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Faculty of Engineering Technology

Design of an Energy Management System for Residential Buildings:

A Sustainable Approach to Optimize Energy Efficiency and PV Integration

Master Thesis

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Abstract

Energy transition plays a crucial role in mitigating climate change. A key element in the energy transition is to integrate distributed renewable energy resources (DERs) into the existing energy systems, however, large-scale integration can pose several challenges to the current energy system such as grid congestion. Energy Management Systems (EMSs) can help to mitigate this problem by increasing on-site self-consumption of renewable energy sources and shaving the peak load using the flexibility of loads and storage. This master's thesis presents the development of a Home Energy Management System (HEMS) designed to enhance the performance of a Photovoltaic (PV) system with a Battery Energy Storage System (BESS). The HEMS helps to achieve higher self-sufficiency ratios (SSR) and self-consumption ratios (SCR) while simultaneously reducing electricity costs by optimally scheduling shiftable appliances to operate during the most optimal times within a dynamic electricity pricing scenario. Different objectives were considered such as reducing costs and increasing the self-consumption of generated PV energy. The results are presented through a comparative analysis of four scenarios for a typical detached single-family house (SFH) (i) without green technologies, (ii) with a PV system, (iii) with PV and BESS, and (iv) with PV, BESS, and HEMS. The results demonstrate that the implementation of a 4 kWp PV system increases the SSR to 26% and the SCR to 34.7%. Including a 6 kWh BESS to the existing PV system, the SSR and SCR rise to 51% and 45.8%, respectively. Additionally, the HEMS led to SSR and SCR improvements in the range of 7.6% to 19.8% and 9.4% to 19.4%, respectively.

Acknowledgments

The present master's thesis is the outcome of my graduation assignment carried out in the research theme *Sustainable Products & Energy Systems.* In the framework of the research group, research is focused on the implementation and integration of renewable and energy-efficient technologies in products, buildings, or local infrastructures.

I would like to thank my supervisor Dr. Elham Shirazi for all the time and support through this graduation assignment.

To my parents, Guillermo Castelán Cedillo y Guadalupe Castillo Feliciano for their unconditional support, love, and encouragement to achieve whatever I propose.

To my brothers Guillermo Eliezer Castelán Castillo and Marcos Omar Castelán Castillo, who inspire me to never give up.

To all my friends who supported me during my master's program

Solo el que cree que puede, se atreve y solo el que se atreve, alcanza.

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Chapter 1

Introduction

The landscape of the ongoing energy transition and the climate change crisis demands not only changes in how we produce electricity but also in how efficiently we consume it and organize our routines linked to energy consumption.

In the context of the residential sector, the current integration of distributed renewable energy sources (DERs), such as rooftop photovoltaic (PV) systems and battery energy storage systems (BESSs) is significantly transforming the energy sector. PV panels can convert sunlight into electricity, allowing householders to generate and consume renewable energy on-site, and BESS can store excess energy generated by PV panels for use during periods of low solar generation or high energy demand. From a social perspective, this has changed the passive behavior of householders from being uniquely energy consumers to being energy prosumers (consume and produce). This change of role has increased the participation of prosumers in the energy system and influenced it more than ever before. Consequently, this new role has also introduced new challenges in maintaining grid stability.

From a technical perspective, the increasing electricity demand due to electrification, and the volatile electricity supply from DERs put significant stress on the electricity grid's capabilities, compromising its reliability and security. To embrace more DERs, and transform the traditional grid into a smart grid, the need for an Energy Management System (EMS) is crucial at all energy system levels for improving energy efficiency.

In general, an EMS is a complex system designed to monitor, control, and optimize energy consumption in buildings or industrial facilities. An EMS coordinates heterogenous loads, intermittent RES, and energy storage systems (ESSs) as shown in Figure 1.1. The EMS technology is based on software and hardware components such as sensors, smart meters, and other monitoring devices to collect (i) internal data on energy usage and performance, and (ii) external data such as the current electricity price, and weather variables. This data is analyzed by the EMS software to identify patterns and opportunities for improvement and then control various systems to optimize energy usage according to a previously defined objective function, which could be for instance, economical, technical, ecological, or social objectives.

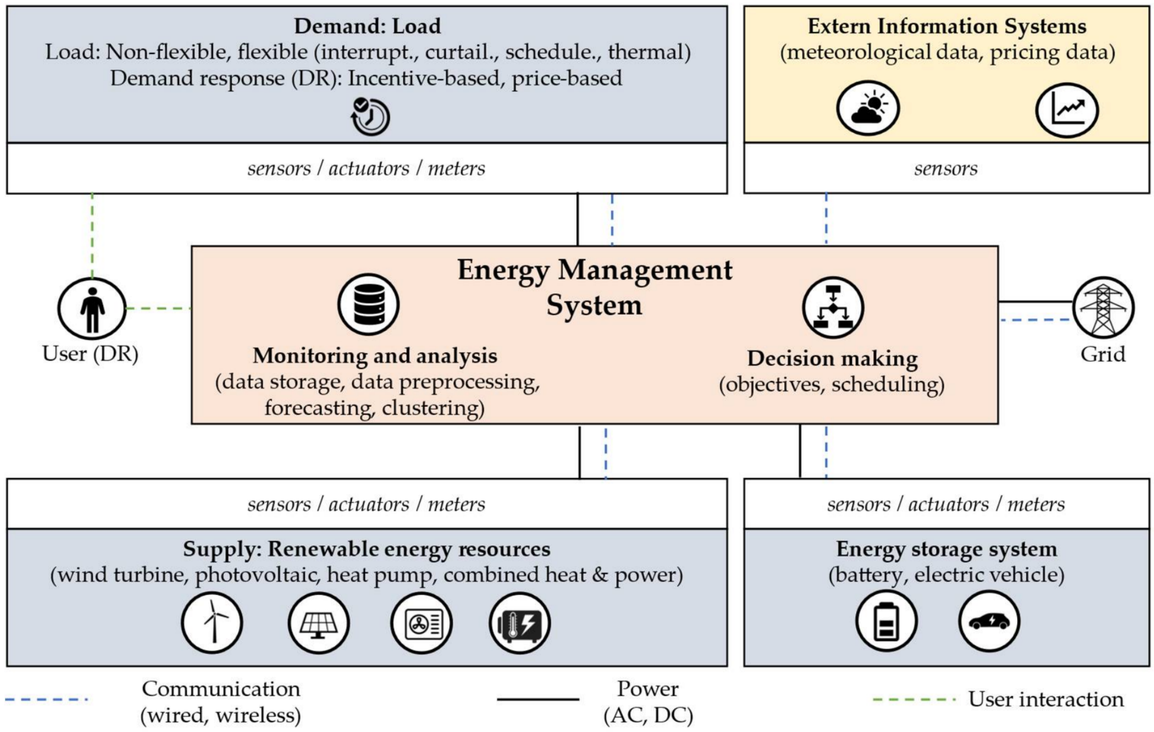

Figure 1.1: Modular infrastructure of an Energy Management System [58]

The EMS technology has emerged as a response to the need for more efficient energy use, driven by concerns about the impact of energy consumption on the environment. The EMS concept has been around for several decades, but it was not until the 1990s that advances in technology and the introduction of smart grid systems made it possible to create more advanced and integrated systems. Since then, EMS technology has continued to evolve, driven by the growing demand for energy efficiency and sustainability.

This thesis focuses on the implementation of an EMS in the residential sector, also known as the Home Energy Management System (HEMS). Despite the current higher demand for heat compared to electricity, it is expected that the decarbonization of transport, heating, and cooling, facilitated by emerging technologies such as Heat Pumps (HPs) and electric vehicles (EVs) will result in an increased demand for electricity.

1.1 Problem statement

Coordinating energy flows with fluctuating loads and variable generation has become increasingly complex. Photovoltaic (PV) systems generate electricity intermittently when there is sunlight, and this electricity is rarely consumed at the same time that is generated. This situation can lead to potential issues with grid stability and reliability. Integrating a Battery Energy Storage System (BESS) can help mitigate intermittency and the mismatch between supply and demand. However, it also adds to the complexity of management requirements. Furthermore, different dynamic tariffs are being introduced in various countries in response to the evolving electricity market, further complicating decision-making. To address these challenges, the implementation of a Home Energy Management System (HEMS) must ensure the efficient management of electricity flows. This involves considering factors such as user preferences, electricity prices, scheduling flexible appliances, CO2 emissions, and the state of charge of battery storage.

1.2 Research questions

To explore the opportunities of HEMS in the ongoing energy transition, the following research questions were formulated:

- ***RQ1:*** *How can the implementation of an HEMS improve the performance of (PV) system with BESS in the residential sector, while reducing the overall energy costs and carbon emissions?*
- ***RQ2:*** *What are the technical, economic, and social challenges that need to be addressed for the efficient operation of an EMS in the residential sector?*
- ***RQ3:*** *How does the householder behavior influence the HEMS design?*

1.2.1 Objectives

The objectives of this study are:

- To design a comprehensive HEMS architecture that integrates a PV system, BESS, and smart appliances
- To assess the improvement performance achieved through the implementation of a HEMS by optimizing energy consumption patterns and potential CO2 emissions and energy costs.
- To contribute to the broader understanding of the role of HEMS in promoting energy efficiency, renewable energy integration, and sustainability in the context of the ongoing energy transition.

1.3 Thesis structure

The structure of this thesis is organized into multiple chapters, this was meant to present the process and results of the conducted research:

Chapter 1 defines the motivation for this work, the problem statement, the research questions, and the objectives.

Chapter 2 presents the literature review, which covers 4 topics: (i) HEMS's goals, objectives, challenges, and opportunities, (ii) the Dutch residential sector, (iii) the evolving electricity market, and (iv) relevant regulations and policies impacting the development of HEMSs.

Chapter 3 outlines the methodology, detailing the concept, model, architecture, and design of the HEMS. It explains the models, data collection methods, modeling of flexible appliances, and the algorithm for decision-making and optimization functions.

Chapter 4 presents the results of the HEMS performance in various scenarios.

In Chapter 5, a comprehensive analysis of the results is conducted, followed by a discussion of the findings, the limitations of the research, lessons learned, and recommendations.

In Chapter 6, the thesis's conclusion is presented.

Chapter 2

Literature review

The literature review is organized into two main areas. The first area (i) focuses on the topics critical for understanding the design and development of HEMS and how they, directly and indirectly, impact the concept and model of HEMS. The second area (ii) focuses on HEMS, goals, objectives, challenges, and optimization algorithms. The first area centers on the Dutch case, where the rapid deployment of household PV systems and transportation electrification is driving the demand for efficient energy coordination. Understanding socio-economic perspectives is vital for co-designing technical solutions that consider human and organizational behavior. This comprehensive approach ensures that the developed HEMS is well-aligned with the requirements of the energy landscape and addresses the complex factors in the residential sector.

2.1 The Residential Energy Sector

Overall, buildings within the European Union (EU) account for **36%** of the EU's greenhouse gas (GHG) emissions and **40%** of its energy consumption [16]. The EU has set a goal to achieve a carbon-neutral future by 2050, with various targets, including the ***improvement of energy efficiency in buildings*** as a critical area where efforts must be ramped up as described in the European Green Deal of 2015 [15]. Specifically, to achieve the target of **55%** GHG emissions reduction by 2030 (49% claimed by the Dutch government [27])-compared to 1990 levels- buildings must cut their GHG emissions by **60%** [15]. Furthermore, the energy consumption of the residential sector must be reduced by 38% -compared to 2005- by 2050 [21].

Buildings can be categorized based on their function, usage, and characteristics. Among these categories, the residential and industrial sectors typically receive the most attention. In 2021, households represented 27% of the final energy consumption in the EU, space heating was the principal contributor with 64.4% followed by domestic hot water (DHW) with 14.5% [17]. These values are particularly aligned with the Dutch residential sector as discussed in Section 2.1.1. *How do buildings contribute significantly to GHG emissions and energy consumption?*

A significant portion of the current EU building stock was constructed without any energy performance requirements, around **90%** of the EU building stock was built before 1990 as shown in Figure 2.1, and approximately **50%** was constructed before the 1970s, before the implementation of building code regulations concerning energy performance [21].

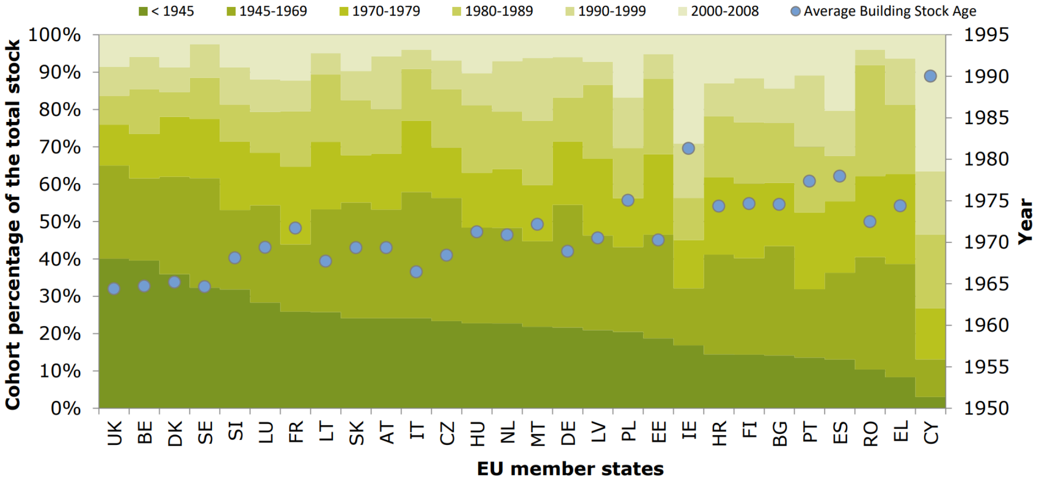

Figure 2.1: Age of the EU building stock [21].

To address this challenge, efforts have been focused on two approaches: (i) the implementation of NZEB and Zero-Emission building (ZEB) policies, and (ii) the encouragement of deep energy renovations. A NZEB is a building that exhibits an exceptional level of energy efficiency while making the most of renewable energy sources to achieve near-zero energy consumption. This can be accomplished by utilizing highly efficient appliances, insulation, and on-site renewable energy generation, all carefully managed. The representation of the characteristics and components of a NZEB is shown in Figure 2.2. Furthermore, a ZEB is defined as a building that relies entirely on energy from renewable sources and does not emit carbon on-site from fossil fuels. According to the European Parliament, all new buildings must be ZEB by 2028 and equipped with solar technologies (2026 for public buildings) [41].

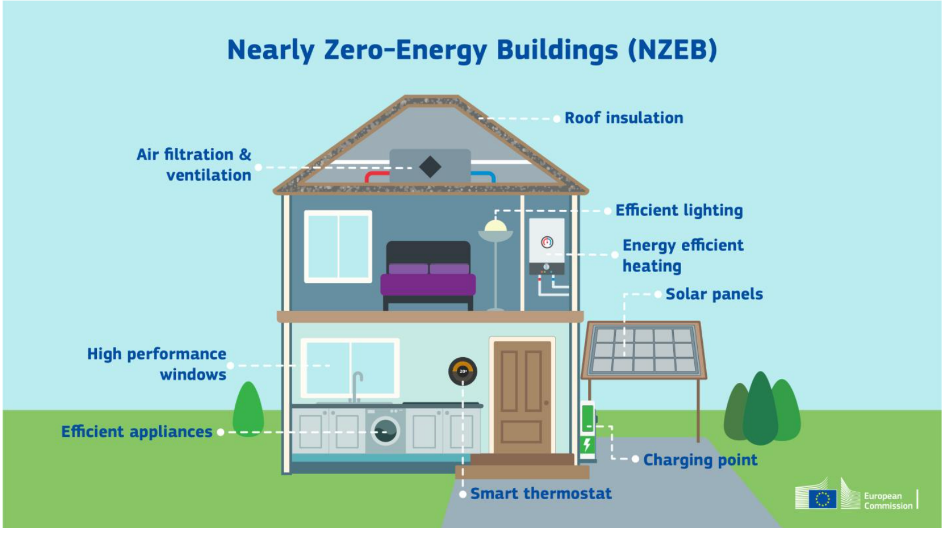

Figure 2.2: Representation of a NZEB [19].

On the other hand, and arguably even more critical, renovation plays a crucial role, as the majority of existing buildings will continue to comprise a significant portion of the European housing stock for the next decades. This means that approximately **75%** of the building stock, which is considered inefficient, must be renovated within the next 25 years [21]. Currently, only between 0.4 and 1.2% of the building stock undergoes renovation each year -across the EU members- and within these renovations energy performance improvements are scarce [21]. Across the EU, deep renovations, which aim to reduce energy consumption by at least 60%, are only carried out in 0.2% of the building stock annually [15]. At this current pace, it is estimated that more than 100 years would be required to renovate the EU building stock [21].

To transform the current residential sector into a more sustainable one, efforts have been focused on integrating rooftop Solar PV systems as part of the NZEB plan. This integration aims to decentralize the energy system and incentivize on-site generation and consumption. A PV system with BESS offers the advantage of allowing the household to draw power from the grid, thus reducing the required battery capacity in comparison to off-grid systems. Meanwhile, any excess electricity can either be fed back into the grid or stored within a BESS. This BESS functionality enables the separation of electricity consumption from electricity generation over time, effectively mitigating the volatility associated with PV systems. Assuming the availability of vehicle-to-grid (V2G) capabilities, EVs could also serve as mobile ESSs, charging during periods of low tariff rates and discharging during peak hours, thereby contributing to the electricity grid's stability [44].

2.1.1 Dutch residential sector

According to the Dutch Central Bureau of Statistics (CBS), in 2021, the average energy consumption per household in the Netherlands was approximately 2,810 kWh of electricity and 1,280 cubic meters (m^3) of natural gas [6]. On average, 1 m^3 of natural gas has an energy content of approximately 10 kWh, then 80% of the total energy consumption comes from natural gas, and around 80% of this gas is used for space heating and DHW as shown in Figure 2.3. In 2018, 90% of the residential heating demand was met by natural gas [33].

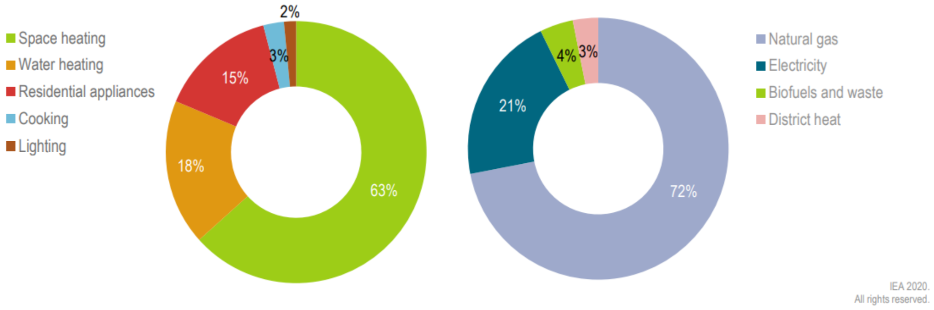

Figure 2.3: Dutch residential energy consumption by use and by fuel, IEA [33].

The amount of electricity consumed is also dependent on the type of dwelling as shown in Figure 2.4. In the case of apartments, the average electricity consumption is approximately half compared to that of detached houses. Specifically, apartments consumed around 2,070 kWh, whereas detached houses consumed about 4,120 kWh [5].

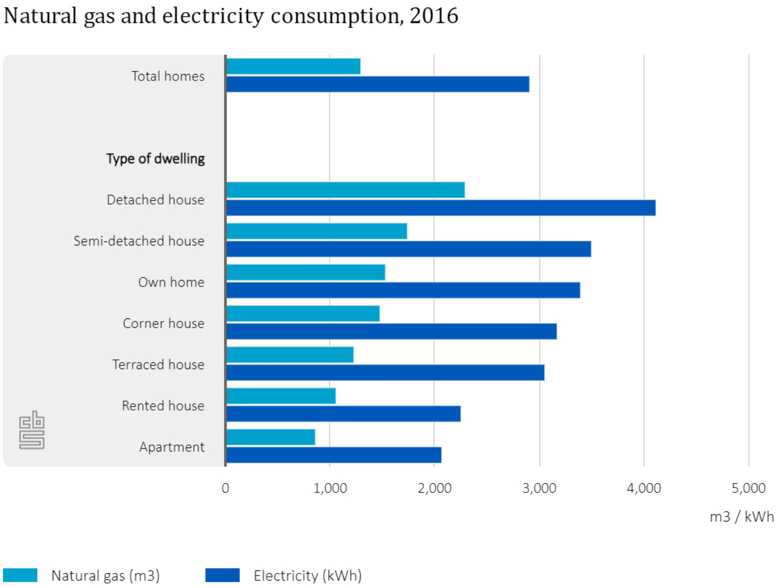

Figure 2.4: Energy consumption by type of dwelling, 2016 [5].

In recent years, there has been an exponential increase in the implementation of PV systems in households, as shown in Table 2.1. According to CBS, the installed capacity has doubled since 2019, and at the end of 2022, approximately **2 million households** (25% of all households) had installed solar rooftop systems [9]. It is assumed that the majority of deployed rooftop Solar PV systems are On-Grid systems, likely attributed to the elevated investment costs of BESSs and the incentives offered by net metering policies, rather than actively encouraging self-consumption.

Table 2.1: Residential Solar PV Capacity

Year	Installations	Installed capacity [MWp]	Number of homes	Percentage
2019	960,248	3,236	7,891,786	12.17
2020	1,267,651	4,488	7,966,331	15.91
2021	1,589,761	5,829	8,045,580	19.76
2022	2,050,687	7,738	8,125,229	25.24

2.2 Electricity markets

Electricity, like any other product, is traded in electricity markets involving bids and pushes for it. Similar to most commodities, electricity prices are determined by supply and demand dynamics. Nevertheless, electricity is unique, and its value depends on the time it is delivered. Consequently, electricity prices fluctuate significantly throughout both the day and the year. These price fluctuations offer not only economic prospects but also facilitate better integration of REs. Understanding the value of electricity and the ongoing changes in electricity markets is the main goal of this section.

Around the world, various approaches exist for organizing political economies, including the electricity markets. Within the context of market economies, differing levels of coordination and government intervention give rise to two distinct models: Coordinated Market Economy and Liberal Market Economy. The former is often associated with a higher degree of collaboration among businesses, labor unions, and the government. The latter, in contrast, is marked by reduced government intervention and regulation. Real-world economies typically demonstrate a mix of these two approaches rather than a strict binary categorization. Electricity is a unique market. Incentives and subsidies from the government are essential to develop technology and create protected spaces to innovate. In the words of Van de Graaf [60]:

> ”Energy markets have never operated fully without government interference, simply because of the strategic importance of energy supply and finance to the state”

During the 1980s, electricity markets were liberalized in the EU, resulting in the separation of generation, grid operation, and retailing. The interactions of stakeholders and markets are graphically illustrated in Figure 2.5. Three markets for electricity were introduced:

1. **Wholesale Market:** This arena serves as the platform where major electricity generators sell their power to suppliers who, in turn, distribute it to end consumers.
2. **Retail Market:** Consumers buy electricity from suppliers who purchase it from the wholesale market. Retail pricing is commonly governed by regulation or subject to competitive dynamics.
3. System (ancillary) services: These encompass functions such as balancing and voltage support.

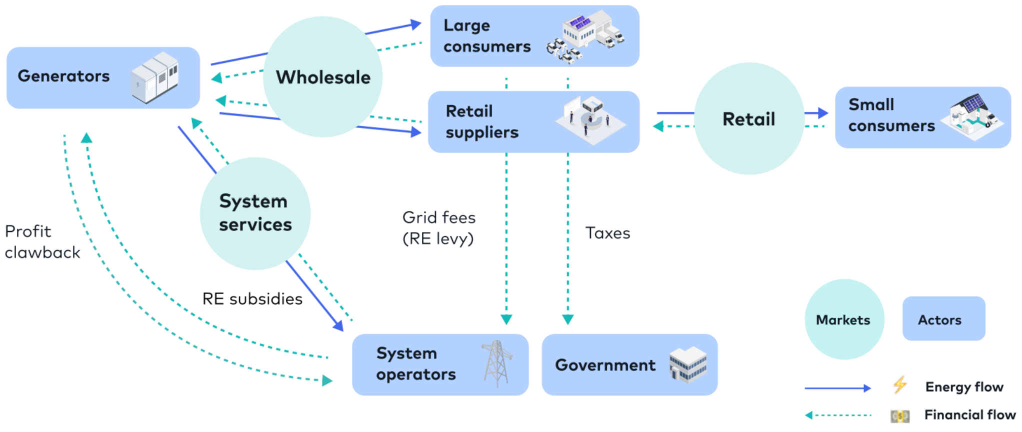

Figure 2.5: Actors and markets for electricity [28].

