

For the space heating balance, the heat generated by the gas boiler and heat pump is utilized to satisfy the space heating demand, as expressed in Equation 3.20.

Box 2: Space heating balance equations

$$E^{space}_{HP}(t) + E^{space}_{GB}(t) = D^{space}_{house}(t) \quad \forall t \tag{3.20}$$

3.2.3 Hot water balance

The hot water balance is ruled by the energy supplied by the gas boiler, heat pump, and electric resistance to charge the hot water tank, as described in Equation 3.21. When the house requires hot water, it is drawn directly from the discharge of the hot water tank, as shown in Equation 3.22.

Box 3: Hot water balance equations

$$E^{water}_{R}(t) + E^{water}_{HP}(t) + E^{water}_{GB}(t) = E^{water}_{WT,L}(t) \quad \forall t \tag{3.21}$$

$$E^{water}_{WT,U}(t) = D^{water}_{house}(t) \quad \forall t \tag{3.22}$$

3.2.4 Energy production equations

The energy production equations, previously introduced in Section 3.1, are represented in Equations 4.8 to 4.10.

Both the heat pump and the gas boiler are capable of producing domestic hot water and space heating, but their capacities are limited, as described earlier. The

equations governing heat production are given in Equations 4.8 through 4.10. These equations represent systems that convert one form of energy into another, interconnecting the three energy balances: electricity, hot water, and space heating. Specifically, the heat pump and electric resistance heater convert electricity into hot water and, for the heat pump, into space heating as well. The gas boiler, on the other hand, converts gas into two forms of energy: heating and hot water, as outlined in Equation 4.10. Additionally, the equations related to the electrical energy generated by solar panels are described in Equation .

Moreover, it is assumed that when the gas boiler is used to produce space heating, it must also produce hot water. However, when it is used to produce hot water, it is not necessarily required to generate space heating, as described by the binary logic in Equations 3.27 to 3.29.

The rationale behind this assumption lies in the operational dynamics of the gas boiler. Once the boiler is running and has reached its operating temperature, its efficiency is maximized. This means that the boiler can produce heat more effectively, making it advantageous to produce both space heating and hot water simultaneously when the boiler is active. While the enthalpy of the exhaust gases is consistently well-utilized, the boiler's thermal inertia plays a key role in its operation. Therefore, when the boiler is already producing heat for space heating, it is logical to also produce and store hot water during this phase to optimize energy use. However, producing space heating is only necessary if there is an immediate demand, as the system typically cannot store heat for space heating. Consequently, when space heating is required, the boiler will produce both space heating and domestic hot water, either for immediate use or for storage.

Box 4: Production assets equations

[H]
Heat pump equation :

$$E^{elec}_{HP,space}(t) \cdot COP^{space}_{HP}(t) + E^{elec}_{HP,water}(t) \cdot COP^{water}_{HP}(t) \leq E^{heat}_{HP,max} \quad \forall t \qquad (3.23)$$

Electric resistance equation :

$$E^{elec}_{R}(t) \cdot \eta_R = E^{water}_{R}(t) \leq E^{heat}_{R,max} \quad \forall t \qquad (3.24)$$

PV panels equation :

$$CF_{PV}(t) \cdot E^{elec}_{PV,max} = E^{elec}_{PV}(t) \quad \forall t \tag{3.25}$$

Gas boiler equations :

$$E^{gas}_{GB,space}(t) \cdot \eta_{GB} + E^{gas}_{GB,water}(t) \cdot \eta_{GB} \leq E^{heat}_{GB,max} \quad \forall t \tag{3.26}$$

$$x^{space}_{GB}(t) \leq x^{water}_{GB}(t) \tag{3.27}$$

$$0 \leq E^{space}_{GB}(t) \leq E^{heat}_{GB,max} \cdot x^{space}_{GB}(t) \quad \forall t \tag{3.28}$$

$$0 \leq E^{water}_{GB}(t) \leq E^{heat}_{GB,max} \cdot x^{water}_{GB}(t) \quad \forall t \tag{3.29}$$

3.2.5 Storage balance

Finally, by incorporating the equations governing storage systems, as presented in Section 3.1 and summarized in Equations 3.30 to 3.37, the complete set of equations that define the household energy management system is obtained.

Box 5: Storage assets equations

Hot water storage balance equation :

$$E^{water}_{WT}(t+1) = (1 - \gamma_{WT}) \cdot E^{water}_{WT}(t) + E^{water}_{WT,L}(t) - E^{water}_{WT,U}(t) \quad \forall t \tag{3.30}$$

$$E^{water}_{WT}(t) \leq E^{water}_{WT,max} \quad \forall t \tag{3.31}$$

$$E^{water}_{WT}(N+1) = E^{water}_{WT}(1) \tag{3.32}$$

Electrical storage balance equation :

$$\begin{aligned} SOC(t+1)_{BESS} = SOC(t)_{BESS} - \gamma_{BESS} \cdot \Delta t \\ + \frac{\eta_{BESS,ch} \cdot E^{elec}_{BESS,ch}(t)}{E^{elec}_{BESS,max}} \\ - \frac{E^{elec}_{BESS,dch}(t)}{\eta_{BESS,dch} \cdot E^{elec}_{BESS,max}} \quad \forall t \end{aligned} \tag{3.33}$$

$$SOC_{BESS,min} \leq SOC(t)_{BESS} \leq SOC_{BESS,max} \quad \forall t \tag{3.34}$$

$$SOC(N+1)_{BESS} = SOC(1)_{BESS} \tag{3.35}$$

$$0 \leq \frac{E^{elec}_{BESS,dch}(t)}{\Delta t} \leq \frac{E^{elec}_{BESS,dch,max}}{\Delta t} \cdot x_{BESS,dch}(t) \quad \forall t \tag{3.36}$$

$$0 \leq \frac{E^{elec}_{BESS,ch}(t)}{\Delta t} \leq \frac{E^{elec}_{BESS,ch,max}}{\Delta t} \cdot x_{BESS,ch}(t) \quad \forall t \tag{3.37}$$

The household energy management system has been thoroughly defined, incorporating all relevant equations from 3.13 to 3.37. This system integrates key components such as solar production, and the demands for electricity, hot water, and space heating, providing a comprehensive representation of the energy dynamics within a typical Belgian household. The chapter has detailed the various energy production and storage assets, along with their operational principles and integration within the broader household energy system.

This comprehensive framework lays the foundation for the next phase, where the focus will shift to the economic optimization of the energy management system. By applying the pricing mechanisms previously discussed, the upcoming chapter will aim to optimize the system's operation to achieve cost-effective and efficient energy management.

Chapter 4

Optimization model description

In the pursuit of optimizing residential energy management, this study presents a linear optimization model designed to minimize the total annual costs associated with household energy consumption. The model aims to determine the optimal energy management strategy by analyzing energy flows on an hourly basis throughout the entire year. Additionally, it evaluates the economic viability of investing in advanced technologies such as heat pumps and domestic battery energy storage systems, offering a comprehensive approach to enhancing energy efficiency and cost minimization.

The core of the model is structured as a linear programming problem, where the objective is to identify the optimal configuration of decision variables that minimize the household's annual energy costs. These decision variables are subject to a set of predefined constraints that ensure the model's outputs are both realistic and applicable, within the operational limits of the household energy system. The model processes a set of inputs, including household energy demands, component capacities, and the specific tariff structure, to define the household scenario and subsequently outputs the optimal energy management strategy on an hourly basis, providing detailed guidance on the most cost-effective practices for the entire year.

Specifically, the optimization algorithm is designed to minimize total system costs by determining the optimal decision variables while adhering to the given constraints. The problem is mathematically formulated as follows:

$$\min \underbrace{\text{Equation 4.1}}_{\text{Objective function}} \quad \text{subject to} \quad \underbrace{\text{Box 2 to Box 5, Equation 4.7 to Equation 4.16}}_{\text{Constraint functions}}$$

This formulation is solved using linear solvers capable of efficiently managing the problem's scale and complexity. Notably, the model covers the entire annual

scheduling horizon, from the first hour of the year t=1 to the last t=8760, ensuring a comprehensive and continuous optimization process. The details of the objective function and the constraint functions are discussed in the subsequent sections of this chapter.

4.1 Objective function

The objective function of the model aims to minimize the household's total annual costs, which are divided into energy costs—encompassing electricity and gas expenses—and the annual amortized costs associated with the installation of new technologies, such as a heat pump or a battery energy storage system.

$$\text{Cost}_{\text{household}} = \text{Cost}_{\text{energy}} + \text{Cost}_{\text{installation}} \tag{4.1}$$

4.1.1 Energy costs

The energy cost component of the objective function is defined according to the type of remuneration for photovoltaic systems: either through a reduction in billed electricity consumption or through compensation based on the quantity of electricity injected into the grid, as explained in Section 2.3.

Reduction in the billed electricity consumption This scenario applies exclusively to households with classic meters, where energy prices are fixed by default. The annual electricity bill is calculated based on the net electricity consumption, which is defined as the difference between the total electricity drawn from the grid and the electricity injected back into the grid. As a reminder, this net energy balance cannot be negative; it must be at least zero.

$$\begin{aligned}\text{Cost}_{\text{energy}} = \max\left(0, \sum_{t=1}^{t=8760} \text{E}^{\text{elec}}_{\text{grid,cons}}(t) - \text{E}^{\text{elec}}_{\text{grid,inj}}(t)\right) \cdot \text{Price}_{\text{elec,fixed}} \\ + \sum_{t=1}^{t=8760} \text{E}^{\text{gas}}_{\text{GB}}(t) \cdot \text{Price}_{\text{gas,fixed}} \\ + \text{Cost}_{\text{cons,fixed}} + \text{Cost}_{\text{inj,fixed}} + \text{Cost}_{\text{gas,fixed}}\end{aligned} \tag{4.2}$$

Compensation based on injection quantity In this scenario, electricity consumption and injection are metered separately, with distinct prices for each. The model accounts for these variables independently, reflecting their individual impact

on the total energy cost. The consumption and injection prices can be fixed (by default for traditional meters) or variable, with monthly or hourly rates (except for gas, which has only monthly rates). Quarterly rates are also possible, but they are not studied in this thesis. The model calculates costs based on these rates, accommodating monthly or hourly variations as required.
The number 8760 in the following equations corresponds to the total number of hours in a 365-day year.

1. Fixed electricity and gas rates:

$$\begin{aligned} \text{Cost}_{\text{energy}} = & \sum_{t=1}^{t=8760} \text{E}^{\text{elec}}_{\text{grid,cons}}(t) \cdot \text{Price}_{\text{elec,fixed}} \\ & + \sum_{t=1}^{t=8760} \text{E}^{\text{elec}}_{\text{grid,inj}}(t) \cdot \text{Price}_{\text{inj,fixed}} \\ & + \sum_{t=1}^{t=8760} \text{E}^{\text{gas}}_{\text{GB}}(t) \cdot \text{Price}_{\text{gas,fixed}} \\ & + \text{Cost}_{\text{cons,fixed}} + \text{Cost}_{\text{inj,fixed}} + \text{Cost}_{\text{gas,fixed}} \end{aligned} \tag{4.3}$$

2. Monthly electricity and gas rates:

$$\begin{aligned} \text{Cost}_{\text{energy}} = & \sum_{m=1}^{m=12} \sum_{t \in \text{month } m} \text{E}^{\text{elec}}_{\text{grid,cons}}(t) \cdot \text{Price}_{\text{elec,variable m}} \\ & + \sum_{m=1}^{m=12} \sum_{t \in \text{month } m} \text{E}^{\text{elec}}_{\text{grid,inj}}(t) \cdot \text{Price}_{\text{inj,variable m}} \\ & + \sum_{m=1}^{m=12} \sum_{t \in \text{month } m} \text{E}^{\text{gas}}_{\text{GB}}(t) \cdot \text{Price}_{\text{gas,variable m}} \\ & + \text{Cost}_{\text{cons,fixed}} + \text{Cost}_{\text{inj,fixed}} + \text{Cost}_{\text{gas,fixed}} \end{aligned} \tag{4.4}$$

3. Hourly electricity rate and monthly gas rate :

$$\begin{aligned} \text{Cost}_{\text{energy}} = & \sum_{t=1}^{t=8760} \text{E}^{\text{elec}}_{\text{grid, cons}}(t) \cdot \text{Price}_{\text{elec, variable t}} \\ & + \sum_{t=1}^{t=8760} \text{E}^{\text{elec}}_{\text{grid, inj}}(t) \cdot \text{Price}_{\text{inj, variable t}} \\ & + \sum_{m=1}^{m=12} \sum_{t \in \text{month m}} \text{E}^{\text{gas}}_{\text{GB}}(t) \cdot \text{Price}_{\text{gas, variable m}} \\ & + \text{Cost}_{\text{cons,fixed}} + \text{Cost}_{\text{inj,fixed}} + \text{Cost}_{\text{gas,fixed}} \end{aligned} \tag{4.5}$$

4.1.2 Installation costs

Installation costs refer to the annual amortized expenses resulting from the investment and installation of new technologies, such as a heat pump or a battery energy storage system within the household. These costs are incorporated into the model as follows:

$$\text{Cost}_{\text{investment}} = x_{\text{inst,HP}} \cdot \text{Price}_{\text{inst,HP}} + x_{\text{inst,BESS}} \cdot \text{Price}_{\text{inst,BESS}} \tag{4.6}$$

where $x_{\text{inst,i}}$ is a binary variable indicating whether the asset is installed ($x_{\text{inst,i}} = 1$) or not ($x_{\text{inst,i}} = 0$). If the asset is installed $x_{\text{inst,i}} = 1$, then an additional cost $\text{Price}_{\text{inst,i}}$, representing the amortized cost due to the installation of this asset, is incurred.

