The Potential of Community Energy Storage for Grid Congestion and Prosumer Profitability in the Netherlands' Residential Solar Market

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by

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Preface

This report details the work undertaken for my Master's Thesis, the final part of the Sustainable Energy Technology program at the University of Delft.

The project began with a question I frequently encountered in the energy industry, given my role as a 'future expert' in the field and my studies in SET. The question was: "What comes after the NEM phase-out? Should we forget about our solar panels?" Although my immediate answer was no, I lacked a solid, profitable solution, as current alternatives were neither convincing nor comprehensive. This led me to explore solutions, and community storage emerged as a particularly fascinating option, especially given my experience in social housing energy systems. I was inspired by the efforts to make solar energy accessible beyond the wealthy, reflecting the diverse Dutch social structure I became part of since moving to The Netherlands. While working in this field was rewarding, I aspired to contribute more through my energy expertise, focusing on community solutions accessible to all.

However, a good idea was just the starting point. My five years of study prepared me well, but the thesis was the most challenging and enlightening journey. It taught me that scientific research is more than an initial enthusiastic idea; it is a dynamic, evolving process of thought. I revised my research questions, shifted my focus, and altered methodologies. After completing my thesis, I truly understood how scientific research is conducted. In these ups and downs, Dr. Rudi Hakvoort, Dr. Pedro Barrios and Dr. Na Li provided immense support and patience, offering valuable feedback.

I am proud to have almost completed this research, and I am very enthusiastic to start contributing to societal welfare and sustainability through my expertise in energy sustainability. This step brings me closer to fulfilling my father's dream of earning a Master's degree. Though he is not here to see this day, a bible verse he shared with me remains a constant inspiration:

"*Let's not get tired of doing good, because in time we'll have a harvest if we don't give up.* " (Galatians 6:9)

Gabriel Yousef
Delft, February 2024

Abstract

With the phasing out of the Net Energy Metering (NEM) scheme, the energy market is shifting towards alternative solutions like independent energy storage, already successful in countries like Belgium and Germany. However, a single solution dominating the market is unlikely due to continuous innovation and the limitations of individual battery systems for prosumers and Distribution System Operators (DSOs). Community energy storage (CES) emerges as a promising alternative but lacks a defined business model, particularly for Dutch residential communities.

This study delves into the implementation of centralized community energy storage systems to boost prosumer profitability and mitigate grid congestion in the Dutch solar residential market, in the wake of the NEM scheme phase-out. Community energy storage applications are identified, along with their respective potential business models. The optimal application, in terms of prosumer profitability and grid relief, is selected, and its associated business model is developed using the Morphological business model designed for energy communities. Furthermore, a practical approach for integration is proposed, based on regulatory and market constraints, to enhance the potential for large-scale emergence. This approach includes defining key roles and responsibilities of stakeholders within the community and the corresponding allocation of value. Subsequently, a technical system design topology is outlined for each defined community. This system design delves into engineering details to analyze the energy interaction possibilities between consumers and the grid, along with the corresponding financial implications. Accordingly, the CES application's performance is simulated and evaluated both technically and financially. The potential is presented by simulating the interactions between the community, the grid, and the optimal battery system. This optimal interaction arises from an optimization problem formulated to provide the optimal battery size and its corresponding energy profiles that minimize the total community cost. Finally, an energy distribution mechanism is carried out through conditional decision making to evaluate the cost and profitability allocation among consumers within the community.

The findings highlights the optimal application of CES, combining energy sharing with energy arbitrage, which significantly enhances the value of prosumers' surplus PV energy, outperforming standard tariffs and avoiding grid feedback charges. This approach also provides consumers with access to more affordable shared community energy, while aiding DSOs in alleviating grid congestion and improving infrastructure capacity. The study suggests that the most effective strategy for widespread CES adoption involves collaboration between housing cooperatives and Energy Service Companies (ESCOs). Financially, this model entails community managers overseeing initial investments, complemented by household contributions via usage-based or fixed service fees. The business model's success is influenced by the type of grid connection, with Behind-The-Meter (BTM) offering flexibility but lacking standardization, and Front-of-The-Meter (FTM) encountering challenges related to community energy taxation. Modelling the optimal operation for both BTM and FTM connections demonstrates a significant decrease of energy costs and contribution to grid relief, highlighting load smoothing and peak shaving as key benefits. The research concludes that centralized CES systems can substantially elevate prosumer profitability and reduce grid congestion, leading to considerable energy savings and enhanced grid performance in the Dutch solar residential market.

To support the expansion of Community Energy Storage (CES) systems and energy communities, policymakers are advised to revise energy taxation policies and create frameworks aiding community grid formation, including simplifying regulations and offering incentives for residential initiatives. Researchers should adopt a multidisciplinary approach to explore regulatory, technical, economic, social, and environmental impacts on CES, focusing on regulatory effects, grid dynamics, cost-benefit models, community engagement, and environmental benefits. Industry stakeholders, such as Distribution System Operators, energy providers, Energy Service Companies, and housing cooperatives, should apply these research insights to develop and implement CES systems, fostering partnerships to address challenges and innovate in energy solutions, particularly in the evolving landscape post-Net Energy Metering, to enhance the role of community storage in sustainable energy systems.

Contents

1 Introduction

Net-metering (NEM) was a crucial policy in the Netherlands for stimulating the solar energy sector. However, due to grid congestion, it will be phased out, decreasing the profitability of prosumers. Current market solutions in the residential sector are inadequate in two key aspects: they do not restore the profitability lost due to the phasing out of NEM, which is referred to as post-NEM, nor do they effectively mitigate grid congestion. This situation paves the way for exploring Centralized Community Energy Storage (CES) as a viable alternative. CES, by balancing local supply and demand, has the potential to ease grid congestion and help prosumers retain financial benefits from their surplus energy production.

The objective of this research is to analyze the emergence and utility of CES, examining its feasibility and potential in enhancing prosumer profitability and alleviating grid congestion post-NEM phase-out. This involves a tripartite analysis encompassing technical challenges, financial viability, and regulatory frameworks, aiming to present an integration strategy for CES in the residential sector in the Netherlands. This leads to the main research question:

How can centralized community energy storage be implemented to improve the profitability of prosumers and alleviate grid congestion following the NEM-scheme phase out in the solar residential market in the Netherlands?

This report is structured as follows: Chapter 2 provides background to contextualize the problem, analyzing the post-NEM phase-out and the potential of CES, along with a literature review and identified knowledge gaps finishing with the research questions. Chapter 3 presents the holistic research methodology. Chapter 4 outlines the data and assumptions used in this research. Chapter 5 details the CES integration analysis, resulting in the final technical and financial integration approach and associated regulatory framework. Chapter 6 presents the system design and discussed the modelling approach. Based on that, Chapter 7 presents the operational results of the system. Chapter 8 offers a discussion on the interpretation of these results, including validation and personal reflection. Finally, Chapter 9 concludes the research by answering the main research question.

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Background

This chapter outlines the background of the Net Energy Metering scheme phase-out, the limitations of current market solutions, and the potential of community storage. Drawing from the literature review, it identifies the knowledge gaps this research aims to address and formulates the research questions accordingly. Section 2.1 provides context about the NEM scheme. Section 2.2 offers an analysis of the post-NEM phase-out period, including current market solutions and their shortcomings in terms of grid congestion and prosumer profitability. Section 2.3 then explores the potential of community energy storage as an alternative solution to these issues. Section 2.5 outlines the defined knowledge gaps of the research. Finally, the main research question and corresponding sub-research questions are stated.

2.1. The Net Energy Metering (NEM) Scheme in the Netherlands

The Net-Metering (NEM) scheme was first instated in 2004 in the Netherlands (ministry of Economic Affairs, 2004), working as the main mechanism motiving citizens to obtain residential Photovoltaic (PV) systems in an attempt to save on electricity costs (Vasseur and Kemp, 2015).

The popularity of the NEM scheme did not fully gain attention from the media and the public until 2008 when it was being debated by the public, grid operators, politicians, and others (Van Aubel and Poll, 2019). It has been set as one of the most important alternatives to achieve the 20% renewable target by 2020 set by the European Union (EU) (Kattenberg et al., 2022). At first, the Advanced Metering Infrastructure (AMI), used for the NEM scheme, was installed on a small scale between 2012 – 2013, but by 2016 almost 3 million homes had this type of metering device installed and it was expected that 80% of homes would have it by 2020 (Netherlands Enterprise Agency, 2018). On a general basis, the NEM scheme allows electricity customers to be credited for any excess generated energy that is produced with the solar power system installed in their households and injected into the grid (Jacobs et al., 2012). The excess generated power under the NEM policy is meant to partially or fully offset the monthly electrical bill for the private household, but clients with excess credits at the end of the billing year receive compensation for any excess energy at a lower cost than the regular kilowatt-hour (kWh) consumed (Kemkens, 2023). The NEM policy only applies to households with an electrical connection equal to or lower than a three-phase connection with an 80 Amps capacity installed. At first, the generation capacity was limited to 3,000 kWh/year, but it was then increased to 5,000 kWh/year in 2011, and finally, this limit was abolished entirely in 2012 (Londo et al., 2020).

2.1.1. Financial Effects of the NEM on the Market

Even though the NEM scheme cannot be accredited as the sole responsible for the rapid and large acquisition of PV technology in the residential sector of the Dutch population, it has indeed accelerated the process and incentivized the general population. As a result of the market conditions, a private household could expect a Return of Investment (ROI) or payback time in as short as 4 to 6 years for PV systems bought after 2020, which means abolishing the Net-Metering scheme would increase that ROI by several years (Londo et al., 2020). The short payback time can be considered a great motivation for the Dutch population to acquire solar PV systems. It is estimated that these subsidies are responsible for increasing the acquisition of PV systems by

14.4%, besides, thanks to those incentives, citizens have also acquired PV systems around 33.2% larger than they would have acquired without the incentives (Kattenberg et al., 2022). Hence, it is expected that phasing out the NEM would have an important impact on the Dutch solar market, but it is also important to analyze why the government is phasing out the NEM.

Analyzing how the revenue is allocated among stakeholders in the NEM scheme and other affected parties, can broaden the understanding of the decision from the Dutch government to phase out the subsidy. Tariff inequality is one of the major socio-economic issues affecting a large part of the population, this can be a major concern because at least 80% of the private householders that acquire PV technology tend to be considerably wealthier than most non-PV owners (Barbose et al., 2018). On top of this, PV-owners will be consuming less power from the grid and non-PV owners will be paying in their majority for the electrical grid infrastructure through higher tariffs on top of the levy tax for using non-renewable energy (Burger et al., 2019;Netherlands Enterprise Agency, n.d.) as electric utilities have been forced to increase the kWh cost charged to regular customers as a tactic to recover losses for net costs of PV-owners (Eid et al., 2014). Large companies that usually provide a stable income for utilities are also switching to renewable energies, which further decreases the income received by these big energy consumer corporation and increases the inequality in the tariffs that mainly affects non-PV owners (Huijben and Verbong, 2013a). There are few studies analyzing this problem, especially for the specific case of the Netherlands. Several other financial issues include the Dutch government perceiving considerable losses caused by a lack of governmental tax incomes as a result of the NEM scheme that has already cost € 400 million to the treasury and the € 23.5 billion investment necessary to put a price cap on electricity for the 2023 year (Enerdata, 2022; dutch News, 2023). Additionally, it is expected that by 2030 the government would also have to pay around € 7 billion for the maintenance of the NEM infrastructure (Londo et al., 2020). All of these would explain some of the major financial reasons why the government is looking to start phasing out Net Metering by 2025.

Reducing the NEM scheme might balance how revenue is allocated and be a first step to equilibrate electrical tariffs in the country. It should be noted that the phasing out of the NEM scheme does not mean that the power injected into the grid by prosumers will go unpaid. The kWh generated and delivered to the grid will still be paid, but it will not be set off against the price per kWh bill of the customer, meaning that it will be worth less than the current value of electricity consumed by a household from the grid. The value for the kWh will be decided by the Government after considering factors affecting the ROI for a PV system in 7 years (Kemkens, 2023; dutch News, 2023). Hence, observing these changes in market conditions, Dutch PV owners who want to take advantage of a PV system might be interested in looking for alternative solutions to the phasing out of the NEM scheme to make sure the value for their generated solar energy is not diminished.

2.1.2. Technical Effects of the NEM on the Market

The increasing number of prosumers who purchase a PV system to take advantage of the NEM scheme is causing several problems, with the most notorious one being network congestion on the power grid (Eid et al., 2014). Network congestion is a phenomenon that occurs when the transmission capacity of the grid is reached because a large number of electricity customers are demanding or injecting power to the grid simultaneously, causing volatility and instability on the power grid, which in the end requires an expensive reinforcement of the network or efficient alternative solutions (Fonteijn et al., 2019; Tennet, 2022). As a consequence of this network congestion, TenneT (transmission system operator (TSO) in the Netherlands) is conducting several studies and has already invested € 4 billion in 2021 to expand the power grid and will increase that amount by an additional € 2 billion in 2025, but this reinforcement of the high-voltage grid will take from 5 to 10 years to be completed. TenneT is also working hand in hand with the Autoritet Consument en Markt (ACM) regulator to find regulations that will ease the problem in the short-term (Tennet, 2022). An additional problem caused by the network congestion is an increased level of GHG emissions caused by an outdated power grid that is not suited for a high bidirectional transmission capacity (Monforti-Ferrario and Blanco, 2021), which is why the grid needs to keep pace with the increasing number of PV-owners. Aside from the network congestions in the power grid, there are several other financial issues derived from the NEM scheme and the rapid acquisition of PV technology by Dutch citizens.

2.1.3. The NEM-scheme phase out

As the Dutch government moves forward with its plan to phase out Net-Metering entirely, it is important to analyze how a prospective future without this scheme would work, its socio-economic impact, and feasible alternative solutions.

Initially, the phasing out of the Net-Metering scheme was programmed to start in 2023, but the Dutch government postponed the process until January 1, 2025. The phasing out of the NEM scheme will occur gradually, in 2025 – 2026 private households will only be able to receive credits for 64% of their generated electricity and a compensation for the remaining energy delivered at a lower tariff. This percentage will be reduced by 9% per year, reaching 55% by 2027, 46% by 2028, and so on until it is phased out entirely (0%) in January 1, 2031 as seen in figure 3 (Kemkens, 2023; van den Berg, 2023). The problem with phasing out NEM is that it will impact several key stakeholders, but it will also have a socioeconomic impact, and will potentially reduce PV acquisition from Dutch private householders (Kattenberg et al., 2022).

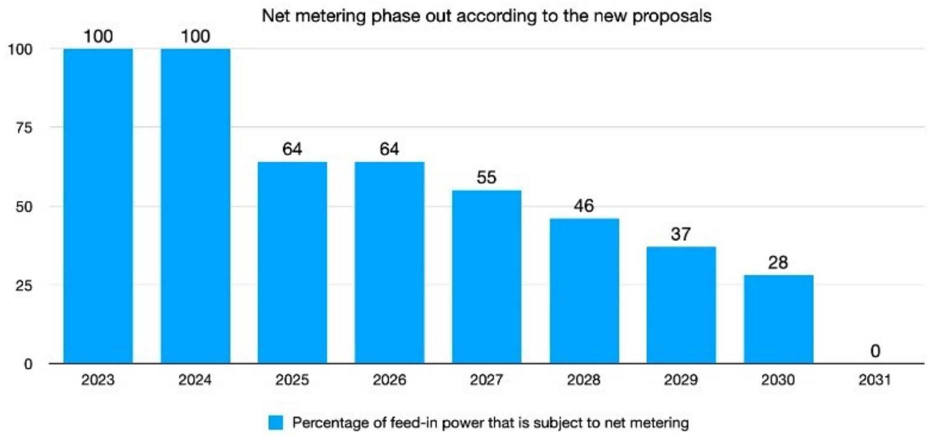

Figure 2.1: Gradual phasing out of the NEM scheme (van den Berg, 2023)

While net-metering is slated for implementation in 2025, energy providers have already begun taking measures in anticipation of the challenges it presents, VandeBron being one of them. The Dutch energy supplier, VandeBron, has introduced a new policy regarding the reimbursement costs for power fed back into the grid by its solar panel customers. Clients are now subject to a fixed daily fee for returning power that they generate but do not immediately consume.

The feedback costs depend on the amount of electricity (kWh) returned to the grid, with the rates being tiered according to the quantities supplied. On average, these costs amount to approximately €10 to €20 per month. The necessity of charging for energy feedback arises as a counter measure to the financial strain on energy suppliers caused by the NEM-scheme. Particularly on sunny days, when an excess amount of electricity is returned to the grid, the price of power can diminish significantly, even turning negative, thus, imposing financial losses on providers. As discussed, regularly, these costs are distributed among all customers, regardless of whether they possessed solar panels. However, VandeBron contends that this approach lacks fairness. Consequently, the company believes that the new policy enables a more equitable distribution of costs.

While VandeBron is currently the only supplier enforcing these costs, other energy suppliers, grappling with the same escalating backfeed costs, might soon follow suit, although their exact plans remain undisclosed. Nonetheless, several energy suppliers, including Essent, Eneco, Oxxio, and Energiedirect, have already opted to temporarily abstain from offering contracts exceeding one-year durations to customers with solar panels, signifying a sector-wide apprehension regarding the current trends in solar energy production and net-metering. Industry exerpts pointed out that this measure by VandeBron shook the PV-market.

2.2. Analysis of Post NEM Scenario

2.2.1. Expected Socio-Economic Impact

Subsidies rolled in the Netherlands are responsible for increasing the number of citizens that have purchased PV technology in the last few years, (Kattenberg et al., 2022). As a result, it can be expected that as the Dutch Government gradually phases out the Net-Metering subsidy, private householders would start feeling less attracted to PV technology and those who would still be, would probably purchase smaller PV system to save money for investment in achieving solar self-consumption. At the end, this could reduce the speed at which the Dutch government achieves its climate goals. One of the most important economic impacts that will cause phasing out of the NEM scheme is an increased payback time for rooftop PV systems. Currently, the payback time of 4-6 years is expected to increase to 8 - 10 years according to a study analyzing this scenario as seen in figure 2.2 (Londo et al., 2020). However, the Dutch consumer protection organization known as Consumentenbond, is demanding guarantees that the payment to PV-owners for the energy injected to the grid during the phasing out of the NEM scheme delivers a payback time of maximum 7 years (dutch News, 2023). This decision carried out by the Dutch government is designed to address socio-economic problems that include tariff inequality and reduced budget due to unpaid electricity import taxes, but will collaterally have an impact on the revenue that prosumers have been receiving up to this point with the current NEM scheme.

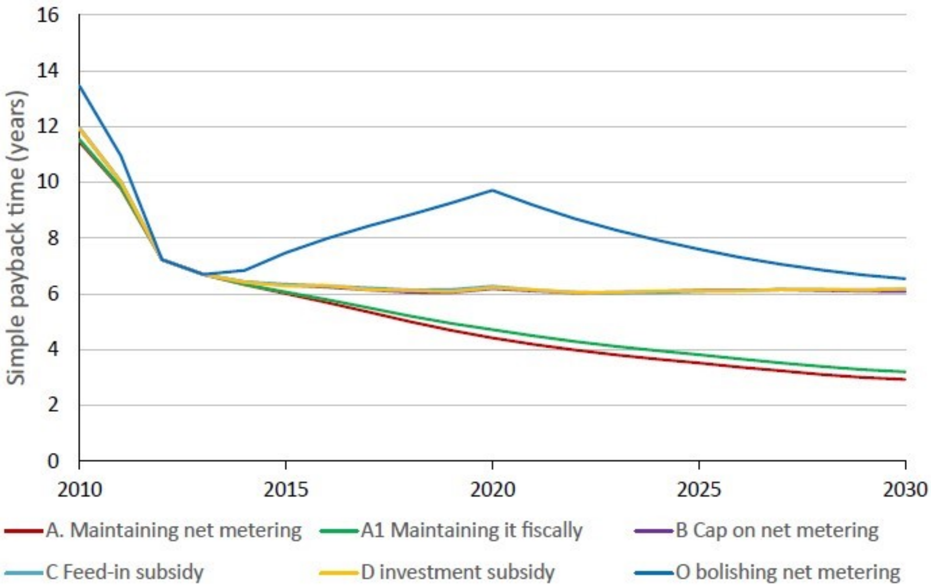

Figure 2.2: ROI for PV systems considering different scenarios (Londo et al., 2020)

2.2.2. Market trends - Post NEM

The Dutch government's NEM-scheme has been crucial in promoting the uptake of solar power systems among residential and commercial consumers. However, the NEM scheme will soon be phased out, leaving prosumers without the financial benefits of sending excess energy to the grid. As a result, several possible solutions have been proposed, including solar self-consumption through the use of battery systems commonly known as home battery systems, community solar projects, and even peer-to-peer electricity trading (DNV and INVEST-NL, 2021;Reijnders et al., 2020;Georgarakis et al., 2021), with home battery systems being the most easily applicable solution.