2.2.1 The merit order model

Taking into consideration that electricity must be generated at the same time that it is consumed, and recognizing the diversity of generators available in the market, the *Merit Order Model* describes the sequence in which power plants are designated to deliver power and fulfill electricity demand in European countries, a graphical representation of this model is presented in Figure 2.6.

On the x-axis, the graph illustrates the generation capacity per energy source, while the y-axis shows the generation cost. The core objective of the merit order is to economically optimize electricity supply by ranking electricity generation sources based on their marginal costs. This prioritizes the sources with the lowest generation costs, which primarily consist of renewable sources, to meet the demand.

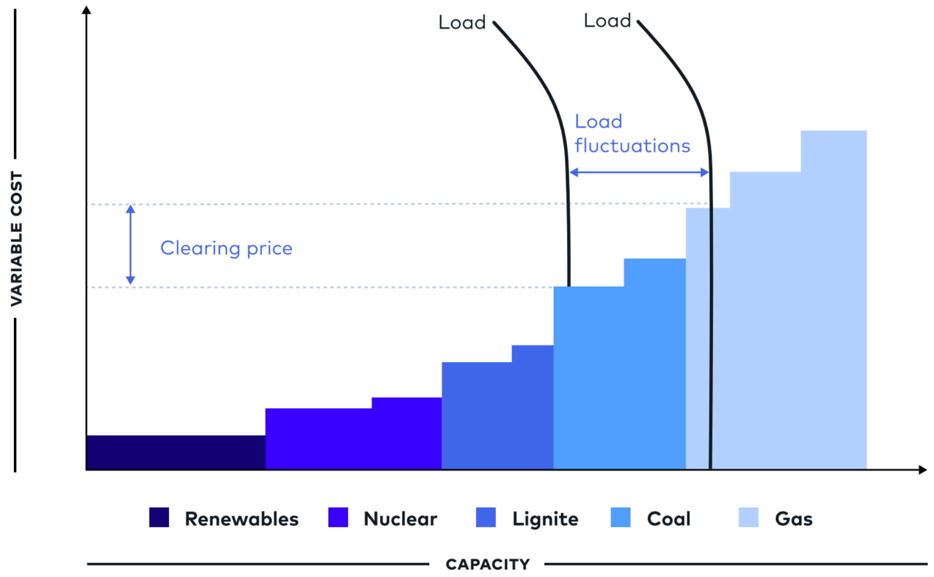

Figure 2.6: Merit order model [28].

The clearing price is determined where power demand and supply intersect. When demand is low, the activation of the cheapest generators is sufficient, while when demand is higher than the capacity of the previous generator, the next-most-expensive plants do so. Consequently, an increased integration of inexpensive renewable electricity displaces fossil fuels from the market due to their inability to compete with lower price levels.

Nevertheless, at the same time it means that if demand is high, the most expensive generation source will set the price. For instance, when demand increases in winter, natural gas power plants generally meet consumption peaks. Given the European market's reliance on the "marginal costs" model, the pricing is often dictated by natural gas. Reducing peak consumption restricts the introduction of pollutant sources such as coal or gas in the generation system.

It is worth mentioning that the merit order is a descriptive model of how markets behave not what they are forced to be or should behave. There is a common understanding that the current electricity markets should be reformed and boost renewables [20].

2.2.2 Local Electricity Markets

In recent years, emerging local electricity markets (LEM) have increased attention and interest. These alternative markets offer novelty approaches to energy acquisition and distribution such as directly buying and selling energy among their participants. LEM often involves a shift towards greater decentralization, increased consumer participation, and a focus on renewable energy sources. These models aim to promote energy democratization, local resilience, and sustainability while addressing the evolving needs and preferences of energy consumers [23]. Two common models are briefly described as follows:

- Energy Cooperatives: Energy cooperatives are member-owned organizations that enable individuals, businesses, or communities to collectively invest in and manage renewable energy projects. They often operate on a cooperative basis, where members have a say in decision-making and benefit from shared ownership and the resulting energy savings. It encourages peer-to-peer (P2P) energy trading [36].
- Virtual Power Plants (VPPs): VPPs aggregate the DER generation and consumption of multiple participants and optimize their collective operation. As a unique entity, this model allows participation in LEMs providing grid services.

2.2.3 Dutch Electricity Prices

Energy crisis linked to global conflicts, and skyrocketing bills for energy has been part of the daily discussion in the last years. In the Netherlands, and across Europe, the wholesale electricity prices started increasing steadily back in July 2021, reached record levels, and remained high during 2022 as shown in Figure 2.7. This increase is largely linked to the global rising prices of natural gas, the Dutch energy system's dependency on natural gas, and the result of the current electricity market mechanisms to set the price according to the merit order model as explained in the previous section.

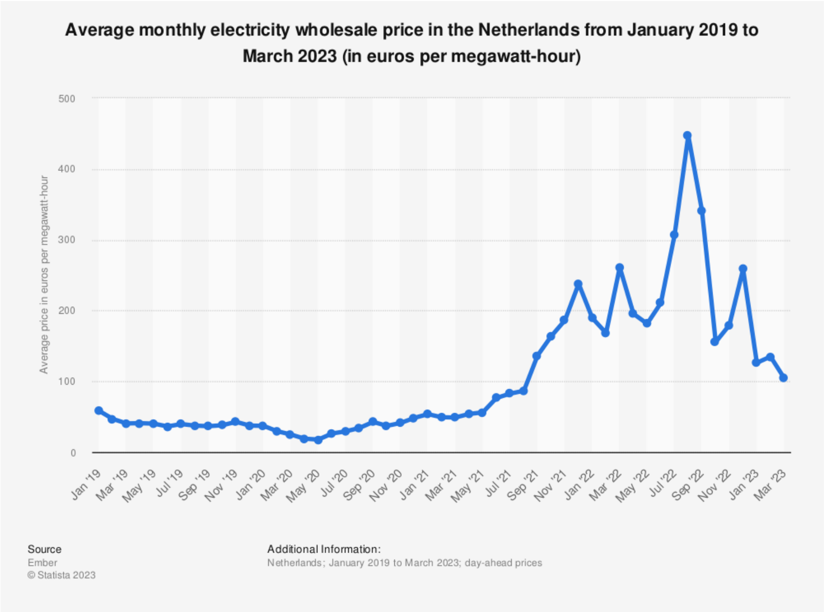

Figure 2.7: Historical Average Wholesale Electricity Price in NL [12]

On the other hand, if we closely examine the hourly electricity prices, we can observe a recurring pattern throughout the day, commonly referred to as the "duck curve," as illustrated in Figure 2.8, depicting historical data for the Netherlands from 2009 to 2023. High prices are evident during the morning hours, typically from 6:00 a.m. to 9:00 a.m., followed by lower prices around noon. The evening hours once again witness a rise in prices, with prices returning to lower levels during nighttime. This pattern can be correlated with systematic behaviors and linked to societal organizational routines.

In the upcoming years, as Solar PV penetration increases in the energy mix, the peak production of Solar PV around noon could potentially lead to a reduction in electricity prices around this time.

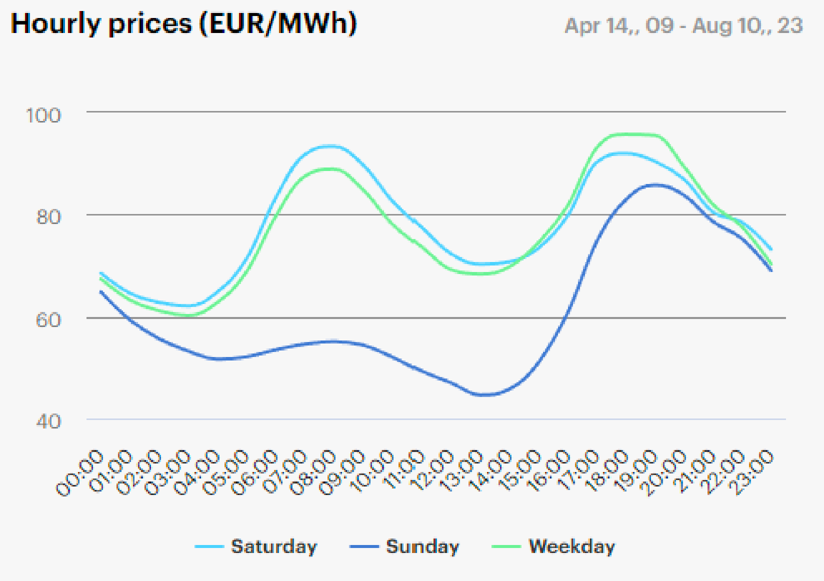

Figure 2.8: Historical Average Hourly Price[35]

Until March 2020, only a small number of retail electricity consumers had agreements incorporating dynamic time-of-use pricing facilitated by smart meters. Several factors contribute to this situation. Firstly, a significant portion of consumers do not possess the necessary smart meters required for active participation in the energy market. Even among those equipped with smart meters, there is often a lack of additional systems capable of automating Demand Side Response (DSR) and enabling flexible utilization of distributed generation. Furthermore, many consumers may not be inclined to engage with the complexities of active market participation. To engage these customers, it is likely necessary to offer energy services that deliver clear advantages with minimal complications [33].

To take advantage of shifting flexible loads at home to a more convenient hour of the day, time-of-use pricing and participation in demand response programs offered by electricity providers are required as will be discussed in 2.2.2. With a fixed energy contract you cannot profit from it if prices fall.

Retail Electricity Price Structure

As described in Section 2.2, the final electricity price that householders pay (retail) is different than the wholesale. The retail price of a product is the final price that a customer will end up paying. On average, Dutch households used to incur a cost of $210 per MWh of electricity (equivalent to 21 cents per kWh) as of 2020, a figure close to the IEA's median benchmark of $200 per MWh. Taxes constituted 26% of the overall cost, which slightly exceeded the median tax rate observed among IEA member nations, standing at 22% as shown in Figure 2.9 [33].

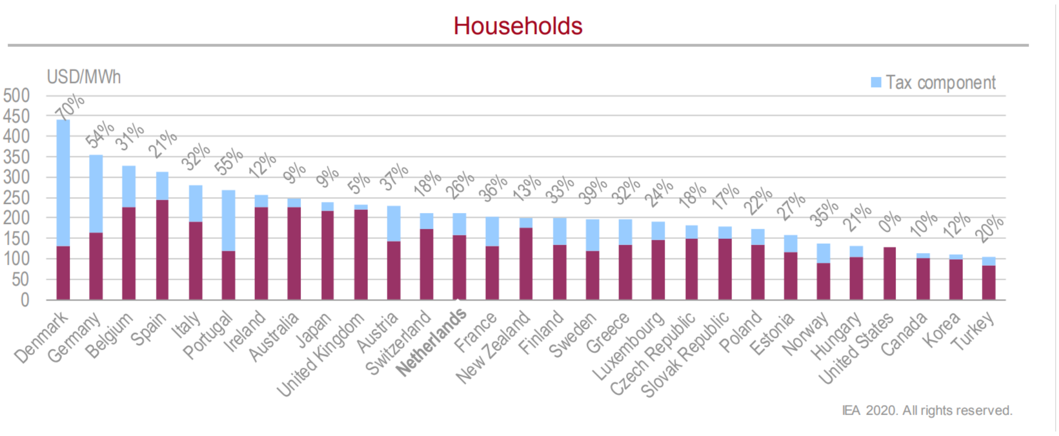

Figure 2.9: Household electricity prices in different countries [33]

The electricity component represents a relatively small portion of retail prices, accounting for approximately one-third of a consumer's ultimate electricity bill. Additional costs such as grid fees, taxes, and surcharges are applied on top of this base rate. The pricing structure for retail electricity can be categorized into 3: (i) Supply costs, (ii) Network costs, and (iii) government-imposed taxes and levies.

(i) Supply costs encompass both variable and fixed components and are paid to the chosen energy supplier (e.g., Eneco, Nuon, Greenchoice in NL). The variable component is paid based on the quantity of energy consumed per kilowatt-hour (kWh) of electricity while the fixed supply cost component accounts for the services provided and remains constant irrespective of energy usage. This fixed component takes the form of a subscription fee, the rate of which can be determined by energy suppliers at their discretion.

(ii) Network costs include expenses for transport and connection to the grid and are charged by grid operators independently for both distribution and transmission grids. For residential consumers, network costs have been fixed, based on the capacity of their grid connection, however, this is going to change in coming years due to the ever-growing integration of emerging technologies such as Heat Pumps and EVs.

(iii) The final element in the electricity pricing structure encompasses government energy taxes and levies, comprising Value Added Tax (VAT or BTW), energy taxes (Energiebelasting), and a sustainable energy premium (SDE, ODE, Environmental Taxes Act) aimed at accumulating funds for sustainable energy projects. These charges are based on the electricity consumption per kWh.

Table 2.2 presents the taxes, levies, and network costs[1] excluding VAT with data from the tax authorities [2] and the CBS [7] for the Netherlands. It is worth noting that the reduction in energy tax of 2022 to cope with the high electricity prices was dismantled for 2023. From January 2023 on, the ODE levy is included in the energy tax.

Table 2.2: Electricity Price Components

Year	Electricity Tax (€/kWh)	ODE (€/kWh)	Network tariff (€/year)	Energy Tax credit (€/year)
2019	€ 0.09863	€ 0.0189	€ 196.96	€ 257.54
2020	€ 0.09770	€ 0.0273	€ 199.88	€ 435.68
2021	€ 0.09428	€ 0.0300	€ 212.69	€ 461.62
2022	€ 0.03679	€ 0.0305	€ 220.76	€ 681.63
2023	€ 0.12599	€ 0.0	€ 282.78	€ 493.27

It is worth mentioning that the specific distribution of these costs varies among countries and changes over time according to regulations, policies, and the electricity market.

Network tariffs

One of the key challenges of the energy transition is the risk of grid congestion when feeding excess electricity from DES, such as PV, into the grid. Simultaneously, there may be potentially high-demand peaks due to EV charging. Several countries have introduced new models for dynamic network tariffs to address these issues [62].

Currently. The Netherlands employs a capacity-based tariff scheme, in which the majority of all low-voltage customers (households) pay the same annual fixed fee. In 2023, the fixed network costs account for approximately 340 Euros per year, inclusive of VAT [7]. This tariff applies uniformly to all consumers with a physical connection (up to 3 x 25 A), regardless of how or when they utilize the network. Consequently, it does not provide any incentives or encouragement for households to use the network more efficiently.

In the past, network tariff designs were designed with a uniform population in mind, where the typical energy demand was below the physical connection limit, with an average household peak consumption of approximately 4 kW [31]. Consequently, the primary cost drivers were associated primarily with establishing the physical connection to the network. However, this situation is currently evolving due to the increasing penetration of EVs and heat pumps within the grid. On one hand, these technologies are essential for decarbonizing the transportation and heating sectors; on the other hand, they exhibit significantly higher power consumption compared to the typical household's peak load.

It is widely acknowledged that network tariffs, which serve as the means to distribute the expenses associated with constructing and maintaining the electricity infrastructure among all users and producers of electricity, must adapt in response to the ongoing transition [11]. Currently, Dutch Distribution System Operators (DSOs) and associated stakeholders are

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[1] Average value, the actual value depends on region and network operator

engaged in discussions regarding revisions to the network tariff framework for the upcoming regulatory period in the Netherlands, in January 2024 [31]. The bandwidth model proposes a monthly subscription based on the consumer's grid usage, which impacts both production and consumption. In Figure 2.10, the bandwidth is depicted in blue, allowing customers to use the grid in this bandwidth without incurring additional costs. The grey areas represent energy consumption that may incur extra charges, such as charging an electric vehicle or exporting excess electricity into the grid at noon.

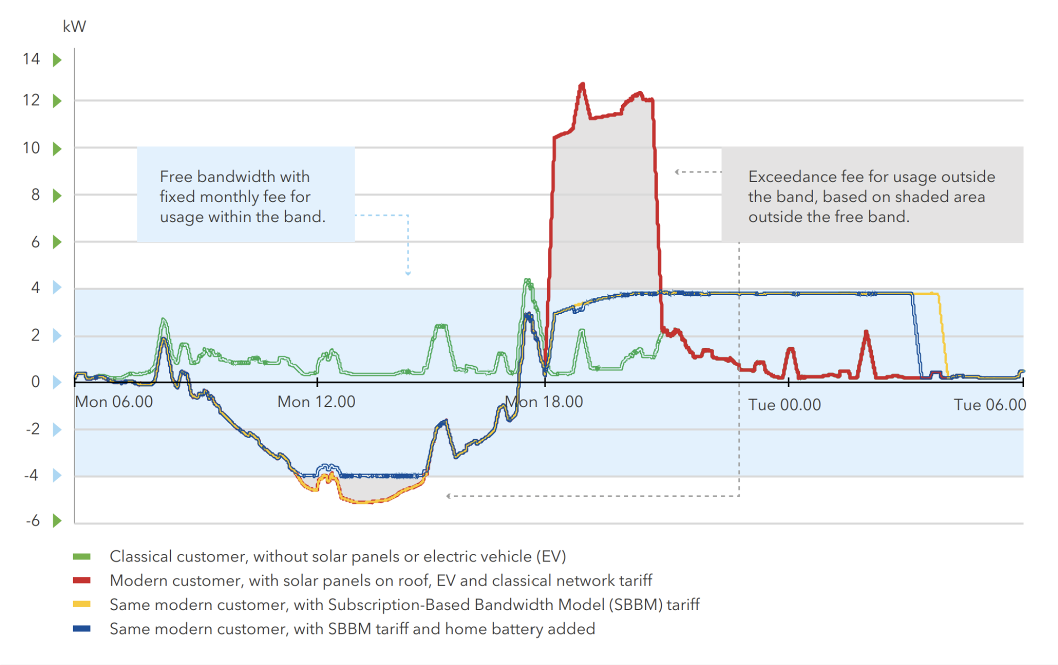


Figure 2.10: Bandwidth tariff scheme [11].

2.3 Regulations and policies

Policymakers in the NL are dedicated to encouraging policies that drastically reduce national GHG emissions, specifically a 49% reduction by 2030, compared to 1990 levels, and 95% by 2050 [27]. To achieve this, one ambitious renewable electricity generation goal was established: increasing the share of renewable energy sources to at least 70% by 2030 as indicated in the National Climate Agreement in June 2019 [24]. To put it in perspective, in 2021, 24% of the electricity was generated by the combination of wind and solar sources, while 62% was still produced from fossil fuels, as reported by the International Energy Agency (IEA) [34].

The Ministry of Economic Affairs and Climate Policy holds responsibility for the development of renewable energy policies. Currently, Rob Jetten serves as the Minister for Climate and Energy Policy [25]. Oversight and regulation of the electricity market fall under the responsibility of the Netherlands Authority for Consumers and Markets (ACM). The ACM, at its core, is established to protect the rights of both consumers and businesses. It oversees and regulates both the wholesale and retail electricity markets. While retail electricity prices are not directly controlled, suppliers are required to submit all prices to the ACM for evaluation, and the ACM possesses the authority to compel suppliers to adjust the prices when necessary [33].

To stimulate the integration of REs in the energy system, various policy mechanisms have been implemented. One such mechanism is the Feed-in Tariffs (FiT), which are designed to accelerate investment in RES by offering a cost-based compensation during long-term contracts for renewable energy producers [10]. FiT is applied in the residential sector as well, where households equipped with PV systems receive compensation for surplus electricity produced but not consumed, which is subsequently supplied back to the grid, and then a yearly balance of production and consumption is made. This scheme is well-known in the NL as *Net metering* as it will be discussed further in the next section. The specific compensation depends on the supplier and the limit established, usually in the range of 4 to 10 cents per kWh [14]. However, incentives will decline, feed-in tariffs are designed to disappear, and this compensation is to be steadily reduced from 2025 [64].

Net metering in the Netherlands

To encourage the adoption of rooftop solar energy systems, the Netherlands introduced net metering in 2004. Essentially, the regulation on net metering states that electricity suppliers are obligated to deduct all the electricity a household feeds back into the grid from the consumed electricity from the grid [39]. For example, during the winter months when householders typically consume more electricity than their PV system generates, they receive compensation for the surplus electricity produced during the summer that was not used. In this way, the grid can be described as an "unlimited battery" as all produced electricity is accounted for and deducted accordingly. Initially, there were restrictions on the amount of power that could be fed back into the grid, but these limitations were removed in 2014 [39].

While this successfully resulted in the desired expansion of installed rooftop solar capacity, it also brought some negative effects: (i) Grid congestion due to vast amounts of feed-in in a low-voltage network, (ii) reduced tax revenue for the government from electricity consumption, and (iii) the net metering regulation fails to incentivize PV system owners to enhance their Self-Consumption Ratio (SCR) [39].

Initially, net metering, originally planned for 2023 but now postponed until 2025, will be slowly phased out. In January 2023, the ACM supported the proposal put forward by the Dutch Minister of Economic Affairs and Climate Policy for dismantling the current net metering scheme as soon as possible [1]. The ACM claims that net metering hinders a more efficient use of the grid and it curbs the adoption of home battery systems.

From the perspective of Netbeheer Nederland, the Dutch network associations, this issue is a serious problem. In May 2020, the Dutch government announced that grid operators were not obligated to provide compensation to owners of solar rooftops whose arrays were disconnected as a result of grid capacity and voltage quality issues[50]. They claim that a rebate for storage systems and intelligent energy management is imperative to promote the smart utilization of solar power [50].

From 2025, the percentage of energy subject to net metering will decrease from 100% to

64%, as shown in Figure 2.11. That means that only 64% of all the electricity you feed back into the grid will be deducted from the energy you consume. With the percentage of energy subject to net metering steadily declining each year until it vanishes in 2031, it highlights the importance of prioritizing on-site consumption of generated electricity over feeding it back into the grid, which technically means increasing the SCR.

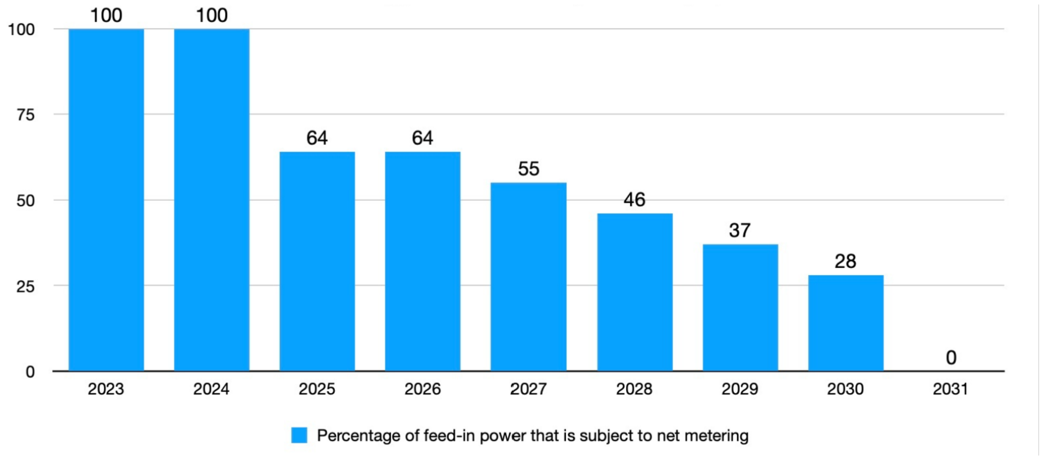


Figure 2.11: Net metering phase out according to the new proposals [64].

2.4 HEMS

The principal goal of a HEMS is to efficiently coordinate energy flows within households and optimize energy consumption by scheduling appliance operations accordingly. Besides the technical aspects, it empowers householders to take control of their energy usage, reduce costs, and actively contribute to a more sustainable energy system.

Demand-side management (DSM): Promotes optimizing energy use, reducing overall energy consumption, and improving energy efficiency. Implementing strategies, including load shifting, energy efficiency programs, and the integration of DERs. HEMS allows householders to participate in demand response (DR) programs by adjusting energy usage in response to grid conditions or price signals [58]. DR encourages consumers to employ their flexibility in a manner that contributes to the stability of the system, as a result, it rewards householders for a grid-stabilizing behavior with financial incentives. Moreover, DR can potentially reduce the need for expensive and slow-paced infrastructure upgrades [46]. Two of the most common DR strategies are explained as follows:

- **Price-based:** Consumers adjust their electricity usage based on the pricing signals received from the electricity market. This could involve reducing consumption during high-priced periods or shifting usage to low-priced periods. Currently, Multistep Electricity Price (MEP), Real-Time pricing, and Time-of-use pricing (TOU) are some pricing strategies adopted [63]. Different pricing schemes combined with HEMS produce different economic effects. For instance, [37] developed a self-scheduling model for HEMS including a novel discomfort index, and formulated it as a MILP multi-objective problem (see Section 2.4.2). The model was tested under TOU and RTP schemes. n

Figure 2.12, a comparison of the cost per appliance on a daily basis, when shifted to off-peak hours, demonstrates a significant reduction.