With the objective function determined, it is essential to establish what the model and decision variables must adhere to in order to minimize this objective function. It is crucial that the model satisfies the system's demands and limitations, as well as the specific conditions of the case study. This will be achieved by defining constraint functions, which will be presented in the following section.

4.2 Constraint functions

The optimization model is governed by a set of constraint functions that ensure the decision variables stay within realistic and feasible boundaries while adhering to the specific constraints of the case study and the requirements of the energy management system. These constraints are divided into two main categories: constraints related to the household energy management system and constraints specific to the study case.

4.2.1 Energy management system constraints

The constraints of the energy management system play a crucial role in ensuring the efficient operation of the household's energy infrastructure. These constraints are defined by the equations presented in the previous chapter and are highlighted within the framed sections for clarity. These constraints include several key components:

- **Supply-demand balance:** The model is required to maintain a consistent energy balance, ensuring that the energy supply always meets the demand. The balances of electricity, hot water, and space heating are each critical to the system's stability and reliability, as illustrated in Box 1, 2, and 3.
- **Asset operation conditions:** These constraints set the operational parameters for energy production assets, ensuring they function within their designed capacities by regulating power output and operating conditions. Box 4 details these limits, ensuring consistent performance of all energy-producing components.
- **Storage conditions:** These constraints are vital for regulating the operations of energy storage. They ensure that both the storage and retrieval of energy occur within the system's established limits, thereby optimizing the overall performance. The conditions ruling storage are depicted in Box 5.

Each of these elements is essential for maintaining the integrity and efficiency of the energy management system, ensuring that it meets the demands of the household while operating within its technical constraints.

4.2.2 Study-specific Constraints

Study-specific constraints are designed to align with the particular characteristics of the case study under analysis. These constraints include prohibiting the simultaneous operation of different heating technologies, limiting the frequency of transitions between these technologies, and incorporating installation costs only when the heat pump/battery energy storage system is used during the year.

No Simultaneity Constraints To reflect the study scenario where households without smart meters cannot manage multiple heating technologies simultaneously, these constraints prohibit the concurrent operation of different heating systems. Consequently, when one technology is active, all other technologies must remain inactive. This condition is enforced by the following equation, which uses binary variables to ensure compliance:

$$x_{\mathrm{GB}}(\mathrm{t}) + x_{\mathrm{R}}(\mathrm{t}) + x_{\mathrm{HP}}(\mathrm{t}) \leq 1 \quad \forall \mathrm{t} \tag{4.7}$$

Here, $x_i(\mathrm{t})$ is a binary variable indicating whether the operational status of each heating technology i is active ($x_i(\mathrm{t}) = 1$) or inactive ($x_i(\mathrm{t}) = 0$).

To properly integrate the operational status of each technology into the model, the energy production of each system is constrained by its respective capacity limits. This is described by the following equations, where the upper bounds of energy production, as shown in Box 4, are enforced:

$$\mathrm{E}_{\mathrm{HP}}^{\mathrm{space}}(\mathrm{t}) + \mathrm{E}_{\mathrm{HP}}^{\mathrm{water}}(\mathrm{t}) \leq \mathrm{E}_{\mathrm{HP}}^{\mathrm{heat,max}} \cdot x_{\mathrm{HP}}(\mathrm{t}) \quad \forall \mathrm{t} \tag{4.8}$$

$$\mathrm{E}_{\mathrm{R}}^{\mathrm{water}}(\mathrm{t}) \leq \mathrm{E}_{\mathrm{R}}^{\mathrm{heat,max}} \cdot x_{\mathrm{R}}(\mathrm{t}) \quad \forall \mathrm{t} \tag{4.9}$$

$$\mathrm{E}_{\mathrm{GB}}^{\mathrm{space}}(\mathrm{t}) + \mathrm{E}_{\mathrm{GB}}^{\mathrm{water}}(\mathrm{t}) \leq \mathrm{E}_{\mathrm{GB}}^{\mathrm{heat,max}} \cdot x_{\mathrm{GB}}(\mathrm{t}) \quad \forall \mathrm{t} \tag{4.10}$$

Number of transitions constraints Given that many Belgian households lack a smart management system capable of automatically switching between heating technologies, manual intervention is required. To realistically represent this scenario, the model imposes a limit on the number of transitions between heating technologies. Specifically, it is assumed that a homeowner is willing to manually switch between technologies a maximum of $\mathrm{N}^{\mathrm{max}}$ times per year.

In addition, frequent switching could lead to reduced system efficiency and accelerated wear of the equipment. For example, each time a heating system, such as a boiler, is turned on or off, it loses energy due to the inherent inertia of the system. It is generally more efficient to keep such systems running for longer periods rather than frequently turning them on and off.

These constraints are mathematically expressed as follows:

$$\sum_{\mathrm{t}=0}^{8760} x_{\mathrm{on}\to\mathrm{off,GB}}(\mathrm{t}) + x_{\mathrm{on}\to\mathrm{off,R}}(\mathrm{t}) + x_{\mathrm{on}\to\mathrm{off,HP}}(\mathrm{t}) \leq \mathrm{N}^{\mathrm{max}} \tag{4.11}$$

$$\sum_{\mathrm{t}=0}^{8760} x_{\mathrm{off}\to\mathrm{on},}(\mathrm{t}) + x_{\mathrm{off}\to\mathrm{on,R}}(\mathrm{t}) + x_{\mathrm{off}\to\mathrm{on,HP}}(\mathrm{t}) \leq \mathrm{N}^{\mathrm{max}} \tag{4.12}$$

In this context, $x_{\mathrm{off}\to\mathrm{on},i}(\mathrm{t}) = 1$ represents a transition from off to on for technology i between time t and t+1, while $x_{\mathrm{on}\to\mathrm{off},i}(\mathrm{t}) = 1$ denotes a transition from on to off. A value of zero indicates no transition has occurred. The model enforces these

constraints by limiting the total number of transitions to a predefined maximum, N^{max}.

The transitions from on to off and from off to on are mathematically defined in Equation 4.13, based on the change in the production state between time t and $t+1$. The state of production can either remain constant, transition from on to off, or transition from off to on, as detailed in Equation 4.14.

$$x_{\text{on}\rightarrow\text{off},i}(\text{t}) - x_{\text{off}\rightarrow\text{on},i}(\text{t}) = x_i(\text{t}+1) - x_i(\text{t}) \quad \forall i \in \{\text{GB}, \text{HP}, \text{R}\} \quad \forall \text{t} \tag{4.13}$$

$$x_{\text{off}\rightarrow\text{on},i}(\text{t}) + x_{\text{on}\rightarrow\text{off},i}(\text{t}) \leq 1 \quad \forall i \in \{\text{GB}, \text{HP}, \text{R}\} \quad \forall \text{t} \tag{4.14}$$

With the installation of smart management systems in households, the constraints related to simultaneity and the number of transitions between heating technologies can be eliminated. These systems can automate the switching process, optimizing energy use without the need for manual intervention. Consequently, it becomes valuable to analyze the system's response without these constraints, as the smart management systems would allow for more dynamic and efficient energy transitions, potentially improving overall performance and reducing energy waste.

Installation cost constraints Installation costs are incurred only if the heat pump and/or the battery energy storage system is used at any point during the year. If these technologies are not used, the associated installation costs are excluded from the total cost calculation.

The installation of technology i is represented by a binary variable $x_{\text{inst,i}}$, which equals 1 if the technology is installed, and 0 otherwise. Therefore, if at any time during the year the BESS or HP is operational, indicated by $x_{\text{BESS,ch}}(\text{t}) = 1$[1], or $x_{\text{HP}}(\text{t}) = 1$, then $x_{\text{inst,i}}$ must be set to 1, as represented in Equations 4.15 and 4.16. This inclusion adds an additional cost to the objective function, as defined in Equation 4.6.

This constraint is enforced by the following conditions:

$$x_{\text{BESS,ch}}(\text{t}) \leq x_{\text{inst,BESS}} \quad \forall \text{t} \tag{4.15}$$

[1]This could also be $x_{\text{BESS,dch}}(\text{t})$, as charging or discharging the battery necessitates its installation.

$$x_{\mathrm{HP}}(\mathrm{t}) \leq x_{\mathrm{inst,HP}} \quad \forall \mathrm{t} \tag{4.16}$$

Finally, it is important to note that certain implicit conditions exist based on the nature of the decision variables. For instance, when a variable is defined as a non-negative real number, this inherently imposes a constraint that the variable must be greater than or equal to zero.

In conclusion, this chapter has outlined a comprehensive linear optimization model designed to minimize the total annual costs of residential energy consumption by determining optimal energy management strategies. The model operates on an hourly resolution over the course of an entire year, taking into account the feasibility of investing in advanced technologies such as heat pumps and battery energy storage systems. Through the careful formulation of an objective function and the implementation of critical constraint functions, the model ensures that the energy management system operates efficiently within realistic boundaries. This approach not only enhances energy efficiency but also provides a robust framework for households to make informed decisions regarding the adoption of new energy technologies, ultimately contributing to cost minimization and sustainability in residential energy use.

In the next chapter, the results obtained from applying this model under various scenarios will be thoroughly analyzed. By examining these outcomes, this thesis aims to provide valuable insights that will help consumers draw general conclusions about the most effective strategies for optimizing their energy management.

Chapter 5

First case study

The first part of the research focuses on a household equipped with a gas boiler, an electric heater, a water tank, and solar panels, which operates under a remuneration scheme based on billed electricity consumption. This household uses a traditional meter that applies a fixed default price. The goal is to determine when it is economically advantageous to switch from the gas boiler to the electric heater. Additionally, the user is interested in evaluating the potential benefits of investing in additional energy assets. As a reminder, as discussed in Section 2.3, under this type of remuneration scheme, there is no temporal significance to when electricity or gas is consumed, nor is there a strong incentive for direct self-consumption of solar energy. However, it is expected that any increase in electricity consumption will be synchronized with solar panel production to avoid losses from non-remunerated energy injections.

Initially, the current scenario is analyzed with and without the integration of solar panels. This is followed by an exploration of strategic investment decisions aimed at enhancing energy efficiency and economic returns.

5.1 Baseline scenario without PV Panels

5.1.1 Optimization results

In the absence of solar panels, the optimization results indicate that the gas boiler is used consistently throughout the year, with the electric heater remaining inactive. The economic analysis yields an annual cost of €3448 for the year 2023, with no significant adjustments in energy consumption patterns required.

5.1.2 Economic analysis

Without solar panels, the household relies entirely on grid electricity, with a 2023 fixed electricity price of €0.405/kWh. The associated annual electricity cost is calculated as:

$$\text{Cost}_{\text{elec}} = \text{Cons}_{\text{elec}} \cdot \text{Price}_{\text{elec,fixed}} = 3500 \cdot 0.405 = 1417.5 \text{ euros} \tag{5.1}$$

For hot water production, the gas boiler is exclusively utilized, resulting in an annual gas cost of:

$$\text{Cost}_{\text{gas}} = \text{Cons}_{\text{gas}} \cdot \text{Price}_{\text{gas,fixed}} = \frac{17000}{0.9} \cdot 0.1075 = 2030.5 \text{ euros} \tag{5.2}$$

The total annual energy cost amounts to €3448, as reflected in the optimization results.