A residential-scale BESS or home battery system, is often based on Lithium-ion batteries with a typical maximum power of 5 kW and maximum capacity of 10 kWh (Verkaik, 2022). They can be used for one of two purposes: solar self-consumption or market participation. Using a BESS for solar self-consumption will allow private householders owning a PV system to store excess generated energy into the BESS instead of sending it to the grid, that energy can be used at night or at times when the PV system is not generating enough power to supply the demand of the load (DNV and INVEST-NL, 2021;Ciocia et al., 2021).

Moreover, since upgrading the grid infrastructure to tackle congestion issues is both expensive and time-consuming. These flexible energy storage systems like batteries have been widely suggested as an alternative method to alleviate grid congestion, thus realizing the goal of the NEM-scheme phase out. Namely, increasing self consumption and decreasing the stress on the grid.

2.2.3. Limitations of resedential batteries for prosumers

Residential BESS have been proposed as a means to maintain the profitability of prosumers following the phase-out of net metering. Various stakeholders have proposed subsidizing residential batteries to encourage their adoption and usage. As, based on previous studies, the current cost of these batteries remains too high to yield a profitable return on investment while the NEM scheme is still active (Verkaik, 2022). More recent studies, concluded that their business case is not positive, even after the NEM phase-out (Kubli and Puranik, 2023).

Despite the potential benefits, residential batteries face several limitations. Firstly, the storage capacity of these batteries is restricted. On average, they possess a capacity of approximately 4 kWh (Verkaik, 2022), while the average residential solar system has a size of 5 kWp. (kijk op Oost Nederland, 2022). This means that during a sunny day, the average battery reaches full capacity within just two hours. Consequently, systems with individual batteries will still generate excess energy that must be returned to the grid, failing to achieve complete self-consumption. As a result, these batteries neither present an optimal business case nor replicate the profitability of net metering. Increasing the capacity of residential batteries is not a viable solution to this issue, as the photovoltaic generation during winter months is insufficient to charge the battery fully, thus compromising the self-consumption criterion. Furthermore, larger capacity batteries demand a more substantial investment.

Previous research has demonstrated this phenomenon by calculating the payback period of batteries using various control methods. The payback period ranges between 8 and 13 years, considering current energy prices, and neglecting the NEM-scheme (Verkaik, 2022). Other studies, considering actual regulations and more practical applications, concluded that post the NEM-scheme, the business case of residential batteries is not positive, with payback periods exceeding the battery lifetime or closely approaching it, based on several use-cases (CE-Delft, 2023). The positive business cases with payback periods within the battery lifetime period are also considered reasonably high as the maximum battery lifespan is 15 years. Notably, aggressive control methods can expedite battery degradation, reducing the lifespan even further. Additionally, these ‘profitable’ control methods necessitate the active involvement of prosumers in curtailing their energy demand for self-consumption, which may not always be feasible. Other profitable control methods in the context of market participation require active trading or the implementation of an energy management system, neither of which are widely adopted. Alternatively, manual trading by the user is possible but can negatively impact the prosumer’s overall welfare, as it requires its active involvement in the process.

The potential profitability of BESS can be significantly improved if they are employed for trading on the wholesale electricity market or participating in other ancillary markets. However, due to their limited capacity, households are unable to directly engage in these markets, as the minimum power bid required for entry far exceeds their capabilities (Verkaik, 2022). Consequently, smaller residential batteries are unable to access these markets. In order to enable market participation for batteries of this size, a collection of storage units could be consolidated and managed by an aggregator. Regrettably, the progress in developing such aggregators is challenging, primarily due to the governance challenges associated with deploying it. (Koirala et al., 2019;Eid et al., 2014).

2.2.4. Limitations of resedential batteries for net congestion

Residential batteries, although offering potential benefits in addressing grid congestion, face inherent limitations that restrict their effectiveness for DSO’s. One such limitation is their inability to fully cover electricity demand during solar peak moments, which leads to excess energy being returned to the grid and only marginal reductions in feed-in peaks during summer months, rendering them incapable of mitigating generation load peaks. This issue is further exacerbated by seasonal variations in photovoltaic (PV) generation, with batteries unable to cover consumption peaks in winter due to insufficient PV-generation and thus available energy in the batteries.

Moreover, when residential batteries are controlled based on wholesale market prices, they can contribute to station overload peaks by creating their own supply and demand peaks (Verkaik, 2022) (Kubli and Puranik, 2023). In a scenario where large-scale integration of residential batteries occurs, these devices may inadvertently create new peaks in the grid system. Such new peaks stem from the simultaneous charging and discharging behaviors of a vast number of batteries, which could lead to unforeseen fluctuations in electricity demand and generation, further stressing the grid and potentially causing instability. Despite these challenges, residential batteries still offer some value to DSOs under medium and low emergence scenarios. However, there is a conflict of interest between the DSO and the prosumer. As the most profitable control methods do not contribute to net congestion reduction, and DSO -favored control methods do not provide optimum profitability for the customer. (Verkaik, 2022).

In conclusion, NEM-scheme phaseout will incentives prosumers to purchase residential batteries to remain their profits. While residential batteries possess the potential to partially alleviate grid congestion, their inherent limitations and the possibility of creating new peaks due to large-scale integration pose significant challenges for the grid. This will limit the effects of NEM phaseout on net congestion.

Nonetheless, the market has also witnessed a surge in alternative solutions for addressing grid congestion (netbeheer Nederland, n.d.). Recent advancements in the energy sector have led to a significant increase in large-scale battery projects. As of February 2023, network operators, encompassing DSO's and TSO's have reported new battery projects with an aggregate capacity of 34 GW. Remarkably, these batteries are anticipated to fulfill diverse purposes, with 43% projected to primarily participate in the balancing market for profitability. Concurrently, it is expected that around 30% of these large-scale batteries will be employed to tackle grid congestion challenges. (Zwang, 2023)

2.3. Alternative Solution

As illustrated, the market does not offer a sufficient solution for challenges that will face the prosumer after the NEM phase out. Moreover, the self consumption motivation due to the NEM-phase out will not directly result in net congestion relief as is expected. Due to the fact that the most straight-forward technical instrument for this purpose, home batteries, have limited capabilities for grid stress.

The industry is therefor exploring other opportunities with the objective of profitability and/or grid congestion relieve. One of the potential solution to the profitability and net congestion simultaneously can be realized through the implementation of community energy systems. As considering a number of prosumers and the grid as a connected energy community provides more possibilities for energy generation and consumption for the community. Several researchers have pointed out that correcting the mismatch between distributed energy resources (DER) generation and consumer demand on a local level, provides an optimal social welfare levels for the whole community . However, this requires proactive anticipation from both prosumers and stakeholders in the chain, as natural market dynamics do not organically incentives community formation.

In order to explore the potential of local energy mismatch correction, the current environment consisting of prosumers, DSO and energy providers should be transformed into an integrated energy community. These energy communities are defined in literature as Integrated Community Energy Systems (ICES), these are localized energy networks that manage local energy generation, delivery, and exchange to meet local energy demands. The European Union directives refer to these systems as renewable/citizen energy communities (Kubli and Puranik, 2023). By incorporating distributed energy resources, energy communities transform communities from mere energy consumers into prosumers, who both consume and produce energy. Energy communities can alleviate local grid issues without the need for network reinforcement by promoting smart local energy management. By efficiently coordinating energy generation and consumption, they can also optimize energy usage, reduce peak demand, and minimize stress on the grid. As a result, these systems contribute to increased energy resilience, reduced greenhouse gas emissions, and lower energy costs for community members (Koirala et al., 2016). These benefits are largely due to their distinction to traditional energy systems as are located near both electricity generation and consumption which leads to improvements in efficiency and reductions in losses (Li et al., 2022).

Energy storage is a crucial component of energy communities, which can be implemented through centralized community storage or decentralized distributed energy sources. Community Energy Storage (CES), in general, have advantages over individual residential storage, as was highlighted by several scholars (Koirala et al., 2019). These benefits include an increase in local self-consumption of energy generation, a reduction in energy imports and network costs for local communities, and added value for grid relief, local balancing, and congestion management. As such, CES offers significant potential for improving the efficiency and reliability of energy systems at the local level (Koirala et al., 2019). These benefits are exploited by connecting the individual generation and consumption units, houses, and adding the buffer system, the battery storage. Creating endless possibilities for energy exchange, that were otherwise not possible with individual energy storage.

Moreover, individual storage systems, create more safety concerns, related to the in-house placement of a battery, which currently does not have a general framework that is adopted by the Dutch government and industry (Kubli and Puranik, 2023).

2.3.1. Community Energy Storage

Community energy storage can be realized in centralized or decentralized form. Decentralized form includes the aggregation of multiple storage units. While centralized CES is based on a central large scale storage unit. Both types have their opportunities and challenges.

Implementing decentralized residential community energy storage solutions that prioritize profitability and network stability presents significant challenges. This approach exposes prosumers to the limitations of residential batteries and creates challenges related to the aggregation and participation of multiple decision points in a community that is technically, financially, socially and policy-wise difficult to govern. Additionally, this aggregation is not supported by universal policies, exposing prosumers to the safety concerns that occur due to the lack of safety frameworks presented priorly.

In contrast, centralized CES solutions rely on safety frameworks that are adopted due to the surge of these large-scale batteries for large-scale applications (Kubli and Puranik, 2023). Moreover, centralised CES provide the benefit of utility-scale storage, leveraging economies of scale to achieve cost efficiency and greater reliability (Koirala et al., 2019). Practical demonstrations such as the Gridflex (GridFlex, 2020) pilot-project in the Netherlands have also illustrated the need for central storage systems, emphasizing the importance of a plug-and-play system for effective energy management and its investment predictability . Additionally, this project demonstrated the difficulty of actively managing a large number of distributed battery systems, both technically and organizationally, as it required the active participation of eight stakeholders, next to the prosumers. This was also pointed out by industry experts. (de jonge Baas, 2022)

To conclude, utility-scale batteries have shown their effectiveness in resolving congestion issues. Therefore, large central community batteries offer a potential solution to the challenges related to balancing the needs of prosumers' profitability and the DSO's network congestion.

However, developing an energy community solution that utilizes community storage to address net congestion and enhance prosumer profitability presents significant challenges. As previously noted, these challenges are primarily technical and financial in nature and are further compounded by the difficulty of establishing an economically viable community that requires the participation of multiple stakeholders (Koirala et al., 2016). Moreover this development is further constrained by the social complexity of community formation and the policies and regulations in a certain region that should be considered.

Due to these reasons, there are currently no successful nor profitable business cases of community storage in the Dutch residential sector. (CE-Delft, 2023) All the propsed solutions on community level are either pilot projects or frameworks that do not transform into large-scale emergence.

The successful implementation of such a solution thus requires careful consideration of the technical and financial limitations involved, as well as the development of effective strategies for stakeholder engagement and community building, that take into account the local regulations. To fully address these issues, it is necessary to study the possibilities and challenges associated with emergence of centralized community storage.

2.4. Literature Review

To explore the challenges and potential in the development of community storage solutions, particularly in addressing consumer profitability and net congestion, a literature review is conducted. The review aims to provide a detailed understanding of the current research landscape in this area, highlighting key studies that assess the feasibility and effectiveness of various Community Energy Storage solutions. This analysis seeks to outline the potential obstacles in implementing CES in the residential sector and to pinpoint critical factors influencing this process. The main goal of this review is to identify the hurdles in creating effective implementation strategies that can optimize the benefits of CES for consumers and DSOs while reducing potential impediments and barriers to adoption. Initially, the review delves into the general frameworks to CES advancement, determining the factors that hinder its progress and the essentials for successful deployment. This includes examining studies that discuss the broad difficulties associated with CES integration, as well as the overarching frameworks and prerequisites necessary for its development, encompassing financial, technical, and governance aspects.

Subsequently, the literature review shifts focus to relevant studies evaluating the feasibility and efficacy of various CES cases. This phase involves a thorough investigation of literature on actual projects to determine whether they meet the previously identified needs and issues.

The implementation of energy communities faces numerous challenges across technical, socio-economic, environmental, and institutional domains (Li et al., 2022) and arise due to the differences between community systems and the traditional centralized energy infrastructure (Li et al., 2022;Koirala et al., 2016), and the multidisciplinary nature of the problem that requires a multitude of technologies, actors, institutions, and market mechanisms for a successful integration, which is complicated.

Technical challenges were identified in literature, the challenges of deployment of ICES are affected by various technical factors, related to the scarcity of public and/or private space required to install power generating units within local communities and the temporal availability of resources and grid connection issues (Koirala et al., 2016)(CE-Delft, 2023).

Energy communities face also financial challenges, including high upfront costs, funding barriers due to banks not providing loans to communities, and difficulties with cost allocation (Koirala et al., 2016). Traditional cost allocation methods based on per capita or peak demand are not always suitable for community systems (Vespermann et al., 2020). The absence of established criteria and approaches for cost allocation in local energy systems poses a significant challenge. Furthermore, the pricing methods for traditional large power systems are not well-suited for communities, as they do not accurately reflect the costs and benefits associated with consumers, prosumers, and the distribution network (Li et al., 2022). Therefore, there is a pressing need to redesign distribution network tariffs to better reflect the true costs and benefits of these systems (Vespermann et al., 2020). Fair cost and benefit allocation is a key issue that determines the success of community storage systems, as investments are either made at the individual household level or community level (Koirala et al., 2016). It is therefor essential that costs and benefits are allocated fairly to those who consume energy and use energy-related services and to those who have made the investments in the system cost. Given the absence of a regulatory body within residential energy communities, the responsibility of cost allocation falls upon the community itself, which must determine an appropriate and equitable approach to distribute costs among its members. However, the literature provides limited guidance on effective cost allocation mechanisms for these communities (Li et al., 2022).

Another significant challenge is determining the proper mechanism for energy exchange within the system. This challenge is closely related to the issue of cost allocation, as it is technically challenging to establish a distribution scheme that enables a fair compensation mechanism. One critical aspect of this challenge is determining the trading mechanism and tariff, which must be designed to ensure that prosumers receive fair compensation for their contributions to the system, and considering that the electrical system design allows that.(Li et al., 2022).

Literature has highlighted other challenges facing the implementation of central storage communities, including social, regulatory, and governance issues. The current regulatory and governance arrangements were not designed to accommodate collective action in the form of local energy initiatives and distributed energy resources such as energy storage. As a result, they do not provide a level playing field. (Koirala et al., 2016) Additionally, current regulation does not *fully* recognize innovative products and services offered by CES, such as ancillary and capacity-related services, which creates regulatory barriers to realizing their full potential (Li et al., 2022).

This lack of appropriate institutional design, , and regulatory frameworks presents a significant challenge for CES implementation (Koirala et al., 2016). Furthermore, the lack of awareness and education among stakeholders regarding the benefits and potential of ICES can further hinder their deployment (Koirala et al., 2019). Moreover, as governments start to cut back on support schemes, literature suggests that it is necessary to develop new regulatory frameworks and business models that encourage economically efficient operation of distributed energy resources (Koirala et al., 2019).

The primary function of community energy and storage solutions is to facilitate energy sharing within the community. However, current policies do not fully support this type of implementation. As when charging and discharging energy consumers are currently subject to energy tax obligations, presenting a significant hurdle. Notably, while large-scale neighborhood battery systems have been exempted from double taxation since 2022, consumers continue to face this issue. This discrepancy makes it challenging for the industry to create a viable business case for energy sharing (Kubli and Puranik, 2023), that benefits the prosumers.

Despite these challenges, there is potential for change on the horizon. The government is working towards more comprehensive regulation of energy sharing within energy communities, buildings, and among active consumers. This effort may include the (potentially free) exchange of electricity between two connections within the same imbalance period (15-minute blocks), offering an alternative to regular electricity consumption. This concept is part of an amendment to the Electricity Directive, currently under negotiation in Brussels as part of the Electricity Market Design package. Once finalized, it will be integrated into Dutch law and regulation. However, several complexities still need addressing, including the logistics of Energy Tax collection and potential tax loss with a zero rate, the interplay with 'net metering', and the technical feasibility of these solutions. Discussions on these topics are actively ongoing between the Ministry of Economic Affairs and Climate, the Ministry of Finance, and market stakeholders. It is anticipated that the regulations for electricity sharing will be more clearly defined by January 1, 2025 (Ministry of EZK, 2023a, 2023d).

2.4.1. CES case studies

A number of literature studies is reviewd, presenting cases of CES integration into the residential sector either in The Netherlands or ones that be applicable to the dutch residential sector. Table 2.1 presents the reviewd papers their focus point and the category of challenges analyzed.The full literature review can be seen in Appendix A.

Source	Focus Point	Category of Challenges
(van Westering and Hellendoorn, 2020)	Integration of community battery stabilizing and controlling loads	Technical
(Reijnders et al., 2020)	Simulation of 24 community batteries providing real-time consumption	Technical
(Aranzabal et al., 2023)	Data from five prosumers with residential batteries was analyzed for a Virtual Power Plant proving economic advantages on a 15-year basis	Technical
(Guedes et al., 2022)	Maximizing revenue from energy transactions in a community using Battery Energy Storage System	Financial
(Safarazi et al., 2020)	Power grid analyzed in three scenarios using agent based model proving autonomy-maximizing strategy as the best solution for energy curtailment	Technical/Financial
(Dong et al., 2021)	Rooftop PV installations in Germany and UK are analyzed proving importance of considering the solar irradiance for the country	Technical/Financial
(Hayat et al., 2022)	Analysis of CES installing proving that eliminating duck curve profile and shaving consumption peaks are possible together given that self-sufficiency is not focused upon	Technical
(Patwari, Sharma, et al., 2022)	Proposal of investment in acquiring community battery by external agent allowing for selling of day-ahead storage rights to community members	Financial/Social
(european Commission, 2022a)	Integration of Battery Energy Storage Systems by several european companies demonstrating effectiveness in industrial and medium scale batteries	Governance
(EU-SysFlex, 2021)	Integration of Renewable Energy Resources into power grid to reduce carbon emissions demonstrating that the approach followed provides a more efficient usage of BESS	Governance
(IRENA, 2019)	Market Integration of Distributed Energy Resources approaches helping CES installers and promoting policymakers	Financial/Governance
(european Commission, 2022b)	Presentation of tools promoting Energy Communities providing technical configuration analysis and business models adaptable to each European country	Technical/Financial

Table 2.1: Summary of the Literature Review

The scope and focus of existing research on integrating community storage into the low voltage grid vary significantly, ranging from highly focused yet lacking in broader vision to overly predictive but missing specificity and practicality. Studies that are practical often fail to address all the necessary components for effective implementation. For instance, while the case of Heetten identifies the technological and market design needs, it lacks recommendations or discussions on governance aspects, as it was executed within a pilot, exempting limiting regulations.

One of the core issues here is the multifaceted nature of CES integration. There are numerous methods to incorporate CES for storing PV energy, but each implementation method significantly influences cost allocation and energy sharing possibilities. Concentrating solely on the engineering level of integration does not provide insights into the business case, rendering the implementation uncertain and unlikely. Conversely, focusing only on frameworks and concepts regarding CES business cases without considering technical implementation, governance, and financial aspects of cost allocation also results in an incomplete picture.