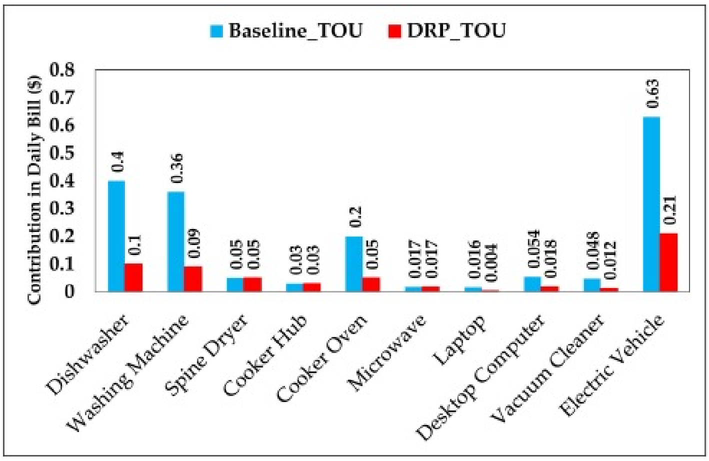


Figure 2.12: Daily appliance's costs based on TOU [37]

- **Incentive-based:** Consumers are offered financial incentives or rewards for reducing their electricity usage during specific times or events, encouraging voluntary participation. In this category, Vivekananthan et. al [61] proposed a new *Customer Rewards (CR) scheme* to shave network peaks and improve the voltage network independent of the cost of the electricity consumption. Alternately it rewards customers based on their willingness to participate in the scheme with an exponential benefit for participating for longer times. As a case study, the CR scheme was implemented for Direct Load Control (DLC), where the overloaded transformer is avoided, as shown in Figure 2.13

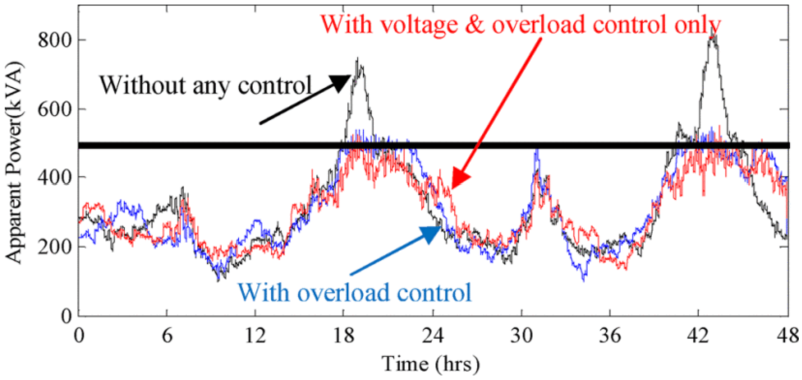


Figure 2.13: Loading 500 kVA transformer[61]

Environmental Impact: HEMS reduces reliance on fossil-fuel-based electricity, leading to a reduction in CO2 emissions and contributing to a more sustainable energy future. It creates awareness among consumers and motivates them to actively participate in power conservation activities [40].

Provide Information about Energy Consumption: HEMS often provides householders with real-time data on their energy consumption, production, and battery status through user-friendly interfaces or mobile apps. This visualization empowers householders to make informed decisions about their energy usage and identify areas for further efficiency improvements.

The direct benefits of HEMS from the householder's perspective are:

- Information on energy consumption and generation
- Automated control of home appliances
- Increase the overall energy efficiency of the household
- Energy savings

2.4.1 Challenges of Implementing HEMS

To fully realize the above goals, HEMS must overcome several challenges. From initial costs and technological complexity to user engagement, the successful implementation of HEMS requires addressing multifaceted issues. Some of the challenges of implementing a HEMS are listed as follows:

User engagement: The successful implementation of HEMS heavily relies on user engagement and active participation. Householders lack awareness and knowledge about the benefits and functioning of HEMS. A study of 632 residents in New York exhibited that *"Low-income households perceived HEMS to be harder to use and less useful, yet still indicated their willingness to adopt HEMS [22].* Educating and empowering householders to understand and utilize HEMS effectively is essential for wide deployment.

Load profile of appliances: Understanding how different smart home appliances consume energy provides valuable information about consumer energy usage. This data is a vital element in the creation of precise and effective load management algorithms. Access to high-quality and diverse data is essential to build accurate models and algorithms that can adapt to different household scenarios [57].

Awareness: Many householders lack awareness of their energy consumption patterns and may not recognize how small changes in behavior can significantly impact energy efficiency. Promoting user awareness and providing real-time feedback can encourage more energy-conscious decisions [22].

Dynamic Tariffs: Dynamic pricing is a fundamental factor, in encouraging consumers to transition their energy consumption from peak to off-peak periods. However, from the consumer's viewpoint, dealing with intricate and extensive data can be particularly challenging [57].

Standarization: *"In different countries, the incentives for prosumers are rarely the same. Consequently, the requirements for a HEMS differ from country to country"* [29].

2.4.2 Decision making

For the HEMS to solve complex scenarios and make decisions considering multiple variables, the EMS requires that the problem is well defined as an optimization problem to either maximize or minimize the result.

Objectives

In the literature of EMS, different objectives are described to manage energy consumption, these objectives can be classified into four categories: (i) economic, (ii) technical, (iii) environmental, and (iv) social. The most relevant objectives for the residential sector are shown in Table 2.3, and an extension of the industrial sector is provided in [58]. The objective of the EMS is commonly called the *objective function*. Different objectives can be part of the same EMS's goals, and often, they can be contradictory between them. For example, maximizing grid support may potentially lead to an increase in the charging and discharging cycles of the battery, while maximizing profit from a dynamic electricity contract could result in higher electricity consumption from the grid, leading to increased CO2 emissions. It is common for modern EMS to consider multiple objectives from different categories, and weights and combine them using the weighted sum method into a single-objective optimization. The most frequently cited multi-objective is minimizing electricity cost and CO2 emissions [58].

Table 2.3: Objectives for Home Energy Management Systems

Economical objectives	**Technical objectives**	**Environmental objectives**	**Social objectives**
Min electricity cost	Min peak average ratio	Min emission	Min discomfort
Min total fuel cost	Min battery degradation	Min electricity consumption	Min waiting time
Min generation cost	Max grid support	Min grid energy use	

Optimization techniques

EMS can implement different optimization techniques to solve the defined objective function. Based on how the optimization problem is formulated and the steps to find an optimal solution, one classification of these techniques is presented in Figure 2.14 [58]. Linear programming (LP) stands out as the most straightforward method that is integrated into HEMS when addressing scheduling optimization problems [57].

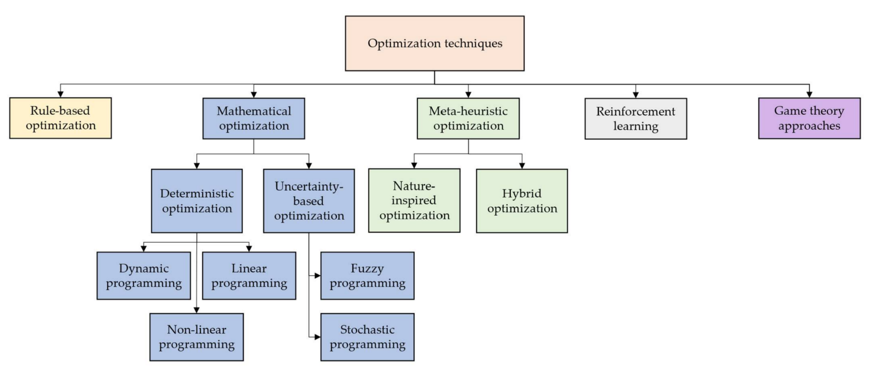


Figure 2.14: Classification of optimization techniques [58]

Bradac et. al [3] formulated and implemented a mixed-integer linear programming (MILP) model aimed at minimizing the total energy costs and reducing power peaks. The study considered six residential dwellings and six types of domestic appliances, including washing machines, dishwashers, and tumble dryers. Furthermore, the research takes into account two pricing tariffs prevalent in the Czech Republic: a flat tariff of 4.37 CZK (approximately €0.18) and a two levels pricing structure, consisting of 4.88 CZK (around €0.20) and 1.99 CZK (approximately €0.081) per kilowatt-hour, as illustrated in Figure 2.16 The total costs are visually depicted in Figure 2.15. The higher consumption of dwellings 1, 3, and 5 was due to consumed electricity for water heating, whereas dwellings 2, 4, and 6 utilized electricity exclusively for common appliances. The authors claimed that the electricity price tariffs offered did not incentivize implementing optimal scheduling when compared to the associated investment costs. Furthermore, it is worth mentioning that the study does not account for the integration of Distributed Energy Resources (DERs).

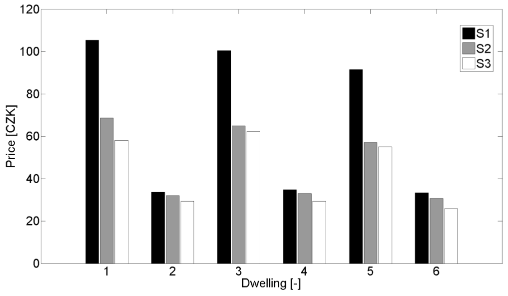
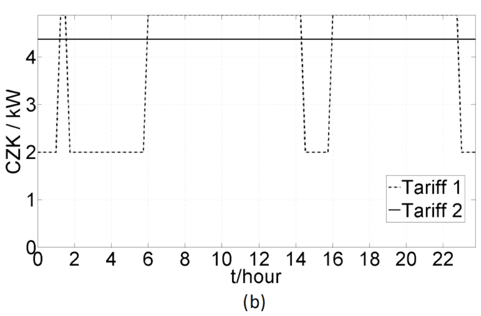


Figure 2.15: Costs per dwelling and tariff [3]



(b)

Figure 2.16: Electricity tariffs [3]

In the group of mathematical programming methods, there is a predominant choice among researchers for tackling multi-objective optimization problems utilizing Mixed-Integer Linear Programming (MILP). This preference is linked to easy-to-implementation, computationally inexpensive, and the availability of commercially accessible solvers [57]. Forecasting models based on artificial intelligence demonstrate a heightened capacity for handling the inherent nonlinearity within input data. However, the adoption of machine learning and deep learning techniques demands the use of costly hardware equipped with parallel processing capabilities [38].

Chapter 3

Methodology

3.1 System Architecture Design

The High-level block diagram of the HEMS is shown in Figure 3.1. The HEMS computes the data of (i) the energy demand (Load Profile) of the household, (ii) the energy supply (PV Generation + Grid), (iii) the BESS (Home Battery), and (iv) day-ahead electricity prices (Retail) to coordinate the power flows and schedule the optimal operation of shiftable household appliances. Depending on the objective, it aims to minimize electricity costs, and CO2 emissions or increase the SCR.

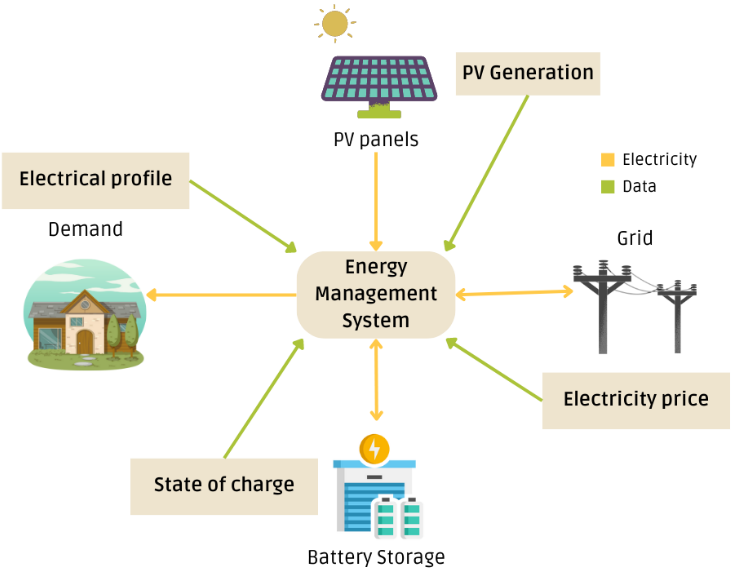


Figure 3.1: Energy Management System Arquitecture

Considering the characteristics of the Dutch residential sector and the prioritization of old buildings and high-consumption households, the energy consumption of a detached single-family house (SFH) with high energy intensity was modeled as detailed in section 3.5.1.

For this household, a grid-connected roof PV system was designed and simulated to partially meet the electricity demand and reduce grid electricity consumption. The simulation's specifications can be found in Section 3.2.1 and Appendix A.2. To enhance the PV system's performance, a basic model of a BESS was implemented to simulate the performance of a hybrid PV system, as elaborated in Section 3.3. The methodology for simulating dynamic electricity pricing is detailed in section 3.5.3. Subsequently, the optimization algorithm and modeling of the objective function are described in Section 3.4.

3.2 PV System

To model the PV electricity generation data, the PV system was simulated in Python using PVLIB[1]. PVLIB is a library of algorithms and routines that are used for modeling and simulating the performance of photovoltaic energy systems, originally developed at Sandia National Laboratories [32].

The electricity output of the PV System primarily depends on factors such as solar irradiance, weather conditions, and solar cell efficiency. PVLIB offers a so-called model chain that allows parameter customization. The model chain is divided into 6 modeling steps: (1) Irradiance and weather, (2) Incidence irradiance (3) Shading and Soiling, (4) Cell temperature, (5) Module output, (6) Inverter DC/AC.

The PVLIB model chain requires the definition of a location and a PV System. The *Sandia Array Performance Model (SAPM)* was used for modeling the PV System [53]. As inputs for the SAPM, the PV module and inverter specifications were retrieved from the Sandia National Laboratories Database, as detailed in the implementation code in Appendix A.2. Initially, a 4kWp fixed-mounting PV system facing south was modeled. The temperature model, *SAMP module*, was employed to calculate both the cell temperature,T_C, and module temperature, T_m, as shown in Equations 3.1 and 3.2. Where E_{POA} is the POA irradiance, E_0 is the reference irradiance ($1000 W/m^2$), T_a is the ambient temperature, WS is the wind speed, and a and b are construction parameters [51].

$$T_m = E_{POA} \cdot \exp(a + b \cdot WS) + T_a \tag{3.1}$$

$$T_C = T_m + \frac{E}{E_0} \cdot \Delta T \tag{3.2}$$

Specifically, the construction and mounting parameters are retrieved from the *close mount glass/glass* model. This model accounts for a mounting configuration where PV panels are installed near the support structure, such as a building roof. This configuration impacts the heat dissipation characteristics of the panels giving a more realistic output.

The DC power output, P_{DC}, given in Equation 3.3, was calculated based on the NREL's *PVWatts DC power model* [52]. Where G_{POAeff} is the effective POA irradiance, γ is the temperature correction, and T_0 is the reference temperature (25^{o}). To calculate the AC

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[1] `https://pvlib-python.readthedocs.io/en`

power output, P_{AC}, from DC power input, P_{DC}, the model implements the *Sandia Inverter Model*, given in Equation 3.4, where C_1,C_2 and C_3 are empirical parameters [56].

$$P_{DC} = \frac{G_{POAeff}}{1000} \cdot P_{DC0}(1 + \gamma_{PDC}(T_c - T_0)) \tag{3.3}$$

$$P_{AC} = \left\{ \frac{P_{AC0}}{A - B} - C(A - B) \right\} (P_{DC} - B) + C(P_{DC} - B)^2 \tag{3.4}$$

$$\begin{aligned}
&where: \\
&A = P_{DC0}\{1 + C_1(V_{DC} - V_{DC0})\}, \\
&B = P_{s0}\{1 + C_2(V_{DC} - V_{DC0})\}, and \\
&C = C_0\{1 + C_3(V_{DC} - V_{DC0})\}
\end{aligned}$$

3.2.1 PV simulation specifications

The simulation specifications for the 4kWp system are detailed in Table 3.1.

Table 3.1: PV Simulation

Simulation Specifications	
Location	Enschede, NL
GPS coordinates	52° 13’ 44.5” N 6° 52’ 26.2” E
Altitude	40 m
PV System	
PV module	SunPower_128_Cell_Module__2009__E__
Surface tilt	35 °
Surface azimuth	180°
Inverter	ABB__PVI_5000_OUTD_US_Z__240V_
Modules per string	5
Strings per inverter	2
PV installed capacity	4kWp
Temperature model	SAMP close_mount_glass_glass
Irradiance model	Plain of Array (POA)
Time	
Start	1-1-2022 00:00
End	31-12-2022 23:00
Resolution	60 min

3.3 Battery Model

This battery model is defined by five initial parameters, capacity, max charging power, max discharging power, charging efficiency, and minimum state of charge (SOC). Moreover, the functionality is carried out by two functions, charge, and discharge, responsible for updating the battery’s state of charge. The algorithm that models the battery performance is straightforward. When the net demand is positive, indicating that the load exceeds the PV generation, there’s a need to either import electricity from the grid or discharge the battery. If the State of Charge (SOC) of the battery minus the net demand remains above the minimum SOC threshold, the battery is discharged, and no grid import is required. Otherwise, the grid supplies the necessary energy, and the battery stores the surplus. Conversely, when the net demand is negative, indicating an excess of PV generation over the load, there are two options: storing the surplus electricity or exporting it back to the grid. If the SOC of the battery plus the surplus energy remains below the battery's capacity, the battery is charged. When the battery is full, any excess electricity is exported to the grid. The implementation code for this algorithm is provided in the Appendix A.4.

Battery State of Charge (SOC): This constraint maintains the battery's state of charge over time, considering the charging and discharging efficiencies.

$$\mathrm{SOC}t = \mathrm{SOC}t - 1 + \eta_{\mathrm{charge}} \cdot E_{\mathrm{charge}} - \frac{E_{\mathrm{discharge}}}{\eta_{\mathrm{discharge}}}$$

Battery Charge/Discharge Limits: These constraints ensure that the battery's charging and discharging rates do not exceed their respective limits

$$0 \leq E_{\mathrm{charge}} \leq \mathrm{MaxChargingPower}$$

$$0 \leq E_{\mathrm{discharge}} \leq \mathrm{MaxDischargingPower}$$

Charging:

$$E_{\mathrm{charge}} = u_{\mathrm{charge},t} \times \mathrm{MaxChargingPower}$$

Discharging:

$$E_{\mathrm{discharge}} = u_{\mathrm{discharge},t} \times \mathrm{MaxDischargingPower}$$

3.4 Optimization model

There are several optimization techniques for scheduling shiftable appliances as reviewed in [58]. The approach employed in this HEMS model is based on solving a mathematical optimization algorithm by formulating an objective function with multiple constraints featuring linear and deterministic relationships. The model is determined over a time horizon T, specifically over a day (24 hours). This time frame is particularly relevant since, in most practical applications, optimal scheduling is determined for the following day, considering day-ahead electricity prices.

The optimization problem is formulated with PYOMO (Python-based optimization modeling package). PYOMO translates the system definition into a mathematical optimization model and triggers the solving process by employing an open-source optimization problem solver, namely GLPK [30]. It enables the formulation of optimization problems in a manner that is similar to the notation commonly employed in mathematical optimization [4]. The formulation of the optimization problem required 3 definitions:

1. **Variables:** Three binary variables, representing the dishwasher (DW), washing machine (WM), and dryer (D), respectively, were defined in a range of the first 22-time slots *(t)* of the time horizon *(T)*. These variables indicate whether the respective appliance is scheduled to start (1) or not (0) for a specific time slot as shown in Equation 3.5 for the DW:

$$DW(t) = \begin{cases} 1, & \text{if scheduled in time t,} \\ 0, & \text{if not scheduled in time t} \end{cases} \tag{3.5}$$

2. **Constraints:** Similarly, three constraints were formulated to ensure that each appliance can only be scheduled once throughout the defined time range. This was achieved by summing the binary variables across the entire time range as shown in Equation 3.6. Additionally, an order constraint was introduced to specify that the washing machine must start and complete its cycle before the dryer starts, preventing any overlap as shown in Equation 3.7. It takes the washing machine 3 hours to complete it, and the last time slot that it can start is the 19th so the dryer starts and finishes in the time horizon.

$$\sum_{t=0}^{22} DW(t) = 1 \tag{3.6}$$

$$WM(t) >= D(t+3) \quad \forall\, t \in T \tag{3.7}$$

3. **The objective function:** The objective function defined calculates the minimum cost of all the combinations associated with scheduling the appliances along the time horizon while considering the hourly retail prices and the respective PV generation. It is important to note that this calculation assumes that the PV generation holds the same price for both exporting and importing energy. Different scenarios for the compensation of the electricity exported can be expected.

   The objective function is formulated as follows:

$$\text{Min} \sum_{t}^{24} \left(E_{\text{grid(t)}} \cdot C_{(t)}\right) - \left(E_{\text{PVExport(t)}} \cdot C_{(t)}\right) \tag{3.8}$$

$C_{(t)}$ be the grid retail electricity price at hour t (EUR/kWh).

$E_{\text{grid(t)}}$ be the energy imported from the grid at hour t (kWh).

$E_{\text{PVExport(t)}}$ be the energy generated by PV at hour t (kWh).

The hourly $E_{grid(t)}$ is composed of the base load, $B_{(t)}$, and the hourly consumption of the shiftable appliances, $E_{DW(t)}$, $E_{WM(t)}$, and $E_{DW(t)}$ if they would have been scheduled at time t. Since the consumption of the appliances takes 3 hours and each hour consumption is different, the sum that minimizes all combinations for scheduling the DW is shown as follows:

$$\begin{aligned}
\text{Min} \sum_{t}^{22} DW(t) \cdot \Big[& \left\{\left(B_{(t)} + E_{DW(t)}\right) \cdot C_{(t)}\right\} - \left(E_{\text{PVExport(t)}} \cdot C_{(t)}\right) \\
& + \left\{\left(B_{(t+1)} + E_{DW(t+1)}\right) \cdot C_{(t+1)}\right\} - \left(E_{\text{PVExport(t+1)}} \cdot C_{(t+1)}\right) \\
& + \left\{\left(B_{(t+2)} + E_{DW(t+2)}\right) \cdot C_{(t+2)}\right\} - \left(E_{\text{PVExport(t+2)}} \cdot C_{(t+2)}\right)\Big]
\end{aligned}$$

3.5 Data collection methods

The data input to the system, as discussed in the previous section, can be classified into 3 categories: (i) Load profile, (ii) Irradiance, and (iii) Electricity price. A standard data resolution of 60 minutes was chosen for the system based on the day-ahead electricity prices format.

3.5.1 Household Demand Profile

Load Profile Generator

The household demand profile of electricity consumption was simulated using the open-source software *Load Profile Generator (LPG)*[2]. The LPG is a modeling tool for residential energy consumption. It performs a comprehensive behavioral simulation of the household's occupants, based on a desire-driven psychological model, as described in [49]. This simulation of residents' behavior is employed to calculate the power consumption of household devices and generate load curves for electricity, gas, and water usage. The LPG tool provides several advantages, including complete customization, utilization of measured device profiles, and the ability to achieve resolutions of up to 1 minute.

It has been extensively validated with actual data and used in several research papers [3]. In the Netherlands, this tool has been used to simulate a neighborhood consisting of 100 households, with varying numbers of electric vehicles (EVs) added. This simulation aimed to assess the feasibility of a new capacity network tariff proposed by Delft University of Technology and the Dutch DSO, Alliander. [31].

Single Family House Model

Household without green technologies: This household consists of a single-family house (SFH) inhabited by two working parents and three children. The SFH is an energy-intensive detached house with an annual consumption of 15,000 kWh for heating (equivalent to approximately 1500 m3 of gas).

For modeling purposes, the temperature profile and location were selected as Hamburg, which is the closest location to Enschede due to the limitations of the software. Nevertheless, Appendix A.1 provides a comparison of average weather variables between Enschede and Hamburg, illustrating the minor differences between these cities and the comparability of this study. The extended description of the householder's activities and the household's device profiles are shown in Appendix A.1.2.