The optimization favors the gas boiler over the electric heater due to the lower cost per kWh of hot water produced by the gas boiler. The cost per kWh of hot water from the gas boiler, denoted as $\text{Cost}_{\text{GB}}^{\text{water}}$, is calculated as follows:

$$\text{Cost}_{\text{GB}}^{\text{water}} = \frac{1 \text{ kWh}^{\text{water}}}{\eta_{\text{GB}}} \cdot \text{Price}_{\text{gas}} \tag{5.3}$$

Similarly, the cost per kWh of hot water from the electric heater, denoted as $\text{Cost}_{\text{R}}^{\text{water}}$, is given by:

$$\text{Cost}_{\text{R}}^{\text{water}} = \frac{1 \text{ kWh}^{\text{water}}}{\eta_{\text{R}}} \cdot \text{Price}_{\text{elec}} \tag{5.4}$$

Using 2023 prices, €0.1075/kWh for gas and €0.405/kWh for electricity, the respective costs are:

$$\text{Cost}_{\text{GB}}^{\text{water}} = 12 \text{ ct€/kWh}^{\text{water}} \quad \text{and} \quad \text{Cost}_{\text{R}}^{\text{water}} = 41 \text{ ct€/kWh}^{\text{water}} \tag{5.5}$$

Given that the cost per kWh of hot water from the gas boiler is consistently lower than that from the electric heater, the gas boiler is utilized throughout the year for hot water production. This remains valid as long as the following condition holds true:

$$\text{Cost}_{\text{GB}}^{\text{water}} \leq \text{Cost}_{\text{R}}^{\text{water}} \Leftrightarrow \frac{\eta_{\text{R}}}{\eta_{\text{GB}}} \leq \frac{\text{Price}_{\text{elec}}}{\text{Price}_{\text{gas}}} \tag{5.6}$$

The threshold for the ratio of electricity to gas prices is approximately 1.089. As long as the price ratio $\frac{\text{Price}_{\text{elec}}}{\text{Price}_{\text{gas}}}$ exceeds this value, it is more cost-effective to use the gas boiler. Historically, this ratio has ranged between 0.17 and 0.29, making the use of the electric heater economically unfeasible [9].

5.1.3 Environmental impact

The continuous operation of the gas boiler throughout the year results in annual CO_2 emissions of approximately 4571 kg, based on an emission factor of 0.242 $kgCO_2$/kWh for natural gas consumption [11]. These emissions reflect the direct impact of gas consumption, excluding any contribution from grid electricity usage.

5.1.4 Conclusion

In the scenario where the household lacks solar panels, the most economically viable strategy is to rely on the gas boiler throughout the year, even in the presence of an electric heater.

5.2 Scenario with PV Panels

5.2.1 Optimization results

The integration of solar panels significantly alters the household's energy management strategy. When the household produces more electricity than it consumes, the excess production is utilized by the electric heater to produce hot water, reducing the overall energy costs. The optimization results show that as PV production increases, a point is reached where all summer hot water demand is met by the electric heater. Beyond this threshold, any further PV production leads to energy loss as the excess electricity is not remunerated.

The optimization outcomes for various scenarios of annual PV production are illustrated in Figure 5.2, with the corresponding annual costs presented in Figure 5.1. These scenarios highlight the shifting dynamics in energy management as PV production increases.

1) Annual PV Production Below 3500 kWh (Scenarios 1-3)
For PV production below 3500 kWh, which corresponds to the household's annual electricity demand, the electric heater remains inactive. The household injects less electricity into the grid (purple column) than it imports from the grid (pink

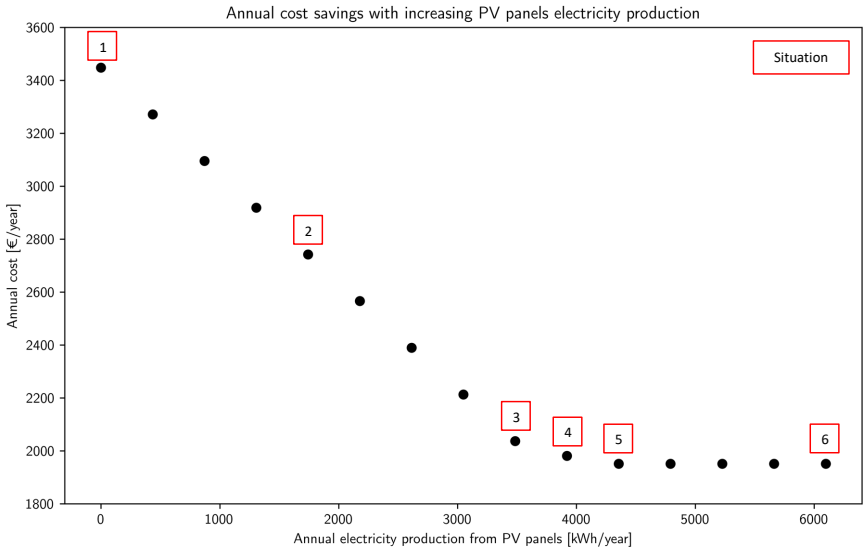


Figure 5.1: Case study outcomes for a household with photovoltaic panels, a gas boiler, an electric resistance heater, and a hot water tank, examining the effects of increasing annual PV production on annual costs. Below 3500 kWh of annual PV production, annual costs decrease linearly. As production increases from 3500 to 4170 kWh, the cost reduction slows, stabilizing when production reaches 4170 kWh or higher.

column), resulting in a linear reduction in annual costs as PV production increases.

2) Annual PV Production Equal to 3500 kWh

At 3500 kWh of annual PV production, the household achieves a balance between electricity injection and consumption, leading to maximum savings of €1417.5, equivalent to the electricity cost.

3) Annual PV Production Between 3500 kWh and 4170 kWh (Scenario 4)

For PV production exceeding 3500 kWh, the excess energy is utilized by the electric heater for hot water production. The annual costs continue to decrease, albeit at a slower rate, eventually stabilizing at €1951.5 when annual PV production reaches 4170 kWh.

4) Annual PV Production Above 4170 kWh (Scenarios 5-6)

When PV production exceeds 4170 kWh, the electric heater meets all summer hot water demand, and any further PV production leads to increased grid injection without additional financial benefits. As a result, the annual costs plateau at €1951.5, indicating no further economic gains beyond this production level.

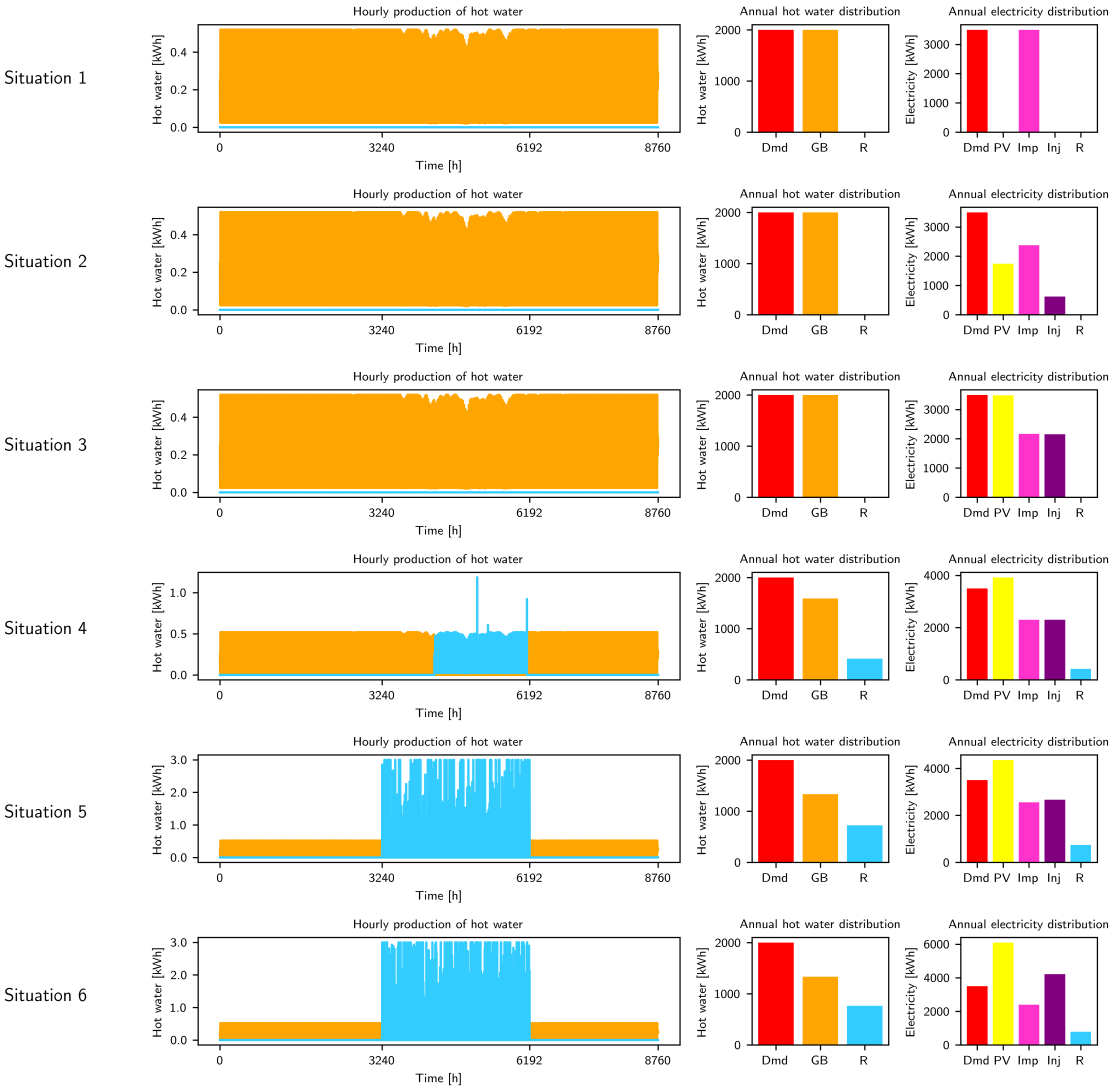


Figure 5.2: Results of a case study analyzing six scenarios with increasing annual PV production for a household equipped with photovoltaic panels, a gas boiler, an electric resistance heater, and a hot water tank. For PV production below 3500 kWh, the electric resistance heater is not utilized. Between 3500 and 4170 kWh, it partially meets the hot water demand during the summer, and beyond 4170 kWh, it fully covers the hot water needs during the summer months.

5.2.2 Advanced scenario analysis

Each kWh generated by the PV system can be utilized in one of three ways:

1. Direct household consumption: Offsetting the purchase of 1 kWh of grid electricity, resulting in a direct saving of €0.405 per kWh.
2. Grid injection: Yielding a remuneration of €0.405 per kWh injected, providing an equal return to direct consumption.
3. Heat production via electric heater: Conversion of 1 kWh of electricity into 0.98 kWh of heat, avoiding the consumption of 1.089 kWh of gas, which equates to a saving of €0.117 per kWh.

The results clearly indicate that the household benefits more from direct consumption or grid injection of electricity rather than using it to produce hot water. The cost curve decreases linearly with a slope corresponding to the electricity price up to 3500 kWh, beyond which the use of the electric heater becomes beneficial. The cost reduction continues at a slower rate of €0.117 per kWh until all summer hot water demand is met by the electric heater at 4170 kWh, after which any further PV production yields no additional economic benefits.

5.2.3 Environmental impact

By substituting gas consumption with electricity for hot water production, the household reduces its carbon footprint by approximately 177 kg CO_2 annually, representing a 4% decrease in emissions compared to scenarios where the electric heater is not utilized.

5.2.4 Price influence

Figure 5.3 illustrates that while energy prices impact the overall cost to the household, they do not alter the optimal energy management strategy. The thresholds at 3500 kWh and 4170 kWh remain critical for the household's energy management system, regardless of price fluctuations, provided the price ratio between electricity and gas remains within the range described in Section 5.1.2.