This crucial challenge is often overlooked in research, which tends to assume seamless distribution without addressing the complexities inherent in existing frameworks, such as billing structures. For example, numerous studies emphasize the benefits of aggregated storage systems in managing demand fluctuations and peak shaving in small-scale systems. However, they often overlook the practicalities of integrating these systems within the current billing frameworks and grid topology. This oversight could impede their widespread adoption, especially when considering issues like double taxation. A comprehensive approach that addresses both the technical and operational aspects, including financial and governance considerations, is essential for the successful implementation and scaling of CES solutions.

2.4.2. Main findings

Due to the lack of community supportive policies and the multi-disciplinary challenges, a business case for energy sharing and community storage is difficult to realize. The lack of adequate business models and cost allocation structures poses a significant challenge for the successful deployment of community energy (storage) systems. Existing energy business models are not suitable for collective action-oriented systems like CES, and the absence of established criteria and approaches for allocating costs in local energy systems further complicates the issue (Koirala et al., 2016). Recent research highlights a growing interest in community systems, contributing through to the objectives, technologies, governance forms, and barriers and drivers of energy communities. However, business model–related aspects have not been equally studied, "*The field of business models for energy communities appears to be surprisingly unchartered terrain*" (Kubli and Puranik, 2023).

Reviewed case studies tend to focus narrowly on individual technologies and implementation challenges, rather than taking a comprehensive approach that accounts for the complex interplay among various elements in the local energy system (Koirala et al., 2016). To achieve successful implementation, it is essential to create an enabling environment for business model innovation, community ownership, participation, and governance through flexible regulation and energy policy (Koirala et al., 2016;Koirala et al., 2019). However, business model proposals in the literature often lack practicality, specificity (Vespermann et al., 2020). They presents general framework for business models, which may not always offer a practical solution that meets the specific needs of the Dutch residential solar sector (Li et al., 2022). Furthermore, the business models suggested in the literature are often qualitative in nature and lack quantifiable outcomes (Li et al., 2022). As a result, it can be challenging to translate these business models into a concrete business case, especially given the difficulty of cost allocation. Additionally, reviewed literature tries to present universal solutions to CES deployment, however, as also suggested by others (Koirala et al., 2016), there is no one size fits all for this problem.

Kublie et al (2023), along with other researchers, highlighted this issue, identifying the development of business models as a significant knowledge gap. They emphasized that while general characterizations of business models contribute to the formation of community energy initiatives, there is an *under-investigation* of tailored business model frameworks and specific cases. In their paper, they presented a business model uniquely designed for energy communities and tested that on existing energy community cases. Interestingly, they emphasized the importance of considering local regulations, such as net metering and feed-in policies. They concluded by suggesting that "*Future research in this field should be oriented towards the practical implementation of energy communities.*" They argue that in order to transform these business models into tangible business cases, it is crucial to address concrete implementation issues within national policy frameworks. This is necessary to achieve a quantitative assessment of their economic viability, technical processes, and sustainability.

Focusing specifically on the residential sector in the Netherlands, their conclusion is in line with the findings from Gridflex and the recent study by CE-Delft, 2023. These context-specific papers, alongside other theoretical reviewed research, collectively conclude that, in this context, community batteries lack a well-defined business case.

In summary, the literature review underscores the critical importance and growing interest in energy (storage) communities, particularly for their potential to address challenges faced by prosumers and the other stakeholders in the solar residential market in the Netherlands. However, it is evident that the current policy landscape and market design present significant barriers to developing viable business cases for residential energy communities in the Netherlands.The scientific literature does not offer a comprehensive solution to this issue. Consequently, policymakers, who are currently examining community energy systems, lack the necessary insights to establish supportive policies.

This gap highlights the urgent need to develop robust business cases specifically tailored to this context, along with the corresponding policy recommendations to facilitate their realization. Additionally, there is a pressing need for the assessment of practical business cases. Such a comprehensive approach is crucial for fully harnessing the potential of community energy storage in the Dutch residential sector, especially in light of the phase-out of the NEM scheme.

2.5. Knowledge Gap

Based on the identified problem statement and the conducted literature review, the following knowledge gaps are identified:

- The literature review highlights the potential fit of central community storage for addressing net congestion and prosumer profitability. However, there is a notable absence of detailed technical integration strategies for CES, which simultaneously consider the associated financial frameworks
- Subsequently, there is a deficiency in financial and technical assessments regarding the impact of central community storage on residential communities in The Netherlands.
- While policymakers are working on supportive frameworks for energy communities, there is a critical need for specific, detailed guidance. This includes identifying effective policy instruments and government interventions conducive to supporting community energy storage, with insights into their optimal structure and scale.
- Finally, this uncertainty leads to a gap in developing practically implementable and economically sustainable tailored business cases, that are sensitive to local regulations and market dynamics.

With the gradual phase-out of the NEM scheme, the market is being compelled to seek alternative solutions to offset the decline in profitability. This shift is leading towards independent storage, which has already established a clear and well-developed business case, as seen in Belgium and Germany. However, it is unlikely that the market will solely rely on this solution, considering the continuous emergence of more innovative alternatives. Notably, solutions involving individual batteries have limited capacities for both prosumers and DSOs, and their business case is not profitable in The Netherlands, even after the NEM phase out. Community energy storage emerges as a potential alternative. Yet, unlike individual batteries, it faces challenges in developing a concise business case in the residential sector, attributed to its inherent complexity and the range of challenges and opportunities it presents. While some business models are discussed in the literature, they often lack practical application and specificity for Dutch housing communities, struggling to advance beyond pilot projects. These models also fail to fully address the intricacies of energy sharing and billing structure policies.

This research aims to bridge the knowledge gap by proposing solutions for the governance and policy support of central community energy storage in the Dutch solar residential sector. It will contribute to existing literature by offering new insights into the technical challenges and opportunities of central community storage, particularly in improving consumers profitability and alleviating grid congestion in residential areas. This will be done by testing community energy solutions across various Dutch communities and define a system that considers the full spectrum of implications: technically, financially, and regulatory.

A business model tailored for CES and an accompany cost allocation scheme specific to central community storage in the Netherlands will be suggested. Furthermore, recommendations will be provided for policymakers on the necessary adjustments needed to foster community energy formation.

2.5.1. Scientific Relevance and Impact

The relevance and impact of this research are heightened by the current discussions in the Dutch government regarding the net metering phase-out. The Ministry of Economic Affairs and Climate Policy is keen to quantify the effect of the NEM-scheme phase-out on the residential sector and the DSO. Additionally, the DSO, Dutch government, and European Commission are exploring ways to stimulate energy communities and determine the required policies and schemes. This research will significantly contribute to these efforts. Moreover, with new technologies emerging post-NEM-scheme phase-out, there is a pressing need for governance and policy support to guide technology adoption decisions. The insights from this research on the technical challenges and opportunities of central community storage will be invaluable to policymakers, network operators, and other energy service providers in the industry.

Based on the identified knowledge gap, the following main research question arises:

How can centralized community energy storage be implemented to improve the profitability of prosumers and alleviate grid congestion following the NEM-scheme phase out in the solar residential market in the Netherlands?

The answer to this question aims to provide a comprehensive analysis regarding the emergence and potential of CES within the specific context of the solar residential market in the Netherlands, particularly following the complete phase-out of the Net Energy Metering (NEM) scheme, thus after 2030.

The ideal answer will encompass a detailed exploration of the necessary considerations for CES implementation, covering financial, technical, and regulatory facets. This involves a granular examination of battery integration from the consumer perspective and then expanding the scope to include the financial and technical outcomes of this integration. A comprehensive value assessment will be conducted, quantifying the monetary value of the solution and evaluating its wider impact. Additionally, the analysis will identify which policies need revision to effectively incorporate CES. Subsequently, the proposed CES solution will be tested across various cases, each representing distinct community types, to evaluate the business model proposed in real-world scenarios. This will lead to the development of potential business cases that can be leveraged by different market stakeholders to monetize this initiative, thereby capturing its value.

In this question, "implement" is thus defined as the tangible application and integration of CES in a manner that is both viable and beneficial, involving strategic planning, financial strategizing, technical designing, and regulatory navigating.

2.6. Research questions

In order to answer the main research question the following sub-questions are formulated.

Since the presented knowledge gap is broad and describes several disciplines from technical to financial and regulatory. It is important to be able to narrow down the research to stay within the objectives of the research, while maintaining the broad scope for the impact on the industry and society.

Main research question

- How can centralized community energy storage be implemented to improve the profitability of prosumers and alleviate grid congestion following the NEM-scheme phase out in the solar residential market in the Netherlands?

Sub research questions

1. *What is the optimal integration approach and its corresponding business model for CES within the residential communities?*

   Community energy storage applications will be identified, along with their respective potential business models. The optimal application, in terms of prosumer profitability and grid relief, will be selected, and its associated business model will be developed. Furthermore, a practical approach for integration will be proposed to enhance the potential for large-scale emergence. This approach will encompass the definition of key roles and responsibilities of stakeholders within the community and the corresponding allocation of value.

2. *What is the optimal system design topology for community storage within each of the defined communities, and what are the associated limitations?*

   A technical system design topology will be outlined for each of the defined communities. This system design will delve into engineering details to analyze the energy interaction possibilities between consumers and the grid, along with the corresponding financial implications. Finally, the regulatory limitations and market design constraints associated with each system topology will be researched.

3. *How does the chosen CES integration method influence consumer profitability for each of the identified communities?*

   The objective is to evaluate the impact of the selected CES system on consumer profitability. The potential of it will be presented by simulating the interactions between the community, the grid, and the optimal battery system. This optimal interaction will arise from an optimization problem that will be formulated to provide the optimal battery size and its corresponding energy profiles that minimize the total community cost. An energy distribution mechanism will then be presented to evaluate the cost and profitability allocation. The final analysis will quantify the overall financial benefit for consumers, thereby validating the efficacy of the proposed CES solution

4. *How does the chosen CES integration method impact grid congestion for each of the identified communities?*

   The prior question provided the optimal parameters for enhancing consumer profitability. In this question, the effect of that optimal solution on grid congestion will be evaluated. Certain design parameters will be adjusted to address grid congestion, leading to a sub-optimal solution that prioritizes prosumer profitability while considering grid alleviation. The outcomes will be compared to scenarios without CES to ascertain the value added by the CES in alleviating grid congestion.

   Each sub-research question will concentrate on a specific aspect and discipline essential for understanding the implementation of CES. By combining the answers from all four sub-research questions, a comprehensive perspective on this subject will be provided. This approach will encompass and address the regulatory, technical, and economic implications relevant to the matter at hand.

3 Methodology

This section presents the methodology used in this research. Section 3.1 elaborates on the approach adopted to define residential communities, establishing the foundational basis for the later parts of this study. Section 3.2 explains the methodology for selecting the appropriate CES integration method, including a discussion on the business model design tool. Section 3.3 outlines the system design and its evaluation metrics. This begins with the optimization problem's objective and the metrics used for analysis, and concludes with the description of the energy distribution mechanism.

3.1. Defining residential communities

To integrate a storage solution into the residential sector, it's vital to first identify and categorize the communities, facilitating the formation of communities around a storage system. Let's delve into the housing types in The Netherlands. As per CBS data (CBS, 2023) , in the Dutch housing stock, Terrace housing comprises 42.2% of the total, equivalent to 8,125,229 residences. Additionally, 36% represents multi-family housing. Combined, these housing types make up 78% of the total housing stock. These structures are often in close proximity, either vertically (as with multi-family apartments) or horizontally (in the case of terrace housing). This proximity is a pivotal element for central community storage. Importantly, these housing types usually already belong to an administrative community. For rental houses, it might be ownership by a housing cooperative, considering nearly 2.4 million (29%) of Dutch homes are owned by such cooperatives. Alternatively, there's the Vereniging Van Eigenaren (VVE) – the Homeowners' Association. Around 1.8 million Dutch homes are VVE-affiliated, encompassing both rented and purchased houses. VVEs come into being when a project gets partitioned into individual units, leading to the division of the plot into apartment rights and the consequent establishment of a VVE. It oversees collective responsibilities, like upkeep of shared building parts.

The aforementioned institutional communities typically encompass both terrace and multi-family housing. These offer a solid foundation for potential energy communities, aligning with the physical constraints of energy communities and fostering the essential social structures to actualize community energy storage, either through a housing cooperation or a Homeowners' Association (VVE).

This research will thefore focus on these two type of communities and verify wheter CES can be of value for each of the community types and how it can be implemented. In the Netherlands, housing types are categorized by the CBS into five categories: terrace housing, multi-dwelling housing, detached houses, and semi-detached houses. As previously mentioned, terrace housing and multi-dwelling (apartment buildings) housing constitute 78% of the total housing stock. Given their proximity to one another and their common association with a social administrative structure, these housing types are aptly suited for community storage applications.

However, these two housing types differ in their building characteristics and the network topology within the grid. Thus, this research will distinguish between these two community types.

3.1.1. Multidwelling community

Multifamily residential, referred to as "meergezinswoningen" in Dutch and also known as multi-dwelling units (MDU), are defined by CBS as "housing units within a building that also contains other residential or commercial spaces. This includes flats, gallery and porch homes, ground and upper-floor residences..." (CBS, n.d). Their close vertical and horizontal alignment makes these houses ideal for community solutions, offering numerous possibilities for interconnections concerning CES.

The network topology for such communities typically involves multiple MDUs feeded froma single cable that is connected to a low-to-medium voltage transformer on the low voltage side. The primary feeding cable from the transformer enters the building and is subsequently distributed to each residential unit.

When these communities are equipped with PV, the solar panels are placed on the roof of the residential building, and a number of panels from the PV-field is connected separately to each residential unit or the whole PV installation is connected to a collective connection. Due to the limited space of the roofs, especially in high buildings, they generally posses smaller scale systems of 1.2-2 kWp. These small PV systems are generally not suitable for resedential batteries due to their limited generation.

3.1.2. Terrace housing community

Terrace housing, known in Dutch as "Rijtjeswoning," pertains to a single-family residence that forms part of a row, typically composed of at least three adjacent houses. Due to their horizontal layout, these communities are well-suited for CES integration. However, they introduce certain challenges. While DMU communities encapsulate interconnections within a singular building, terrace housing relies on street infrastructure for such connections.

Though terrace housing communities in the Netherlands exhibit a wide variety of designs and layouts, they often share a similar network topology. It's common for multiple housing units to be interconnected, subsequently linking to a low-to-medium voltage transformer.

These type of houses generally posses higher capacity PV-systems, 5 kWp on average, due to the large avilable space space on each roof.

Figure 3.1: Left: MDU community. Right: Terrace housing community.

3.2. Business Model Development

To define the optimal integration method for community storage in each specified community, the application for community energy storage should be presented, based on that the value proposition of the storage system will first be established, followed by an examination of instruments to capture this value. Leading to the development of the suitable business model.

Subsequently, the focus will shift to the technical integration of CES within the grid, including implications for application, with particular attention to grid compatibility and technical design requirements.

Additionally, the financial and regulatory implications associated with each model will be analyzed, emphasizing the billing structure within residential communities and the policy frameworks governing energy communities. Based on this analysis, an integration strategy for each community will be determined, adhering to either the current regulatory framework or incorporating realistic exemptions necessary for a feasible and profitable technical integration strategy for prosumers and grid relief Deviations from existing regulations, deemed essential for these strategies, will be outlined as policy recommendations, assisting in the formulation of new regulations as previously discussed.

The business model will be developed using the morphological approach (Kubli and Puranik, 2023), which is particularly tailored for creating business models in the context of energy communities. This approach builds upon previously established frameworks and synthesizes elements from several well-known business model frameworks. These include the business model triangle, the business model canvas, key business model attributes, front- and back-end business model innovation, and strategies for multi-sided platforms.

This method specifically tailors the dimensions of business models to meet the unique needs and characteristics of energy communities. With five primary dimensions, it employs the morphological box technique. This technique is crucial for integrating various design options across multiple dimensions, resulting in a comprehensive and cohesive business model configuration. This adaptability is especially beneficial for energy communities, which often have diverse objectives and serve multiple functions. The five business model dimensions are the following:

- **Community value proposition:** The set of benefits or value that an intervention provides to the diverse stakeholders within the community.
- **Energy community members:** The involved stakeholders.
- **Key functions:** The main core activities that are executed.
- **Energy value capture:** Monetization mechanisms and instruments to capture the identified value.
- **Network effects:** The potential (indirect) added value and efficiency due to the community formation and growth.

Each of the business model dimensions has a set of design options that enable to configurate the model according to the specific needs of the community, as can be seen in figure 3.2. The chosen application will be subjected to these design options leading to the optimal business model.

Business model dimension	**Energy community design options**					
Community value proposition	Generating renewable energy	Increasing self-consumption	Increasing grid reliability	Reducing energy consumption	Reducing energy costs	Becoming a living lab
Energy community members	Residential prosumers	Large-scale prosumers	Local energy producer	Energy service company	Community platform operator	
Energy value capture	Revenues from energy services	Saving energy costs	Revenue from external services	Community service fee	Data valorization	
Key functions	Facilitating P2P trading	Aggregating energy and flexibility	Managing storage systems	Co-optimizing energies	Coordinating partners	
Network effects	Peer effects & creating a community feeling	Economies of scale and scope	Learning effects	Co-benefits and co-amortization of investments		

Figure 3.2: The Morphological box used for energy community business models development (Kubli and Puranik, 2023)

3.3. CES system design

After specifying the full integration strategy containing the business model and its financial, technical and regulatory constraints, a CES system design will presented. To evaluate the performance of the CES integration method, the optimal system interaction should be modelled, thus the process of energy exchange between the prosumer, the grid and the storage system. This will validate the adaptability of the community storage solution within existing communities.

In order to do so the system design will be configurated from an engineering scale, as in community energy systems, the specificity of the connection method and connection point is crucial for the options of business case formation and congestion relieve. This design will be from the scale of the meterboard to the LV-MV transfomrer.

3.3.1. Optimizing the CES system

In order to test the potential of the system design, an optimization problem will be formulated. The primary objective of this optimization problem is to show the potential value of the optimal community energy storage, having the optimal size and if it was to be controlled by an ideal control methodology. The optimization problem will be formulated and described based on the selected application presented in section 5, thus it will be explained in details in section 6.3.

The optimization problem will be computed for a duration of a year with hourly resolution. It will take into account the initial investment cost, the corresponding WACC, the operation cost of the battery system, the energy prices, the consumption and generation profiles of all the prosumers for that year. Based on this it will maximize the value, or minmize the total electricity cost from the whole community perspective. The yearly optimal value will be assumed to be constant for the lifetime of the storage system to calculate the payback period and the total value of the system. The choice to expand the yearly results over the lifetime will be validated and verified.

The output of the optimization problem will be the optimal battery size, the charging/discharging profile of the battery. The corresponding SOC profile of the battery and the community energy purchase and sale volumes. All these values will be calculated for a duration of a year with an hourly resolution.

3.3.2. Financial evaluation metrics

Modelling the CES solution allows to understand the energy operation in the community and verify whether this can enhance the consumers profitability and alleviate grid congestion. To robustly answer this, both profitability and grid congestion relief must be clearly defined, and the evaluation metrics for them should be determined.

In order to evaluate the proposed solution financially, from the prospective of the prosumer, and quantify the total added value of the storage system of the community , 'Net Value' will be used. The concept of 'Net Value' for a community stands as a measure of the added value brought by the proposed CES when compared to the prevailing status quo, which functions without the benefits of NEM. It's pivotal to differentiate between the profitability experienced by the consumers and the net value. The reason being, depending on the tariff structure, a fraction of this net value might be requisitioned for the operations of the CES.

To comprehensively gauge the net value, multiple parameters will be taken into account:

- Initial Investment: The upfront capital required to implement the proposed solution.
- Payback Period: The duration within which the initial investment is expected to be recouped through the savings or benefits realized by implementing the CES.
- Net Value for Community: This metric specifically quantifies the accumulative annual energy cost savings attributable to the CES when compared to the baseline scenario.