3.5.2 Irradiance

Hourly *Plain of Array (POA)* irradiation data and meteorological data were retrieved from PVGIS [4] to provide more realistic PV generation data [18]. POA irradiance represents the irradiance that reaches the PV module (incidence irradiance), accounting for its orientation

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[2] `https://www.loadprofilegenerator.de/`

[3] `https://www.loadprofilegenerator.de/references/`

[4] `https://re.jrc.ec.europa.eu/pvg_tools/en/`

and tilt, rather than assuming a flat ground surface. The raw data from PVGIS was processed, and the resulting POA irradiation components are shown in Figure 3.2. Mathematically, POA irradiance is given by Equation 3.9, where E_b is the beam or direct component, E_g is the ground reflected, and E_d is the sky diffuse [55].

$$E_{POA} = E_b + E_g + E_d \tag{3.9}$$

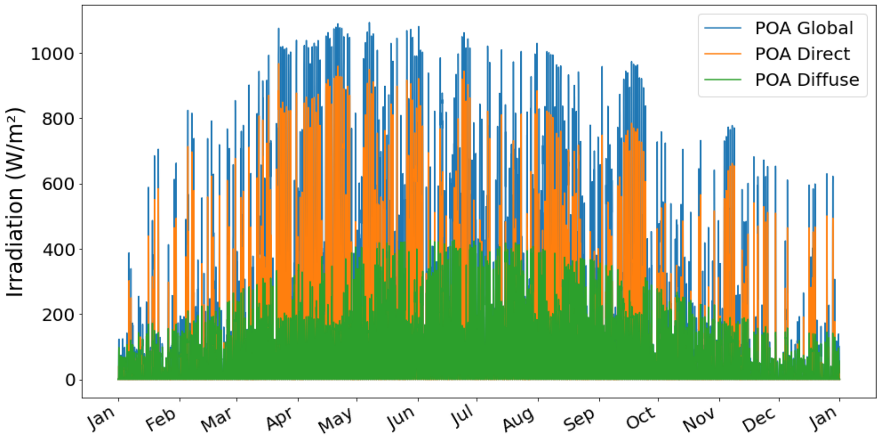

Figure 3.2: POA irradiation at 35º tilted, Enschede.

3.5.3 Retail dynamic electricity prices

The electricity price fluctuates throughout the day due to various market mechanisms in Section 2.2. Retail dynamic electricity prices were modeled and scaled for the year 2022, following the price structure described in Section 2.2.3 using data from the hourly dataset *Wholesale day-ahead electricity price data for European countries*, obtained from Ember [13], which is cleaned and sourced from ENTSO-e (European Network of Transmission System Operators). This dataset was cross-checked using the IEA's online tool, *Real-Time Electricity Tracker* [35]. This dynamic rate structure based on the day-ahead wholesale energy prices, is commonly referred to in the literature as Real-Time Pricing (RTP) [43].

The retail electricity price in EUR/kWh is formulated in equation 3.10, where it comprises the wholesale electricity price,$E_{Wholesale}$, along with electricity taxes and levies, as well as the supplier purchasing fee, S_{fee}, inclusive of VAT.

$$R_p = (\frac{E_{Wholesale}}{1000} + E_{Tax} + ODE_{Tax} + S_{Fee}) \cdot VAT \tag{3.10}$$

This led to a reasonably accurate estimate of actual retail prices when compared to the average consumer prices per kWh of variable costs for electricity delivery, as reported in [7]. This comparison is illustrated in Figure 3.3. The differences arise because the retail price was calculated with a fixed VAT rate throughout the entire year, whereas in reality, during 2022, network costs and fixed delivery rates were subsidized in the second half of the year with a reduction in the VAT rate from 21% to 9% [26].

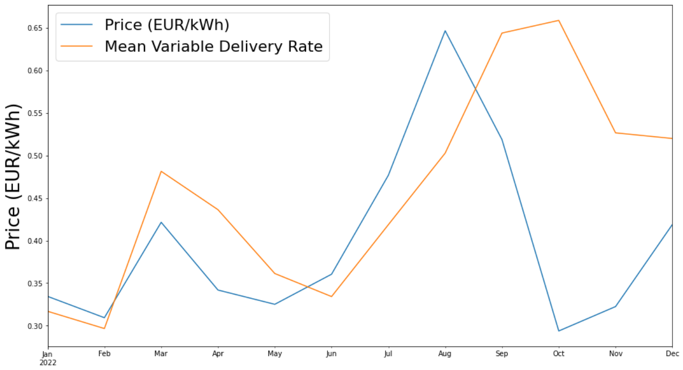

Figure 3.3: Monthly average retail and variable delivery rate

The final electricity cost, denoted as C_{Annual}, is formulated in Equation 3.12, using a calculation process similar to that employed by CBS [8]. The annual cost includes fixed costs such as network costs N_{Fixed} and supplier's fixed expenses S_{Fixed}, variable costs associated with the annual electricity grid consumption, and government subsidies (Energy Tax Credit), all inclusive of VAT.

$$C_{Annual} = C_{Fixed} + C_{Variable} \tag{3.11}$$

$$C_{Annual} = N_{Fixed} + S_{Fixed} + (E_{Grid} \cdot R_p) - E_{Credit} \tag{3.12}$$

3.6 Performance Indicators

To be able to compare and evaluate the different case scenarios, evaluation metrics, and performance indicators become essential tools for evaluating the effectiveness of energy systems, especially in the context of integrating renewable energy. The SSR, as expressed in Equation 3.13, represents the percentage of consumed renewable electricity generated on-site relative to the total electricity consumption of the building. A higher SSR indicates a greater system's ability to generate enough energy from renewable sources to meet its energy demand without relying on external sources. This results in potential electricity cost reduction and increased energy independence.

$$SSR\ (\%) = \frac{Renewable\ energy\ consumed}{Total\ energy\ consumption}\ x\ 100 \tag{3.13}$$

The SCR, as expressed in Equation 3.14, calculates the ratio of consumed renewable energy to the total renewable electricity generated on-site. It is valuable for grid-connected systems with distributed generation, such as solar panels on rooftops, where optimizing on-site consumption of renewable energy can lead to financial advantages and improvements in grid stability.

$$SCR\ (\%) = \frac{Renewable\ energy\ consumed}{Total\ renewable\ energy\ generated}\ x\ 100 \tag{3.14}$$

Achieving high values for both SSR and SCR aligns with sustainability objectives, encourages the utilization of renewable energy, and contributes to the development of a more sustainable energy system. In the context of addressing congestion issues in the grid, the

SCR becomes more important, particularly when considering the current surplus of energy being exported to the grid.

3.6.1 CO2 emissions

With different generators being switched throughout the day, measuring the CO2 emissions related to the electricity grid involves calculating the amount of CO2 emitted per unit of electricity generated. CO2 emissions associated with electricity consumption can vary over time due to changes in the energy mix. The real-time electricity production emissions depend on the energy mix at the current time. This can be checked by country in NOWTRICITY [5]. In 2022 the average emissions of the Netherlands were **481 g CO2eq/kWh**. 16% of the electricity was produced from renewable sources [47].

In comparison, the CO2 emissions associated with the consumption of photovoltaic (PV) electricity are generally very low because solar PV systems generate electricity without direct emissions of CO2 during their operation. However, there are some indirect emissions associated with the manufacturing, installation, and maintenance of PV systems. Emission factors reported in Life-cycle studies ranged from around 20 to 70 grams of CO2 equivalent per kilowatt-hour (g CO2e/kWh) of electricity generated over the lifetime of the PV panel [45]. According to the IPCC 2014 and NREL, the median value is 40 g CO2eq/kWh [48]. With the current grid mix, consuming on-site PV electricity reduces CO2 emissions, this can also be calculated as avoided CO2 emissions.

Several factors influence the CO2 emission factor of batteries, including the energy sources used in manufacturing, the energy efficiency of the production process, the materials employed, and the efficiency of the battery during its operational life. An estimation of $150 - 200 kgCO2-eq/kWh$, for the battery production was obtained from [42]. Assuming a lifespan of 10, the daily CO2 emissions were allocated. In general, the CO2 emissions were calculated with Equation 3.15, where E_{grid}, is the sum of energy imported from the grid. To calculate the net CO2, this value is changed for the net demand, E_{net}, which includes the exports.

$$CO2 = \frac{E_{grid} * 481}{1000} + \frac{E_{PVtotal} * 40}{1000} + B_{CO2} \tag{3.15}$$

3.6.2 Optimised scheduled

A distinction is made for the household appliance performance:

"Non-optimised": refers to the practice of using household appliances at times that are most convenient for the household's daily routine, regardless of whether it aligns with periods of lower electricity prices or the availability of electricity generated from solar panels.

"Optimised": is employed to describe a systematic approach wherein the operation of appliances such as dishwashers, washing machines, and dryers is scheduled to coincide with periods of the lowest electricity prices during the day or when there is a significant surplus of electricity generated from PV panels. This optimization strategy seeks to maximize cost savings and enhance the efficient utilization of renewable energy resources.

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[5] https://www.nowtricity.com/country/netherlands/

Chapter 4

Results

This chapter starts exploring the results of the modeled components of the HEMS. Then, it presents the household performance in four progressive scenarios involving the implementation of green technologies. This analysis reveals the HEMS's potential impact on household energy resource management, including the SSR, SCR, and CO2 emissions, while also addressing its cost implications within three pricing schemes. The considered scenarios are described as follows:

1. **Base scenario:** SFH without green technologies
2. **PV scenario:** SFH with a PV system
3. **PV and BESS scenario:** SFH with both a PV system and a BESS
4. **HEMS scenario:** SFH with a PV system, BESS, and EMS

4.1 Household modeling results

The output data of the simulation was processed in Python to obtain the following results. The hourly electricity profile is illustrated in Figure 4.1 indicating a total consumption of **6,077.94 kWh** of electricity. The monthly sum is presented in Figure 4.2. On average, the monthly electricity consumption is **506.49 kWh**. It is noteworthy that in August, the predefined two-week holidays significantly reduce electricity consumption.

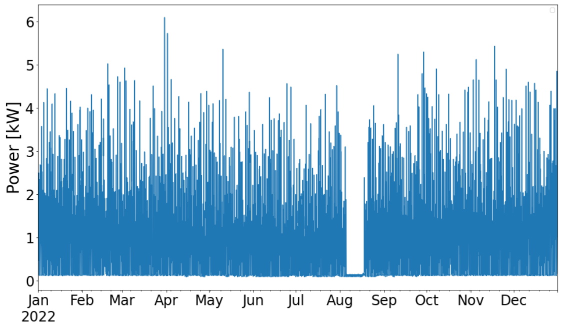

Figure 4.1: Yearly power demand

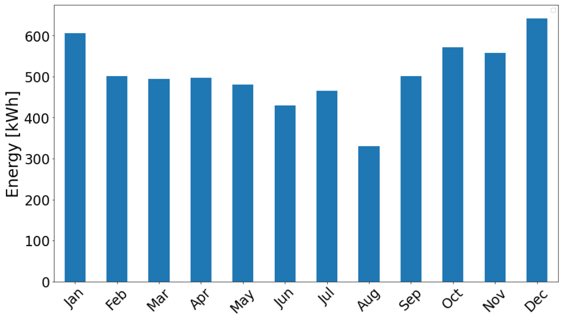

Figure 4.2: Monthly energy demand

One of the output files generated by LPG is the hourly profile data for individual devices. This dataset was analyzed to identify the top 10 electricity-consuming devices and to determine which devices could be shifted to align with the objective of the HEMS. Specifically, the dishwasher (DW), dryer (D), and washing machine (WM) were selected as shiftable devices. The device profiles were then utilized to disaggregate the base load from the total household load.

The monthly energy consumption contributions of these selected devices to the total load are depicted in the stacked bar plot shown in Figure 4.3. In total, the DW, D, and WM consume **443.87 kWh**, **489.32 kWh**, and **266.27 kWh**, respectively. Furthermore, the monthly appliance consumption of these devices is illustrated in Figure 4.4. On average, the monthly electricity consumption for the DW, D, and WM are **36.95 kWh**, **40.77 kWh**, and **22.18 kWh**, respectively.

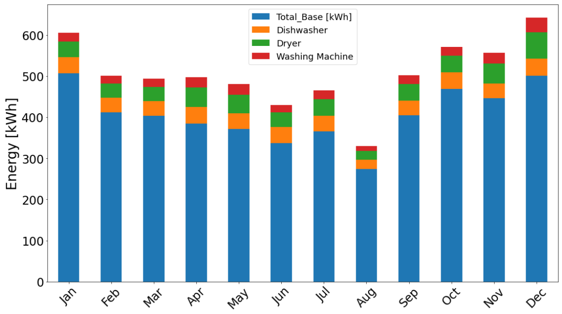

Figure 4.3: Monthly demand contribution

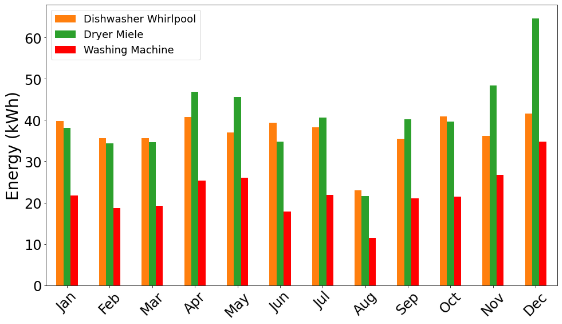

Figure 4.4: Monthly appliance's consumption

The first week of January is depicted in Figures 4.5 and 4.6 as an example of the total daily consumption of the household and the consumption range of the shiftable appliances. It can be observed this week that the DW is utilized more frequently than the WM, resulting in a higher annual electricity consumption. January is one of the highest energy consumption months. Annually, on average, the total daily electricity consumption is **16.65kWh**.

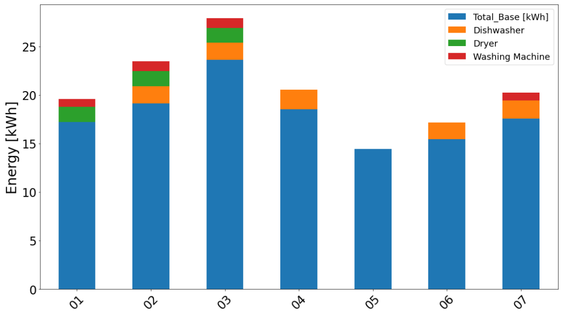

Figure 4.5: Daily consumption contribution in January

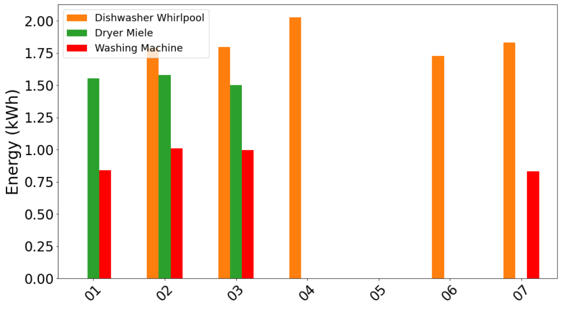

Figure 4.6: Daily appliance's consumption in January

The hourly load profile for the first three days of January is exemplified in Figure 4.7. The purple line represents the total load, comprising the base load (in blue) and the shiftable appliances. It is worth noting the composition of the peak load.

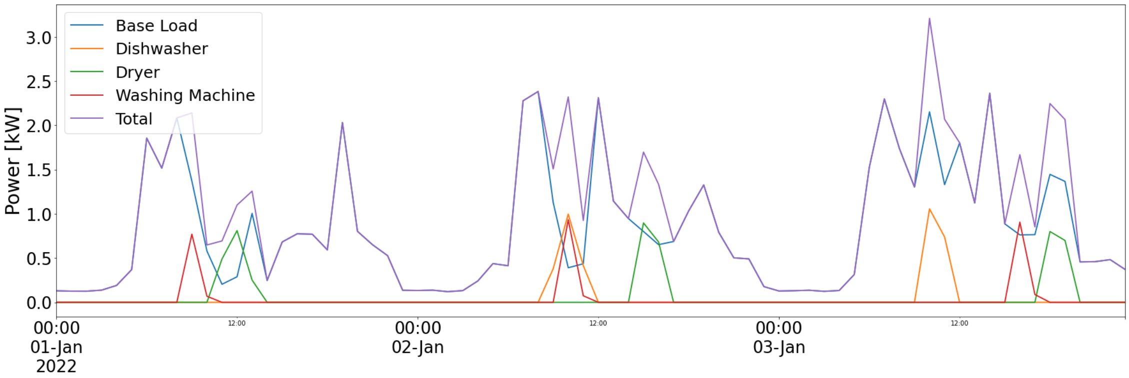

Figure 4.7: Stacked load profile 72 hours

4.2 PV Generation

The yearly PV output for a 4kWp system is shown in Figure 4.8, and the monthly sum is shown in Figure 4.9, resulting in a total output of **4,571.03 kWh**. The annual yield is 1.1427 kWh/kWp.

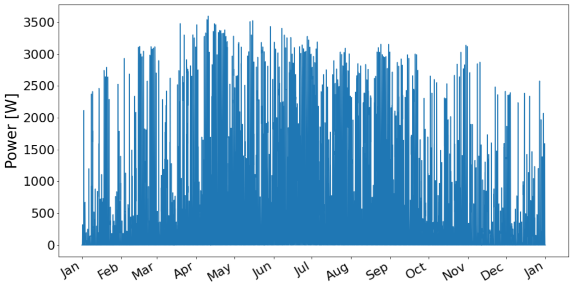

Figure 4.8: Yearly 4kWp power output

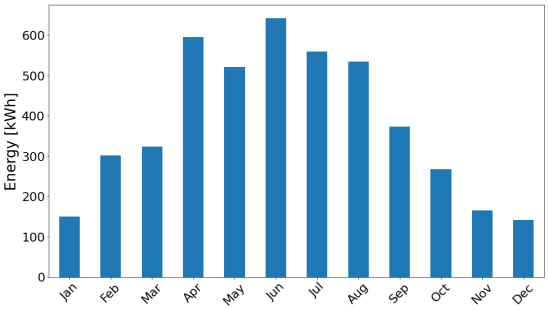

Figure 4.9: Monthly PV generation

The process was iterated by varying the installed PV capacity from 3.2 kWp to 5.6 kWp, equivalent to using between 8 to 14 PV modules, each rated at 400Wp. The annual output of these PV systems is compared to the annual load, as shown in Figure 4.10. The mismatch between the monthly demand and the monthly PV generation prevails in the winter months when the PV installed capacity increases, as shown in Figure 4.10. For the 4kWp system, an area of 21 m2 is required.

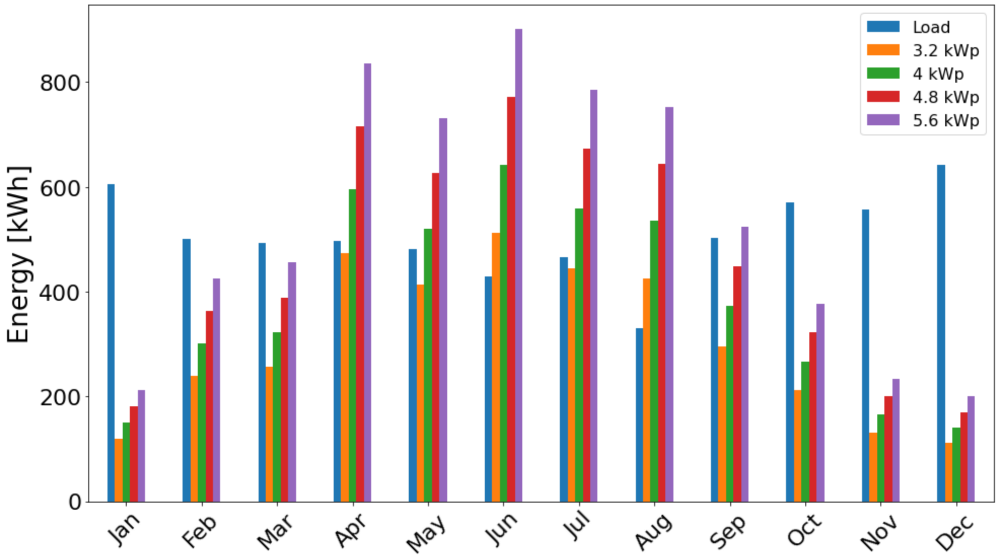

Figure 4.10: Monthly energy PV generation

4.3 SFH without green technologies

For the base scenario, the typical detached SFH with 100% of its electricity supplied by the grid, the electricity consumption accounted for **6,077.94 kWh** per year as described in Section 3.5.1. With a CO2 emission factor of 481 g of CO2 per kWh for the Dutch electricity grid, the total yearly emissions amount to **2,923.49 kg of CO2**, which is approximately 3 tons of CO2 annually, considering just electricity.

With a fixed tariff of 40 cents per kWh, the variable electricity cost would be **€ 2,431.17** per year, around 200 euros per month without considering fixed costs, and the Dutch energy tax refund. Similar values were found for a household of 5 people in Amsterdam [54]. With an RTP scheme, the cost would be even higher, specifically **€ 2,519.69**.

4.4 SFH with PV system

The annual energy generated by the 4kWp PV system has the potential to meet the demand from April to August as shown in Figure 4.11. However, due to the mismatch of supply and demand throughout the days, the green bar of the figure represents the actual amount of PV energy consumed on-site. This is calculated as the load minus the energy still imported from the grid, $E_{imported}$. Figure 4.11 serves to visually emphasize the potential energy that is available for consumption rather than being exported to the grid.

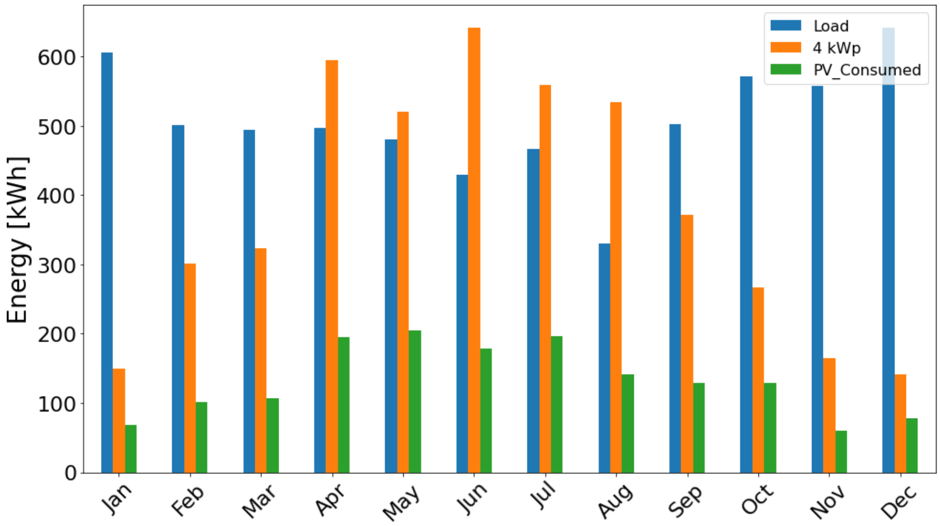

Figure 4.11: Monthly PV consumed

To illustrate the mismatch of supply and demand, Figure 4.12 presents data for the first three days of January and the first three days of June. Net demand is calculated simply as the load minus the PV generation. During winter, the PV generation does not cover the load, and positive values of net demand indicate the energy still required to be imported from the grid, as depicted mostly in the down net demand graph. On the other hand, during the summer, PV generation is significantly higher and consistent throughout the day. However, since electricity is not consumed at noon, there is a pronounced peak of electricity export into the grid. Later, when peak power consumption occurs around 7 p.m., it is not met by PV generation, resulting in the need to import electricity from the grid.