5.2.5 Conclusion

For households generating less electricity than their annual consumption, relying solely on the gas boiler is the most cost-effective strategy. However, for those producing around 20% more than their consumption, using the electric heater

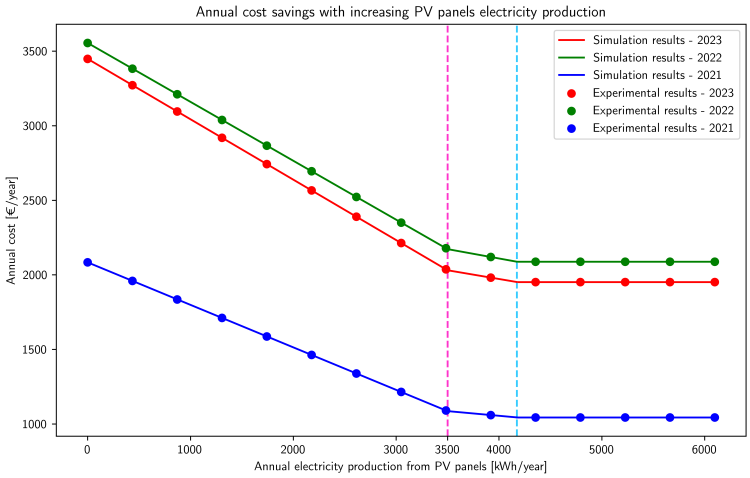


Figure 5.3: Impact of energy prices on annual household costs, evaluated using price data from 2021 to 2023. While energy prices influence the overall cost, they do not affect the optimal energy usage strategy. Key thresholds at 3500 kWh and 4170 kWh remain critical for the household's energy management system, regardless of price fluctuations.

during summer months is beneficial, though the economic and environmental gains are modest, around 4%. The study also highlights that under a fixed tariff remuneration structure, there is no significant incentive to align consumption with production periods, making investments in storage systems unnecessary.

5.3 Investment Analysis

The limited potential of the electric resistance heater, which only meets summer hot water demand and covers a mere 4% of the household's annual thermal needs, results in minimal economic and environmental benefits. In scenarios with high PV production, a significant portion of the generated energy remains unused, prompting consideration of an investment in a heat pump. Unlike the electric resistance heater, a heat pump can provide both space heating and hot water throughout the year, leading to greater cost savings and a substantial reduction in greenhouse gas emissions.

5.3.1 Results

Figure 5.5 illustrates the optimal scheduling for various scenarios of annual PV production, while Figure 5.4 details the corresponding annual costs. These sce-

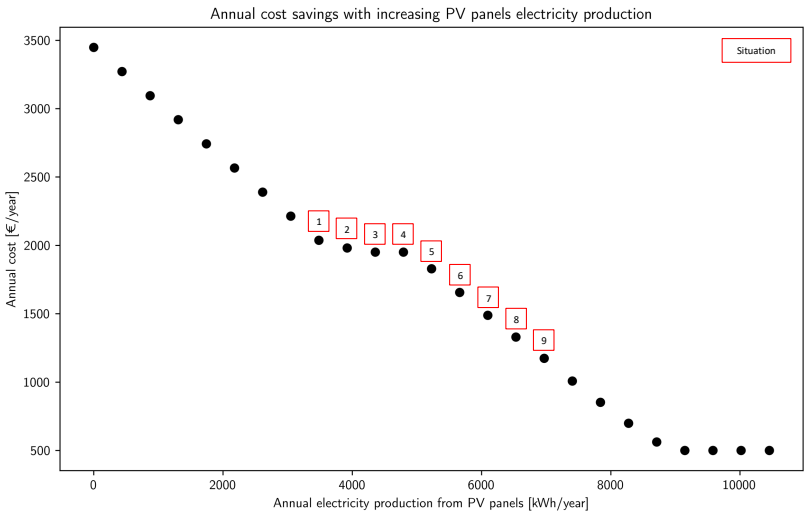


Figure 5.4: Annual cost results for a household equipped with photovoltaic panels, a gas boiler, an electric resistance heater, and a hot water tank, examining the impact of increasing PV production and the potential benefits of investing in a heat pump.

narios examine the impact of different levels of PV production on the utilization of the electric heater and heat pump, as well as on overall annual costs.

Investing in a heat pump becomes financially advantageous when annual PV production reaches approximately 5000 kWh, as depicted in Figures 5.5 and 5.4. At this production level, the heat pump begins to replace the electric resistance heater, resulting in a renewed decrease in annual energy costs with a relatively linear reduction, as shown in Figure 5.4. The heat pump operates in tandem with the gas boiler, and as solar production increases, the heat pump's contribution to the household's heating needs grows while reliance on the gas boiler diminishes. Once PV production exceeds approximately 9000 kWh per year, the heat pump is capable of fully meeting the household's heating demands, effectively reducing net electricity consumption to zero. At this stage, the only remaining costs are the initial investment in the heat pump, around €500, along with the fixed electricity costs.

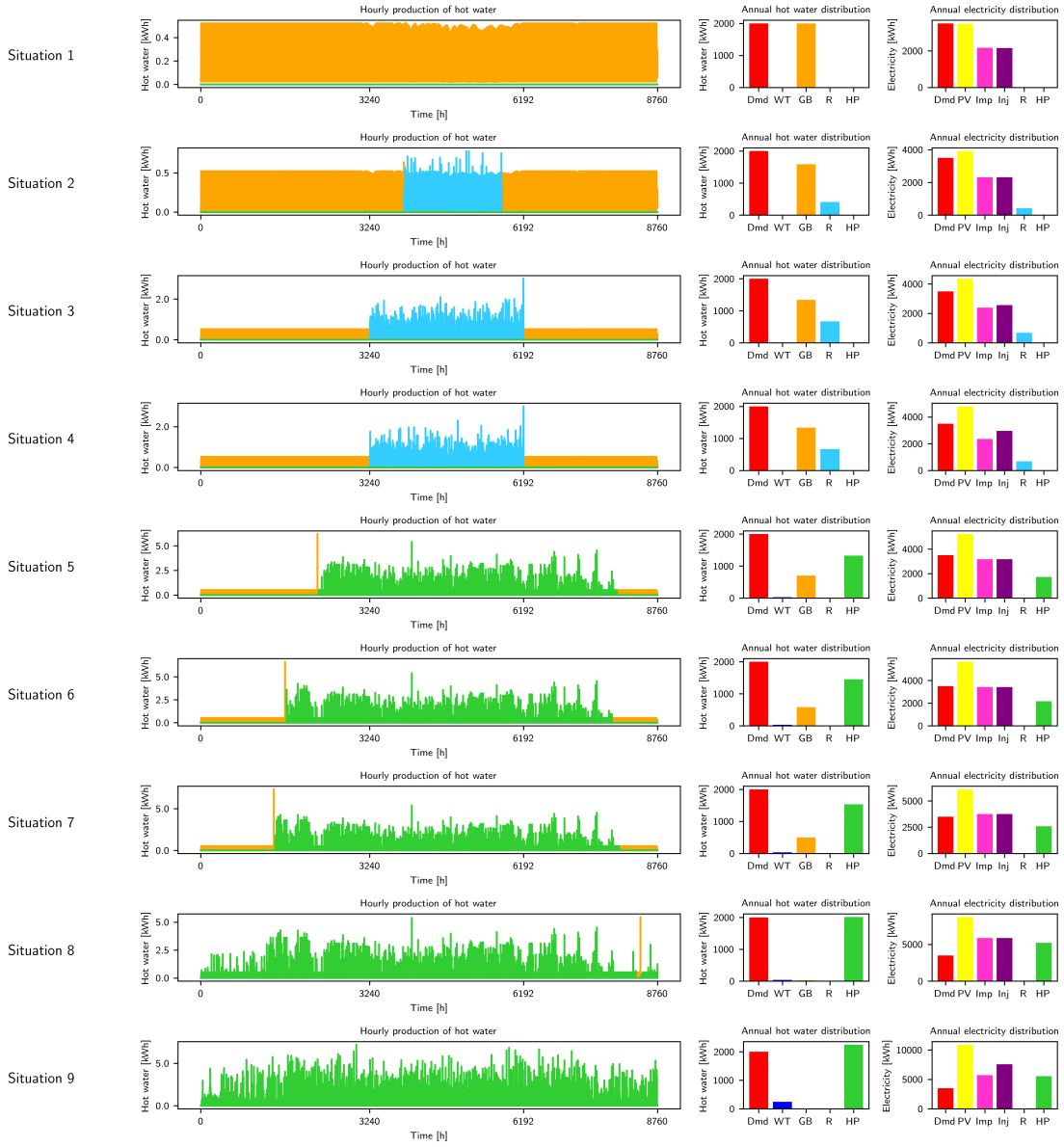


Figure 5.5: Representation optimal utilization of the electric resistance heater and heat pump across different annual PV production scenarios for a household with a gas boiler and hot water tank. It demonstrates how, with increasing PV production, the electric heater's contribution to summer hot water needs and the shift to the heat pump, especially as production surpasses 5000 kWh annually.

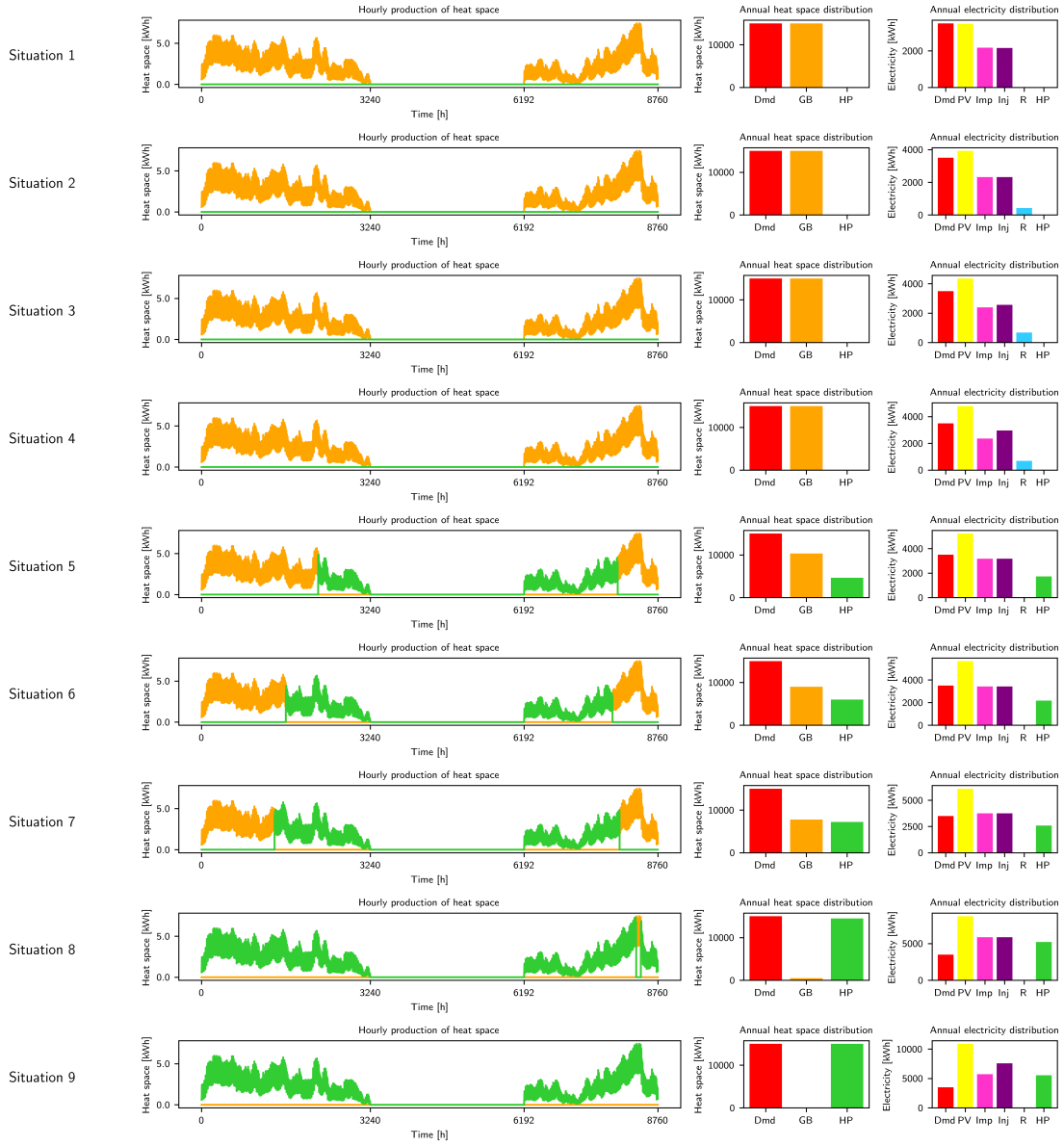


Figure 5.6: Results from a case study showing the effect of increasing annual PV production on space heating and hot water production for a household equipped with photovoltaic panels, a gas boiler, an electric resistance heater, and a heat pump. This figure illustrates how the use of the electric resistance heater diminishes and is eventually replaced by the heat pump as PV production rises, particularly after 9000 kWh per year.