By evaluating these parameters, the financial viability of the CES is holistically assessed, considering both the consumers and investors. This dual-perspective approach ensures a comprehensive understanding of the financial implications and benefits of the CES.

3.3.3. Technical evaluation metrics

This set of metrics evaluates the effectively of the solution for grid relief. Grid congestion relief, in the context of this research, pertains to the capacity of the CES solution to alleviate the pressure on the grid, particularly during peak demand periods. Grid relief through storage systems has two performance indicators, load smoothing or peak shaving. While the intricacies of grid congestion can be complex, this research aims to provide a simplified yet insightful analysis using four pivotal metrics, to measure these two performance indicators:

(a) Yearly Energy Export: This quantifies the total annual energy that the community feeds back into the grid. It serves as an indication of the surplus energy that the community generates but does not consume.
(b) Yearly Energy Import: This represents the total energy procured from the grid by the community on an annual basis. It provides insights into the community's dependency on the external grid, especially during periods when local generation might be insufficient.
(c) Peak Feed-in Power: One of the chief concerns for grid operators is managing peak loads. This metric, hence, denotes the maximum instantaneous power fed from the community to the grid. It offers insights into the potential stresses the community might place on the grid during periods of high local generation.
(d) Peak Consumption Power: Conversely, this metric signifies the maximum instantaneous power drawn by the community from the grid. It provides an understanding of the community's peak demand and the associated pressures on the grid infrastructure.

The parameters will be modelled and tuned using these metrics as indicators, the first two metrics assess the load/generation smoothing performance of the battery, while the metrics **(c)** and **(d)** evaluate its peak shaving capabilities. The final results will then be compared to the reference point. The overarching aim is to ascertain whether the CES can contribute to deferring or even obviating the need for grid reinforcement, especially concerning cable and transformer capacities. In all of the proposed solutions, consumer profitability will be prioritized and the affect on grid congestion will be evaluated as an added advantage, since the main focus of this research is consumers profitability.

3.3.4. Energy Distribution Strategies

The optimization problem will produce an annual profile with hourly resolution, illustrating energy exchanges between the community, including the battery system, and the grid. To determine the distribution of costs and profits among each community member and the battery system, a criterion for energy distribution is needed. Energy will be allocated through an energy flow mechanism, which will be addressed in detail in section 6.4. This mechanism prioritizes flow and efficiency by distributing the required energy each hour equally according to the needs of every household at that hour, in proportion to the load/generation volume of each household. To achieve this distribution, the output of the optimization problem will undergo a decision-making process calculation, providing the energy profile for every household for the entire year. This is especially important when the community's battery partly covers the load or stores excess energy, which complicates how energy and costs are shared.

To manage this distribution effectively, energy distribution criteria are needed, determined through Case-Based Logic, to handle various scenarios and ensure each household's energy needs are met throughout the year. The system aims to generate an hourly energy exchange profile for each household, detailing energy bought from or sold to the grid, shared within the community, or with the battery. This data helps in allocating costs accurately. The calculation uses both individual and aggregated data on energy consumption and generation, as well as battery usage, to adjust for each household's energy flow. Conditional decision-making, based on specific criteria for each hour, ensures that the system can adapt to different energy scenarios, aiming for a balanced and efficient distribution of energy and costs across the community.

4
Data

This chapter details the assumptions and required input data for the optimization problem, as well as the methods used to derive this data. The argumentation for the community case selections is presented in Section 4.1, along with the methodology for deriving household generation and consumption data. Section 4.2 introduces the data used to simulate hourly annual energy prices. Lastly, Section 4.3 discusses the storage system parameters and assumptions.

4.1. Community Profiles

This research examines two distinct community types: Multi-Dwelling Units (MDUs) and Terrace Housing communities. A representative case study will be selected for each community type.

To create representative community samples, data from De Zoncorporatie was used. a company specializing in solar energy for social housing cooperatives. From them a database was obtained containing 15000+ solar residential installations. These are categorized based on community type, either THC or MDU. Moreover they contain the number of panels installed on each address and their corresponding peak power. Based on that the average peak power and number of panels is calculated for an average TH and MDU community. The results are presented in table 4.1, as was discussed priorly, MDU units generally posses smaller PV systems, compared to TH communities.

Community type	Residential units	Solar panels	Peak power
MDU	30	4	400 Wp
THC	20	7	400 Wp

Table 4.1: Community cases

4.1.1. PV generation data

To obtain the hourly pv generation data for the constructed communities, a simulation will be conducted using PV-syst, a project-based software tool tailored for solar energy projects. PV-syst simulates a diverse range of solar energy systems and offers a high degree of flexibility and precision. Each community type will undergo separate simulations. The output will contain only the PV generation of the installed solar systems without considering the load of each house. Additionally, PV-syst can supply real-time data concerning energy exchange with both the grid and the battery system. If the load data is used as input. However, this function will no be used and the net load will be calculated manually.

The simulation process in PV-syst necessitates a detailed and structured input to derive the desired results, the system input is the following:

- Community Samples: Based on the community definitions, representative residential structures are chosen. These are representations of actual residential buildings that portray the energy consumption and generation profiles of the respective communities, defined earlier. The chosen structures are modelled in 3D in AutoCAD. This is followed by the integration of PV panels using the Virtuosolar plug-in, ensuring photovoltaic installations' realistic representation and configuration. The resultant 3D CAD models, inclusive of their photovoltaic elements, are then imported into PV-syst.

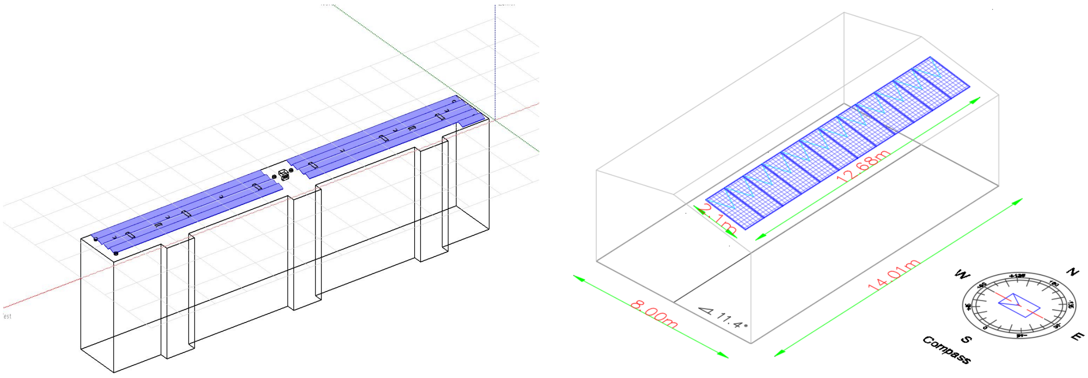

Figure 4.1: Left: MDU community. Right: Terrace housing community.

- PV system configuration: Within PV-syst, the photovoltaic system is technically defined. This includes specifying panel models, their physical arrangement, the type and model of inverters used, system orientation, tilt, and other vital parameters impacting energy yield.

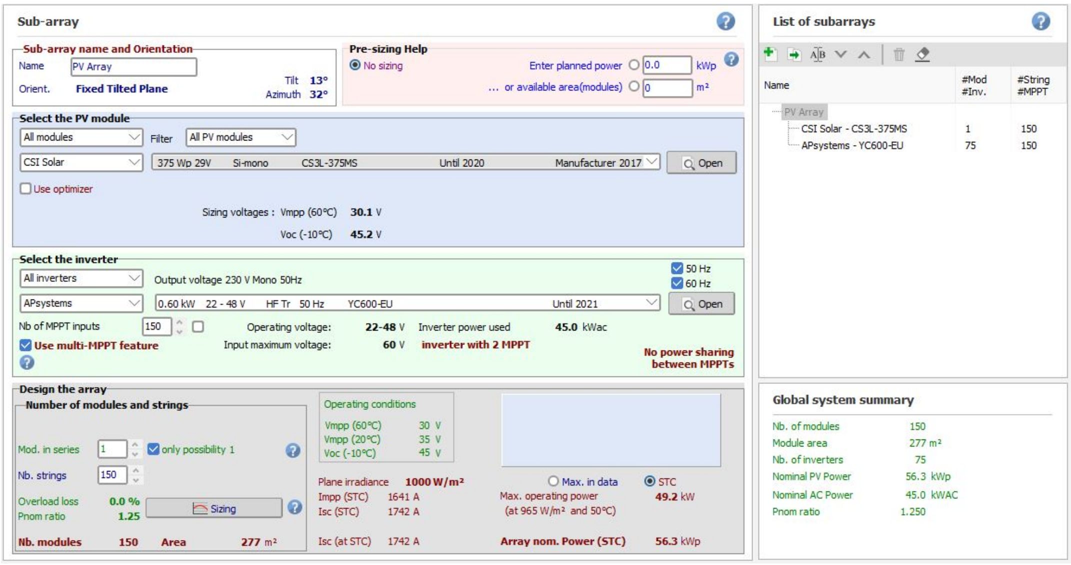

Figure 4.2: PVsyst system configuration input

- Geolocation & Meteorological Data: Each sample is anchored to a specific geographical location to factor in the sun path and irradiance levels. To further enhance simulation accuracy, historical or projected meteorological datasets (e.g., TMY - Typical Meteorological Year) for the location are fed, accounting for solar irradiance, temperature, and other relevant variables.

Based on this the following aggregated community generation is obtained (figure 4.3), for TH and MDU communities.

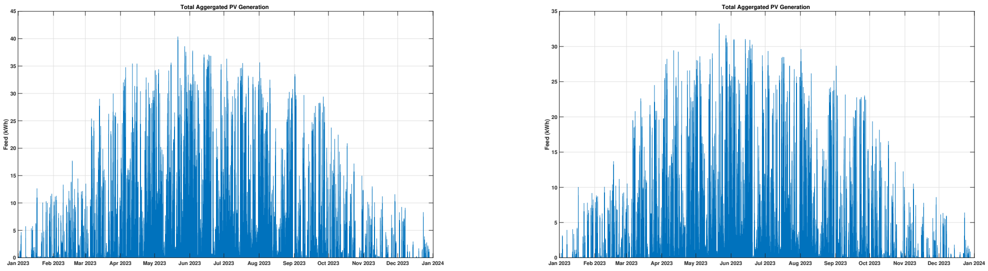

Figure 4.3: Aggregated PV generation Left: TH community. Right: MDU community

4.1.2. Load data

For the analysis of household electricity demand profiles within the community, data from the GridFlex Heeten project was utilized Hayat et al., 2022. This dataset, comprising electricity consumption and gas usage recorded minutely, was collected from August 2018 to August 2020 across 77 households in Heeten, The Netherlands. Each household was equipped with an Energy Management System for minute-by-minute consumption data acquisition. In instances where a battery system was in place, the battery management system was integrated with the EMS. Similarly, households with PV systems had a pulse meter installed, connected to the EMS for independent measurement of the output. All collected data was transmitted to a cloud server via Wi-Fi, enabling participants to monitor their energy usage through a dedicated app. However, as noted by the dataset publishers, the energy data often exhibited gaps due to communication issues, leading to incomplete records for some households. For the purposes of this research, the focus will be on the average power usage of each household, excluding contributions from PV and battery systems, measured for each minute and expressed in kilowatts (kW).

Data processing involved transforming the dataset from minute-by-minute to hourly values, categorized per household. Then data for the full year of 2019 was selected to showcase the seasonal variations in consumption throughout the year. The subsequent step addressed missing data points. Monthly hourly averages were computed by organizing the time-series data into groups based on each month and hour, and calculating the mean for each group. When encountering missing values, denoted as NaNs in the dataset, these were replaced with the corresponding monthly average for that particular hour and month. This method is predicated on the assumption that missing data can be suitably approximated by the typical value for that time period, thus preserving the dataset's continuity and integrity for comprehensive analysis. However, this method had limitations. Some households exhibited entire months without data, rendering the monthly average imputation infeasible. Due to the significant inaccuracies in data points of these households, they were excluded from the analysis. Consequently, the number of viable households for the optimization study was reduced to 51. The average electricity consumption among these remaining households was recorded at 3290 kWh.

In this study, to accurately represent the varying electricity consumption patterns associated with different types of housing, diverse combinations of households from the dataset were selected to correspond to each community.According to Milieucentraal (2022), the average electricity consumption for an apartment (MDU) in The Netherlands with two or more households is 2210 kWh, whereas a single house typically has an average consumption of 3040 kWh. To accurately reflect the average electricity consumption in Dutch communities, a mix of the 51 households was selected to align with these national averages.

For terrace housing communities, a selection of 20 houses resulted in an average consumption of 3003 kWh. However, due to the fact that the village of Heeten mainly includes terrace houses, it was not possible to form a group from the 51 houses that matched the low average consumption of around 2210 kWh for MDUs. Therefore, to simulate the lower consumption characteristic of apartments, 16 of the 30 selected houses in this category were adjusted by reducing their consumption by a factor of 1.5. This adjustment led to an average electricity consumption of 2266 kWh for the MDU community, closely mirroring the expected consumption pattern.

Figures 4.4 and 4.5 display the outcomes of the data processing, showing the annual consumption for every household in each respective community. Figure 4.6 illustrates the aggregated load demand for each community. Figure 4.7 compares the aggregated generation power to the aggregated load power, highlighting the mismatch between the two and the resulting net grid import or export. Lastly, tables 4.2 and 4.3 provide a summary of the consumption and generation profiles by presenting the annual consumption, annual generation, and the net grid-import and export for each of the communities.

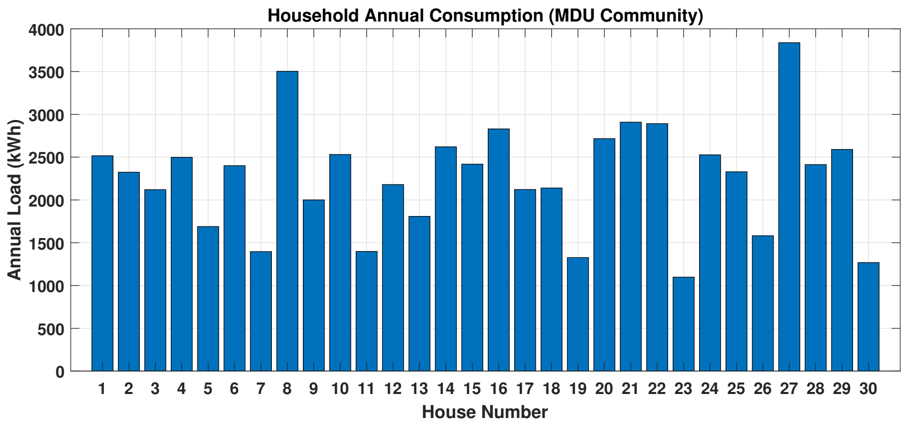

Figure 4.4: MDU household consumption.

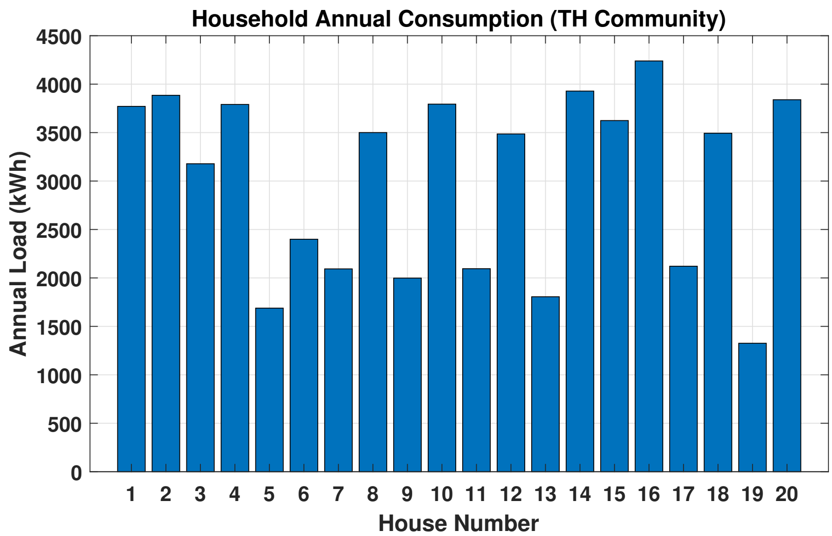

Figure 4.5: TH household consumption.

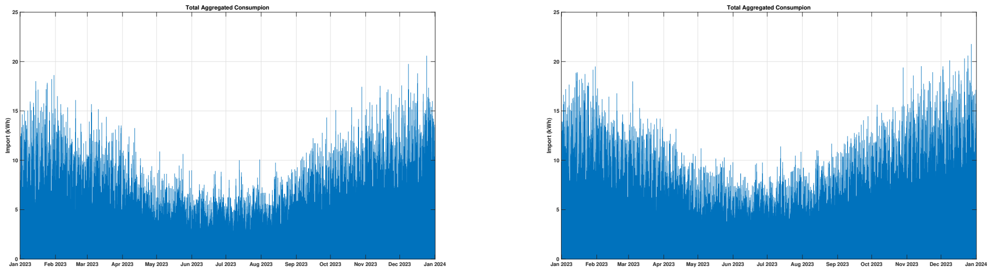

Figure 4.6: Aggregated PV Consumption Left: TH community. Right: MDU community

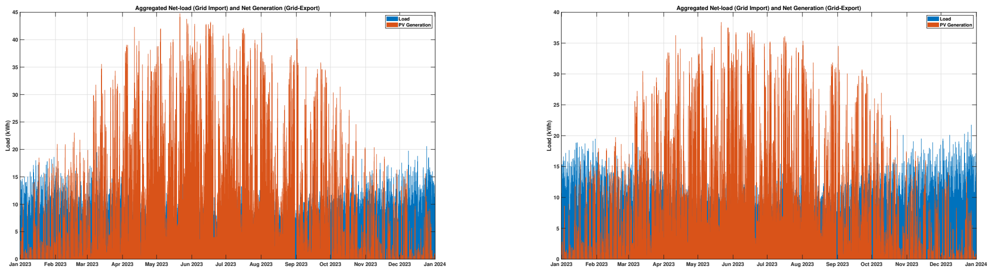

Figure 4.7: Aggregated PV generation Left: TH community. Right: MDU community

Consumption (kWh)	Generation (kWh)	Grid import (kWh)	Grid export (kWh)
67992	43190	48247	23447

Table 4.2: MDU community: Energy load and Generation (annual)

Consumption (kWh)	Generation (kWh)	Grid import (kWh)	Grid export (kWh)
60094	50388	40674	30970

Table 4.3: TH community: Energy load and Generation (annual)

4.2. Energy prices

In order to caclulate the costs within the optimiztion problem a yearly energy price profile is needed. The energy market offers three primary types of contracts, each catering to different consumer preferences in terms of pricing stability and engagement with energy market fluctuations.

1. Firstly, fixed energy contracts provide a high level of predictability and financial stability. In these contracts, the price per unit of energy is set at a fixed rate and remains unchanged throughout the contract term, which can range from one to several years. This type of contract is ideal for those who prefer a consistent energy bill, allowing for straightforward budget planning without the need to worry about market volatility impacting costs.

2. Variable energy contracts, on the other hand, offer a degree of flexibility but with less price security. The rates in these contracts are typically adjusted monthly, reflecting the current trends in the wholesale energy market. This means that while consumers might benefit from price drops, they are also exposed to potential increases. These contracts often don't have a fixed end date, offering the freedom to switch providers without facing penalties. They are well-suited for consumers who are comfortable with some level of uncertainty in their energy bills and are willing to take the risk for potentially lower rates.

3. Lastly, dynamic energy contracts are the most flexible and market-responsive option available. The pricing in these contracts change on an hourly basis, based on real-time market prices. This type of

contract demands a more active approach to energy management from the consumer, who can potentially take advantage of low-price periods but also needs to be prepared for sudden price hikes. Dynamic contracts are ideal for engaged consumers who are adept at monitoring market trends and adjusting their energy usage accordingly to optimize costs. While these type of contracts follow real-time market prices, they are not a live representation of it. As energy service providers might have other profit maximizing strategies to slightly adjust the prices from the exact price.