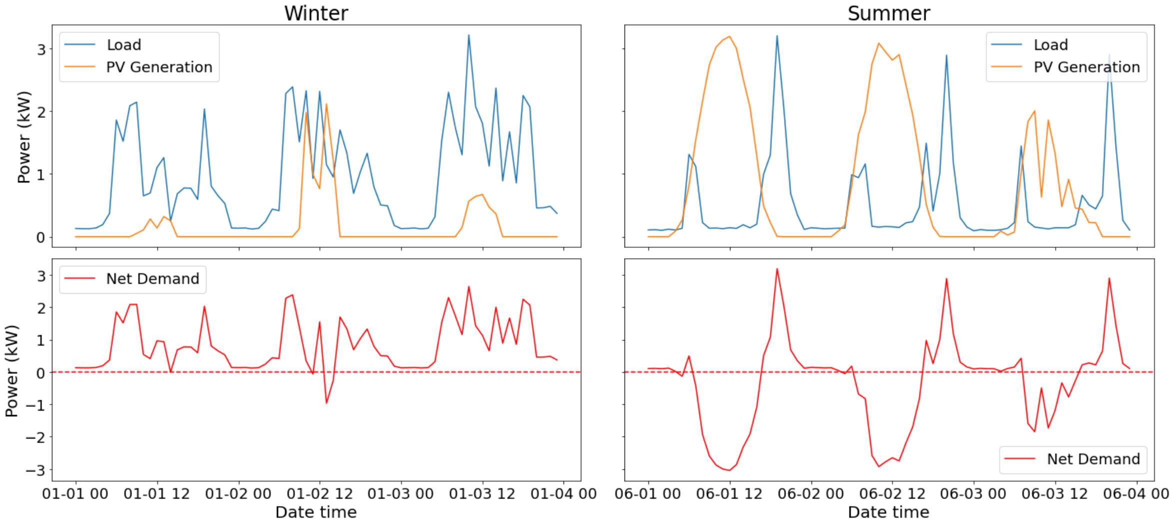

Figure 4.12: Household supply and demand performance with PV

Annually, energy imports from the grid decreased from 6,077.94 kWh, entirely sourced from the grid to **4,487.95 kWh** with the implementation of a PV system. This reduction means that **1,589.99 kWh** were supplied by the PV system, resulting in an SSR of **26.1%**. A total of 1,589.99 kWh were consumed on-site, accounting for **34.7%** of the 4,571 kWh generated by the PV system, while the remaining 2,981.04 kWh (or 65.3%) were exported into the grid. This means that a SCR of 34.7%.

Calculating the CO2 emissions, a total of **2341.54 kg of CO2**, with 2,158.7 kg of CO2 coming from the grid imports and **182.8 kg of CO2** coming from the PV generation. This accounts for a reduction of 581.94 kg of CO2, which represents a **19.9%** decrease in CO2 emissions. If we consider the CO2 emissions avoided by the cleaner energy produced by PV (40g from PV against 481g of CO2), the net CO2 emissions from the household account for **724.8 kg** of CO2 with Equation 4.1, which represents a **75%** decrease in CO2 emissions.

$$Net_{CO2} = E_{net} \cdot \frac{481g}{100} + E_{pv} * \frac{40g}{1000} \tag{4.1}$$

When it comes to the electricity costs, with a fixed tariff of 40 cents per kWh, the annual cost without net metering would be **€ 1,795** per year, 635 EUR reduction represents 26%. With the current net metering scheme, the cost would be **€ 602 EUR** since the balance between electricity consumed and produced is positive. The latter represents a **cost reduction of 75%**. With the RTP scheme, the annual cost would be 801 EUR, without an optimized schedule.

The results of the sensitivity analysis varying the PV installed capacity are shown in Figure 4.13. The left y-axis displays percentages corresponding to the SSR and SCR indicators, and it is aligned with the total baseline CO2 emissions (shown on the right y-axis) for clarity. As the installed capacity increases, the system's output also rises, leading to an increase in SSR within the household. However, this results in a higher volume of electricity fed into the grid, leading to a decrease in SCR. It is noteworthy that the impact on the reduction of CO2 emissions through increased installed capacity is virtually zero. Furthermore, if we consider the net CO2 emissions, it falls under 0 with a 5.6kWp system.

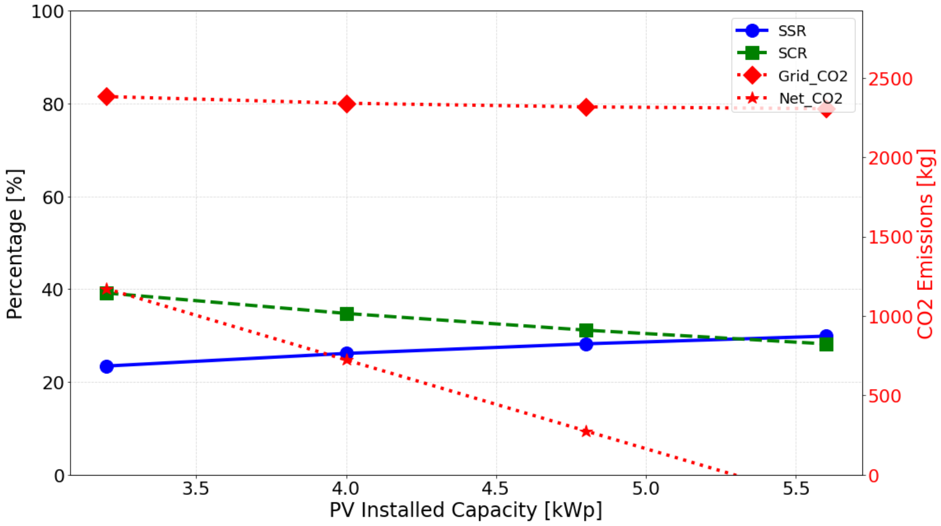

Figure 4.13: Sensitivity analysis varying PV installed capacity

4.5 SFH with PV system and Battery

In this scenario, a BESS is implemented to store the excess energy generated by the PV system and to deploy it when the PV generation is insufficient to meet the demand. The analysis covers the entire year, with the two aforementioned scenarios serving as examples, two battery capacities, 6kWh and 12kWh, are illustrated in Figures 4.14 and 4.15.

On the first day of January, in both capacity scenarios, no excess energy is generated, and the battery remains discharged until the following day when it is partially charged with surplus energy as shown in the green line state of charge. In the summer months, the battery exhibits a cyclic charging and discharging pattern. Horizontal lines indicate instances where the battery is constrained by its maximum charging power, and the PV generation exceeds the battery's capacity, resulting in the export of electricity (inverted peaks). For reference, on peak days, the 4kWp PV system can generate up to 28.7 kWh, in combination with a lower demand or mismatch as shown in Figure 4.14, the batter's capacity is insufficient to store all the generated electricity, and the electricity needs to be exported to the grid. By implementing a 12 kWh battery capacity, there is no need to import electricity from the grid during these particular three summer days, as illustrated in Figure 4.15. Nonetheless, there is still a requirement to export the excess energy.

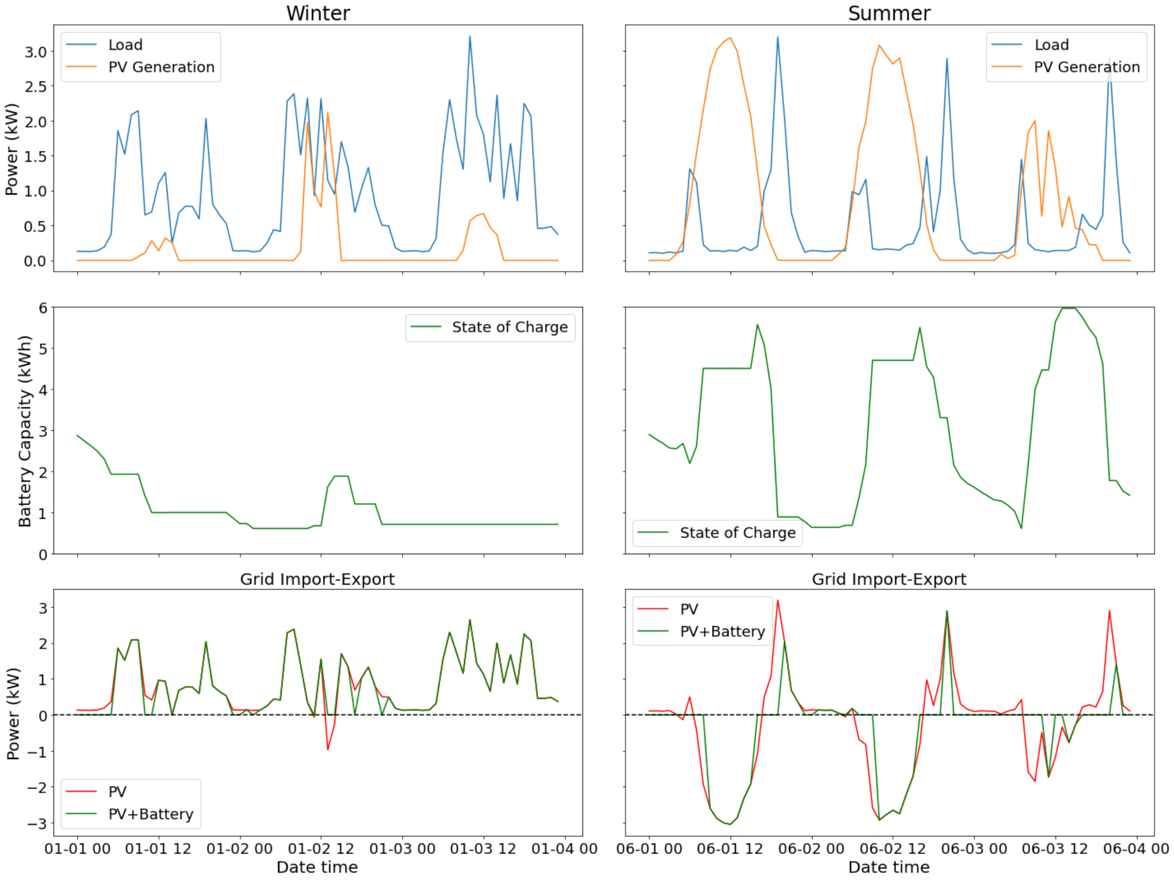

Figure 4.14: Performance Household with PV and 6kWh Battery

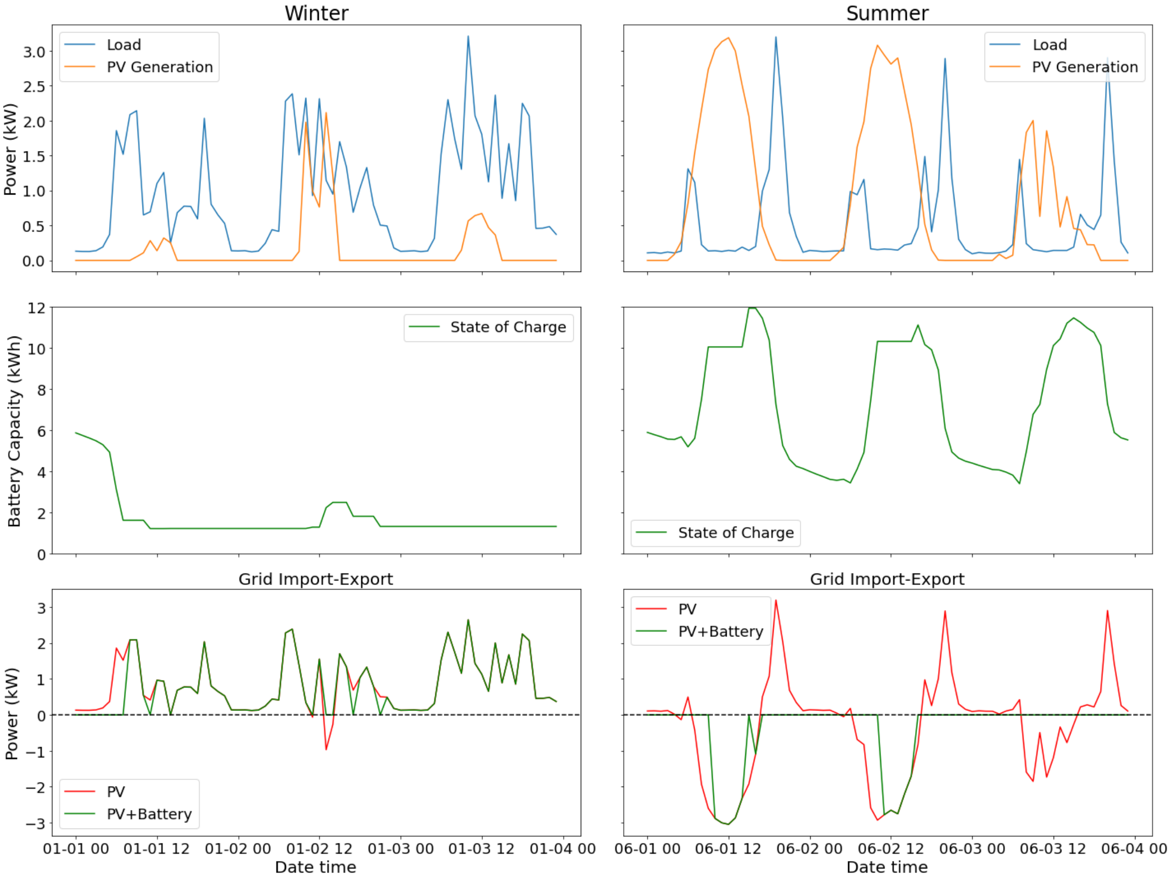

Figure 4.15: Performance Household with PV and 12kWh Battery

In Figures 4.16 and 4.17, the monthly contribution to the on-site consumption of PV-generated energy, by the 6 kWh and 12 kWh batteries is represented by the red bars. With a 12 kWh battery, the monthly SCR reaches nearly 100% from October to January.

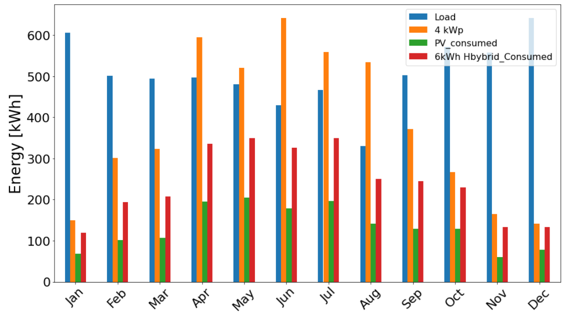

Figure 4.16: PV system performance with 6kWh Battery

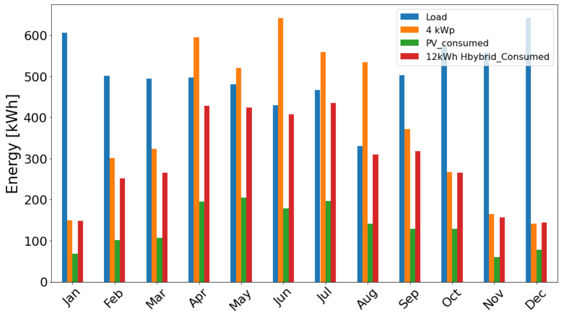

Figure 4.17: PV system performance with 12kWh Battery

Annually, with the PV system and BESS implemented, the annual consumption from the grid decreased significantly to **3206.27 kWh**. Out of the 4,571 kWh generated by the PV system, **2,871.67 kWh** were used to cover the load with the assistance of the 6kWh battery, constituting 47.2% of the annual consumption covered by PV. This reflects a SSR of **47.2%.** The PV energy consumed accounts for 62.8%, of the total generated whereas 37.2% (1,699.33 kWh) was injected into the grid, resulting in a SCR of **62.8%**.

Calculating the CO2 emissions with the 6 kWh battery, we have **1,845 kg of CO2**, where 1,542.2 kg of CO2 comes from the grid imports, 182.8 kg of CO2 from the PV generation, and 120 kg from the battery. This represents a net reduction of 1,078 kg of CO2, which represents a reduction of **36.8%** of the CO2 emissions compared to without green technologies. The annual cost without net metering would be **€ 1282.51** per year, 1148.66 EUR reduction represents 47.2%. With the current net metering scheme, the cost would still be €602.

The sensitivity analysis increasing the battery capacity is shown in Figure 4.18. With a battery of 10kWh, the CO2 reduction would be a reduction of 43% of CO2 emissions. Increasing the capacity over 10kWh does not reduce the CO2 emissions or increase the SSR and SCR.

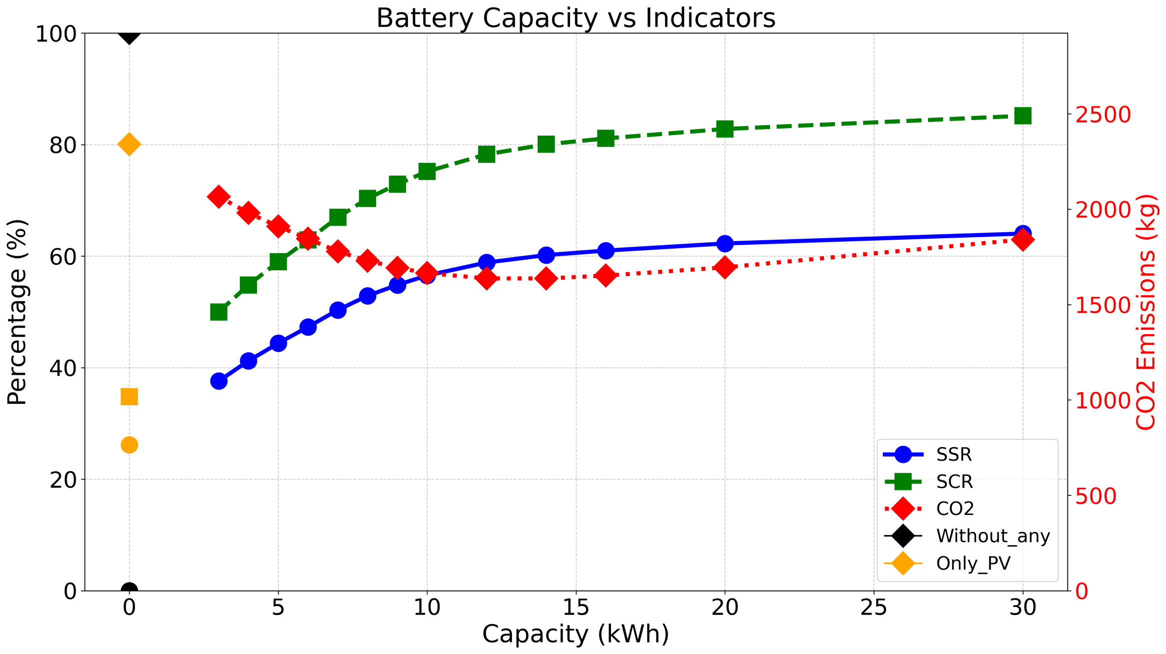

Figure 4.18: Battery Sensitivity Capacity Results

4.6 SFH with PV system, Battery, and HEMS

To assess the performance enhancement of the HEMS in a SFH equipped with a PV system and BESS, one day from each month was chosen for comparing the results of optimal scheduling of shiftable appliances. The selection of these days followed the following procedure: (1) Monthly performance of the SFH with PV and BESS was simulated, and the energy exported was resampled on a daily basis, (2) Select the day with the highest energy exported, considering two aspects: (i) The total daily load composition includes shiftable appliances, otherwise nothing can be optimally scheduled, and (ii) appliance consumption occurring once per day, to ensure a fair and meaningful comparison. The performance comparisons, both with and without HEMS, for one day in January, March, and June, are shown in Figures 4.19, 4.20, 4.21, and respectively. The time horizon was chosen from 03:00 to 03:00 am of the next day. The total load (blue line) is decomposed into the base load (green line) and the shiftable appliances. The rest of the months are shown in the Appendix A.6.

For the 20th of January, Figure 4.19, the total load was 18.65 kWh and the PV generation was 14.34 kWh. With only the PV system, the daily SSR and SCR are calculated at **9.76%** and **12.7%** respectively. Adding the 6kWh battery, it is charged during the day and starts discharging at 3 p.m., reducing the total energy imported and exported as shown in the bottom left graph, the SSR and SCR are calculated at **49.2%** and **43.1%** respectively. After shifting the appliances under the peak solar generation, there is still enough energy to charge the battery, and the afternoon power peak of 4kW around 7 p.m. can be shaved to 2kW. The SSR and SCR are increased to **76.8%** and **79%** respectively.

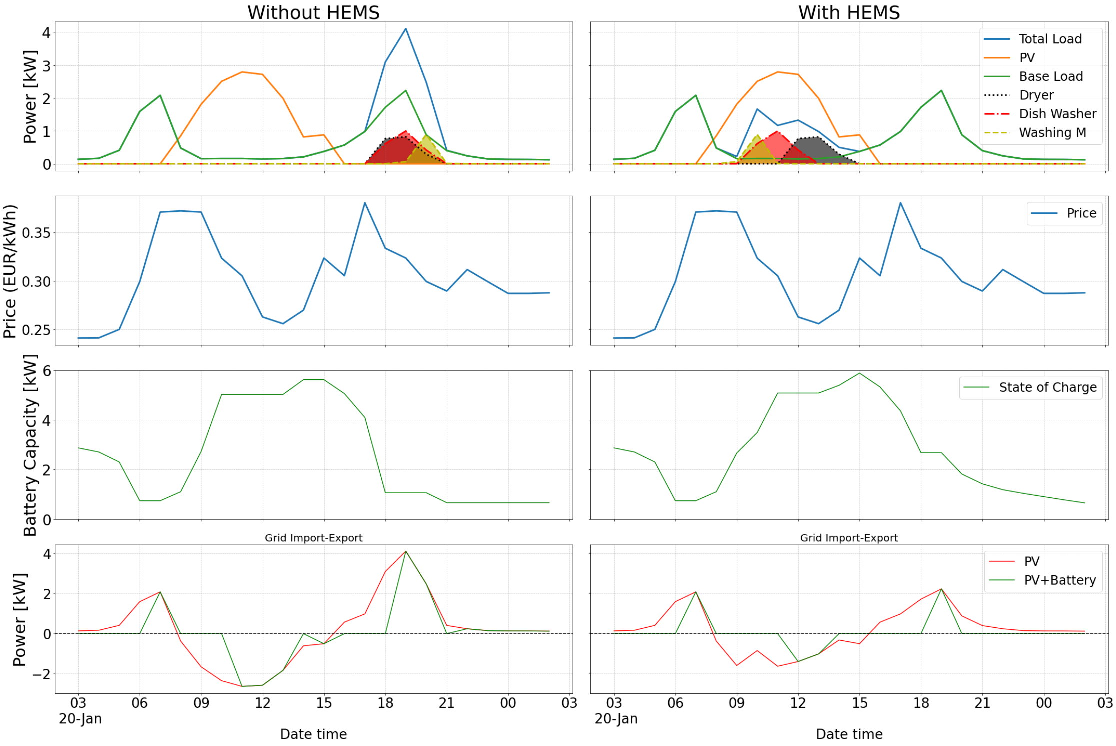

Figure 4.19: Comparison performance with optimal scheduling in January

For the 30th of March, Figure 4.20, the total load was 19.61 kWh and the PV generation was 22.48 kWh. One particular characteristic is the 6kW peak, one of the highest of the year. With only the PV system, the daily SSR and SCR are calculated at **20.7%** and **18.1%** respectively. The battery is kept charged during the day and quickly discharged at 6 p.m., the SSR and SCR increased to **54.6%** and **34.3%** respectively. After shifting the appliances under the peak solar generation, there is still enough energy to charge the battery, and the afternoon power peak of 6kW around 6 p.m. can be shaved to 2kW. The SSR and SCR are increased to **81.9%** and **58.1%** respectively.

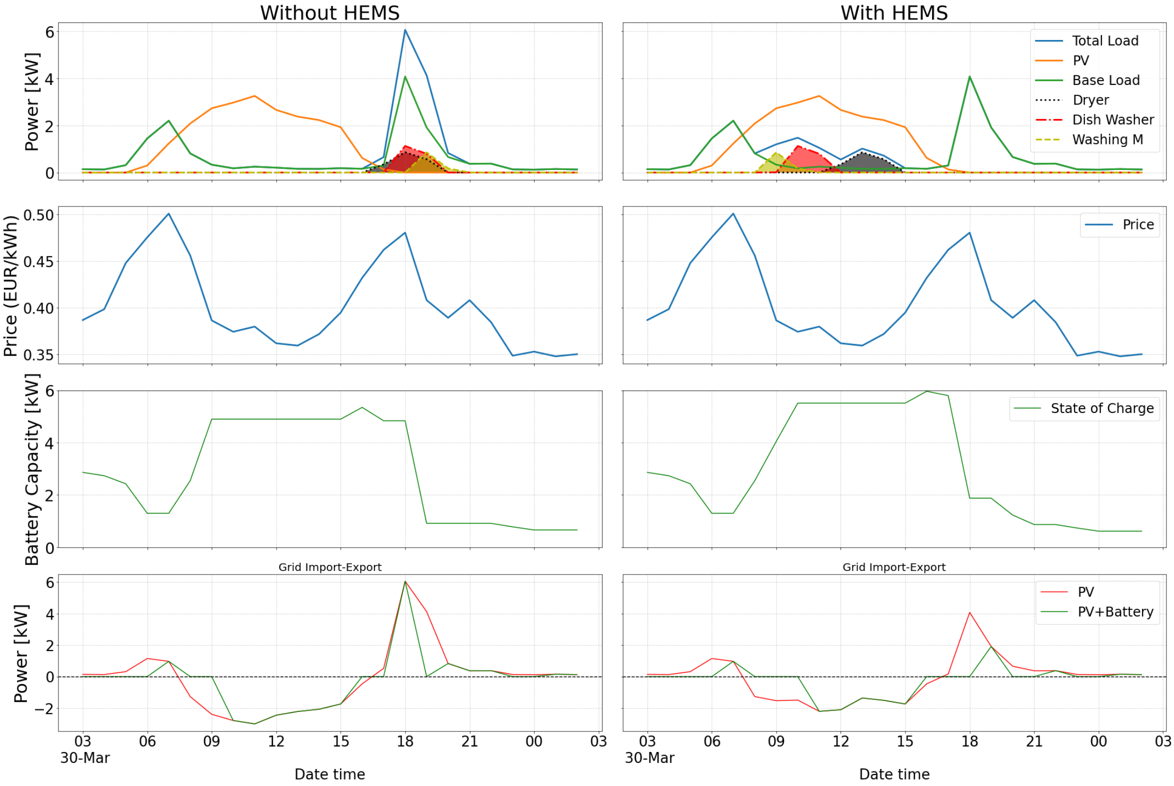

Figure 4.20: Comparison performance with optimal scheduling in March

For the 7th of June, Figure 4.21, the total load was 12.94 kWh and the PV generation was almost double, 23.06 kWh. With only the PV system, the daily SSR and SCR are calculated at **28.05%** and **15.74%** respectively. A considerable amount of energy is exported during the day due to the high PV generation and demand mismatch. The battery can only charge a small portion of the total generation and the SSR and SCR increased to **69.6%** and **26.05%** respectively. After shifting the appliances under the peak solar generation, the battery can cover the rest of the night's demand. The SSR and SCR are increased to **100%** (as shown in the absence of green peaks) and **43.1%** respectively.