5.3.2 Economic and environmental analysis

The presented results are further clarified by comparing the cost curves of two scenarios: one with electric resistance heating combined with a gas boiler, and the other with a heat pump supplementing or replacing the gas boiler.

The first cost curve, as analyzed in the previous section, is depicted in blue in Figure 5.7. The second curve represents the scenario with a heat pump installed. Initially, the annual costs are higher due to the amortized investment in the heat pump, approximately €500. However, as discussed earlier, the net energy savings from using the heat pump eventually outweigh the operational costs, making it an economically viable option as annual PV production increases.

For the heat pump, each kilowatt-hour of electricity is converted into heat with a coefficient of performance that varies depending on whether it is producing hot water or space heating, and is also influenced by weather conditions. While it is complex to simulate an exact cost curve due to these variables, boundary conditions can be established according to the lowest COP for hot water and the highest COP for space heating. The actual cost reduction will fall between these boundary cases, with the green line in the case study representing a mean COP that fits the observed results (dotted green curve).

The intersection between the cost curves indicates the point at which it becomes more cost-effective to use the heat pump rather than the electric resistance heater. As shown, when annual PV production reaches approximately 5000 to 6000 kWh, transitioning to a heat pump becomes more economically beneficial. Between 6000 and 9000 kWh, the heat pump operates in combination with the gas boiler, with the proportion of heat provided by the heat pump increasing alongside solar production. Beyond 9000 kWh of annual production, the heat pump alone is sufficient to meet the household's heating needs, effectively eliminating the need for the gas boiler.

Environmental impact: This transition not only offers economic benefits but also has a significant environmental impact by substantially reducing gas consumption compared to scenarios relying solely on the electric resistance heater.

Price influence: The economic benefit of investing in a heat pump is influenced by energy prices, as illustrated in Figure 5.8. However, based on recent price data, it can be concluded that a production level of around 5000 to 6000 kWh annually makes this investment profitable.

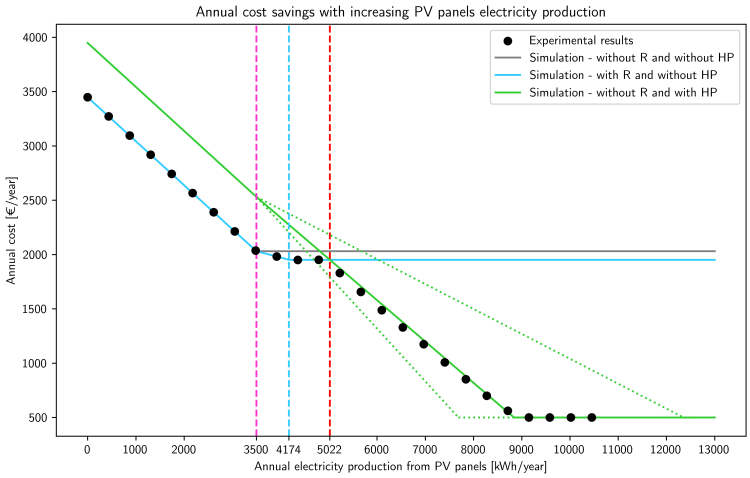


Figure 5.7: Comparative analysis of annual costs for scenarios with and without a heat pump. The figure shows the intersection point where it becomes more cost-effective to switch from electric resistance heating to a heat pump as annual PV production increases, particularly between 5000 and 6000 kWh, highlighting the economic and environmental benefits of this transition.

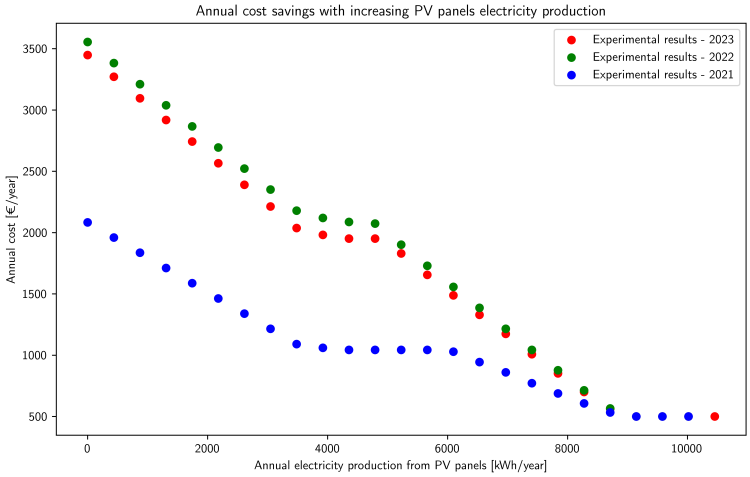


Figure 5.8: Impact of energy prices on the economic feasibility of investing in a heat pump for a household with PV production. The figure suggests that, given the variability in prices, the threshold at which a heat pump becomes financially beneficial lies between 5000 and 6000 kWh of annual PV production.

5.3.3 Conclusion

Investing in a heat pump becomes financially viable when annual PV production exceeds 6000 kWh, typically corresponding to a household generating more than 50% of its annual electricity consumption. As production increases beyond this threshold, the heat pump gradually replaces the gas boiler, leading to further economic reductions. Once annual production surpasses 9000 kWh, the household's energy costs are primarily limited to the heat pump's investment and fixed charges. However, it is important to note that these results are highly dependent on prevailing energy prices.

Conclusion

For households operating under a remuneration scheme based on electricity consumption, the optimal strategy depends on the balance between electricity production and consumption. If annual PV production is less than annual electricity consumption, it is most economical to rely solely on the gas boiler. For households producing 20% more than their consumption, using the electric heater during summer months is recommended. For those generating 50% more than consumption, investing in a heat pump is advised. The analysis also shows that in this remuneration scenario, there is no significant emphasis on self-consumption or the timing of energy use, making investments in thermal or electrical storage unnecessary.

Chapter 6

Second case study

This chapter delves into the energy management of a residential household equipped with a hybrid energy system comprising a gas boiler, an electric heater, a water tank, and solar photovoltaic panels. The household operates under a dual remuneration model, where compensation is provided for electricity injected into the grid. The primary objective is to optimize the conditions under which the transition from gas heating to electric heating during summer months is economically viable and to assess the potential economic benefits of investing in additional energy infrastructure.

As discussed in Section 2.3, the remuneration structure inherently favors self-consumption, given that the feed-in tariff for excess solar energy is considerably lower than the retail price of electricity consumed from the grid. Consequently, it is hypothesized that the temporal alignment of energy consumption with periods of peak solar generation will become increasingly critical compared to earlier scenarios without solar generation.

First, a review of household energy management systems will be conducted, both with and without solar panel integration. An examination of strategic investment choices intended to improve financial returns and energy efficiency will come next.

6.1 Baseline scenario without PV panels

In the absence of solar panels, the economic model remains consistent with that of first case, where no remuneration for electricity generation is available. Here, the optimal strategy is to rely exclusively on the gas boiler throughout the year, as the marginal cost of operating an electric heater does not justify its use.

6.2 Scenario with PV panels

The integration of solar panels introduces a significant shift in the energy pricing structure, wherein the costs are now bifurcated into distinct consumption and injection tariffs. Unlike the previous scenario, where consumption and injection were combined and compensated at a single rate, this case provides a more detailed analysis by separating these two components. Therefore, in the results presented, in addition to managing domestic hot water, it becomes crucial to focus on the year-round management of both electricity consumption and injection. First, the scenario is examined under fixed pricing, which represents the general case applicable to all meter types. Subsequently, the influence of variable pricing is explored.

6.2.1 Optimization results

The optimization of energy consumption, under various scenarios of annual photovoltaic production, is presented in Figure 6.2 and 6.3. The corresponding annual costs are illustrated in Figures 6.1. These results underscore the influence of varying levels of PV generation on the operational dynamics of the electric heater and the overall annual energy expenditure.

1) Annual PV Production Below 500 kWh (Scenarios 1-2)
In scenarios where annual PV production remains below 500 kWh, the household's solar generation is insufficient to meet its electrical demand. As a result, no surplus electricity is available for grid injection, and the household continuously relies on grid imports (pink curve) to satisfy its energy needs. The solar generation curve (yellow curve) consistently falls short of consumption requirements, leading to a linear reduction in costs as grid imports decrease with increasing solar production. The electric heater remains idle, with the gas boiler providing all thermal energy.

2) Annual PV Production Between 500 and 3000 kWh (Scenarios 3-7)
When the annual PV production surpasses the household's immediate consumption needs, a portion of the surplus energy is utilized by the electric heater to produce hot water during specific periods of the year, as indicated by the blue columns in the results. The remaining surplus is then injected into the grid, represented by the purple columns. The optimization algorithm carefully determines the optimal times for using the electric heater to maximize self-consumption throughout the year. As PV output increases, the electric heater gradually plays a more significant role, leading to a non-linear reduction in annual energy costs.

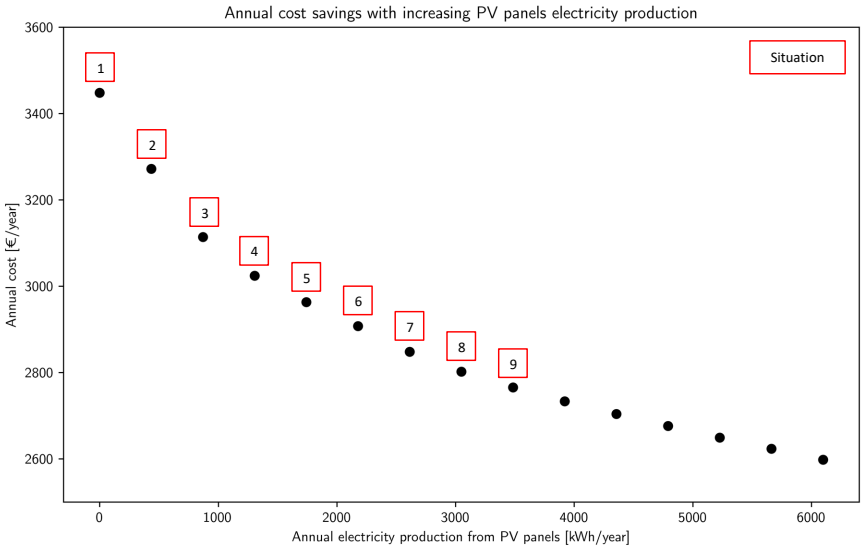


Figure 6.1: Annual energy costs for the second case study, illustrating the impact of increasing annual PV production on a household equipped with photovoltaic panels, a gas boiler, an electric resistance heater, and a hot water tank. The figure demonstrates how cost reductions increase continuously with PV production.

3) Annual PV Production Exceeding 3000 kWh (Scenarios 8-9)
When annual PV production exceeds 3000 kWh, the electric heater can fully meet the household's hot water demands during the summer months. Beyond this production level, any additional solar energy is injected into the grid, but at a lower compensation rate due to reduced feed-in tariffs. The resulting cost reduction curve flattens, reflecting a more gradual decline in annual expenses. This occurs because the cost savings from using the electric heater to produce hot water were more substantial than the returns from injecting excess energy into the grid. As a result, further increases in PV production lead to smaller reductions in costs, primarily due to the lower financial benefit from grid injection.

These findings align with the expected importance of maximizing self-consumption within the household. By strategically synchronizing the use of the electric heater with periods of peak solar generation, the household can significantly enhance its self-consumption. This approach not only minimizes energy costs but also underscores the critical role of thermal storage, particularly in hot water tanks, in efficiently managing surplus solar energy, developed in the rest of this chapter.