In this paper, the focus is on simulating dynamic contracts, as they are more effective in illustrating market dynamics and in capturing the relationship between energy demand and financial incentives for consumers. This selection is particularly relevant considering the storage system in question is aimed primarily at enhancing self-consumption within the community and facilitating energy sharing, rather than being utilized for energy arbitrage. Under these conditions, fixed and variable contracts might produce similar outcomes due to the limited price variability within a day. These types of contracts also present a lower risk for the storage owner. However, they offer reduced potential benefits due to the narrower price spread. Consequently, an analysis centered on dynamic contracts is considered more suitable for the objectives of the paper.

A significant challenge in choice is the absence of publicly available data on hourly prices for dynamic contracts over an entire year. To overcome this limitation, an approximate hourly price portfolio for a year will be approximated by combining monthly averages from consumer payment data obtained from CBS and day a-head prices, since dynamic pricing are a rough representation of the real-time wholesale market. This method provides a practical solution to simulate the market dynamics under dynamic contract scenarios more comprehensively and realistically

In order to accurately reflect the prices consumers are exposed to under a dynamic contract, the day-ahead market prices will first be converted from euros per megawatt-hour (€/MWh) to euros per kilowatt-hour (€/kWh). Following this conversion, the prices will be adjusted to include the energy tax of €0.1525 per kWh. It is important to note that in dynamic contracts, even in instances of negative market prices, consumers are still liable for the energy tax, potentially resulting in a net positive price. Should this adjusted price (original price plus energy tax) be positive, the consumer is effectively purchasing energy and must therefore pay Value Added Tax (VAT) at the rate of 21%. Conversely, if the price, inclusive of the energy tax, remains negative, the consumer is not technically buying energy. Instead, they are being compensated for energy usage and are thus exempt from paying VAT. According to this transactional method, the day-ahead market data was processed. To ensure these prices align with the monthly averages as reported by CBS data, a normalization and averaging process will be applied. This process will adjust the hourly prices to match the CBS-reported monthly averages, thereby providing a realistic representation of the actual costs incurred by consumers each hour under a dynamic contract.

For the feed-in tariff, post NEM-scheme a constant value is considered. This value is calculated by averaging the rates from the 10 largest energy service providers in 2023, resulting in a feed-in tariff of €0.074 per kWh (Overstappen.nl, 2023). Fees for grid export, as previously discussed and imposed by some energy providers, will not be considered in this analysis, as they are not yet a widespread measure adopted by all energy providers.

The data processing results in the following hourly profile, figure 4.8 shows the original day ahead prices and the obtained consumer prices. Figure 4.9 shows the variations within a day for two chosen days, one in a summer day and one in a winter day.

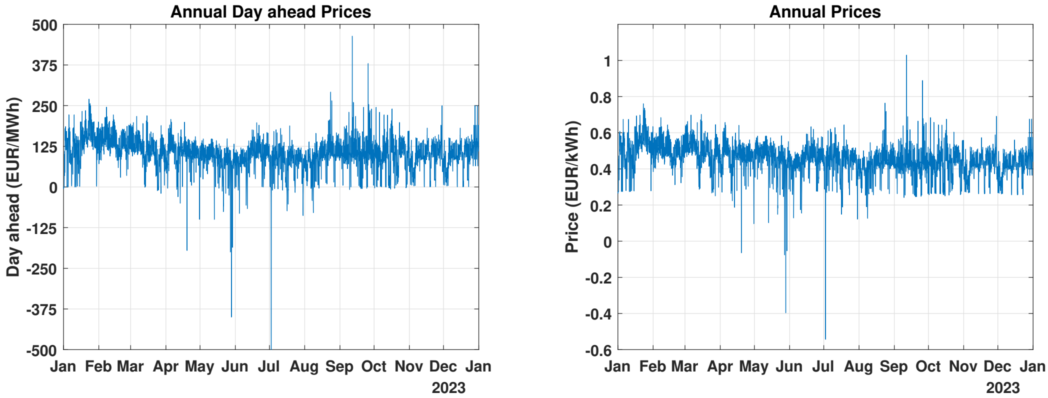

Figure 4.8: Left: day ahead prices. Right: Calculated consumer prices

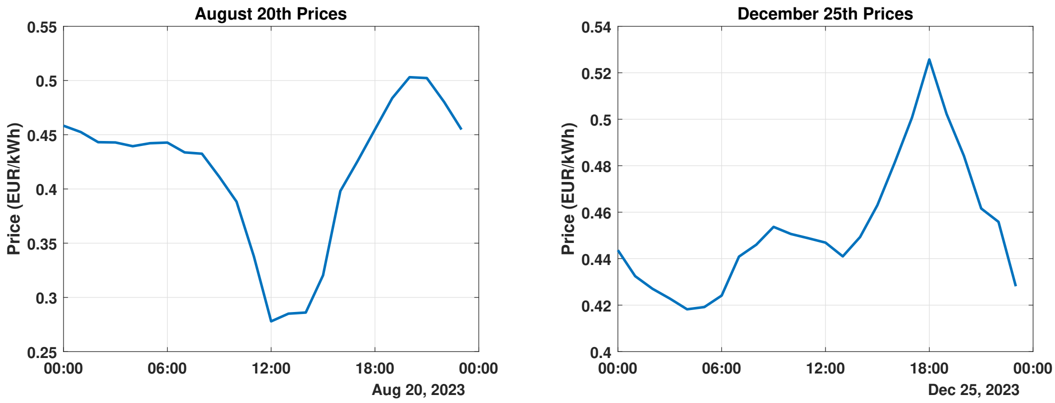

Figure 4.9: Price fluctuations within a day. Left: summer-day Right: winter day

4.3. Community Storage Parameters

4.3.1. Price

This section outlines the assumed battery parameters. As reported by CE Delft in 2021, while various large-scale battery technologies are available on the market, Lithium-ion remains the leading choice due to its superior efficiency, cost, and energy density ratio. The cost for community-scale Li-ion battery systems was found to range from 251 to 438 €/kWh, averaging around 307 €/kWh. Although there is a possibility that prices have decreased since the study in 2021, this research will proceed with a conservative capacity price assumption of 400 €/kWh to include installation costs and initial grid connection fee.

The storage system operational cost can be divided into two categories, Fixed Operations and Maintenance (FOM) and variable operation costs. According to W.Cole and A.Karmakar, 2023, which conducted an extensive literature review of general battery systems assumptions. A value of 0 for VOM can be chosen. For FOM there are more differences in literature. One of the primary differences in the level of FOM was whether augmentation or performance maintenance were included in the cost. Lower FOM numbers typically include only minmal functional maintenance while higher FOM numbers include some capacity additions or replacements to address degradation. A high value assume that the FOM cost will counteract degradation such that the system will be able to perform at rated capacity throughout its lifetime according to W.Cole and A.Karmakar, 2023. In their paper they concluded that a FOM value of 2.5% of the $/kW capacity cost is a good representation. However, due to high maintenance personnel cost and yearly grid tarifs which are either fixed or a variable an FOM value of 2.5% of inital cost will be assumed. Porivding a much higher cost, making the assumption generally more conservative. A value of 2.5% of the initial cost was also used in a recent paper regarding storage systems specifically in the Netherlands CE-Delft, 2023.

Finally, a Weighted Average Cost of Capital (WACC) of 8% will be used for the financial calculations. Although this figure is relatively high, it is justified by the inherent uncertainties associated with storage system investments, as outlined in CE-Delft, 2021. Storage systems, not being widespread, face challenges related to policies and business cases. Therefore, in their research, a WACC of 8% is recommended to account for these uncertainties.

4.3.2. Technical specifications

The market currently offers a variety of large-scale batteries suited for residential intraday storage applications. Required capacities range from 60 to 250 kWh, and products from multiple manufacturers are available.

Such batteries typically have a low C-rate, with charging/discharging capabilities ranging approximately between 0.3 and 0.5 C. However, newer models from leading manufacturers like Alfen and Huawei offer higher C-rates. For instance, the Luna2000-1/200kWh models achieve C-rates of up to 1C. For this research, a more conservative C-rate of 0.8 is selected. Additionally, these modern batteries feature a high depth of discharge (DOD); therefore, a State of Charge (SOC) between 10% and 90% will be assumed. While this may affect the battery's lifespan, a high FOM value has been chosen to account for necessary replacements due to degradation, leading to an assumed battery lifetime of 15 years. A round-trip efficiency of 90% is used, which is a reasonable representation based on prior research (W.Cole and A.Karmakar, 2023). Another critical aspect of large-scale storage systems is their spatial integration in residential areas. Drawing from previous projects in the Netherlands, an average physical space requirement of 7.5m2 is assumed for systems up to 0.4 MWh, inclusive of all supporting electrical components (W.Cole and A.Karmakar, 2023). This is comparable to the space needed for a typical low-voltage to medium-voltage (LV-MV) station found in every resedential neighbourhood.

The final battery parameters are detailed below, and Figure 4.10 illustrates the Huawei Luna2000-1/200kWh battery, as a reference to the scale of batteries proposed in this research.

Technology	Li-ion
Capacity (kWh)	50-250
Investment Price (€/kWh)	400
WACC	8.0%
FOM	2.5%
C-rate	0.8
SOC max	90%
SOC min	10%
Lifetime (Years)	15
Dimensions	1810-2135-1200 (mm)

Table 4.4: Battery parameters

Figure 4.10: Huawei luna2000-1/200kwh

5

Community storage integration

This chapter outlines the approach to community storage integration. Section 5.1 introduces potential applications for centralized community storage, along with the community value proposition for each application. Section 5.2 discusses the general implications encountered in these applications and the regulations creating this implications Finally, Section 5.4 details the final business model design, elaborating on each dimension, and concludes with the business case design.

5.1. CES applications

Based on the reviewed literature, there are a large number of applications for CES that derive from the multiple business models possible. In The Netherlands there are however two primary applications for community batteries, with energy trading being the most significant, due to it having a clear well-defined business case. Energy trading here is defined as participating at the ancillary markets, thus trading energy outside the community instead of Intra-trading. However, the study on large-scale grid batteries concluded that the business case is only marginally profitable in some markets (CE-Delft, 2023). The profitable potential is estimated at 1 to 2 GW by 2030. For community batteries, this means that the FCR market and aFRR market are profitable. These markets, however, are expected to become quickly saturated due to the ongoing development of large-scale grid battery projects, which have lower normalized costs. The APX day-ahead market and the imbalance market are not expected to be profitable under the current policy around 2030. However, the same study also found that under current policies, home and community batteries would increase peak loads on the network if they operate in energy trading in the day-ahead market (CE-Delft, 2023). This is attributed to their collective activation during periods of low energy market prices, as was also pointed out by other researchers (Verkaik, 2022). While the study highlighted that community batteries have the potential to alleviate grid congestion by up to 30%, this was obtained with congestion relief being the primary purpose of the storage system and the researchers did not identify a viable business case for this objective.

An alternative application, is energy intra-trading , or sharing within the community. This application of the community battery resembles the 'storing of excess solar energy' case of the home battery. Households owning solar panels can supply their excess energy to the community battery, after which their neighbors or they themselves can use this energy at a different time. In theory, households without solar panels also benefit from the solar energy of their neighbors with panels. This is an example of an energy community and/or energy cooperative, where households exchange energy among themselves.

5.1.1. Value propsition of Energy sharing

Energy sharing presents a threefold community value proposition in the post NEM-scheme context, this value is represented by increasing-self consumption, and reducing energy costs and increasing gird reliability according to the business model design options methodology. Specifically the following community values can be defined :

1. For prosumers, it offers an opportunity to derive greater value from their excess produced PV energy

compared to standard feed-in tariffs set by energy suppliers. Additionally, it spares them from incurring charges imposed by energy supplier for feeding energy back into the grid.

2. For consumers, energy sharing allows them to avoid purchasing energy directly from traditional suppliers by instead buying shared energy from their neighbors, which could potentially be more cost-effective.

3. For DSOs, this process of energy sharing can aid in alleviating grid congestion by diminishing demand peaks on cables and transformers, thereby enhancing the capacity utilization of the infrastructure.

The consumer-prosumer value proposition is relatively straightforward to define and quantify, although there are various methods to capture it within the confines of different ownership models and the regulatory, technical, and market boundaries. However, the grid relief value proposition is more challenging to define and convert into a revenue stream for the battery owner. This difficulty largely stems from the complexities involved in monetizing the value of congestion relief.

5.1.2. Grid relief value

The value proposition of congestion relief within the framework of energy sharing can be captured through two primary instruments considering the Dutch grid frameowrks: Grid-transport tariffs and congestion management. These tools offer strategic ways to harness the benefits of alleviating grid congestion.

Grid-transport tariffs

Currently the electricity demand of households is increasingly variable. While the average peak load of household appliances stands at 1 kW, peak demand can surge up to 11 kW at times, for example during electric vehicle (EV) charging. With grid-transport tariffs consumer pay a fixed cost for the maximum capacity contracted. This high capacity is utilised for a small period of times during peaks, and for the majority of the time it is not used, therefore they are paying a high price for this peaks power moments. This inefficient capacity utilisation results in an expensive tariff structure, since each household is being considered an independent point of connection. Storage systems can function as a buffer enabling peak shaving of load and generation, therefor lowering the peaks observed by the grid operator. Community energy storage adds an extra functionality as community sharing can effectively smooth demand peaks across the community by aligning local generation with consumption. This alignment reduces the burden on grid tariffs and prevents local congestion. It means that a consumer doesn't need to contract for very high capacities to cover peak demands, which occur infrequently. Instead, they are only limited by the technical capacity of their connection, as long as the total community power remains within its contracted maximum boundaries. With Behind the Meter (BTM) solutions consumers can directly capture this value through preventing capacity enhancement, for example a consumer with a small connection of 3x25A pays a fixed capacity tariff of € 322,83 according to Stedin. after electricfiyng the house for electric coocking and EV, his contracted capacity might not be enough. Enhanving his connection to a 3x35A results in a yearly capacity tariff of € 1614,14. Through the flexibility provided by community storage and energy sharing this enhancement can be postponed resulting with a yearly net value of € 1.380,31.

However, With Front of the Meter solution, where the battery is placed at the utility side, this is not directly possible. As tough energy sharing peaks will still occur within the community boundaries, however they will be smoothed only relative to the grid outside the community. This is not directly possible to capture. Currently it is only possible under what is called Group transport agreement (Groeps-transportovereenkomst) or Groeps-TO. The Group transport agreement (Groeps-TO) is an arrangement where network operators and groups of connected users agree on transport capacity (GTV). This system replaces individual transport rights with collective agreements, allowing individuals to potentially use more capacity than their original allocation, as long as the group stays within its collective limit. The Group-TO enhances network efficiency by encouraging staggered usage among users, which optimizes the overall network capacity. The total power allocated to a group is not a mere sum of individual capacities, considering the network operator's assumptions about the simultaneous use of the network. This approach offers more certainty and coordinated use of the network for the network operators.

An estimation of monetary value of this measure is hard to present as it is recently introduced and does not have a large number of use-cases (Netbeheer-Nederland, 2023).

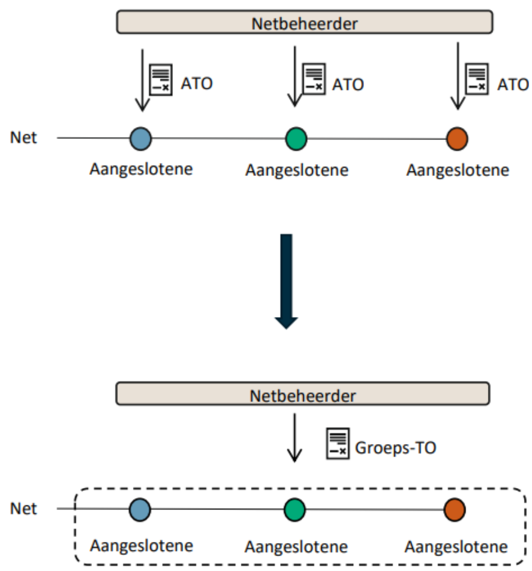

Figure 5.1: Individual capacity contracts compared to group capacity contracts (Netbeheer-Nederland, 2023)

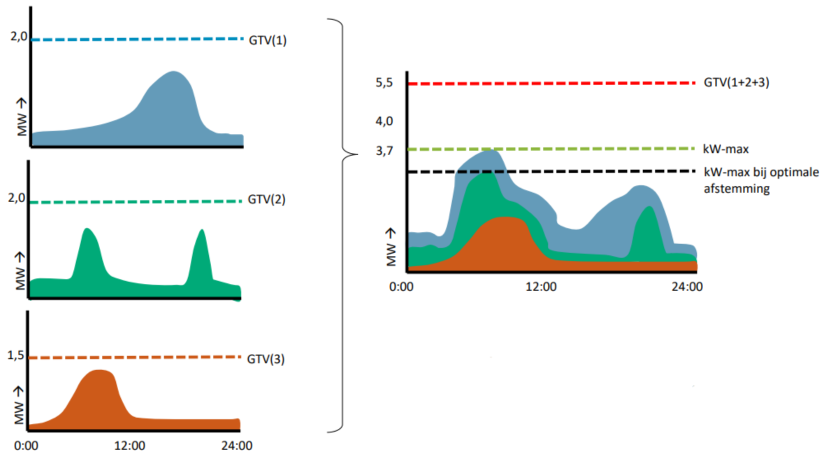

Figure 5.2: Power capacity reudction in Groeps-TO)(Netbeheer-Nederland, 2023)

Other tariff designs that improve the value proposition for grid-transport costs reduction are also being studied. Network operators are currently developing a new tariff system tailored for small consumers, aimed at replacing the existing capacity tariff (CE-Delft, 2023). Among the various alternatives being explored, the most promising is 'Time-of-Use Pricing.' This model adjusts network tariffs based on the time of usage, encouraging households to consume or feed electricity back into the grid when the combined cost of electricity and network tariffs is at its lowest. This system ensures lower network tariffs for many hours of the day, but they will increase during periods of high anticipated network load. With introduction of such schemes, the value proposition of grid congestion through grid tariffs, will have more potential.

Congestion management:

The network operator is responsible for funding congestion management as a means to prevent or resolve network congestion. The decision to either continue with congestion management or to upgrade the network hinges on the associated costs.

Currently, congestion management is not implemented in low-voltage networks. Nevertheless, the established financial limit for congestion management is 1.02 €/MWh-transport capacity/year for medium voltage. Should congestion management extend to low voltage, the cost parameters might vary. This cap represents the maximum expenditure permissible for the network operator. CE Delft has calculated that for a low-voltage (LV) network segment of 500 kW, akin to the capacity of an MS/LS station, the total budget would be: 1.02 €/MWh/year * 0.5 MW * 8,760 hours/year, equating to 4,500 €/year (CE-Delft, 2023).

Moreover, network operators are implementing the 'Reinforce Unless Decision Framework', a strategy that may replace or coexist with congestion management (TenneT, 2018). This approach mandates that each investment in the electricity infrastructure be appraised against alternatives, such as deploying batteries, effectively acting as a permanent form of congestion management. This consideration is reflected in the annual costs to the network operator per kW for a new house, based on a simultaneous capacity of per kW. The annual expenditure for the network operator is estimated to be between € 20 to € 30 per kW per house for network investments in a residential setting (CE-Delft, 2023). Thus, this figure can be perceived as the value threshold for congestion management within this new framework.

5.2. Implications of CES for energy sharing

Energy sharing offers a multifaceted value proposition. However, capturing the full spectrum of benefits associated with CES energy sharing introduces a range of complexities - social, technical, and regulatory - that must be addressed to develop a viable business case. This case should also contribute to managing grid congestion and leverage it effectively. For a profitable energy sharing community system to function optimally, it requires the collaborative efforts of the community, energy providers, and community members and other stakeholders involvement. This collaboration entails establishing frameworks for accurate energy flow monitoring and regulation, taking into account transport costs and grid infrastructure usage, which are currently lacking.The Gridflex pilot project serves as a significant example of such collaborative efforts. Its aim was to manage grid usage and costs through partnerships between the community, service providers, and DSOs. This project underscored the necessity for clear regulations on community energy trading and agreements on grid use with DSOs.