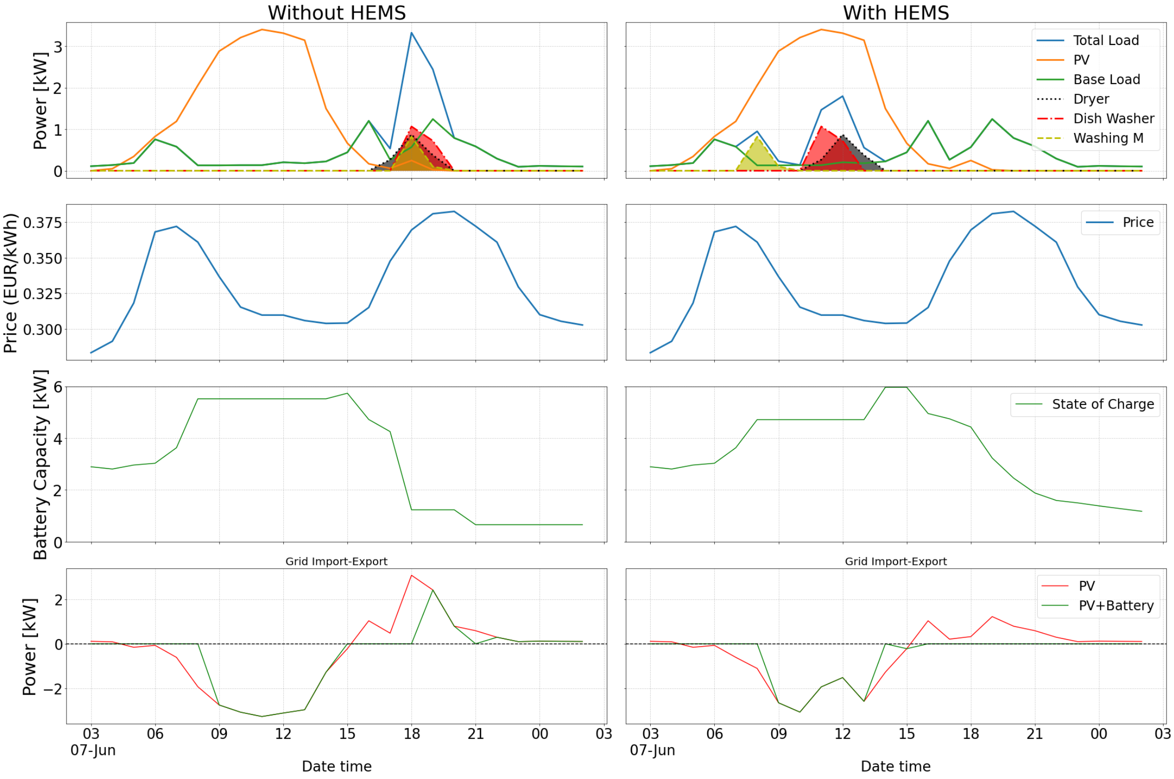

Figure 4.21: Comparison performance with optimal scheduling in June

Figure 4.22 collects the results of the SSR for the 12 days in their three different scenarios: PV (Photovoltaic), PVB (Photovoltaic with Battery), and HEMS (Home Energy Management System). The x-axis represents the days of the months, and the y-axis represents the SSR in percentage (%). The PV scenario has the lowest SSR as expected, and the improvement of adding a BESS (green line) is consistent on all the days. HEMS increased further the SSR by **19.8%** on average, being June 7th the highest (30.3%) and September 7th the lowest (3%)

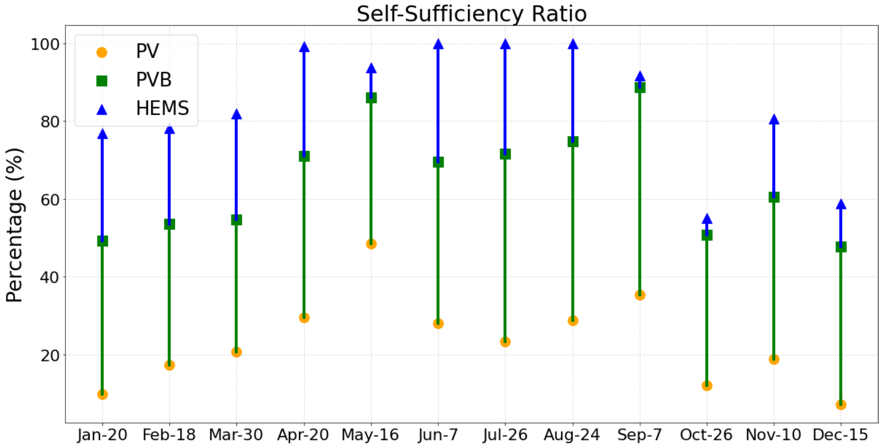

Figure 4.22: Comparison performance SSR

Similarly, Figure 4.23 collects the results of the SCR. Contrary to the previous consistent improvement of the battery, it shows a better performance during the winter months because the PV generation available to consumed is lower than in summer and the effect is significantly higher. HEMS increased further the SCR by **19.4%** on average, being January 20th at the highest (35.87%) and September 7th at the lowest (3.2%).

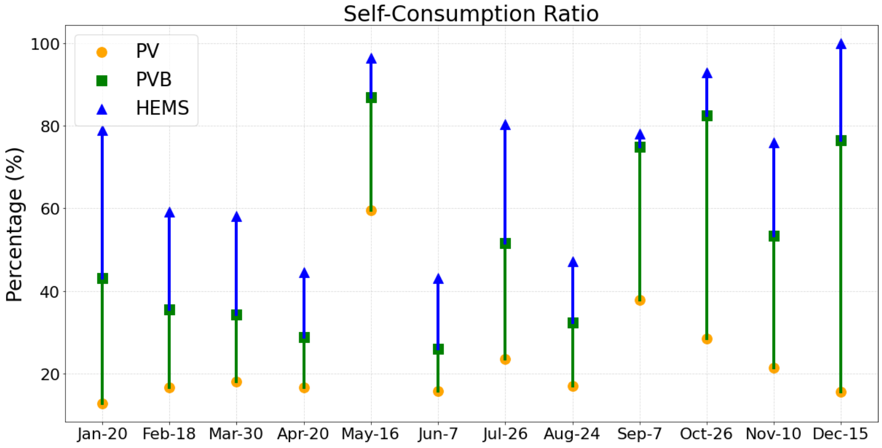

Figure 4.23: Comparison performance SCR

4.6.1 Impact on Carbon Emissions and Energy Cost

Figure 4.24 displays the results of the daily CO2 emissions for the four scenarios. Overall, the HEMS further reduced the CO2 emissions by **19%** compared to the PV system with battery scenario. It's worth noting that the implementation of a BESS has the highest and most consistent improvement of the 3 technologies. Excluding May 16th, the PV system has a low contribution to reducing the CO2 emissions associated with grid consumption, but the highest impact considering the net CO2. On average, the PV system reduced the emission by 14.4%, the system with battery decreased them up to 51.6%, and the HEMS further by 70.5%

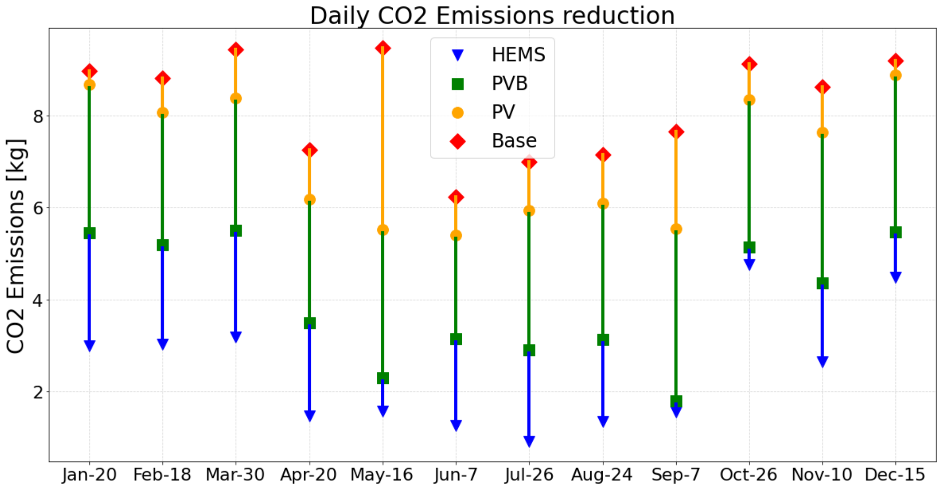

Figure 4.24: Comparison performance CO2 emissions

Figure 4.25 shows the daily costs for January 20th in different price scenarios with the progressive technologies integrated. For the (ii) scenario without net metering and a fixed price (blue bar), implementing a PV system only decreases the cost by 10% (without considering any compensation) while selling the extra energy in a dynamic price scenario lowers the cost close to the net metering scheme. The lowest costs are achieved when implementing a HEMS for the three price schemes. Net metering scenario is still the lowest hindering the benefits of implementing BESS and HEMS.

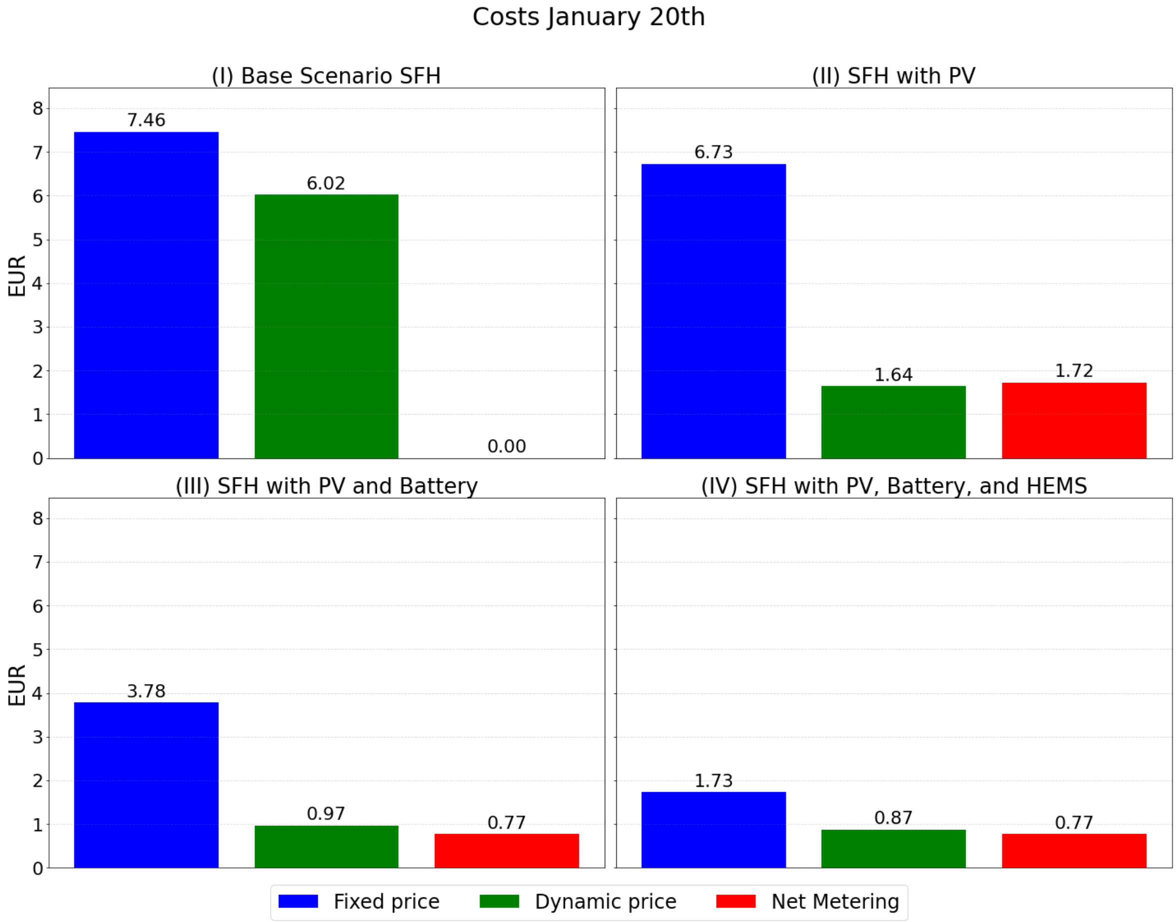

Figure 4.25: Comparison cost price scheme per scenario on January 20th

On average, the daily costs per different price schemes and scenarios are shown in 4.26. The base scenario correlates the daily higher cost With the higher annual cost as shown in Section 4.4 of implementing a dynamic price tariff without any optimization. On days when the PV generations are high, selling the surplus energy in a dynamic scheme current has a lower cost than a fixed tariff. Implementing a BESS lowers the costs even further as well as with the HEMS. The net metering scheme presents the lowest costs except in the HEMS scenario as shown in Figure 4.26. It does not incentivize on-site self-consumption.

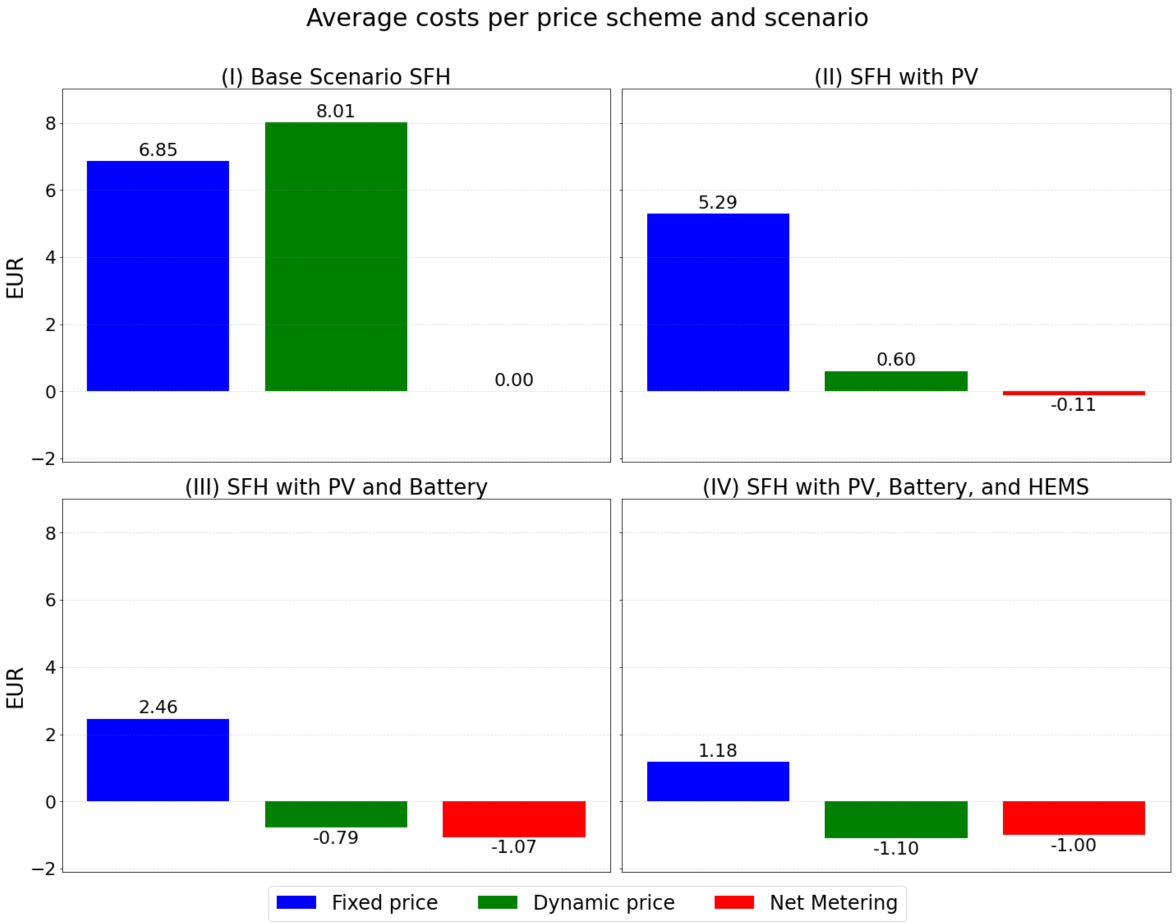

Figure 4.26: Comparison average costs per price scheme per scenario

Chapter 5

Discussion

This chapter is divided into three sections: (i) the interpretation of the results and their implications; (ii) a reflection on this study considering its imitations, methodology, and influence on the results and (iii) lessons learned and recommendations for future research.

5.1 Interpretation of the results

- **SFH with PV:** With the current net metering law, a higher PV installed capacity results in lower costs and reduced net CO2 emissions. However, the initial investment in PV panels is higher, and limitations such as required space and physical grid connection can restrict the installed capacity. Moreover, uncontrolled generation can lead to increased grid congestion. Furthermore, seasonal demand in winter cannot be exclusively met by installing additional panels due to lower irradiation during these months. Home battery capacity is primarily useful for short-term peak shaving to meet daily demand.

- **SFH with PV and BESS:** Implementing a 6 kWh BESS helps mitigate peak-load consumption, but it still requires importing energy and exporting excess electricity to manage high energy volumes. Although a larger battery capacity would be more effective, the increased cost makes it financially impractical. The approach in this thesis is to demonstrate how a system with a 6 kWh battery, integrated with a HEMS, can enhance its performance to be on par with a 12 kWh system. With the current net metering, implementing a battery does provide an economic incentive.

- **SFH with PV, BESS, and HEMS:** The dynamic electricity price presents an opportunity to reduce costs when a HEMS can automate the decisions based on the current electricity market. Changing from a fixed contract to a dynamic contract is not advised without the smart appliances and the infrastructure required to exploit the benefits of RTP.

  In general, the cost reduction on energy can potentially lower the payback time of PV systems and BESS. In this way, the implementation of HEMS stimulates the integration of more PV Systems without the current risks and limitations of grid congestion.

5.1.1 Social implications

- **Routine changes:** HEMS empowers householders to change their passive behavior in the energy system into an active role by providing flexibility in their energy consumption. This behavior change involves adopting new practices and routines, which can be difficult to modify if the householders do not have a strong motivator. It has commonly been assumed that energy savings are the main driver for participating in DR programs. A survey study of 1,468 Finnish residential consumers revealed a preference for financial incentives over environmental incentives [59]. In the same study, the consumers had a higher expectation of compensation for shifting heating loads than for electrical loads.

- **Socialized network costs:** While more uncontrolled DERs are deployed, grid congestion problems arise, and grid infrastructure upgrades are necessary. The increments for the upgrade network costs are equally socialized, and this could lead to an unfair distribution of the costs for the use of the grid. With the ongoing changes in the network tariffs from the fixed-tariff model to the proposed subscription-based bandwidth, DNV expresses:

  > Customers who cannot afford or opt away from high-power demanding technologies (light users) should not be forced to finance the grid expansion triggered by other grid customers (heavy users) [11]

  .

- **Community approach:** This thesis focused on HEMS's goal of optimizing energy consumption and generation within individual households. However, another approach could have contemplated the performance within a community with a shared objective. In this way, peer-to-peer trading can change the HEMS or influence their objectives, since the price is not the only achievable objective. Moreover, multiple HEMS with the same objective function of reducing costs could potentially lead to a massive schedule of appliances at the lowest electricity price, creating a new peak demand and hindering the self-consumption of renewable sources.

- **Adoption costs:** One of the immediate challenges facing the adoption of HEMS is the initial investment required. The integration of smart technologies and devices can be expensive for householders, posing an economic barrier. While long-term savings are possible through reduced energy consumption, the high upfront costs may dissuade some from adopting these systems. This represents an opportunity that can be addressed with new business models.

- **Unpredictable behavior:** Householder's behavior can be unpredictable, as shown in the simulation conducted in this thesis, where family members could use appliances multiple times per day. Addressing RQ2, the unpredictable behavior requires that the HEMS be capable of scheduling multiple times an appliance as required.

5.2 Limitations

The household model: The base scenario was modeled as an energy-intensive household, this resulted in an annual electricity consumption of *(6077 kWh)* which is 40% higher than the average *(4270 kWh)* detached households in the NL. To put in perspective, considering the total energy demand (21,077 kWh) and with an energy performance of 140 kWh/m^2/year, this corresponds to a house with an area of 150 m^2. The HEMS was designed to optimize electricity consumption. However, it can also be employed to optimize heating in combination.

The HEMS results were reported and compared on a daily basis. To obtain yearly results, daily simulations have to be carried outperformed, regardless of the frequency of appliance usage. This approach ensures that the annual impact is not overlooked and allows for meaningful comparisons with other scenarios. Moreover, this thesis primarily focuses on the year 2022. Nevertheless, it is important to recognize that annual variations can either support or undermine the RTP scheme. Therefore, evaluating different years can provide a more accurate estimation of the system's performance.

There are different types of dynamic electricity prices, this thesis focused on the RTP scheme, but other alternatives include the TOU scheme, where a simple distinction between peak hours and off-peak hours establishes two different tariffs for the day.

The objective functions are interconnected. For example, one objective aims to maximize the consumption of renewable electricity, resulting in reduced imports from the grid. Consequently, total electricity costs and CO2 emissions decrease. Conversely, when cost reduction is the primary goal, the most economical option is to utilize the cheapest electricity source, which is typically the PV generation, leading to an increase in SCR. In most cases, optimization scheduling prioritizes on-site PV generation use, regardless of the specific objective. However, there are scenarios, particularly during periods of low PV generation, where the optimal scheduling may favor using appliances when electricity prices are at their lowest outside of the PV generation. We aim to consider more than just the electricity price to avoid potential issues.

5.3 Recommendations

Power peak consumptions are generally caused by the use of multiple appliances at once, distributing these loads throughout the day reduces by a factor of two the power peaks. Forecasting and clustering algorithms can identify patterns and trends in energy data, the trend is to utilize machine learning algorithms to develop better EMSs. The use of combined objectives avoids to use of most electricity when it's cheaper, as it would increase the CO2 emissions and stress the grid capabilities.

The positive impact of peak-shaving on the grid and the combination of a neighborhood with multiple EMS was not evaluated. Moreover, future studies could consider the integration of emerging technologies like HPs and EVs which will play a vital role in the coming years.

Chapter 6

Conclusion

Implementing a HEMS offers a promising solution to address the complex challenges posed by the changing energy landscape while promoting sustainability and resilience in our energy systems. The performance improvement resulting from the implementation of a HEMS is particularly noticeable during the summer months when a greater proportion of PV electricity can be utilized. In contrast, during the winter months, the inclusion of a BESS alone is sufficient to manage the lower excess generation. Nevertheless, the HEMS also enhances performance during winter by optimally scheduling appliances to utilize electricity during periods of lower electricity prices.