Figure 6.2: Distribution of hot water production in the second case study, showing six scenarios with varying levels of annual PV production for a household equipped with photovoltaic panels, a gas boiler, an electric resistance heater, and a hot water tank. This figure highlights the contribution of the electric heater as PV output increases.

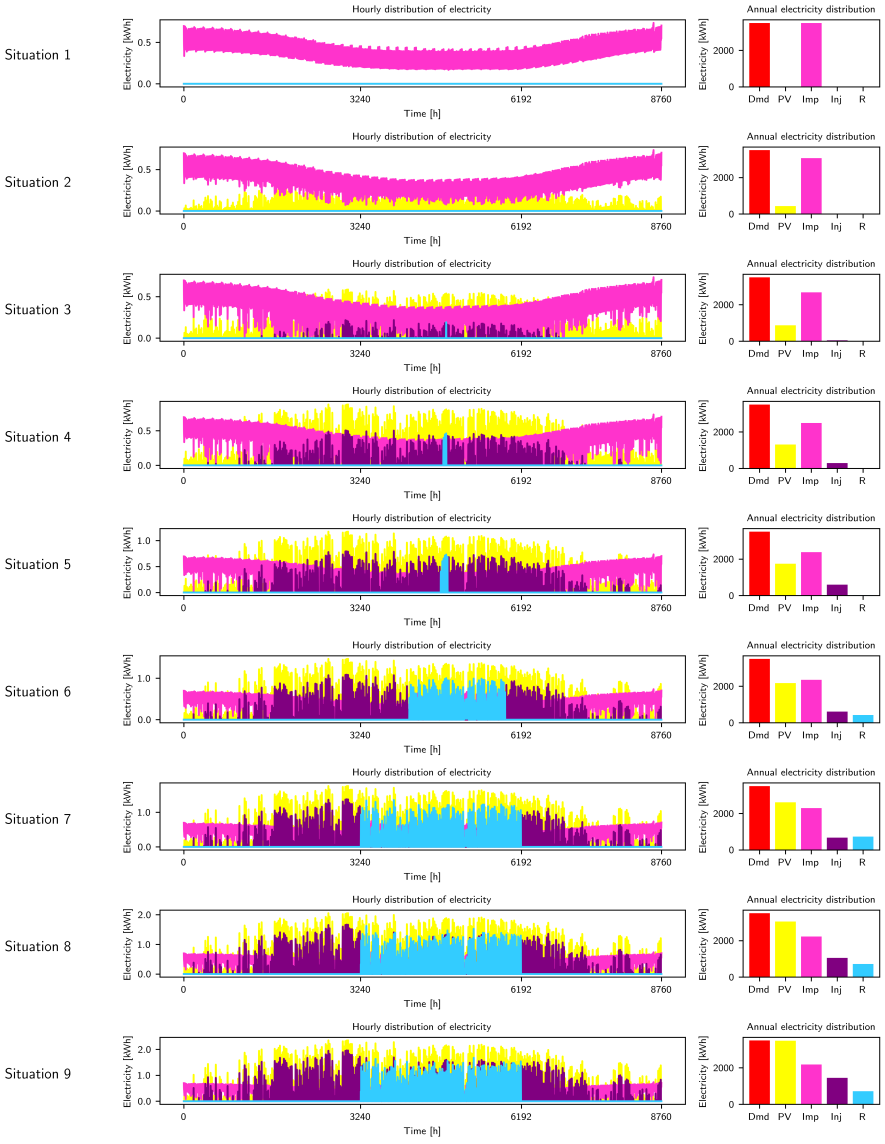


Figure 6.3: Distribution of electricity consumption and injection in the second case study, analyzing six scenarios with different annual PV production levels for a household equipped with photovoltaic panels, a gas boiler, an electric resistance heater, and a hot water tank. The figure illustrates how electricity usage patterns evolve with increasing PV generation, emphasizing the importance of optimizing self-consumption.

6.2.2 Advanced scenario analysis

Each kWh generated by the PV system can be utilized in one of three ways:

1. Direct household consumption: This offsets the purchase of 1 kWh of grid electricity at a retail price of €0.405, resulting in a direct savings of €0.405 per kWh.

2. Grid injection: This yields a remuneration of €0.046 per kWh injected, providing a significantly lower return.

3. Heat production via electric heater: Conversion of 1 kWh of electricity into 0.98 kWh of heat avoids the consumption of 1.089 kWh of gas, at a cost of €0.1075 per kWh of gas, i.e. a saving of €0.117 per kWh.

It is clear that maximizing direct consumption within the household yields the greatest economic benefit per kWh of solar energy produced, making self-consumption more advantageous than either grid injection or conversion to thermal energy. The optimization results support this strategy, consistently favoring the minimizing of grid dependency. Consequently, the first kWh of solar energy produced annually will be used to reduce grid imports, leading to a decrease in annual costs with a slope corresponding to the cost of electricity consumption, as illustrated in Figure 6.4.

Once solar production consistently exceeds consumption, the surplus can be allocated either to hot water production or grid injection. The optimization algorithm prioritizes hot water production during periods of high solar output, low electricity demand and minimal thermal requirements, resulting in a non-linear cost reduction. The reduction in costs is non-linear as it results partly from the savings achieved by using the electric heater instead of the gas boiler and partly from earnings through grid injection. When hot water demand is fully met by the electric heater, any additional solar energy is injected into the grid, leading to a linear cost reduction, proportional to the injection price, as shown in Figure 6.4.

Strategic implications The results presented here identify the optimal periods for utilizing the electric heater; however, these periods are optimized based on specific climatic conditions and household demand patterns. Interpreting these results as fixed recommendations is not practical, as weather conditions can vary significantly from year to year, and household energy consumption, while simulated in this study, will differ widely between households. Consequently, unlike previous cases, drawing definitive conclusions is more challenging and sensitive

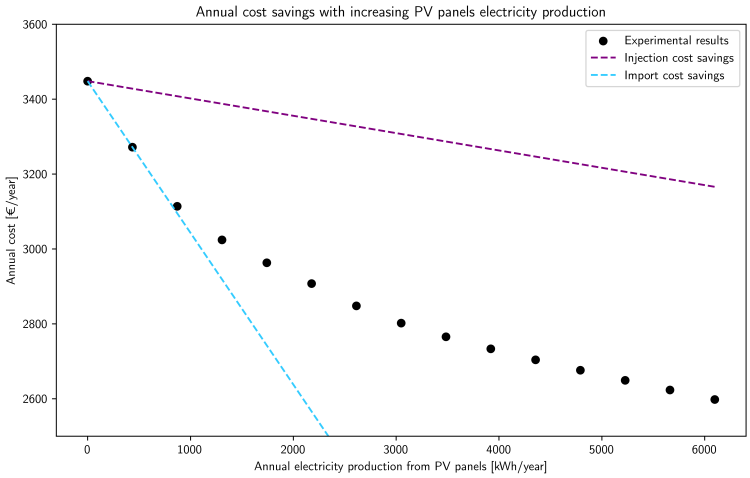


Figure 6.4: Cost reduction trends based on varying levels of PV production, illustrating the economic impact of injection and import remunerations.

to these variables. It is more appropriate to provide a general guideline for when to use the electric heater rather than prescribing an exact schedule.

For households generating less than 500 kWh of solar energy annually—roughly equivalent to the output of 2-3 solar panels—the use of the electric heater is economically unprofitable. Conversely, for households producing around 3000 kWh annually, transitioning to electric heating for hot water production during summer months becomes advantageous.

Role of thermal storage in the hot water tank The hot water tank functions as a crucial thermal energy storage system, capturing and storing excess energy generated by the electric resistance heater during periods of peak solar production. This approach optimizes self-consumption by deferring the use of stored thermal energy to periods of lower solar output, thereby minimizing the reliance on grid electricity at standard consumption rates. The effective management of this thermal storage is essential for maximizing energy efficiency and minimizing costs. Figure 6.5 illustrates this concept, demonstrating the role of the hot water tank as a thermal energy storage solution derived from solar PV production.

Influence of dynamic pricing The analysis primarily presented results based on a fixed tariff structure. The introduction of a variable tariff does not significantly alter the management strategy for the electric heater and the overall analytical

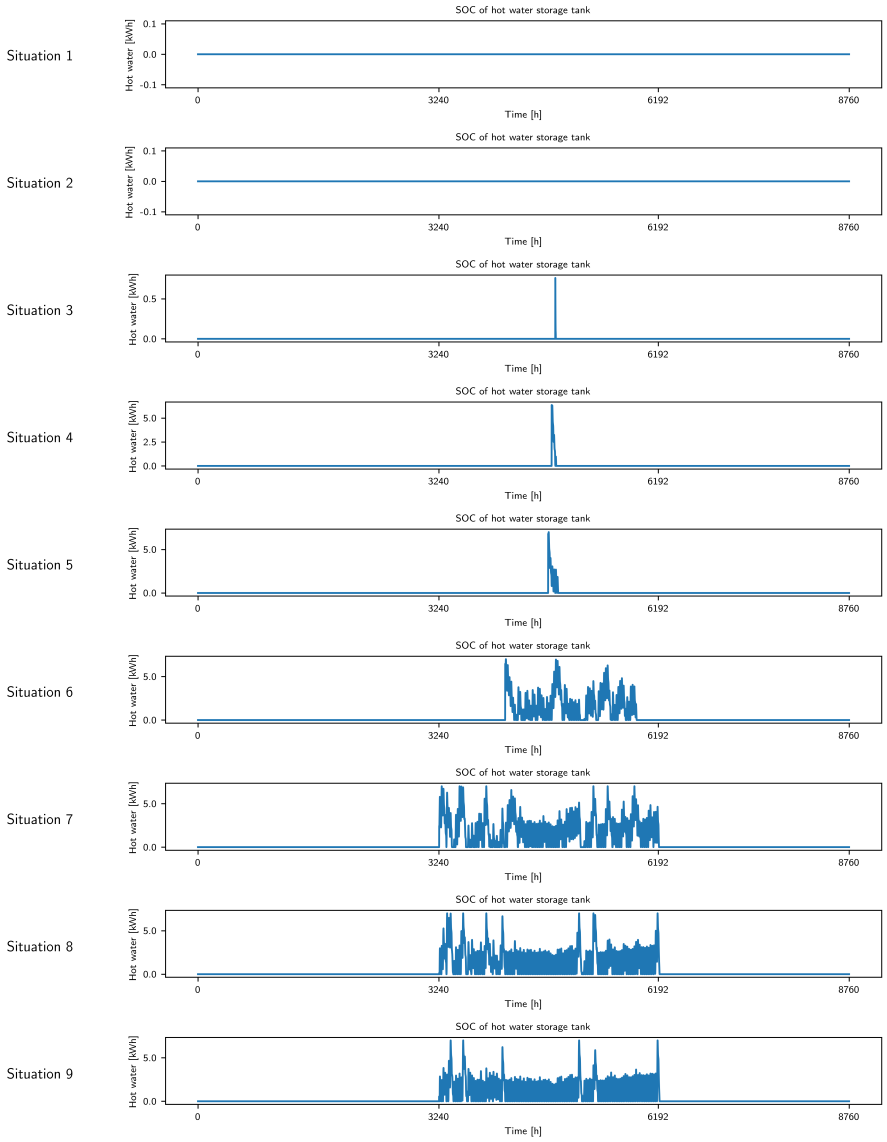


Figure 6.5: Role of the hot water tank as a thermal energy storage system for solar-generated electricity, emphasizing its importance in enhancing self-consumption and reducing reliance on grid electricity during periods of low solar production.

framework remains consistent. The primary difference occurs when the optimization algorithm determines the most suitable period for activating the electric heater; in this case, it considers in addition the varying electricity prices in addition to the other factors previously discussed. However, this approach diminishes the practical applicability of the results, as it requires advance knowledge of monthly electricity prices. Since future prices are inherently unpredictable, relying on a fixed tariff provides a more robust and relevant basis for decision-making for future advice for consummers. Consequently, fixed pricing provides a more stable and reliable foundation for long-term energy planning.

Figure 6.7 illustrates that while the timing of electric heater usage may shift under variable pricing, the overall energy management strategy remains largely unaffected. Once solar production surpasses a certain threshold, the use of the electric heater throughout the summer is economically advantageous.