Therefore, it's crucial to thoroughly explore the implications of a CES energy sharing system. This exploration is necessary to design a system that effectively captures the presented values. To present a successful business case, these implications must be addressed, either through policy adjustments or innovative designs that circumvent these challenges.

5.2.1. Storage connection topology

There is a nuanced distinction in the connection topology of storage systems observed in literature. These systems can be positioned either behind the meter, at the customer's premises, or in front of the meter, on the utility side. Storage systems placed in front of the meter either support the electrical grid's operation by providing flexibility services, including frequency regulation, voltage control, peak shaving, and load leveling. Additionally, they may participate in electricity markets for energy arbitrage, including day-ahead, intraday, or balancing markets. Such systems are often under the ownership and operation of independent power producers or various energy service companies. As discussed, In the context of The Netherlands, the ancillary markets already present a favorable business case for largeer-scale (40-200 MWh batteries on these markets. Conversely, residential batteries are typically installed behind the meter. The primary purpose of these behind-the-meter (BTM) storage systems is to manage electricity costs, promote energy independence, offer backup power, and enhance self-consumption of onsite-generated power, particularly from renewable sources like solar panels. Advantages of BTM systems include demand charge reduction, resilience during power outages, participation in net metering programs, and shifting energy use to different times.

Large-scale storage systems are commonly front-of-the-meter (FTM) implementations. However, in certain cases, large-scale systems are placed BTM for industrial applications or at solar/wind parks in congestion areas. Here, their role is to moderate peak production or reduce consumption peaks, discharging during peak demands for industrial installations. For the case of centralized community storage, community battery cases in literature are primarily placed FTM. Decentralized aggregated community storage is an example of BTM community storage applications. However, centralized storage BTM poses challenges, as a large-scale BTM storage connection to a number of household within a community is not straightforward, and a unified meter for an entire community is generally nonexistent, unlike industrial storage systems.

Nevertheless, regardless of whether the placement is FTM or BTM, integrating central storage systems within community energy frameworks encounters technical and regulatory challenges. This aspect is often overlooked in literature, as identified earlier as a knowledge gap. Each integration strategies has a limited set of options for business cases. As it is constrained by existing regulations, billing mechanisms, market restrictions, and grid requirements that are dependent on the point of connection within the grid. For instance, with decentralized storage, current billing methodologies and regulations do not readily facilitate energy sharing within a community, such as through aggregation. Similarly, for centralized storage, distributed charging and discharging are not adequately supported by current tariff designs and grid requirements.

Stored energy value

To provide a realistic assessment the economics of the storage system, the stored energy value should be identified and quantified, being an important metrics in this assessment. The stored energy value is dependent on the connection topology of the storage system and subject to all regulation and taxes associated with it.

The tariff decomposition presented in Appendix A.3 reveals that the base energy cost constitutes only about 40% of the total price paid by consumers. The remaining portion comprises fixed supply costs, grid-transport tariffs, and combined charges for energy tax, and VAT. Therefore, the actual value of stored energy encompasses not just the base energy price but also these additional costs that a customer incurs to access a kWh of stored energy. Based on this the transport tariffs VAT and energy taxes are collectively considered as energy access costs.

Cost Item	**Electricity price (€/kWh)**
Base energy price	€0,1959
Transport tarif	€0,0287
Energy tax	€0,1260
VAT	€0,0736
Total	**€0,4242**

Table 5.1: Cost overview of Electricity

Consequently, the value of each stored kWh can be defined as the equivalent cost of purchasing that kWh from the grid at time t instead of discharging it from the battery. For instance, if a consumer would pay €0.42 to consume a kWh from the grid at time t, the actual value of that kWh of energy at the same time is also €0.42. This principle also applies to solar-generated energy; its actual value, when the generation is equal to or less than consumption, is the price a consumer would pay for grid energy if the solar energy were unavailable, which would again be €0.42. If the generation exceeds the consumption, the value is dependent on the feed-in scheme and is equal to the feed-in tariff, which is probably lower.

Given that a substantial part of the kWh price is attributed to access costs, the actual value of stored energy greatly exceeds the base energy price, underscoring the significant value added by energy storage. The net value of stored energy is thus calculated as the actual value of the stored kWh at time t minus the access costs for that kWh and the value of any excess PV energy used to charge the battery at time $t-1$. Without a battery, the value of excess PV energy would correspond to the feed-in tariff. The formula is represented as:

$$\textit{Net value} = \textit{Actual Value} - \textit{Access Costs} - \textit{Excess PV Value} \tag{5.1}$$

In scenarios where a residential battery is installed behind the meter without the NEM scheme, and electric losses are disregarded, access costs are nullified since the consumer does not incur taxes or network fees to access the energy stored in their battery. The net value is calculated according to the following equation:

$$\textit{Net value} = 0.4242 - 0.00 - 0.074 = 0.3502\text{€}/\text{kWh} \tag{5.2}$$

Double Taxation

As previously discussed, front-of-the-meter (FTM) solutions are the most straightforward method for implementing community energy storage within. However, a bottleneck with this implementation when used for energy sharing is the access cost, mainly including taxation. Because a community battery gets its own grid connection, it is also subject to taxation. In the case of a small capacity connection, even double taxation applies: both when charging and discharging.

Under the current billing structure, when FTM solutions are employed, the energy stored by the prosumer is transferred through their meter to the grid, and then to the battery for charging. When accessing the stored energy, the battery, located on the grid side from the prosumer's perspective, discharges the energy. Administratively, this is treated as selling energy back to the prosumer, similar to purchasing it from the grid. The financial disadvantages for prosumers become apparent when examining the net value of stored energy, defined earlier:

$$Net\ value\_FTM = €0.4242\,(including\ access\ costs) - Access\ Costs - €0.074 \tag{5.3}$$

$$Net\ value\_FTM = Base\ Load\ Energy\ Price - €0.074 \tag{5.4}$$

From this equation, it is evident that the margin for net value , or the price spread, is significantly smaller for community batteries placed FTM compared to behind-the-meter placed residential batteries placement from the consumer's prospective. Moreover, from the battery owner perspective, when the customer , thus sells his excess PV to the battery, charging the battery, this taxation is also going to occur as the battery system is going to effectively purchase the energy from the prosumer, paying the taxes.

This problem of double taxation is according to one of the main obstacles for storage business cases (CE-Delft, 2023). The problem from the battery owner perspective, of large scales systems used for energy trading was identified by governmental bodies in The Netherlands which adjusted the law making large scale batteries, either community or grid, free from paying taxes when charging and discharging the batteries. Improving their margins, or spread prices and leveraging the business case. Starting from 2022 a law was passed that includes the supply of electricity to an organizational unit operating an energy storage facility, is not subject to taxation. For an organizational unit operating an energy storage facility to be free from double taxation, it must have a large capacity connection higher than (>3x80A) (Tweede-Kamer, 2019). However, double energy taxation still exists for energy storage with a small capacity connection (<3x80A), such as residential connections, as can be seen in fig 5.3.

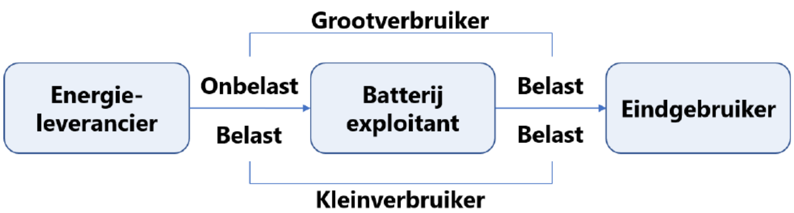

Figure 5.3: Double taxation scheme for large and small capacity consumers (Witteveen Bos, 2023).

The Ministry of Finance has therefore recently conducted research into possible solutions to avoid this double energy taxation for consumers, specifically testing for feasibility. The conclusion of the research is that abolishing double taxation for small consumption is very challenging (Energy-Storage-NL, 2023). The taxation exemption provides an advantage for community batteries over residential batteries. However when the community batteries discharges, and sells the stored energy, consumers are still eligible for this taxation. Providing a disadvantage for community batteries compared to residential batteries from the prosumers perspective.

5.2.2. New policies

As highlighted in previous sections, energy sharing through community storage has the potential to both alleviate stress on the grid and increase profitability for prosumers. Despite its potential, this concept is not yet fully supported by existing regulations and billing frameworks. However, there is a growing recognition of the importance of community energy systems in government policies. For instance, the concept of energy sharing is detailed in the Energy Act, which is based on European frameworks (CE-Delft, 2023).

Furthermore, the government intends to regulate energy sharing within energy communities, between buildings, and among active consumers more specifically. This involves the (potentially free) exchange of electricity between two connections within the same imbalance period (15-minute blocks), as an alternative to regular electricity consumption. The specifics of energy sharing are currently being refined in an amendment to the Electricity Directive, part of the ongoing negotiations in Brussels regarding the Electricity Market Design package. Once established, these directives will be implemented into Dutch law and regulations. However, several issues, including the feasibility of collecting energy tax and/or tax losses with a zero tariff, the interaction with 'net metering', and technical implementation, are still being discussed. These talks are ongoing between the Ministry of Economic Affairs and Climate and the Ministry of Finance, along with market parties. It is expected that the regulations for sharing electricity will be more specifically defined by around January 1, 2025 (Ministry of EZK, 2023a, 2023d).

The outcomes of these discussions are already apparent, with several measures, previously mentioned, such as alternative transport tariffs, Group-TO, tax exemption, and Reinforce Unless, currently being developed. The aim of these initiatives is to stimulate flexibility within the energy systems which will enhance the opportunities for community energy sharing.

5.3. Business model developement

After outlining the community value proposition of energy sharing within the community, and emphasizing the ways it can be captured, along with potential challenges it might face and the policies addressing these issues, the final business model will be constructed using the morphological approach and applied to the residential community case.

Community Value proposition

As previously discussed, the main community value propositions are increasing self-consumption, reducing energy costs and Increasing grid reliability. Specifically, this value is expressed in offering higher prices for excess energy sold back to the grid, increasing self-consumption through intra-day storage to reduce total energy costs, and contributing to grid relief through load and generation peak-shaving and smoothing.

Energy community members

The primary stakeholders and community members are the residential prosumers. The system setup and configuration may be further facilitated by an Energy Service Company (ESCO) or a community platform operator. Within the residential context, housing cooperatives or Home Owners' Associations play a pivotal role in community formation. They can act as the community platform operator or community manager. These entities can facilitate and initiate cooperation with ESCOs, or they might handle the collective investment and include it as part of a service package provided to the tenants. The presence of an administrative body through the housing cooperative is crucial, as it can unify the community's collective objectives or manage and distribute the value obtained.

Energy value capture

The energy capture mechanism can be categorized into two main areas: (1) Capturing the value of prosumer savings, and (2) Capturing the value of grid relief.

The capture of consumer profitability value will occur through energy sharing. This can be achieved either by selling excess energy to neighbors or to the battery system for a compensation higher than the standard feed-in tariff, or by purchasing community energy sourced from neighbors or the battery system. This revenue stream can be structured in various ways, employing different billing mechanisms. One method is kWh tariffing, similar to traditional electricity systems. This can also involve live pricing in an intra-community market that provides price signals based on the energy provider's pricing. This ensures that the pricing incentivizes consumers to share within the community rather than importing from or exporting outside the grid. Alternatively, energy flow optimization can be used, where consumer behavior is not the primary consideration, but rather the system operator distributes energy based on flow and efficiency optimization. In this scenario, prosumers pay a fixed monthly cost as a community contribution, paid in advance. At year's end, the community operator calculates actual energy consumption and reconciles this with the paid advance amount. If the actual costs are lower than the advance amount, a partial refund is issued. Conversely, if the annual costs exceed the advance amount, an additional payment is required.

This system mirrors traditional electricity billing and is familiar in residential communities. It's also a common method for billing operational service costs and other energy expenses, like collective heating via a central boiler or collective solar installations. An advantage of this system is that it typically doesn't require prosumers to alter their consumption behavior, potentially increasing social acceptance of the system.

The other essential value proposition to consider is grid relief or grid services. The community contributes to the grid by reducing the load on cables and transformers, thereby resolving or preventing grid congestion. This contribution has the potential to postpone the need for grid enhancements. Prosumers can potentially capture this value directly with behind-the-meter (BTM) solutions, providing additional capacity room without enlarging the contracted capacity connection. Another way to capture this value is through a Groeps-TO contract, as was discussed earlier for front-of-the-meter (FTM) implementations. However, the monetary value of this approach can be difficult to estimate.

Furthermore, grid relief can also be leveraged by the community operator through congestion management or the Reinforce Unless Decision Framework, particularly if the community energy storage (CES) can offer significant value in terms of grid relief.

Key functions

The primary functions in an energy community are those of the community operator and the community manager. In residential communities, the community manager, often a housing cooperative, is tasked with coordinating partners. Their initial focus is on forming a community of residential prosumers and consumers, followed by engaging external partners. This includes appointing community operators, such as an Energy Service Company (ESCO), and managing the interests and stakes of external entities in the energy community, like the Distribution System Operator (DSO) and energy providers.

The community operator and manager jointly bear the responsibility for establishing both the physical and financial infrastructure necessary to facilitate peer-to-peer (P2P) energy trading within the community. Additionally, the process of energy trading and aggregation needs to be efficiently managed and optimized to ensure seamless operation with the storage system. These technical processes and key functions are undertaken by the community operator.

Network effects

Within residential communities, housing cooperatives can leverage their existing tenant networks to offer community energy solutions as part of the service packages provided to tenants, thus enhancing network effects. This approach significantly simplifies community formation compared to starting from scratch without an intermediary facilitator. The 'peer and community effect' aspect of network effect design underscores that innovations spread not only due to their functionality and cost benefits but also through social processes influencing innovation diffusion. People often get inspired by their peers, leading them to view a product differently solely for this reason.

Furthermore, these network effects will be more pronounced in terms of operation through economies of scale and scope. In larger communities, energy sharing opens up more opportunities for matching generation and consumption, thereby enhancing system operation and efficiency. Establishing larger networks improves energy flow in energy trading, potentially leading to smaller storage requirements and reduced total costs. In addition, the fixed costs associated with community systems are distributed across a larger population in bigger communities. On the supply side, larger-scale energy communities are more likely to access new revenue streams (e.g., participating in national balancing power markets, in addition to peak shaving services) because many energy/flexibility applications require a minimum size requirement to participate.

5.3.1. Business case design

The final business model design, according to the Morphological approach be seen in the Morphological box presented in table 5.2

Business Model Dimension	Energy Community Design Options
Community value proposition	Reducing energy costs Increasing selfconsumption Increasing grid reliability
Energy community members	Residential prosumers Community platform operator Energy service company
Energy value capture	Revenues from energy services Saving energy costs Community service fee Revenue from external services
Key functions	Managing storage systems Co-optimizing energies Aggregating energy and flexibility Facilitating P2P trading Coordinating partners
Network effects	Peer effects & creating a community feeling Economies of scale and scope Co-benefits and co-amortization of investments

Table 5.2: Morphological approach business model dimensions

In this research, the community structure is assumed as follows: the members are residential consumers and prosumers, with the housing cooperative acting as the community manager and an ESCO facilitating the technical system. The community manager bears the responsibility for the initial investment. Homeowners compensate for their benefits through individual contributions, which can vary. These contributions could be in the form of variable monthly payments based on usage or a fixed cost integrated into the existing service package. Additionally, the community manager, in collaboration with the ESCO, provides congestion management to the grid, creating an additional method for value capture.

This model is prevalent in the residential sector's energy interventions, where housing cooperatives manage collective energy-saving initiatives through external ESCOs. These cooperatives then redistribute the costs and benefits to homeowners using the billing structures outlined.

6

CES design and modelling

In the previous section, the chosen business model and its corresponding business case description were presented. This section focuses on explaining the system topology required to actualize the business model, addressing both technical and financial implications. It also introduces the methodology used to evaluate the system's operation. Section 6.1 details the physical system topology for each community, along with the associated assumptions. Section 6.2 outlines the approach for sizing the storage system. Section 6.3 presents the optimization problem designed to model the ideal operation of the proposed system. Finally, Section 6.4 describes how the optimal energy profiles for community operation are distributed within the community. .

6.1. Physical system topology

As highlighted in the previous chapter, energy sharing presents a substantial business case in terms of consumer profitability and congestion relief. However, implementing this model through central community energy storage on a front-of-the-meter (FTM) basis subjects it to comprehensive regulations and market conditions, such as access costs and taxation.

Consequently, it can be argued that for the purpose of energy trading, behind-the-meter (BTM) storage is more advantageous, even within the context of community storage. This approach, while less straightforward, offers benefits with a central storage unit. Despite limited discussion in the reviewed literature, **BTM** integration is entirely viable, particularly for **Multi-dwelling communities**. The close proximity of residential units in these communities, both horizontally and vertically, simplifies the logistics of implementing BTM storage solutions through an external micro-grid independent of the central grid, connecting all the houses to each other and to the storage system. The feasibility of setting up cable infrastructure serving this micro-grid, contained within the building, facilitates the creation or modification of infrastructure independently of the grid.

For Terrace Housing communities, implementing BTM storage presents additional challenges as it a similar micro-grid setup requires adjustments to street infrastructure. From a practical, financial, and regulatory standpoint, it becomes challenging to propose such a solution. Therefore, an **FTM** system design will be further explored for **terrace housing communities**.

6.1.1. Multi-dwelling community

As previously discussed, the central storage unit will be implemented BTM, enabling it to "supply" energy to prosumers without having to "sell" that energy over the meter. This approach overcomes the storage access costs as previously defined, making the system independent of the DSO and energy service providers.

This means that one central storage unit will be distributed and connected to all participating prosumers without using the current grid infrastructure. To explain this micro-grid implementation, a comprehensive layout of the interconnection between the grid and prosumer is necessary.

Starting from the prosumer side, energy flows in and out of the residential unit through the distribution board, as illustrated in Figure 6.1. Here, every load is connected to a specific load group. The main electricity inflow from the grid enters the house through the main power supply, passing through the energy meter. As shown in Figure 6.1, when PV panels are installed in a house, an additional distribution group is added, but with PV generation flowing into the panel of the house rather than a load drawing power from the main connection. This setup ensures that load distribution grids are supplied with PV power without needing to access power from the main connection. This implies that no power will pass through the energy meter and nothing will be registered. If the generated power exceeds the load, the excess energy will flow through the main connection to the grid, passing the bi-directional energy meter, and will be registered for transactions either through net energy metering (NEM) or a feed-in tariff (post-NEM).

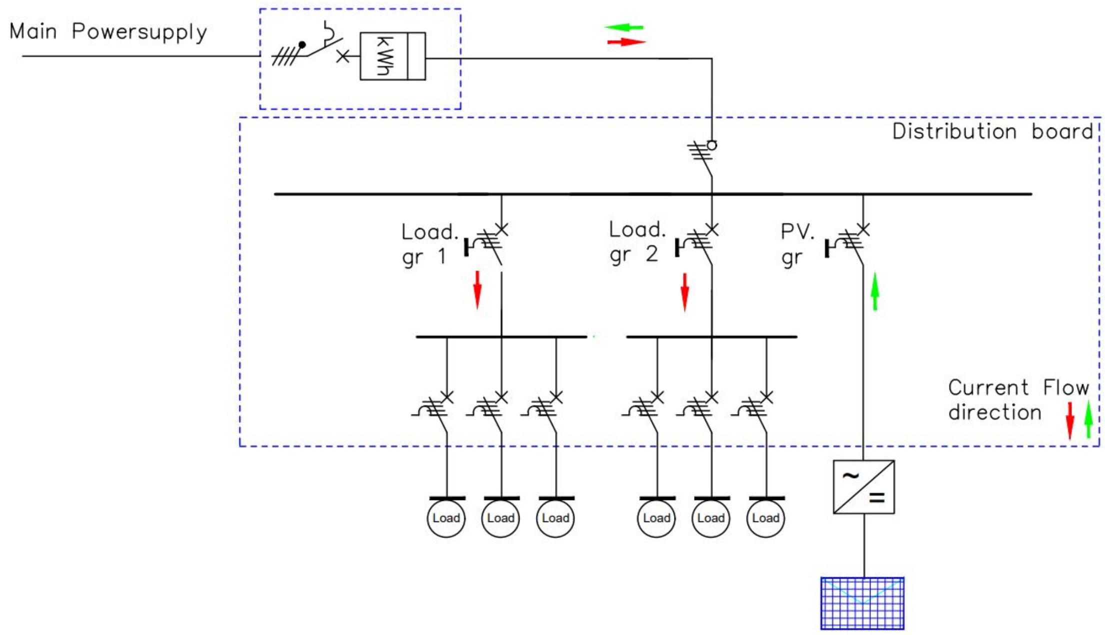

Figure 6.1: Single line diagram of a distribution board of a residential unit (MDU/TH)

Integrating a battery behind the meter means that this storage unit will connect to an additional bidirectional distribution group within the distribution board. Consequently, energy can flow to and from the residential unit without undergoing transactional processes, as it does not pass through the transactional meter, as indicated in Figure 6.2.