The HEMS capitalizes on the flexibility of appliances to synchronize with PV generation, effectively shaving peak power consumption and subsequently reducing electricity costs and CO2 emissions. This thesis has provided empirical evidence of the HEMS's effectiveness in reducing daily costs and lowering CO2 emissions. Notably, the lowest costs are achieved when implementing a HEMS and optimizing appliance scheduling under a Real-Time Pricing (RTP) scheme.

The results demonstrate the significant impact of a 4 kWp PV system on the SSR, increasing it to 26%, and the SCR, which rises to 34.7%. Furthermore, the addition of a 6 kWh BESS to the existing PV system further elevates the SSR to 51% and the SCR to 45.8%. In addition, the HEMS has consistently shown enhancements in SSR and SCR within the range of 7.6% to 19.8% and 9.4% to 19.4%, respectively.

This thesis highlights the potential of HEMS as a key enabler for sustainable and cost-effective residential energy management. It not only mitigates peak demand but also reduces the overall environmental footprint, aligning with the broader goal of a Net Zero Emission by 2050.

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tocchapterAppendix

Appendix A

Appendix

A.1 Load Profile Generator

A.1.1 Climate and Weather in Enschede and Hamburg.

Temperature: The daily average high and low air temperature at 2 meters above the ground. Clear Ski: The percentage of time the sky is clear, mostly clear, or partly cloudy (i.e., less than 60% of the sky is covered by clouds). Hours of Daylight: The number of hours during which the Sun is at least partly above the horizon. Wind Speed: The average of mean hourly wind speeds at 10 meters above the ground.

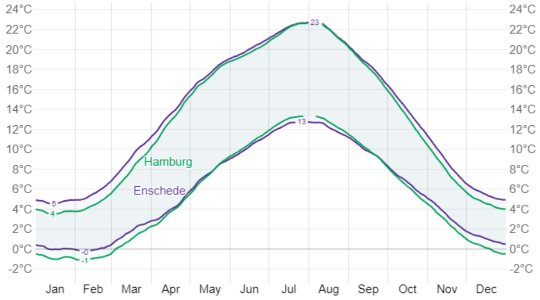


Figure A.1: Average High and Low Temperature.©WeatherSpark.com

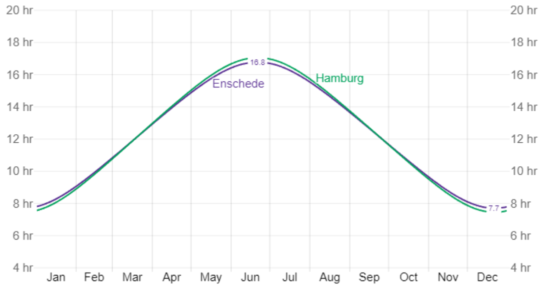


Figure A.2: Hours of Daylight.©WeatherSpark.com

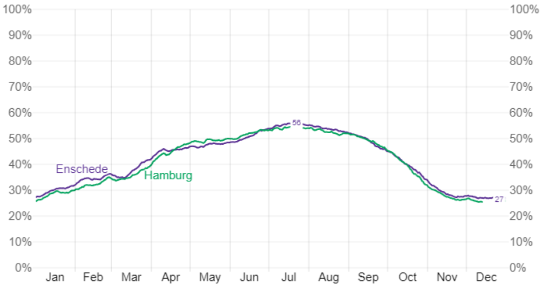


Figure A.3: Chance of Clearer Skies.©WeatherSpark.com

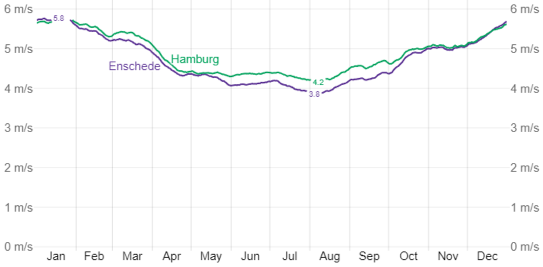


Figure A.4: Average Wind Speed.©WeatherSpark.com

A.1.2 Householder's activities

The activity percentages of the householders are described in the next graphs:

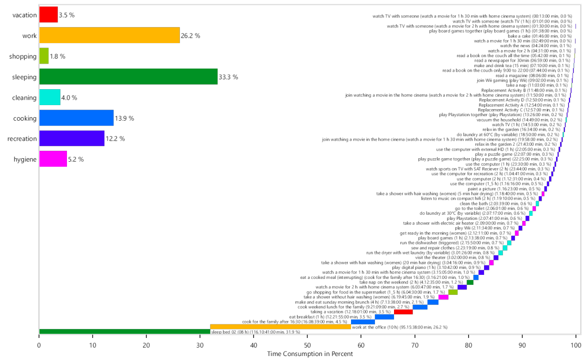


Figure A.5: Liz (35 years Female)

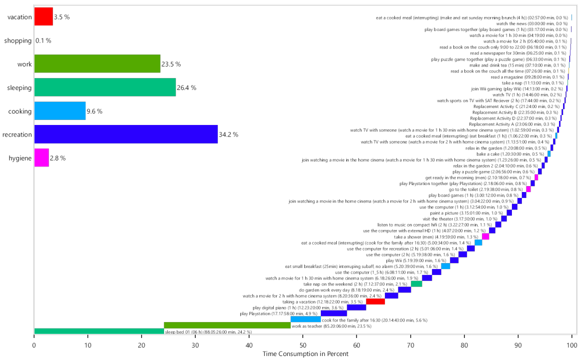


Figure A.6: Nate (40 years Male)

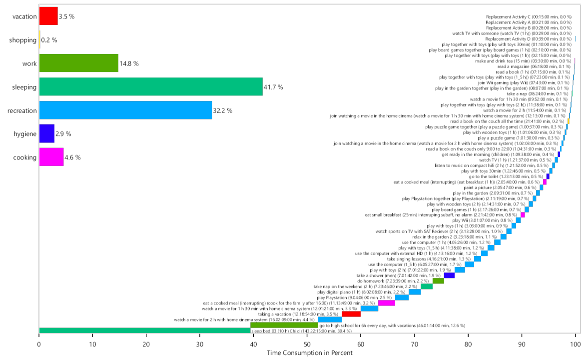


Figure A.7: Mark (13 years Male)

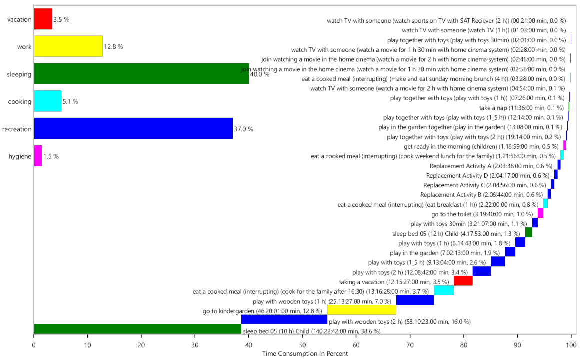


Figure A.8: Zoe (4 years Female)

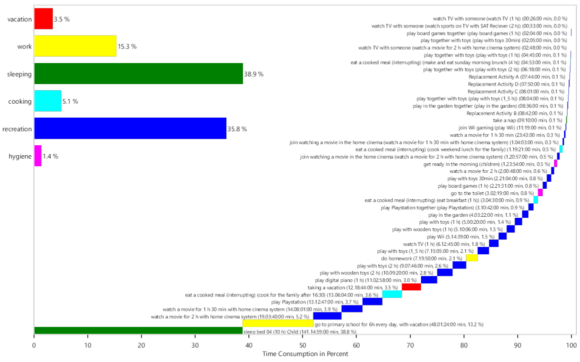


Figure A.9: Will (6 years Male)

A.1.3 Device profiles

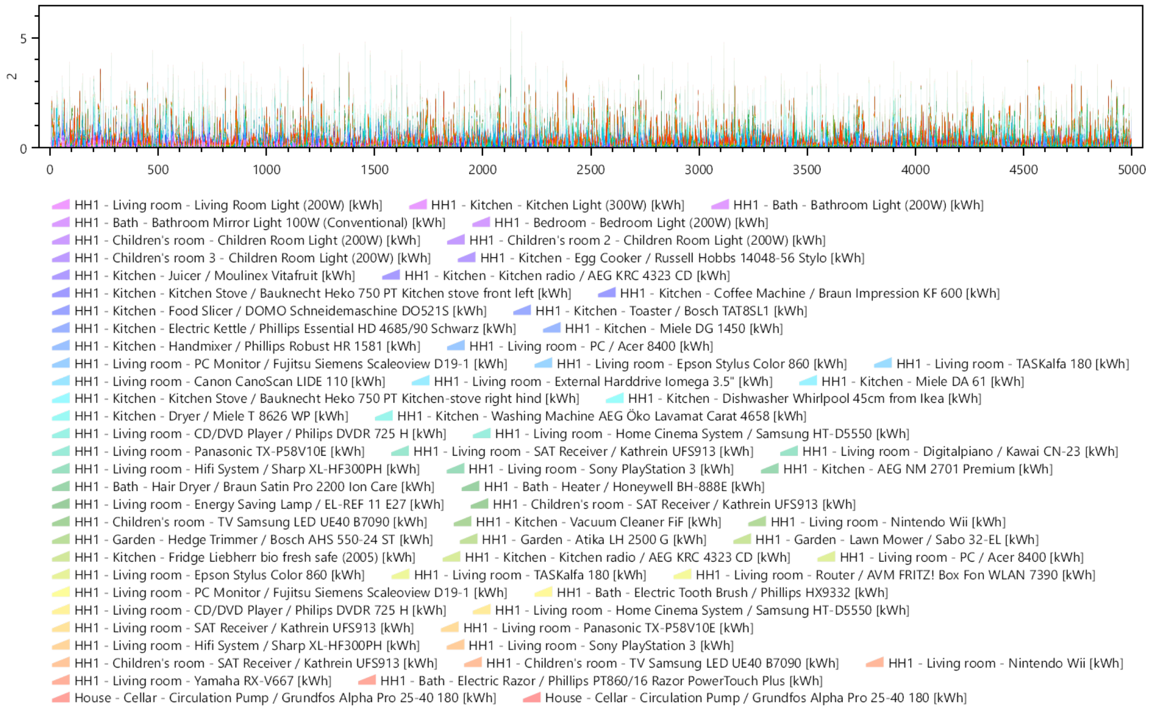
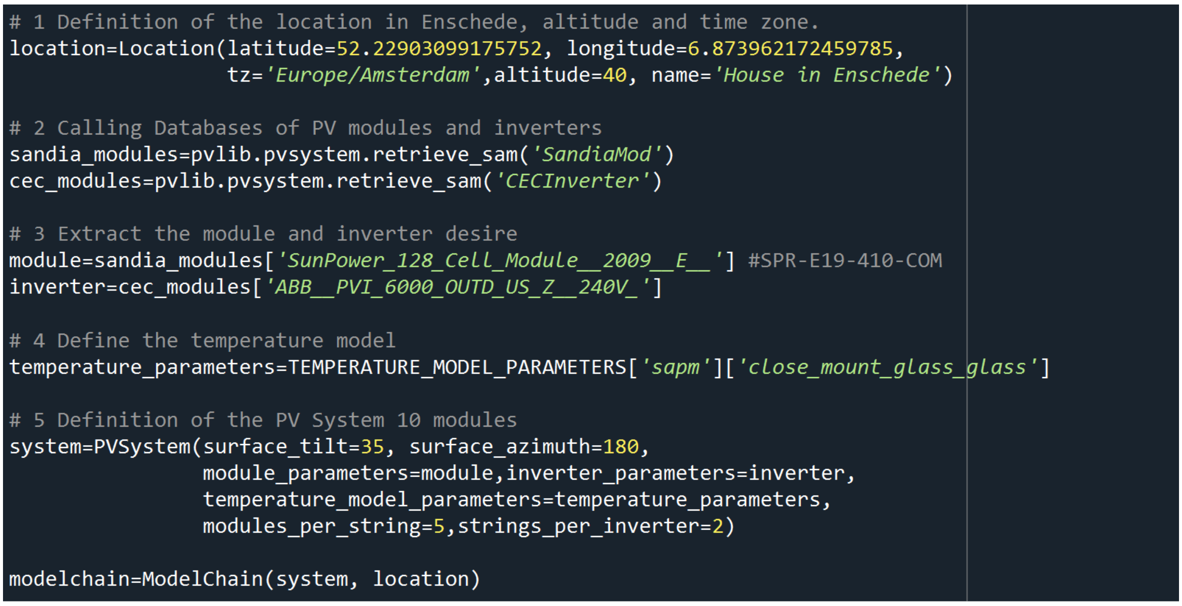


Figure A.10: Hourly Device Profile for the first 5000 hours

A.2 PV Simulation

The Python code to model the PV system is shown in Figure A.11.



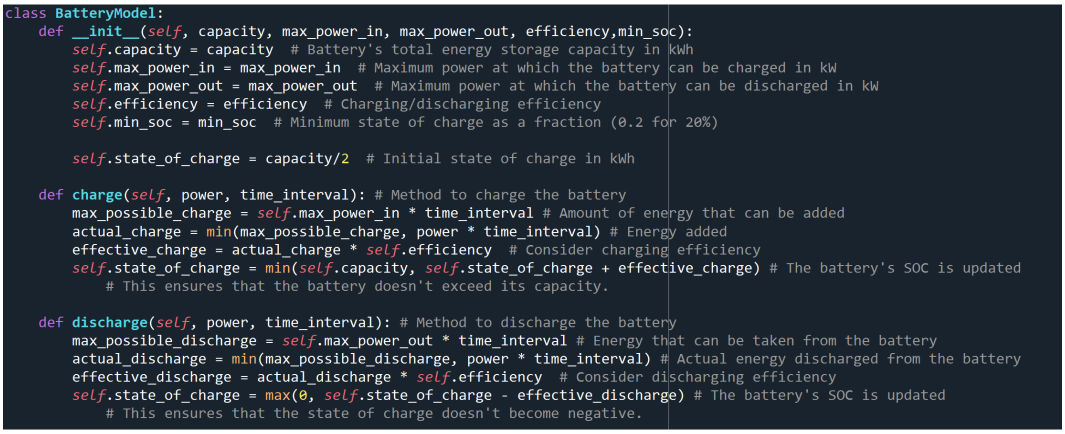
```
# 1 Definition of the location in Enschede, altitude and time zone.
location=Location(latitude=52.22903099175752, longitude=6.873962172459785,
                  tz='Europe/Amsterdam',altitude=40, name='House in Enschede')

# 2 Calling Databases of PV modules and inverters
sandia_modules=pvlib.pvsystem.retrieve_sam('SandiaMod')
cec_modules=pvlib.pvsystem.retrieve_sam('CECInverter')

# 3 Extract the module and inverter desire
module=sandia_modules['SunPower_128_Cell_Module__2009__E__'] #SPR-E19-410-COM
inverter=cec_modules['ABB__PVI_6000_OUTD_US_Z__240V_']

# 4 Define the temperature model
temperature_parameters=TEMPERATURE_MODEL_PARAMETERS['sapm']['close_mount_glass_glass']

# 5 Definition of the PV System 10 modules
system=PVSystem(surface_tilt=35, surface_azimuth=180,
                module_parameters=module,inverter_parameters=inverter,
                temperature_model_parameters=temperature_parameters,
                modules_per_string=5,strings_per_inverter=2)

modelchain=ModelChain(system, location)
```

Figure A.11: PV system model chain

A.3 Retail Price

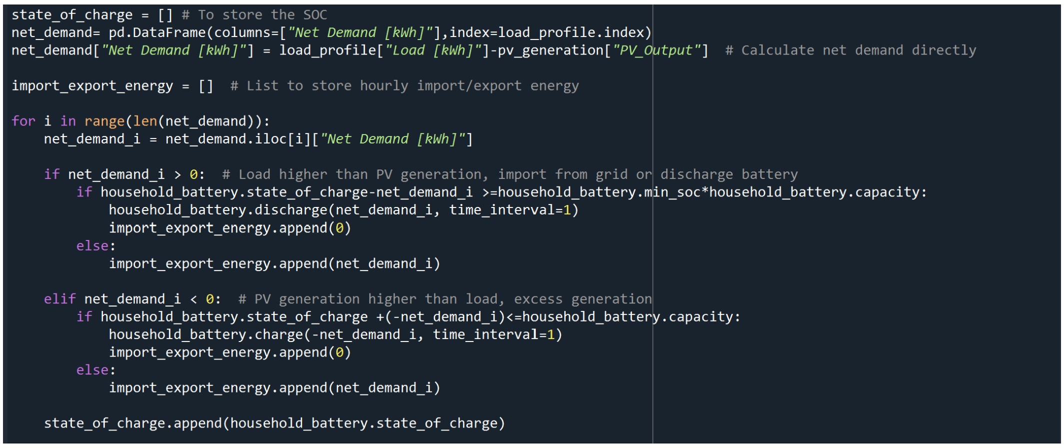
A.4 Battery Model

The battery model was programmed in Python as illustrated in Figure A.12. The operation of the battery is shown in Figure A.13



```
class BatteryModel:
    def __init__(self, capacity, max_power_in, max_power_out, efficiency,min_soc):
        self.capacity = capacity  # Battery's total energy storage capacity in kWh
        self.max_power_in = max_power_in  # Maximum power at which the battery can be charged in kW
        self.max_power_out = max_power_out  # Maximum power at which the battery can be discharged in kW
        self.efficiency = efficiency  # Charging/discharging efficiency
        self.min_soc = min_soc  # Minimum state of charge as a fraction (0.2 for 20%)

        self.state_of_charge = capacity/2  # Initial state of charge in kWh

    def charge(self, power, time_interval): # Method to charge the battery
        max_possible_charge = self.max_power_in * time_interval # Amount of energy that can be added
        actual_charge = min(max_possible_charge, power * time_interval) # Energy added
        effective_charge = actual_charge * self.efficiency  # Consider charging efficiency
        self.state_of_charge = min(self.capacity, self.state_of_charge + effective_charge) # The battery's SOC is updated
            # This ensures that the battery doesn't exceed its capacity.

    def discharge(self, power, time_interval): # Method to discharge the battery
        max_possible_discharge = self.max_power_out * time_interval # Energy that can be taken from the battery
        actual_discharge = min(max_possible_discharge, power * time_interval) # Actual energy discharged from the battery
        effective_discharge = actual_discharge * self.efficiency  # Consider discharging efficiency
        self.state_of_charge = max(0, self.state_of_charge - effective_discharge) # The battery's SOC is updated
            # This ensures that the state of charge doesn't become negative.
```

Figure A.12: Battery model



```
state_of_charge = [] # To store the SOC
net_demand= pd.DataFrame(columns=["Net Demand [kWh]"],index=load_profile.index)
net_demand["Net Demand [kWh]"] = load_profile["Load [kWh]"]-pv_generation["PV_Output"]  # Calculate net demand directly

import_export_energy = []  # List to store hourly import/export energy

for i in range(len(net_demand)):
    net_demand_i = net_demand.iloc[i]["Net Demand [kWh]"]

    if net_demand_i > 0:  # Load higher than PV generation, import from grid or discharge battery
        if household_battery.state_of_charge-net_demand_i >=household_battery.min_soc*household_battery.capacity:
            household_battery.discharge(net_demand_i, time_interval=1)
            import_export_energy.append(0)
        else:
            import_export_energy.append(net_demand_i)

    elif net_demand_i < 0:  # PV generation higher than load, excess generation
        if household_battery.state_of_charge +(-net_demand_i)<=household_battery.capacity:
            household_battery.charge(-net_demand_i, time_interval=1)
            import_export_energy.append(0)
        else:
            import_export_energy.append(net_demand_i)

    state_of_charge.append(household_battery.state_of_charge)
```

Figure A.13: Algorithm to operate battery

A.4.1 Big BESS capacity

With a 70kWh battery, during winter it would discharge in 2 days and we will require the grid again as shown in Figure A.14. In summer it would reach its full capacity in 3 days of peak production and low consumption and it will continue exporting

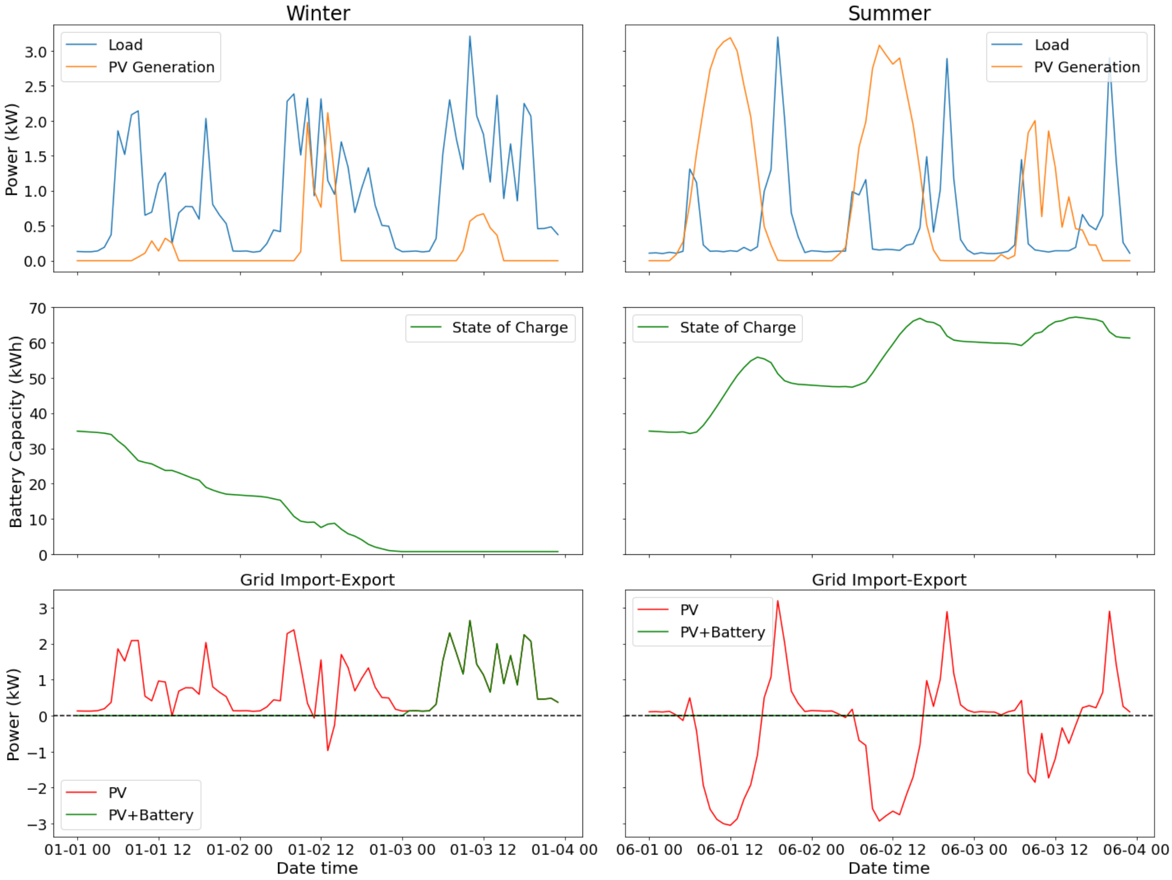


Figure A.14: Performance Household with PV and 70kWh Battery

A.5 Optimization Model

The Formulation of the optimization model is shown in FigureA.15.

```
# Create a Concrete Model
model = pe.ConcreteModel()

model.DW = pe.Var(range(22), within = pe.Binary) #x indicates when to start the DishWahser 1 if start at this time 0 otherwise
model.WM = pe.Var(range(22), within = pe.Binary) #x indicates when to start the Washing Machine 1 if start at this time 0 otherwise
model.D = pe.Var(range(22), within = pe.Binary) #x indicates when to start the Dryer 1 if start at this time 0 otherwise

# Objective: Minimize cost as if we get money from PV Injection
model.objective = pe.Objective(
    expr=sum(model.D[t] * (Retail_Price["Price (EUR/kWh)"][t]*(Base[t]+E_D_1- pv_generation["PV_Output"][t])
                          + Retail_Price["Price (EUR/kWh)"][t+1]*(Base[t+1]+E_D_2- pv_generation["PV_Output"][t+1])
                          + Retail_Price["Price (EUR/kWh)"][t+2]*(Base[t+2]+E_D_3- pv_generation["PV_Output"][t+2]))
              +
              model.DW[t] * (Retail_Price["Price (EUR/kWh)"][t]*(Base[t]+E_DW_1- pv_generation["PV_Output"][t])
                                  + Retail_Price["Price (EUR/kWh)"][t+1]*(Base[t+1]+E_DW_2- pv_generation["PV_Output"][t+1])
                                  + Retail_Price["Price (EUR/kWh)"][t+2]*(Base[t+2]+E_DW_3- pv_generation["PV_Output"][t+2]))
              +
              model.WM[t] * (Retail_Price["Price (EUR/kWh)"][t]*(Base[t]+E_WM_1- pv_generation["PV_Output"][t])
                                  + Retail_Price["Price (EUR/kWh)"][t+1]*(Base[t+1]+E_WM_2- pv_generation["PV_Output"][t+1])
                                  + Retail_Price["Price (EUR/kWh)"][t+2]*(Base[t+2]+E_WM_3- pv_generation["PV_Output"][t+2]))
              for t in range(22)),
    sense=pe.minimize)

model.one_time = pe.Constraint(
    expr = sum(model.D[i] for i in range(22)) == 1)
model.one_time2 = pe.Constraint(
    expr = sum(model.DW[i] for i in range(22)) == 1)
model.one_time3 = pe.Constraint(
    expr = sum(model.WM[i] for i in range(22)) == 1)
# Constraint: Dryer (D) cannot start before Washing Machine (WM)
model.dryer_after_washing_machine = pe.ConstraintList()
for t in range(19):
    # The Dryer (D) can only start if the Washing Machine (WM) started and finished already
    model.dryer_after_washing_machine.add(model.WM[t]>= model.D[t+3] )

# Solve the Optimization Problem
solver = pe.SolverFactory('glpk')  # Solver
results = solver.solve(model)

# Print the Results
if results.solver.status == pe.SolverStatus.ok and results.solver.termination_condition == pe.TerminationCondition.optimal:
    print("Optimal Solution Found")
else:
    print("Solver did not find an optimal solution")
model.pprint()
```