Comparative analysis of price variations over multiple years, as shown in Figure 6.6, demonstrates that despite annual price fluctuations, the fundamental management strategy is not impacted. The recommended operational behavior remains consistent, although the annual costs may vary depending on the specific pricing of each year.

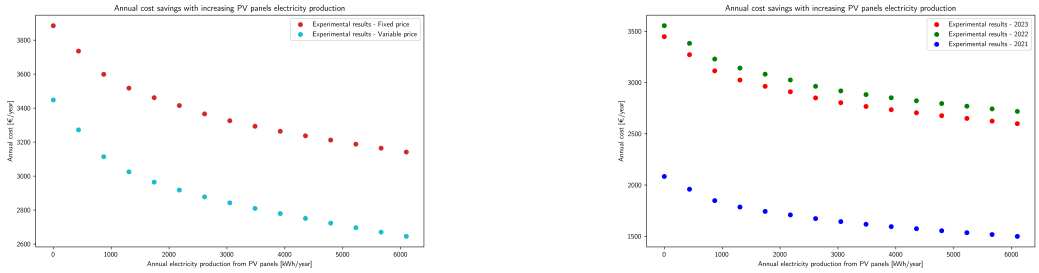


Figure 6.7: Comparison of annual energy costs under different pricing tariffs (fixed and dynamic) on the left, and across varying energy price years on the right. Despite fluctuations in electricity prices and tariffs, the recommended energy management strategy remains consistent. This indicates that even with these fluctuations, using the electric heater during summer under fixed pricing continues to be a reliable strategy for cost savings.

6.3 Investment analysis

This section evaluates the potential advantages of investing in a heat pump and a battery energy storage system. As illustrated in Figure 6.8, the analysis indicates



Figure 6.6: Impact of dynamic pricing on the timing of electric heater usage. While the timing adjusts to optimize for lower prices, the overall strategy remains effective. This suggests that even with variable price, using the electric heater during summer under fixed pricing remains a reliable approach for cost savings.

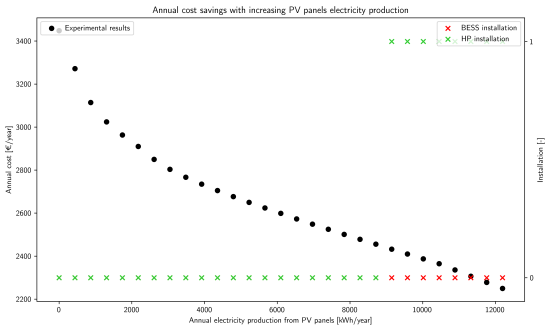


Figure 6.8: Evaluation of the economic viability of investing in a heat pump and a battery energy storage system, highlighting the substantial solar production required to justify such an investment.

that investment in a BESS is not recommended. In contrast, a heat pump becomes a viable option only when annual solar production approaches approximately 9000 kWh, which corresponds to the output of around 21 solar panels. This level of solar production is substantial and is highly sensitive to fluctuations in energy prices. Indeed, energy prices play a pivotal role in determining the economic feasibility of these investments, as presented in previous Chapter. The 9000 kWh threshold should not be considered an absolute benchmark, as it will vary significantly with changes in energy prices, as discussed in the previous case study.

Justifying the investment in a heat pump requires a solar production level that is far higher than what is typically achievable by an average household's solar installation. Therefore, under the scenarios analyzed, investment in a BESS is not advisable, and a heat pump is only economically viable at considerably high levels of solar production.

Impact of CO_2 emissions cost

In the future, the cost associated with CO_2 emissions from households is likely to become increasingly significant. In Belgium, discussions are advancing around the implementation of a carbon tax for households. The introduction of a CO_2 tax is expected to drive up the cost of natural gas, thereby accelerating the economic payback period for investments in heat pumps as gas prices rise. Moreover, considering that the market price of heat pumps has not yet fully stabilized due to the technology still being relatively novel [11], there exists the potential for a scenario where the combination of a CO_2 tax and decreasing heat pump prices could render the installation of heat pumps financially viable.

The results of this second case study are presented in Figure 6.9. As illustrated,

there is a specific combination of heat pump price reductions and CO_2 tax levels that shifts the investment preference towards heat pumps. Furthermore, an increase in solar energy production significantly accelerates the adoption of heat pumps.

It is important to critically evaluate these results, which are based on the energy prices of 2023 used as a baseline scenario. These prices are unlikely to remain constant in the coming years. As demonstrated, the profitability of a heat pump installation is highly sensitive to energy price fluctuations. However, this analysis illustrates the range of possibilities enabled by linear optimization models, underscoring the importance of understanding both the limitations and the opportunities these models present, which will be discussed in the next chapter.

6.4 Conclusion

For households generating solar electricity close to their annual consumption levels, utilizing the electric heater for summer hot water production proves to be economically advantageous. This approach maximizes the use of excess solar energy, reducing reliance on grid electricity and lowering overall energy costs. The focus on self-consumption highlights the importance of efficiently managing the hot water tank as a thermal storage system, ensuring that solar energy is effectively utilized throughout the day.

However, the analysis shows that investing in additional infrastructure, such as a heat pump or a battery storage system, does not offer significant economic benefits for the average household under the scenarios considered. The high costs of these investments outweigh the potential savings, making them less viable options for most households.

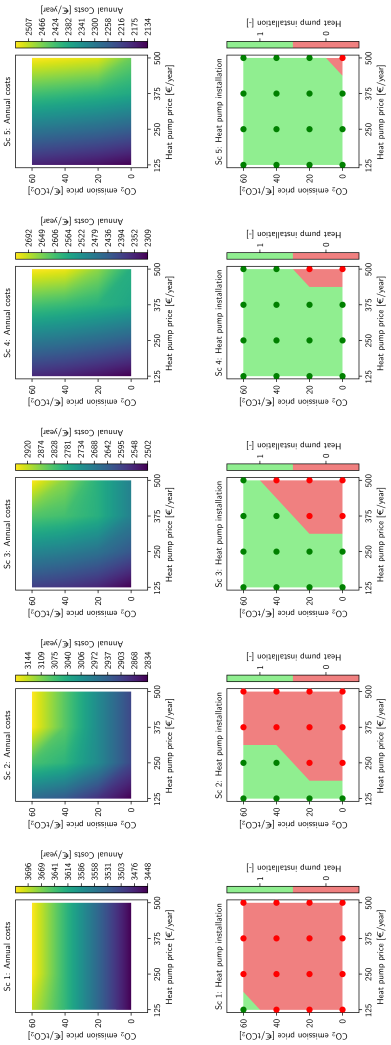


Figure 6.9: Analysis of the impact of a CO_2 tax combined with a reduction in the installation costs of heat pumps on the decision to install heat pumps. Five scenarios are presented, ranging from 0 to 20 solar panels. The faster the solar production increases, the sooner heat pumps are installed. Additionally, as the CO_2 tax increases and the price of heat pumps decreases, the installation of heat pumps occurs more rapidly.

Chapter 7

Model limitations and future research directions

The energy management model developed in this thesis has demonstrated substantial potential for optimizing energy consumption in residential settings, particularly in terms of economic savings and environmental impact. However, like any model, it is not without its limitations.

7.1 Model limitations

Understanding these limitations is crucial for interpreting the results accurately and identifying areas where the model could be refined or extended.

1. **Sensitivity to price fluctuations**: One significant limitation of the model is its sensitivity to fluctuations in energy prices and technology costs. These variables can greatly impact the recommendations for investment and energy optimization, highlighting the importance of accurate price forecasting. However, this sensitivity also introduces substantial uncertainty, particularly in the face of unforeseen market changes, thereby limiting the robustness of the model's projections.

2. **Economic focus at the expense of comfort**: The model predominantly focuses on the economic aspects of energy management, such as cost reduction and optimization of self-consumption. While these are critical factors, the model does not consider user comfort, which is a vital component of residential energy management. Consequently, the model may propose economically optimal solutions that do not meet the comfort expectations of occupants, potentially limiting the practical applicability of the recommendations.

3. **Uncertainty in future technology costs**: The model's reliance on current technology cost data, such as those for heat pumps, introduces uncertainty regarding future price changes. Technological advancements, policy shifts, or market dynamics could significantly alter these costs, affecting the accuracy of long-term investment recommendations. Failure to take account of the uncertainties associated with future costs could lead to sub-optimal decision-making for long-term investments.

4. **Use of fixed profiles**: The model employs historical consumption patterns and weather data to estimate solar energy production and household needs. This static approach does not account for potential future climatic variations or extreme weather events, which could significantly impact energy performance. This limitation reduces the model's ability to make robust forecasts in the context of climate change.

5. **Lack of system inertia modeling**: The model assumes instantaneous and smooth management of energy assets, neglecting the inertia associated with the start-up and shutdown of these systems. This simplification may result in an overestimation of the efficiency of the proposed energy management strategies, as it overlooks the delays and costs linked to system operations.

6. **Standardized household consumption profiles**: The model relies on standardized consumption profiles based on historical averages, which may not accurately reflect the behaviors of individual households. For households with consumption patterns that deviate significantly from the norm, the impacts on self-consumption and cost savings could be misrepresented, reducing the precision of the model's outputs.

7.2 Future research directions

While the current model provides a solid foundation for domestic energy management, several enhancements could be made to increase its robustness and relevance, particularly in addressing future challenges in the energy sector.

1. **Dynamic control of consumption and production**: A promising direction for future research involves the dynamic control of household energy assets. Rather than relying on manual operation, future models could incorporate real-time management of multiple assets, individually and collectively. This would involve the integration of real-time climatic and domestic data, allowing the model to dynamically adjust energy recommendations based on current weather conditions and specific household parameters, such as

indoor temperature, humidity, or solar irradiation levels. The use of smart sensors to provide accurate, real-time data would be essential for the success of this approach.

2. **Making loads controllable**: Another area for future exploration is the active management of household appliances. For example, scheduling energy-intensive tasks, such as running a washing machine, during periods of lower electricity prices could significantly enhance energy efficiency. Introducing greater flexibility in load management could better align energy consumption with periods of high production, improving overall energy use.

3. **Comprehensive investment analysis**: To improve the model's relevance, it is essential to conduct a comprehensive investment analysis that includes acquisition and operating costs of energy technologies, as well as available financial incentives, potential taxes (such as carbon taxes), and long-term impacts on property value. This analysis should also account for risks associated with energy price fluctuations and regulatory changes, providing a holistic view of the economic landscape.

4. **Incorporating additional energy assets**: Future models could benefit from integrating additional energy assets, such as electric vehicles or combined heat and power systems (CHP). Incorporating these technologies would allow for a more comprehensive approach to domestic energy management, optimizing the interaction between these systems to maximize efficiency and cost savings.

5. **Development of a machine learning module**: Integrating a machine learning module could enable the model to adapt dynamically to the specific habits of each household. By analyzing real data collected over an extended period, the model could improve the accuracy of its forecasts and recommendations, continuously refining its strategies to better meet individual household needs.

6. **Analyzing dynamic hourly pricing**: Exploring dynamic pricing models for electricity that respond to grid demand could provide valuable insights into how households might optimize energy use under different pricing scenarios. Such an analysis could help determine the most efficient strategies for managing energy use in ways that benefit both the household and the broader energy grid.

7. **Integration of space cooling management**: With the ongoing impact of climate change altering global weather patterns, the demand for space cooling is projected to increase, even in regions that have historically experienced

cooler climates. The integration of space cooling systems into energy management models presents a significant opportunity to enhance overall energy efficiency. Furthermore, during periods of low heating demand in the summer, the elevated need for space cooling, coinciding with peak photovoltaic generation, offers a promising avenue for optimizing self-consumption of PV energy.

7.3 Conclusion

The model developed in this thesis provides a strong foundation for understanding the potential economic and environmental benefits of optimized energy management in residential settings. However, recognizing the model's limitations is essential for accurately interpreting the results and for guiding future research efforts. The suggested future research directions highlight the significant potential for enhancing the model's robustness, relevance, and applicability in the context of evolving energy systems and environmental challenges. By addressing these limitations and exploring these avenues for improvement, future models could play a crucial role in advancing sustainable and resilient energy management practices in households.

Conclusion

This thesis has investigated the challenge of optimizing energy management in Belgian households, particularly focusing on the integration of solar panels. While many studies have addressed energy systems, few have specifically considered the unique Belgian context and the current issue households face, such as determining the optimal timing and methods for utilizing various energy assets to maximize the benefits of solar panel integration.