Exiting the distribution panel, the newly added AC group connects through new cables to the Aggregated Connection Unit (ACU). This unit serves as the interconnection point between each separate residential unit in the community and the battery. Through the new cables and the ACU, all houses within the community will be directly connected, allowing energy sharing and aggregation with full freedom of transaction, independent of the DSO and energy companies' tariff structures. To monitor the energy flow in and out of each house, an energy meter will be installed between the battery and the consumer side, facilitating cost allocation based on each household's contribution and usage.

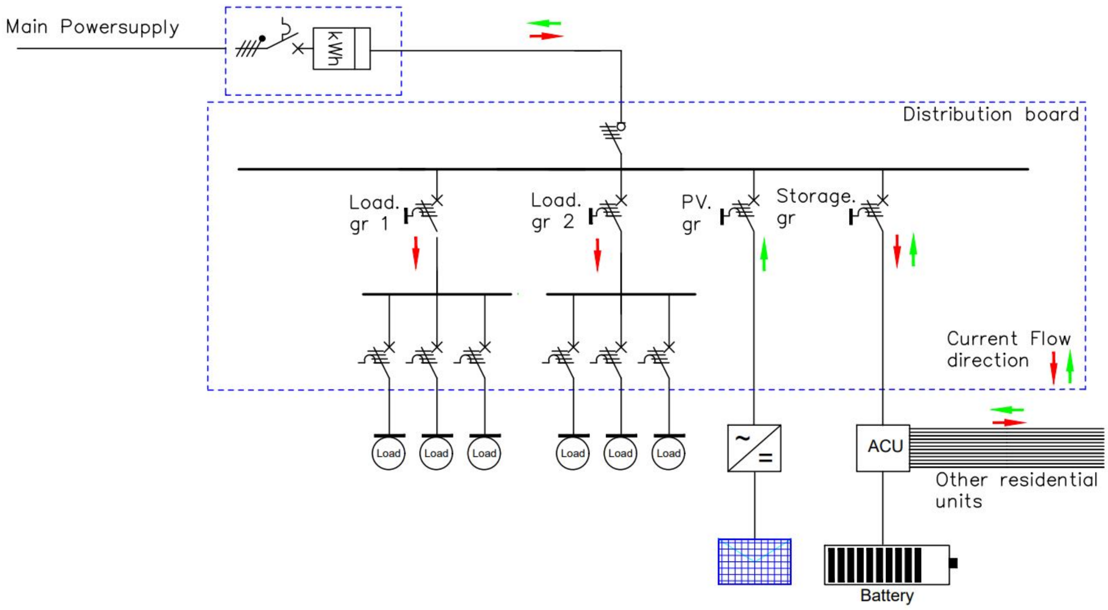

Figure 6.2: Single line diagram of a distribution board of a residential unit (MDU/TH) connected to CES

The ACU aggregates the community's energy inflow and outflow, supplying the net charge to the central storage unit for either charging (positive charge) or discharging. This topology connects distributed prosumers through the ACU, enabling micro-grid formation through direct external connectivity. The community can thus share energy generation and demand smoothing, even without a storage system. This interconnection significantly enhances system efficiency, reduces net losses, and directly contributes to grid relief through load and generation smoothing.

On the other side of the ACU, the central storage unit is connected through its own grid connection from which energy flows in the battery, charging it at moments of low prices and low demand, to supply it later to the community. Figure 6.3 illustrates the complete system topology.

This connection topology effectively creates a residential micro-grid, fully independent of the DSO and energy providers, granting the community complete control over its energy transactions.

For Multi-Dwelling Unit (MDU) communities, this topology is particularly feasible since the cables are encapsulated within the residential building. Establishing this new infrastructure is possible, and the associated costs are considerable. This connection type is also currently employed when installing PV systems on residential building roofs. As previously discussed, a large PV field is installed on the building's roof, with a number of panels separately connected to each residential unit through its cable from the roof to the distribution board. Figure 6.3 illustrates the a simplified system overview for an MDU building.

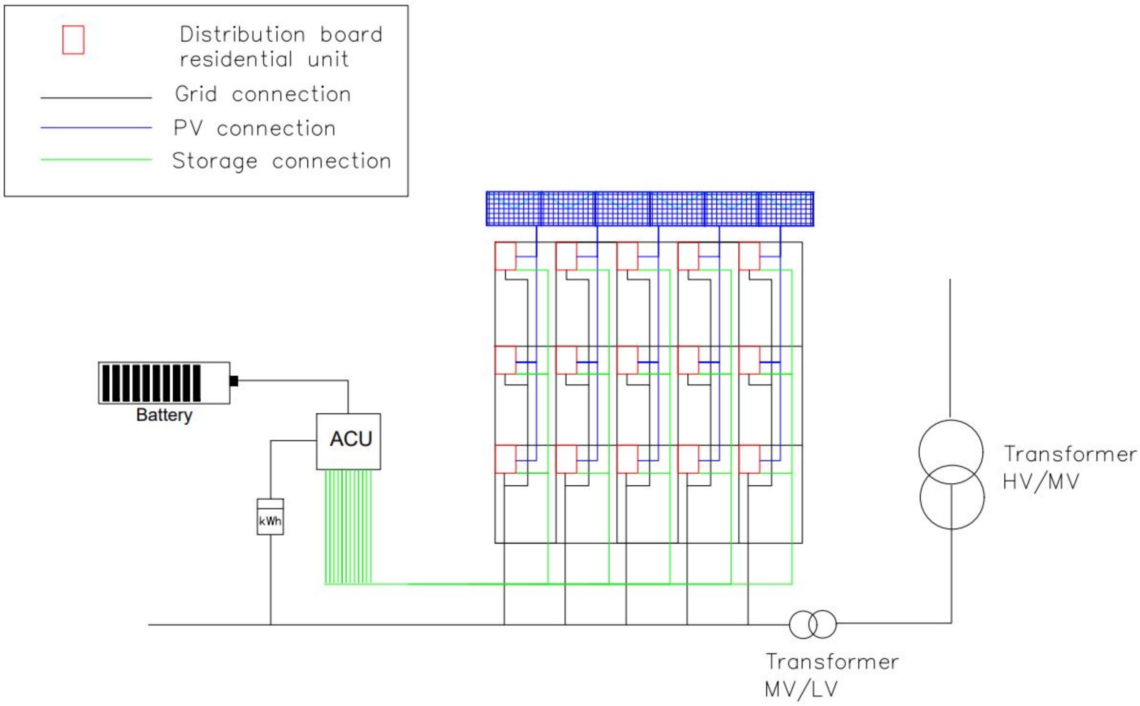

Figure 6.3: Schematic of the CES connection topolgy within the LV-grid of MDU communities

General assumptions

The proposed implementation of the Community Energy Storage system offers significant benefits to residential units. It enables prosumers to discharge energy without incurring access costs, and also allows them to reduce their peak power consumption. This reduction makes them eligible for lower capacity contracts, enabling cost savings without the need to formally establish a community, as the created physical micro-grid effectively does this. While this integration appears practical and profitable, its actual realization presents several challenges.

If the community storage is utilized as a service for charging and discharging energy, this energy will not be considered as sold energy, and therefore, the discharged energy will not be subject to taxation since it doesn't pass through the main electricity meter. This approach is similar to the current implementation with solar panels, where the PV panels supply energy to consumers, who may not be the owners of the PV system, through an independent infrastructure connected to the prosumer. This supplied PV energy is also not subject to any taxation. This arrangement enables prosumers to buy less energy, pay fewer taxes, and reduce their power capacity.

The community battery system operates on a similar principle but differs in that it connects several consumers within the community to form a micro-grid. Presently, there are no specific policies covering the formation of such micro-grids, which do not fall under the supervision of traditional grid operators. Additionally, there are no regulations specifying how these micro-grids can be connected to the regular grid, and it remains uncertain whether the proposed mechanism will be accepted by various stakeholders, who might oppose it. According to Liander Liander, n.d, it is not allowed to connect two consumers directly to each other behind the meter without involving an energy service provider or an ESCO. However, in the designed case, the ESCO contracted by the housing cooperation will furfill this function, making this implementation potentially possible.

Based on this topology the following assumptions are in place with regards to the costs:

- When the battery system is charged from prosumers, it is exempt from charges such as taxation or grid tariffs, similair to charging a home battery.

- Discharging energy from the battery to consumers is free of access costs, as the energy is directly supplied without being administratively sold.
- Charging the battery from the grid incurs taxation on this energy. Despite new regulations stipulating tax exemption for charging, this energy will not be sold to the end customer, who would otherwise be taxed. In this scenario, the battery is treated as the end consumer and is therefore subject to taxation.

6.1.2. Terrace Housing community

For terrace housing communities implementing the pruposed BTM system poses greater challenges due to the spacing of the houses. The new cables connecting the ACU to the multiple households would need to be laid underground. This process is not only relatively costly but also more demanding in terms of obtaining necessary permits. And therefore quite infeasible. For this type of community a traditional FTM connection will be used. This means that the system proposed for this community is very realistic and has to deal with all the priory presented implications.

The layout for an FTM community energy system is very straightforward, as can be seen in Figure 6.4. The battery is placed on the LV-grid at central connection point that feeds in all the residential units within the community behind the LV-MV transformer. With this the central battery is connected to the units within the community through the existing grid thus subjecting it to grid-transport tariffs. The battery charges though excess energy of prosumers that is fed into the grid, while it discharges by selling this energy back to the prosumers.

Moreover, since the battery has its own connection to the grid, it can also charge at times with low energy prices, to discharge at times of higher prices ensuring that the prosumers can benefit from the storage capacities, and alleviating the consumption peaks on the transformer since they will be resolved locally on the LV-grid.

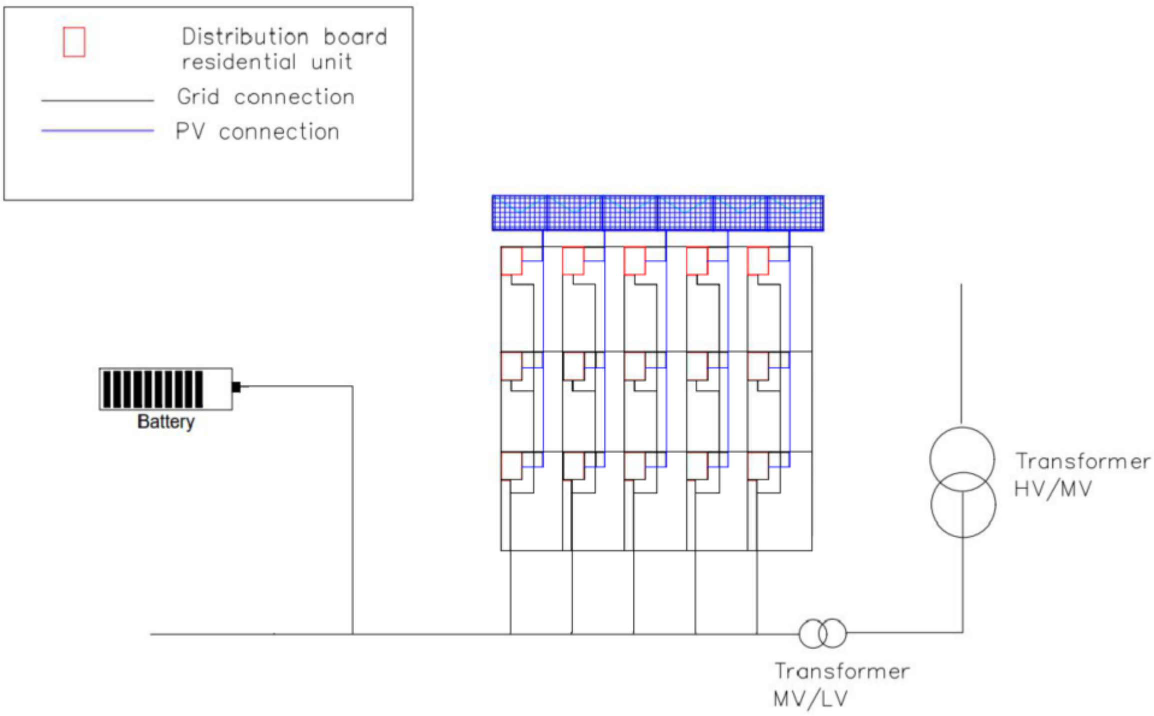

Figure 6.4: Schematic of the CES connection topolgy within the LV-grid of TH communities

General assumptions

The proposed FTM system is designed in compliance with current regulations and policies. Consequently, it will subject prosumers to access costs each time they wish to access the stored energy. However, these access costs do not include individual transport tariff. This can be overlooked since the community can operate a Group Transport Order (Groeps-TO), allowing it to share the transport tariff based on the community's capacity. In this framework, since the battery effectively sells energy to its consumers, it will be exempt from taxes when charging, particularly when receiving energy from prosumers or from the grid.

Additionally, an alternative scenario will be explored. This scenario assumes an idealized community collaboration, where the community is taxed and tariffed as a collective entity rather than on an individual house basis. This model is similar to the Groeps-TO setup with grid tariffs and aligns with the likely outcomes being developed under the European and Dutch frameworks previously discussed.

6.2. Storage sizing methodology

The control strategy for both presented storage system is straightforward: it will be used for energy sharing through intra-day storage, storing excess energy generated during the day for use at night either to the same customer or to the community. However, the variability of sunlight hours throughout the seasons in The Netherlands presents a significant challenge for battery sizing.

Sizing the battery based on summer sunlight hours means that during much of the winter, the battery will have a low State of Charge (SOC) and its capacity will be underutilized. Conversely, sizing it based on winter sunlight hours will result in the battery failing to capture the majority of summer generation, negatively impacting the business case and offering minimal grid relief, as summer peak loads will still occur.Therefore, a detailed control methodology is essential for any chosen battery size, aiming to maximize utilization and, consequently, profitability and potential grid relief.

As observed in the data discussed in Section 4 for the MDU community, a battery arbitrarily sized at 100 kWh, focused on purchasing maximum excess energy from the community and redistributing it, does not fully utilize the battery's capabilities. During winter, the battery is mostly empty, while in sunnier seasons, it is frequently full. Over a full year, the battery remains empty on 65% of the days and fully charged on only 6%. Moreover, it fails to reduce the community load's generation peaks. With or without this battery, the grid-export peak due to PV-generation remains 33.26 kW, occurring on a sunny day, the 20th of May, as per the studied data. The energy stored in the battery for the first six months of the year is illustrated in Figure 6.5.

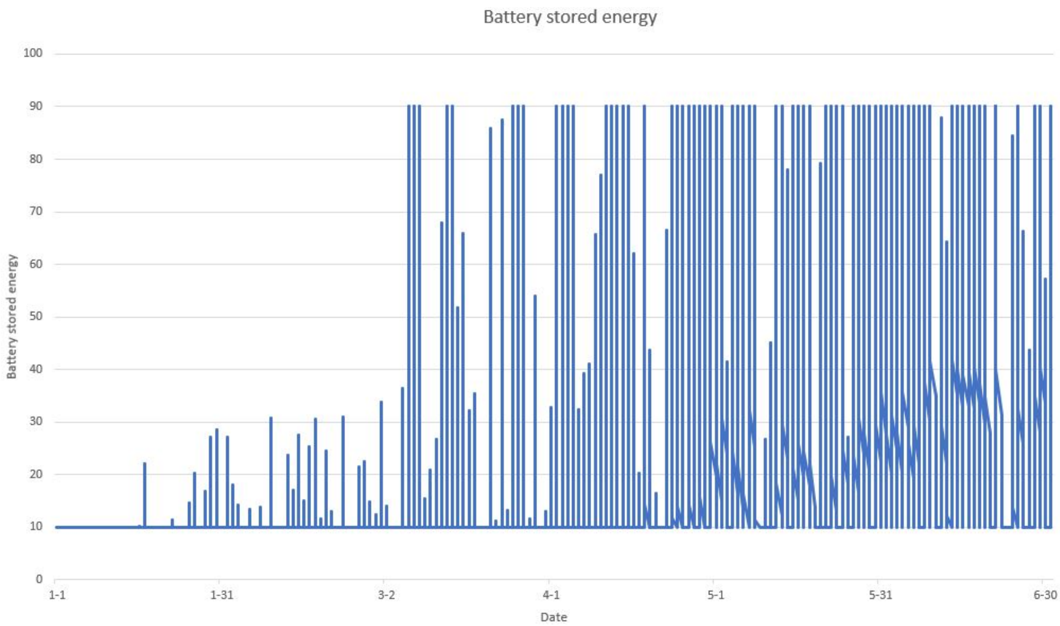

Figure 6.5: Energy stored in a 100 kWh battery for the first six months of the year

Given this variation in seasonal generation, it is evident that any battery size will be inefficient if charged solely from the PV generation and will not significantly contribute to peak grid relief. It is thus beneficial to utilize the battery for energy arbitrage from the grid during low-generation seasons, and adjust charging behavior to smooth the overall load and reduce feed-in peaks. This implies that when the battery is not fully charged, it can be charged from the grid at low prices and discharged to consumers later at higher prices, creating a microgrid that can be powered either by the grid or PV generation and distributed among all prosumers.

Given the complexities of battery sizing and energy interaction mechanisms resulting from the control strategy, it is not feasible to justify them analytically. Therefore, formulating an optimization problem becomes necessary to determine the optimal battery size and energy operation for a given community. This will demonstrate the potential of an ideal storage system with an optimal energy management system.

6.3. Optimization problem

The optimization problem formulated to assess the feasibility of Community Energy Storage in the identified communities aims to demonstrate the potential value of an optimally sized community energy storage system, assuming it is managed by an ideal control methodology. This optimization will be applied to both integration topologies for the communities under consideration.

In this scenario, the focus is on the total community rather than on the battery owner or individual consumers. Based on this topology, the objective function will be designed to maximize the net value of the CES for the whole community, and minimize the Community Energy Cost (CEC). Below the equation for the yearly community energy cost:

$$\textit{Annual CEC} = \textit{Annual Energy Purchase Cost} - \textit{Annual Energy Sale Cost} \tag{6.1}$$

The problem to be solved is then the following:

$$\textbf{Maximize} \quad \sum_{t=1}^{T} (CEC_{\,without\ CES} - CEC_{\,with\ CES}) - \textit{Cost of Battery Investment} \tag{6.2}$$

This equation provides the maximum ratio of added monetary value attributed to the CES over the system's lifetime relative to the initial battery investment. The decision variables are thereby the capacity of the battery, the amount and time of energy traded between the prosumer, battery and grid.

Some manipulations will be done to this objective function before solving the full problem.