Figure A.15: Formulation of the optimization model

A.6 HEMS Results

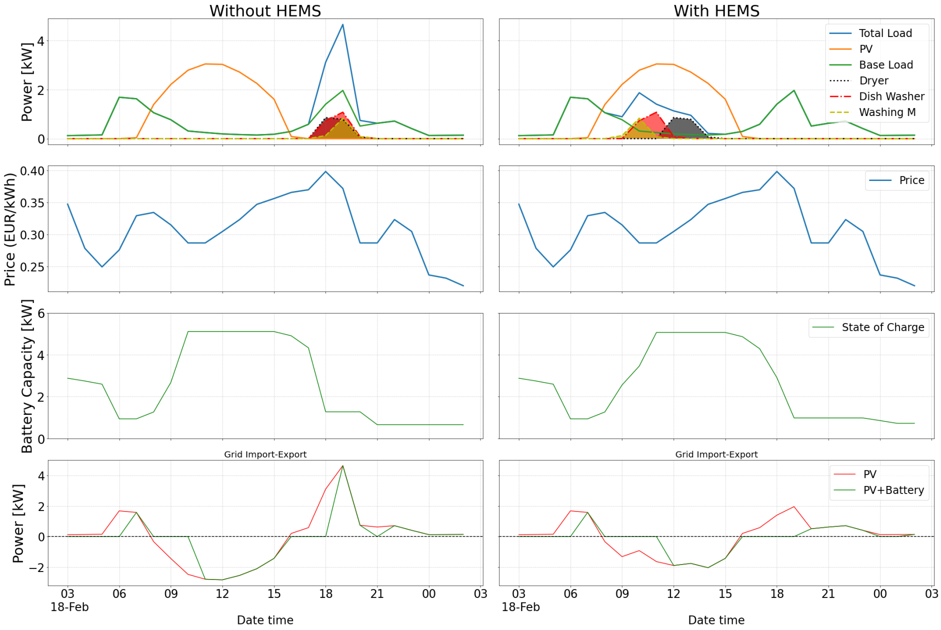


Figure A.16: Comparison performance with optimal scheduling in February

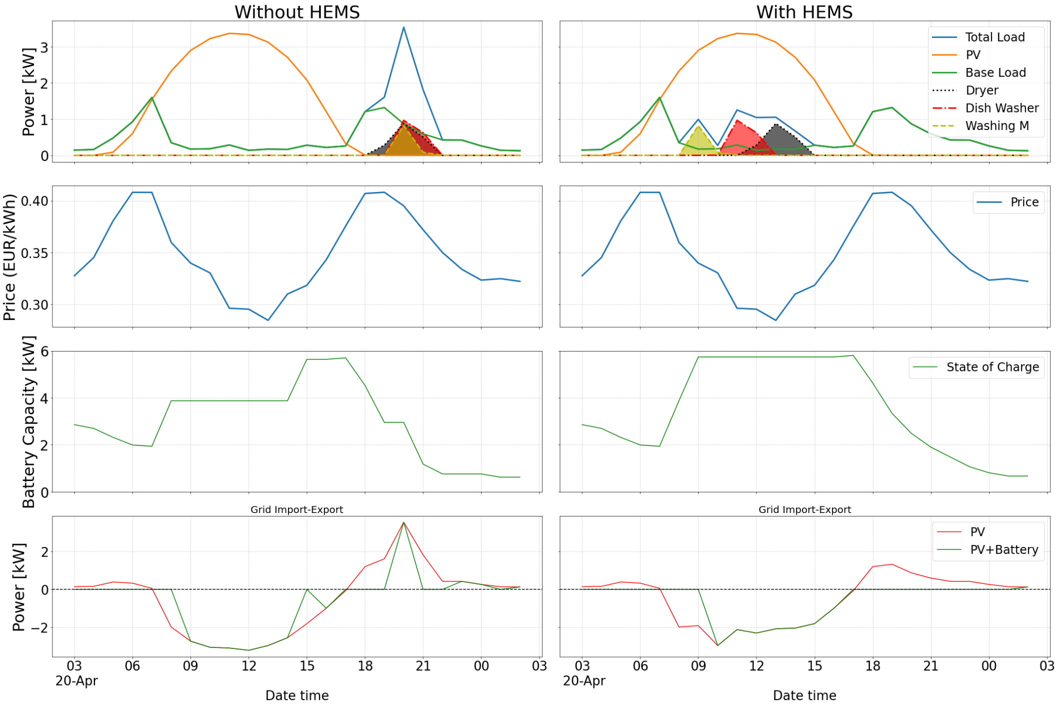


Figure A.17: Comparison performance with optimal scheduling in April

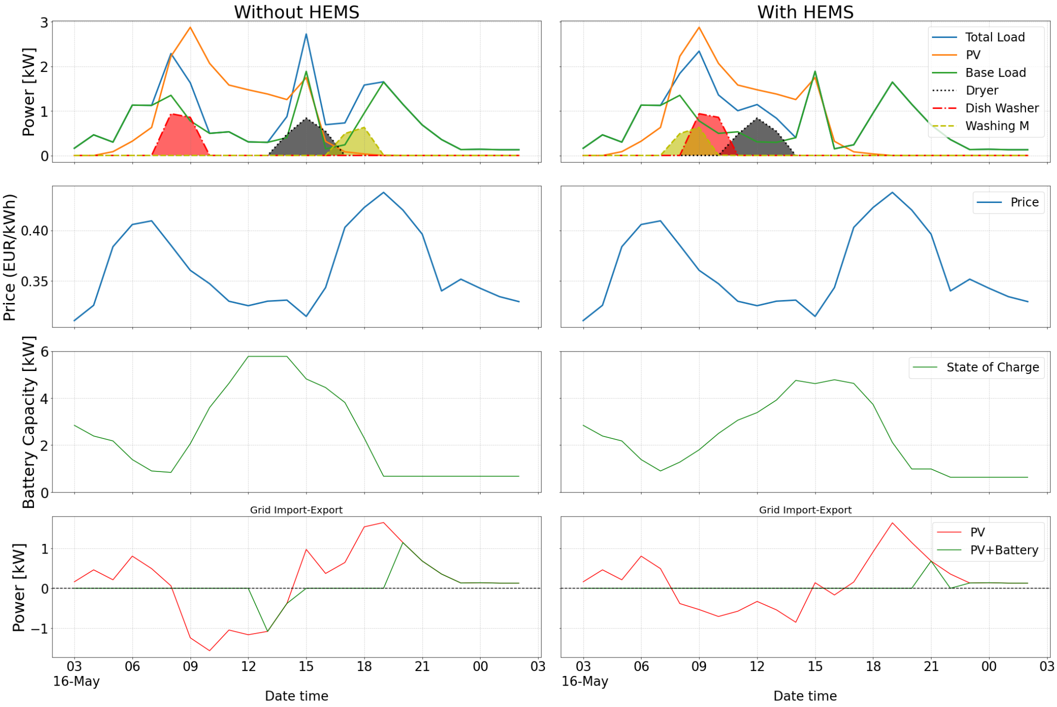


Figure A.18: Comparison performance with optimal scheduling in May

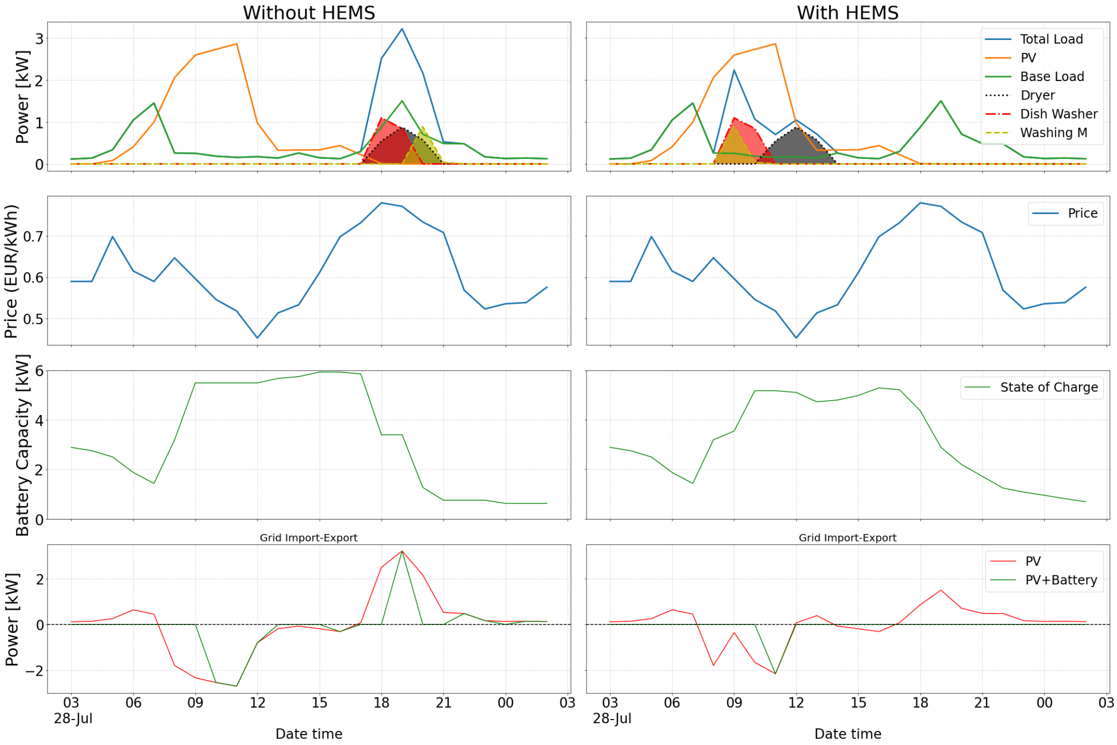


Figure A.19: Comparison performance with optimal scheduling in July

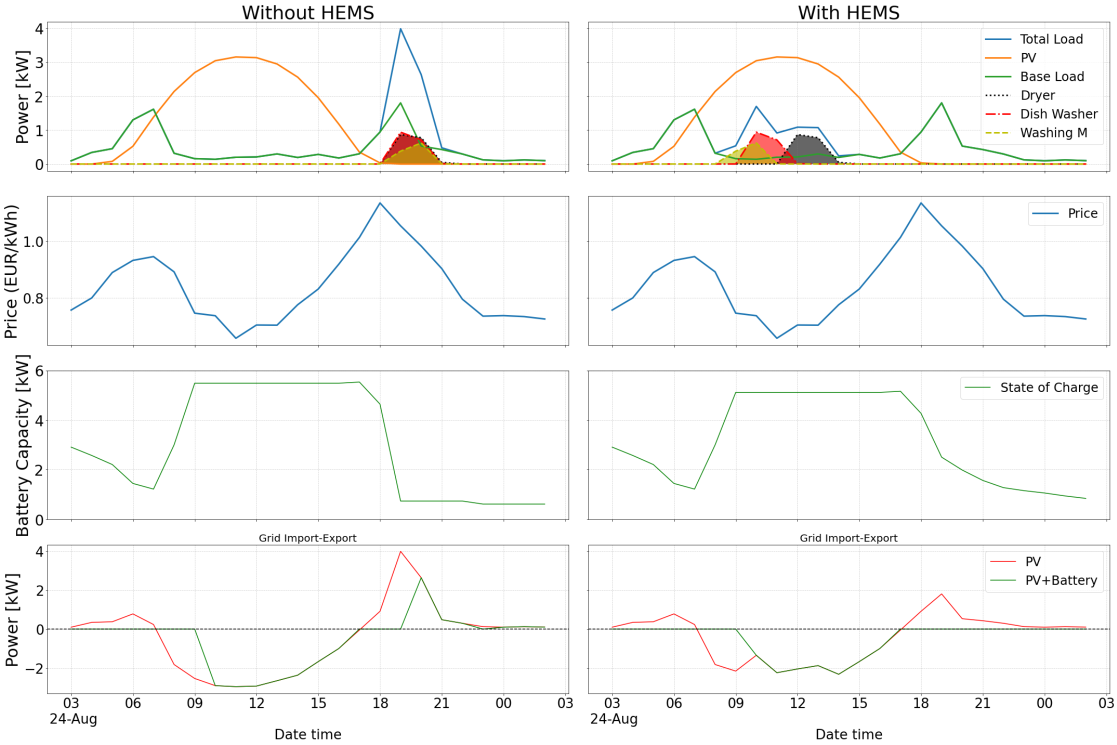


Figure A.20: Comparison performance with optimal scheduling in August

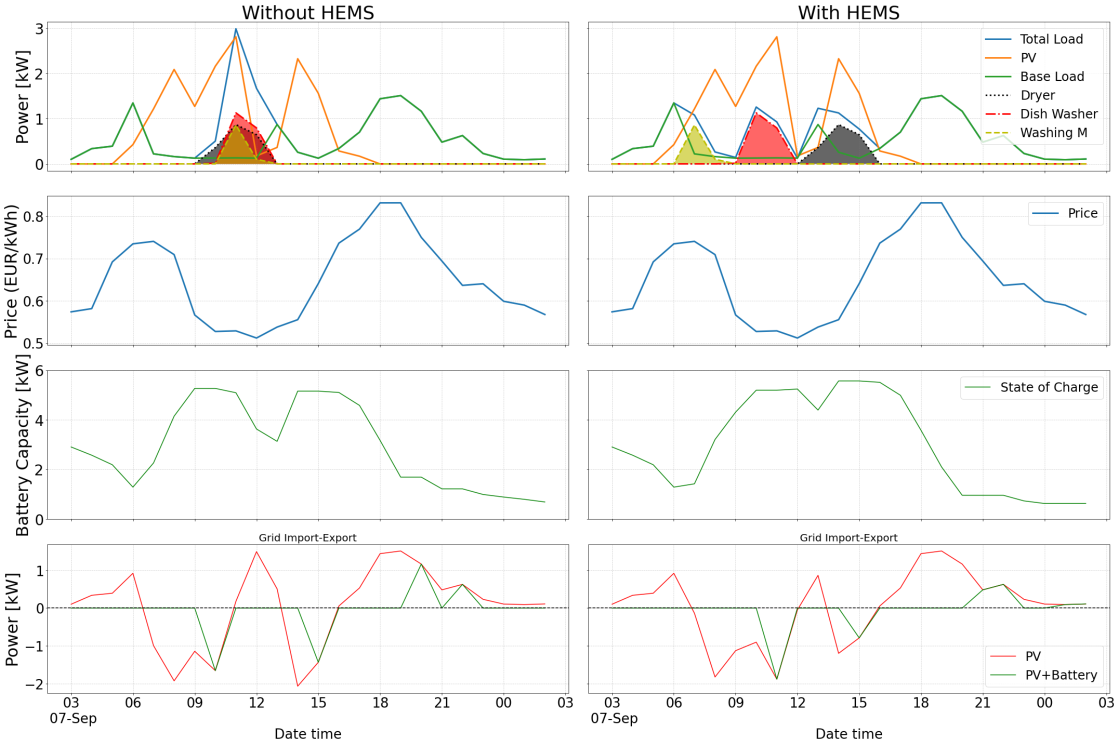


Figure A.21: Comparison performance with optimal scheduling in September

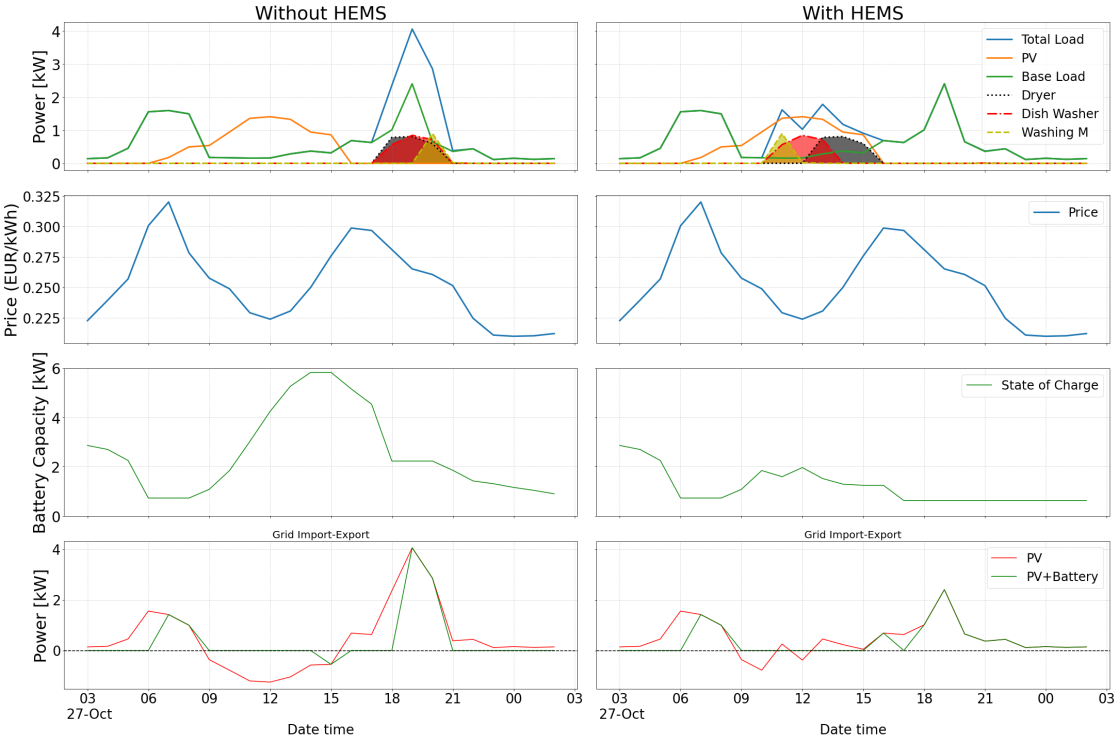


Figure A.22: Comparison performance with optimal scheduling in October

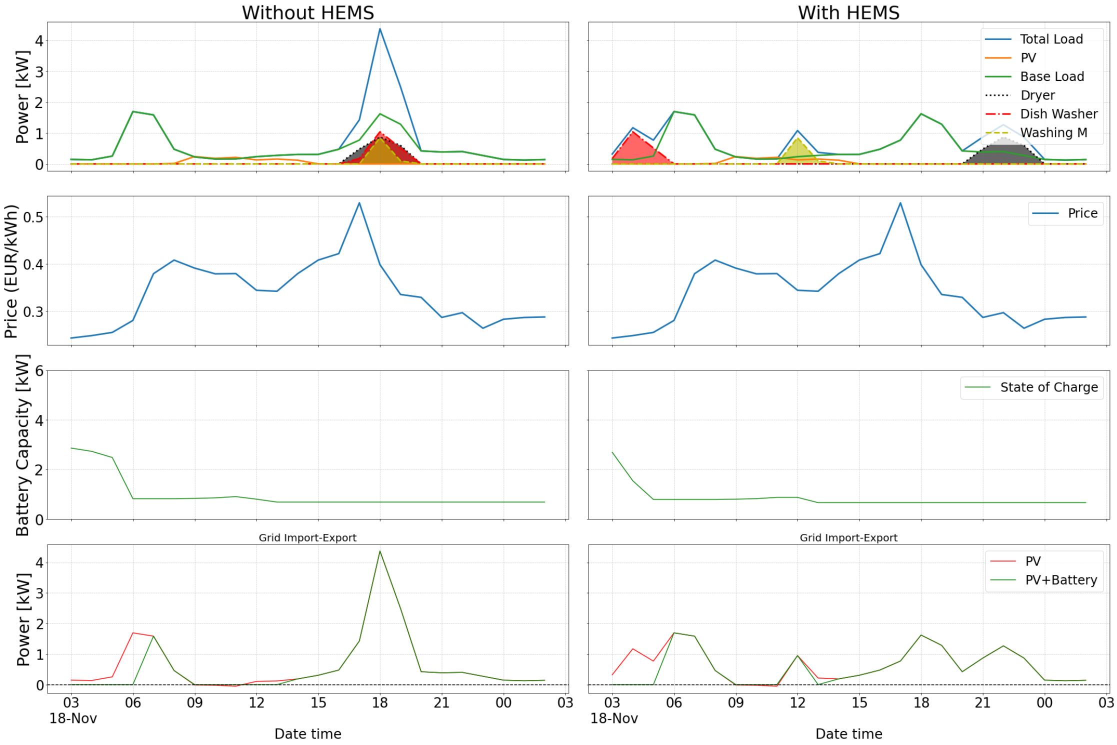


Figure A.23: Comparison performance with optimal scheduling in November

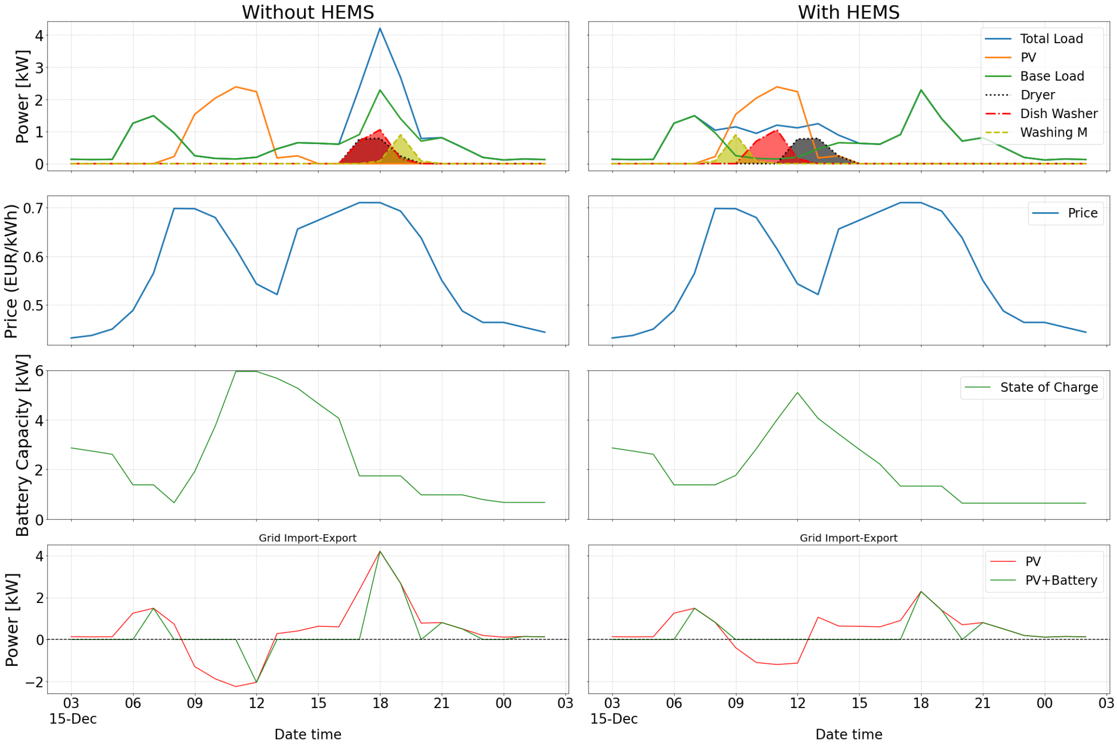


Figure A.24: Comparison performance with optimal scheduling in December