The research first examined the Belgian landscape, taking into account the country's solar potential, the specific energy demands of Belgian households, and the various compensation mechanisms available for solar panel energy injection. This contextual analysis laid the foundation for developing a robust linear optimization model aimed at reducing annual energy costs. This model represents a practical tool that users can tailor to their individual circumstances, offering a means to make informed decisions about their energy management.

Two practical case studies were explored, each based on an average household scenario. The findings revealed that, in the first compensation scheme, households that produce less energy than they consume annually have no incentive to use an electric resistance heater. However, when production exceeds consumption by 20%, it becomes beneficial to use excess energy for heating sanitary water during the summer months, though this benefit is limited to that particular application. Investment in a heat pump becomes economically viable only when the household produces at least 1.5 times its annual consumption, and in such cases, direct self-consumption of solar production does not offer additional advantages.

In the second compensation scheme, a household that produces energy equivalent to its consumption is encouraged to use an electric resistance heater throughout the summer. Here, self-consumption plays a critical role, and the strategic storage of hot water at key times is essential. However, under these conditions, the installation of a heat pump is not financially advantageous.

The sensitivity of the model to fluctuations in energy prices was also highlighted, pointing to certain limitations. Nevertheless, this model provides a valuable starting point for approximating current scenarios, and its potential for further development is promising. Future research could adapt this model to include dynamic pricing, the integration of smart systems within homes, the management of controllable assets, and considerations for CO2 emission pricing, among other factors.

In conclusion, the work presented in this thesis opens up new avenues for enhancing energy management in the residential sector. By focusing on practical, context-specific solutions, it contributes to the broader goal of making the residential energy sector more efficient and sustainable.

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Appendix A

Energy pricing

An in-depth examination of the energy pricing scheme in Belgium is essential for identifying the most efficient methods for integrating PV panels into residential settings. In this chapter, the focus is on how the pricing mechanisms are defined and how they can influence the adaptation of the consumption and facilitate or hinder the adoption of PV technology in homes.

In Brussels, the residential costs of electricity and gas are distributed as illustrated in Figure A.1. Theses costs comprised of several elements that compensate various market actors. The energy bill, whether for gas or electricity, are composed of energy costs, network usage costs, and taxes and surcharges.

- Energy Costs refer to the contribution to energy producers and suppliers. It is the only component of the energy bill that is open to competition; hence, this component varies from one supplier to another.
- Network Usage Costs are related to contributions to the transmission network operators and distribution network operators. This contribution is approved by Belgian regulators : the Belgian Federal Commission for Electricity and Gas Regulation (CREG) and the Brussels regulator for electricity and gas pricing, namely BRUGEL.
- Taxes and Surcharges are imposed by public authorities, primarily to finance a range of solidarity mechanisms and initiatives to promote better energy use.

Network usage costs, taxes, and surcharges are the fixed components of the energy price. However the energy cost component varies depending on the energy supplier subscription, which is discussed in the next section.

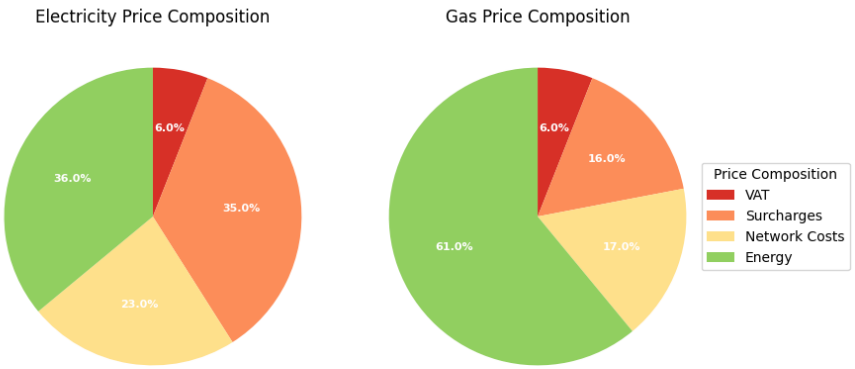


Figure A.1: Electricity and gas residential price compositions in Brussels. Source : CREG website [51]

A.1 Energy provider power bill

To determine energy costs, energy providers establish price tariffs through contracts applied to the quantity of energy consumed by households, whether for gas or electricity.

This chapter focuses on two critical components: firstly, the pricing tariff for electricity and gas subscribed to by households; and secondly, how the consumed quantity of electricity and gas are calculated. Lastly, the chapter discusses the integration of solar panels and their potential to reduce a household's energy bill.

In this section, the term "energy" refers to both gas and electricity, as they are calculated similarly by providers but with different tariff prices. To avoid redundancy, the term "energy" is used throughout.

A.1.1 Energy provider consumption energy price

The total annual cost of energy from energy suppliers include fixed costs and proportional costs which are, respectively, unrelated and influenced by the amount of energy consumed.

As shown by Equation (A.1), the total annual cost of energy, denoted $\text{Cost}_{\text{energy}}$, from energy suppliers are composed of fixed costs $\text{Cost}_{\text{energy,fixed}}$, i.e. the annual

fixed fee in €/year , and the proportional costs $\text{Cost}_{\text{energy,prop}}$, i.e. the consumption cost in €/kWh [1] which depends on the consumed amount of energy $\text{Cons}_{\text{energy}}$.

$$\text{Cost}_{\text{energy}} = \text{Cost}_{\text{energy,prop}}\left(\text{Cons}_{\text{energy}}\right) + \text{Cost}_{\text{energy,fixed}} \tag{A.1}$$

The energy suppliers offer several proportional cost options, such as fixed energy pricing or variable energy pricing, which are described in the following sections.

A.1.1.1 Fixed proportional energy pricing

Fixed energy pricing involves setting a constant price per unit of energy consumed throughout the year. Equation ((A.2)) establishes that the proportional cost of energy corresponds to the fixed annual price, denoted by $\text{Price}_{\text{energy,fixed}}$, applied to the quantity of energy consumed :

$$\text{Cost}_{\text{energy,prop}}\left(\text{Cons}_{\text{energy}}\right) = \text{Price}_{\text{energy,fixed}} \cdot \text{Cons}_{\text{energy}} \tag{A.2}$$

The fixed pricing method does not financially encourage adjusting consumption across different periods, whether during the day or over specific months, because the price remains constant throughout the year.

A.1.1.2 Variable proportional energy pricing

In the case of variable energy pricing, the price per unit of energy consumed fluctuates throughout the year. While the variable proportional price is fixed for a specific period, this fixed price can change from one period to the next. For instance, the proportional price varies hourly (hourly rate), monthly (monthly rate), or quarterly (quarterly rate)[2]. Energy consumed during each fixed period is billed at the corresponding period's price. The total energy cost is the sum of all quantities consumed over each period of the year at their respective prices.

As indicated by Equation (A.3), the proportional cost of energy during the period i, $\text{Cost}_{\text{energy,prop}}(i)$, corresponds to the variable price fixed for the period i, $\text{Price}_{\text{energy,variable}}(i)$, applied to the quantity of energy consumed during the period i, denoted $\text{Cons}_{\text{energy}}(i)$. The total annual proportional energy cost is determined by summing the proportional costs of energy across all periods:

[1] "A measure of electricity defined as a unit of work or energy, measured as 1 kilowatt (1,000watts) of power expended for 1 hour" [52]

[2] Gas does not have an hourly variable price, only monthly, quarterly, or annual rates.

$$\text{Cost}_{\text{energy,prop}} = \sum_{i \in \text{periods}} \underbrace{\text{Price}_{\text{energy,variable}}(i) \cdot \text{Cons}_{\text{energy}}(i)}_{\text{Cost}_{\text{energy,prop}}(i)} \tag{A.3}$$

The variable pricing structure motivates consumers to modify their energy usage in response to fluctuating prices. For example, in winter when gas prices typically increase, it becomes advantageous to decrease consumption to avoid higher costs. The flexibility in pricing encourages adaptive consumption behavior, in contrast to fixed energy pricing.

A.1.2 Energy meters

Measuring energy consumption is crucial for efficient household energy management and for establishing energy prices by suppliers. Energy meters play a pivotal role in this process by quantifying the electricity or gas consumed.

An energy meter is a device designed to measure the amount of electricity or gas used in a household, recording consumption in kilowatt-hours (kWh) for electricity and cubic meters (m^3) for gas. In Belgium, two primary categories of meters are recognized: smart meters and classic meters [53].

The type of meter installed significantly affects the data accessible to energy providers for annual billing, thereby directly influencing annual costs, as discussed in this section [54].

A.1.2.1 Smart energy meters

The smart meter, also known as the communicating or digital meter, is a device that monitors and records household energy usage accurately, continuously and in real-time [55]. The smart meter, depicted on Figure A.2, is equipped with a communication module that enables it to communicate with the network operator [56]. Consequently, the network operator can interact with the meter to facilitate network management and also provide new services to customers such as dynamic pricing [56]. This capability allows energy suppliers to accurately generate billing statements [55]. Therefore consumers are billed based on their exact consumption at the accurate price, without any annual adjustments or estimates [54]. Moreover, these meters can provide house energy management systems through smart electric charging, new heating systems or electricity storage, for example [57].




Figure A.2: Smart meters presented by Sibelga [58] & [57].

Pricing with smart energy meters If a household subscribes to a fixed-rate energy tariff, there is no financial incentive to adjust consumption regardless of the type of meter installed, as explained in Section A.1.1.1. Adapting consumption is economically advantageous under variable-rate plans with smart meters. Indeed, with smart meters accurately measuring and communicating actual consumption during each pricing period, precise billing based on usage is ensured. For instance, during periods of lower energy prices, there is a financial benefit to consuming energy and utilizing smart home management systems like energy storage.

A.1.2.2 Classic energy meters

Classic meters, also known as electromechanical or traditional meters, incrementally store the quantity of electricity or gas entering the household [53]. They do not record consumption quantities during specific periods; rather, they accumulate the total energy that enters the house. As a result, these meters display the cumulative total of energy usage over time, measured in cubic meters (m^3) for gas and kilowatt-hours (kWh) for electricity, as illustrated in Figures A.3 and A.4. Unlike smart meters, classic meters cannot communicate consumption information to the energy provider. To determine consumption for a specific period, a human must take readings at the beginning and end of that period, as depicted on Figure A.4 [54]. This lack of detailed data makes it impossible to provide precise consumption patterns as with smart meters. As a result, energy providers cannot ascertain how energy usage is distributed over the day or even throughout the year [54].

Pricing with classic energy meters As previously discussed, unlike smart meters, classic energy meters do not provide precise timing information about energy consumption. For fixed energy pricing, this lack of detailed consumption data is inconsequential, as there is no financial incentive for households to alter their energy usage, as detailed in Section A.1.1.1. However, for variable energy pric-



Figure A.3: Gas classic meter in m^3 [59].



Figure A.4: Electricity classic meter reading in kWh [60].

ing, accurate timing information is crucial to apply different rates across various periods effectively. In the absence of precise consumption timing data, energy providers resort to estimating virtual periodic consumption based on average consumption profiles [54]. This approach involves distributing by fixed factors energy usage throughout the year, resulting in the application of a virtual fixed price per kWh annually. Consequently, since the variable energy pricing is virtually fixed, it provides no incentive for consumers to adjust their consumption behaviors.

For instance, the virtual fixed price for a classic meter subscribed to a monthly variable tariff is calculated using the following equation, where $\mathrm{CD}(i)$ denotes the consumption distribution for month i as applied by the energy provider:

$$\mathrm{Price}_{\mathrm{energy,fixed,virtual}} = \sum_{i=1}^{12} \mathrm{Price}_{\mathrm{energy,variable}}(i) \cdot \mathrm{CD}(i)$$

Note: It is possible to gain some insights into consumption distribution through more frequent readings (e.g., monthly instead of yearly) and specific daily metering periods (e.g., bi-hourly or exclusive night metering) [61]. Although these classic meter variations may affect the final price, they do not influence electricity usage behavior, as classic meters consistently result in applying fixed pricing, as explained earlier.

In conclusion, with a classic energy meter, regardless of the tariff structure applied, there is no encouragement for consumers to modify their energy usage patterns. For smart meters, a fixed subscription plan similarly offers no motivation to adjust consumption. However, under a variable subscription plan with smart meters, there is an incentive for consumers to adapt their energy usage based on the pricing of each period.

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