First since, the Community electricity energy cost without CES is a constant over the time period and does not contain any decision variables. it will be removed from the objective function. Moreover, since there is no data to represent the full period of the battery life time, and simulating such data will have great uncertainty as it is dependent on so many external factor. The cost of battery cost will be normalized to the yearly cost of the investment over the life time of the battery. And T the time period of the problem will represent one year.

$$\textbf{Minimize} \quad \sum_{t=1}^{T} (\mathrm{CEC}_{with\ CES}) + \text{Annual Cost of Battery Investment} \tag{6.3}$$

The Cost of battery investment is represented by the following equation:

$$\textit{Cost of Battery Investment} = \textit{Battery capacity}(kWh) \times \textit{capacity cost}(€/kWh) \tag{6.4}$$

The annual cost of battery investment will be the cost divided by the lifetime of the battery. The WACC of the investment will be considered in a later stage.

As can be seen the cost of battery investment is dependent on the battery capacity which a decision variable in this optimization function, however other decision variables are also dependent on the battery capacity as input, namely the yearly community energy cost. Since a large battery will enable more storage capacity and a lower energy purchased from the grid. which will make the optimization problem difficult to solve linearly. The optimization problem will therefor be solved in two steps. First the community energy cost will be minimzed for a large specified range of battery capacities.

$$\textbf{Minimize} \quad \sum_{t=1}^{T} \textit{Annual Community Energy cost} \tag{6.5}$$

This will provide the optimal energy operation profiles for each of the specified battery capacities. The net electricity cost to be minimized is then represented in the following objective function:

$$\textbf{Minimize} \quad \sum_{c_B=1}^{C_{Bn}} \textit{Annual CEC}(C_{B_n}) + \text{Cost of Battery Investment}\,(C_{\mathrm{B}_n}) \tag{6.6}$$

With yearly community energy costs and battery investment costs , both specified for each battery capacity $c_B \in \{c_{B1}, c_{B1}, \ldots, C_{Bn}\}$ [kWh]

The full optimization problem then becomes

$$\textbf{Minimize} \sum_{t=1}^{T} \left(\lambda_{buy}^{t} \cdot P_{buy,grid}^{t}(C_B) - \lambda_{sell}^{t} \cdot P_{sell,grid}^{t}(C_B) \right) + C_B \times B_{cost} \tag{6.7}$$

Where:

- T: Number of hours
- $P_{buy,grid}^{t}$: Electricity purchased from the grid by the community at time $t \in \{1, 2, \ldots, T\}$ [kWh]
- $P_{sell,grid}^{t}$: Electricity sold to the grid by the community at time $t \in \{1, 2, \ldots, T\}$ [kWh]
- E_{comm}^{t}: Aggregated community load demand at time $t \in \{1, 2, \ldots, T\}$ [kWh]
- P_{PV}^{t}: Aggregated solar generation at time $t \in \{1, 2, \ldots, T\}$ [kWh]
- C_B: Battery capacity $c_B \in \{c_{B1}, c_{B1}, \ldots, C_{Bn}\}$ [kWh]
- P_{char}^{t}: Electricity charged to the battery at time $t \in \{1, 2, \ldots, T\}$ [kWh]
- P_{dis}^{t}: Electricity discharged from the battery at time $t \in \{1, 2, \ldots, T\}$ [kWh]
- η_{Bat}: Battery charging/discharging efficiency
- E_{bat}^{t}: Electricity stored in the battery at time $t \in \{1, 2, \ldots, T\}$ [kWh]
- λ_{buy}^{t}: Price for buying electricity from the grid at time $t \in \{1, 2, \ldots, T\}$ [€/kWh]
- λ_{sell}^{t}: Price for selling electricity to the grid at time $t \in \{1, 2, \ldots, T\}$ [€/kWh]
- $P_{buy,grid}^{max}$: Maximum power that can be drawn from the grid [kW]
- $P_{sell,grid}^{max}$: Maximum power that can be fed into to the grid [kW]
- $P_{bat,max}$: Maximum power that can be charged/discharged to the battery [kW]
- $E_{bat,max}$: Maximum energy that can be stored in the battery [kWh]
- SOC_{min}: Minimum State of Charge of the battery
- SOC_{max}: Maximum State of Charge of the battery
- SOC_{init}: Initial State of Charge of the battery

Decision Variables:

1. **Battery State of Charge Limits:**
   This constraint ensures that the electricity stored in the battery at any time t stays within the minimum and maximum state of charge limits, scaled by the battery capacity C_B.

$$SOC_{min} \times C_B \leq E_{bat}^{t} \leq SOC_{max} \times C_B$$

2. **Battery Charging Power Limits:**
Limits the power charged to the battery at any time t to not exceed the maximum battery charging power.
$$0 \leq P^t_{char} \leq P_{bat,max}$$

3. **Battery Discharging Power Limits:**
Restricts the power discharged from the battery at any time t to be within the maximum discharging capacity.
$$0 \leq P^t_{dis} \leq P_{bat,max}$$

4. **Grid Selling Power Limits:**
Ensures that the power sold to the grid at any time t does not exceed the maximum allowable selling power. $P^{max}_{sell,grid}$, can further be adjusted for peak shaving.
$$0 \leq P^t_{sell,grid} \leq P_{sell,grid,max}$$

5. **Grid Buying Power Limits:**
Ensures that the power bought from the grid at any time t does not exceed the maximum allowable buying power. $P^{max}_{buy,grid}$, can further be adjusted for peak shaving.
$$0 \leq P^t_{buy,grid} \leq P_{buy,grid,max}$$

6. **Battery Capacity Decision Variable:**
Represents the decision variable for the battery capacity, chosen from a predefined set of possible capacities.
$$C_B \in \{C_{B_1}, C_{B_2}, \ldots, C_{B_n}\}$$

Constraints:

1. **Energy Balance of the System:**
This constraint ensures that the net electricity sold to or purchased from the grid at any time t is balanced by the difference between PV generation, community demand, battery charging, and discharging.
$$P^t_{sell,grid} - P^t_{buy,grid} = P^t_{PV} - E^t_{comm} - P^t_{char} + P^t_{dis}$$

2. **Initial Battery State of Charge:**
Sets the initial state of charge of the battery, considering the initial capacity, charging efficiency, and discharging.
$$E^1_{bat} = C_B \times SOC_{init} + (\eta_{Bat} \times P^1_{char}) - \left(\frac{P^1_{dis}}{\eta_{Bat}}\right)$$

3. **Battery State of Charge for Subsequent Time Periods:**
Describes the state of charge of the battery for each time period t, accounting for the previous state of charge, efficiency, and charging/discharging activities.
$$E^t_{bat} = E^{t-1}_{bat} + (\eta_{Bat} \times P^t_{char}) - \left(\frac{P^t_{dis}}{\eta_{Bat}}\right)$$

4. **Battery Simultaneous Charging-Discharging:**
Ensures that the battery does not simultaneously charges and discharges in a single time period t.
$$P^t_{char} \times P^t_{dis} = 0$$

5. **Battery Grid Discharging:**
Prevents the battery from discharging its stored energy to the grid.
$$P^t_{dis} \times P^t_{sell,grid} = 0$$

Two versions of each community problem will be carried out. First the optimization will be solved without limits on $P_{sell,grid,max}$ and $P_{buy,grid,max}$ prioritizing only prosumer profitability and neglecting grid relief through peak shaving. The second version of the optimization is executed by setting $P_{sell,grid,max}$ and $P_{buy,grid,max}$ to self-inputted values. These values will be set according to the potential for peak relief obtained through community storage calculated in the recent paper published by CE-Delft, 2023. The consumption peak will be constrained by a 20% decrease of the original peaks and the generation peaks will be constrained by a 30% decrease of the original values constrained

6.4. Energy Distribution

The optimization problem will yield an annual profile with hourly resolution, depicting the energy exchanges between the community, including the battery system, and the grid. However, to assess the distribution of costs and profits among each community member and the battery system, a criterion for energy distribution is necessary. This becomes particularly crucial in scenarios where the load is partly met by the battery or a portion of the excess energy is stored. Such scenarios present complexities in energy distribution among consumers, thereby posing challenges in the allocation of costs. For example, in instances where some households within the community have excess PV generation, yet this surplus is lower than the aggregate load of the community, the surplus is not exported to the grid. Instead, it is redistributed within the community according to the optimal flow approach. Residences that have produced more energy than they need will provide their surplus to a community energy pool. On the other hand, residences with a net energy deficit, will draw energy from this pool. The distribution of surplus energy calculated based on the proportion of their energy needs in relation to the total energy needs of the community at that time. This means homes with higher energy requirements will receive a larger share of the excess energy. As a result, these homes will need to purchase less additional energy from outside sources. While this approach may lead to increased electrical losses, since energy may have to be transmitted no necessarily through the path of leas resistance, it nevertheless ensures a sub-optimal distribution that effectively balances the generation and consumption needs of every house throughout each hour.

To achieve this, a set of energy distribution criteria must be established to analytically determine the hourly energy distribution through a Case-Based Logic. This represents the arithmetic operation that an ideal energy management system would perform. The main goal of this calculation is to address every possible scenario for distributing energy among community members throughout the year.

6.4.1. Parameters

The objective is to create an hourly energy profile for each household, for every hour in the entire year and including the following variables:

Output parameters	**Description**
buy_h^t	Energy purchased from grid
sell_h^t	Energy sold to grid
to-com_h^t	Energy provided to community
from-com_h^t	Energy drawn from community
to-bat_h^t	Energy provided to battery
from-bat_h^t	Energy drawn from battery

Table 6.1: Output variables of each household

Based on this output data the energy exchange for each household with the grid, community and battery can be specified. From these values the cost allocation parameters can be set. To calculate these values the following decision input variables will be used:

Input parameters	Description	Source
$P^t_{buy,grid}$	Aggregated net load	Aggregated household data
$P^t_{sell,grid}$	Aggregated net generation	Aggregated household data
$P^t_{h,buy,grid}$	Individual net load	Individual household data
$P^t_{h,sell,grid}$	Indivdiual feed-in	Individual household data
P^t_{PV}	Aggregated PV generation	PV generation data
P^t_{Char}	Battery charge volumes	Optimization problem
P^t_{Dis}	Battery discharge volumes	Optimization problem

Table 6.2: Decision variables of calculation

The input data in this case will be the individual and the aggregated data, based on the individual load data $P^t_{h,load}$ and individual generation profiles $P^t_{h,PV}$. The net load and feed-in $P^t_{h,buy,grid}$ and $P^t_{h,sell,grid}$ will be calculated as follow:

$$P^t_{h,buy,grid} = \mid P^t_{h,load} - P^t_{h,PV} \mid \tag{6.8}$$

$$P^t_{h,sell,grid} = \mid P^t_{h,PV} - P^t_{h,load} \mid \tag{6.9}$$

With t every hour in the timeperiod T and h every household in H

$$t \in \{1, 2, \ldots, T\}$$

$$h \in \{1, 2, \ldots, H\}$$

6.4.2. Conditional Decision-making

The input data will be subjected to conditional statements. Based on these conditions, a specific case will be identified and assigned to each hour. Subsequently, each case will have its unique formula used for calculating the desired output. The calculation will be applied to every hour of the year, during which the values of the decision variables will be assessed. Based on these values, the six specified variables for each household will be calculated for that particular hour. The conditional statements are outlined below. The full conditional decision-making process including the calculations for each case is detailed in Appendix A.4.

- Case 1: IF $P^t_{Dis} = 0$ AND $P^t_{PV} = 0$
- Case 2: IF $P^t_{PV} > 0$ AND $P^t_{sell,grid} = 0$ AND $P^t_{Dis} = 0$ AND $P^t_{char} = 0$
- Case 3: IF $P^t_{PV} = 0$ AND $P^t_{Dis} > 0$ AND $P^t_{buy,grid} = 0$
- Case 4: IF $P^t_{PV} = 0$ AND $P^t_{Dis} > 0$ AND $P^t_{buy,grid} > 0$
- Case 5: IF $P^t_{PV} > 0$ AND $P^t_{Dis} > 0$ AND $P^t_{buy,grid} = 0$ AND $P^t_{sell,grid} = 0$
- Case 6: IF $P^t_{PV} > 0$ AND $P^t_{Dis} > 0$ AND $P^t_{buy,grid} > 0$
- Case 7: IF $P^t_{PV} > 0$ AND $P^t_{char} > 0$ AND $P^t_{sell,grid} = 0$
- Case 8: IF $P^t_{PV} > 0$ AND $P^t_{sell,grid} > 0$ AND $P^t_{char} = 0$ AND $P^t_{Dis} = 0$
- Case 9: IF $P^t_{PV} > 0$ AND $P^t_{char} > 0$ AND $P^t_{sell,grid} > 0$

7

Results

This chapter showcases the results obtained from the proposed system design and the problems identified in the previous chapter. It begins with the Multi Dwelling Unit (MDU) community. In Section 7.1, the optimization results are displayed, illustrating the overall impact on the aggregated community and delving into specific days to demonstrate the various battery operation modes. Section 7.1 also reveals the outcomes of the energy distribution, detailing the operation of each household in the community and the storage system. Moreover, section 7.1 then presents the financial aspects of the system, derived from the obtained results and the developed business model. Following this, section 7.2 provide analogous results for the Terrace housing community.

7.1. Multi-Dwelling Community

7.1.1. Optimization results

This optimization model was run to analyze the optimal energy operation of the optimal battery size for every community. First the optimization was solved without limits on $P_{sell,grid,max}$ and $P_{buy,grid,max}$ prioritizing only prosumer profitability and neglecting grid relief through peak shaving. The second version of the optimization was run by setting $P_{sell,grid,max}$ and $P_{buy,grid,max}$ to self-inputted values based on the required transformer load/feed-in relief in the community thus simulating profitability and peak shaving.

7.1.2. Community profitability

As demonstrated in Table 7.1, prioritizing profitability leads to the selection of a larger battery size. This increase in size facilitates more efficient energy capture and energy arbitrage, thereby improving the financial viability. It's important to note that the energy cost calculations presented here solely account for direct energy savings. They do not include potential revenue from other streams, such as transport capacity reductions or congestion management earnings. The payback period calculated does however consider the FOM of the system. Furthermore, the table reveals that the profitability difference between peak shaving and non-peak shaving options is marginal, with both scenarios exhibiting identical payback periods.

Storage Option	Energy cost	Battery size	Energy savings	Payback period
CES -(no peak shaving)	€ 14,718.73	80	€ 6,042.93	8 years
CES peak shaving	€ 15,013.64	75	€ 5,748.01	8 years
Without	€ 20,761.65	-	-	-

Table 7.1: Financials of the CES Solution with and without Peak Shaving

7.1.3. Grid relief

In terms of grid relief, there is a substantial difference between the scenarios. In the peak shaving options, where $P_{sell,grid,max}$ and $P_{buy,grid,max}$ are reduced to 30% and 20% of their values in the absence of the battery, the impact is markedly distinct from the non-peak shaving options, where these parameters are left unbounded.

Storage option	Net Load (kWH)	Net Feed-in (kWh)	Peak load (kW)	Peak feed-in (kW)
Without	48248	23447	21.77	33.25
With CES	36678	8023	72.26	32.41
Difference (%)	**-23.9%**	**-66.0%**	**232%**	**0.46%**

Table 7.2: CES Grid Impact Without Peak Shaving - Battery Size = 80 kWh

The 80 kWh battery provides marginally improved profitability; however, it significantly strains the electrical grid. The enhanced profitability arises not just from the 5 kWh increase in battery size, which allows for greater storage capacity and access to lower prices, but primarily due to the lack of grid stress constraints. This enables the battery to charge up to its maximum capacity when prices are low. Although this strategy is highly profitable, it induces grid stress during periods of low prices. This stress is evidenced by a 232% increase in peak load, primarily due to the battery charging at its maximum capacity during periods of low electricity prices. Despite its considerable size, this battery system does not effectively harness generation peaks, resulting in no change in peak generation. This behaviour is illustrated in Table 7.2.

However, when $P_{sell,grid,max}$ and $P_{buy,grid,max}$ are bounded by their maximum values, both the demand and feed-in power peaks decrease significantly, by 21.9% and 30.8% respectively, as presented in Table 7.3. Furthermore, the total yearly load is smoothed, as evidenced by a substantial decrease in the yearly energy sold and purchased. This effect is also depicted in Figures 7.1 and 7.2.

Storage option	Net Load (kWH)	Net Feed-in (kWh)	Peak load (kW)	Peak feed-in (kW)
Without	48248	23447	21.77	33.25
With CES	36785	8446	17	23
Difference (%)	**-23.8%**	**-64.0%**	**-21.9%**	**-30.8%**

Table 7.3: CES Grid Impact Without Peak Shaving - Battery Size = 75 kWh

According to this the no peak shaving design will be discarded and the following results are all based on the peak shaving scenario.

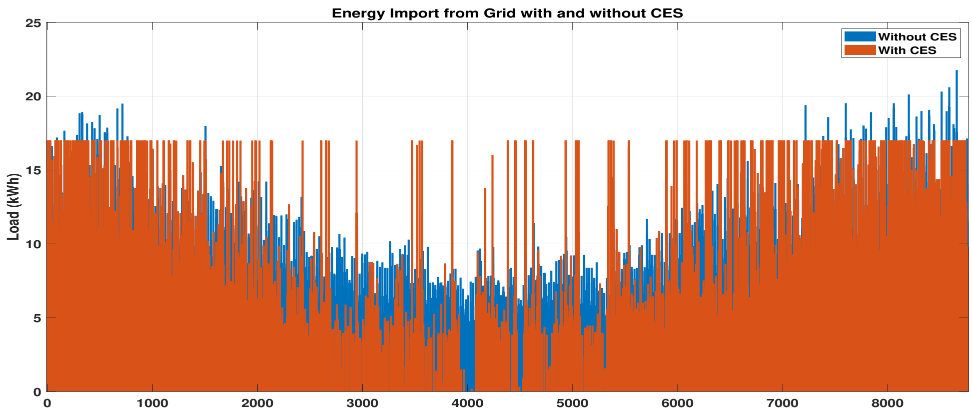

Figure 7.1: Annual grid import per household, with and without CES (Peak shaving)

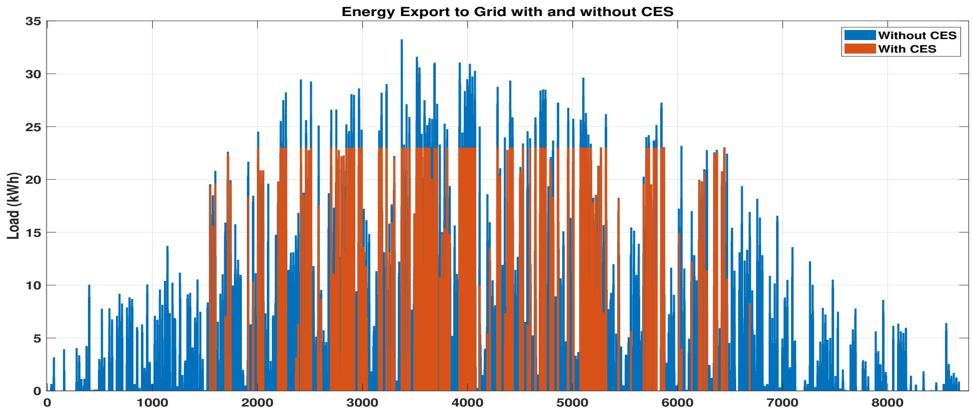

Figure 7.2: Annual grid import per household, with and without CES (Peak shaving)

7.1.4. Operation modes

Energy Sharing

When examining the system operation, we observe distinct modes and functions of the battery. A notable mode is energy sharing. On days like July 14th 2023 shown in figure 7.3, in this figure **Buy** is the aggregated energy bought/imported from the grid by all households. Buy_CES is the aggregated energy imported from the grid by all the community including all households and the battery. As can be seen AS illustrated, some houses generate surplus energy while others have a net load. Energy sharing occurs within the micro-grid if the total net generation is less than the total net consumption. During these periods, no energy is fed back to the grid; all excess PV energy is shared within the community. Consequently, the net consumption significantly decreases, particularly noticeable between 10:00 and 15:00, Buy compared to Buy_CES. Additionally, energy previously stored in the battery is supplied to prosumers during evening hours, reducing grid import (Buy_CES) to zero between 19:00 and 21:00. On such days, the total net load (grid import) decreases by 21%, and grid export is entirely eliminated.

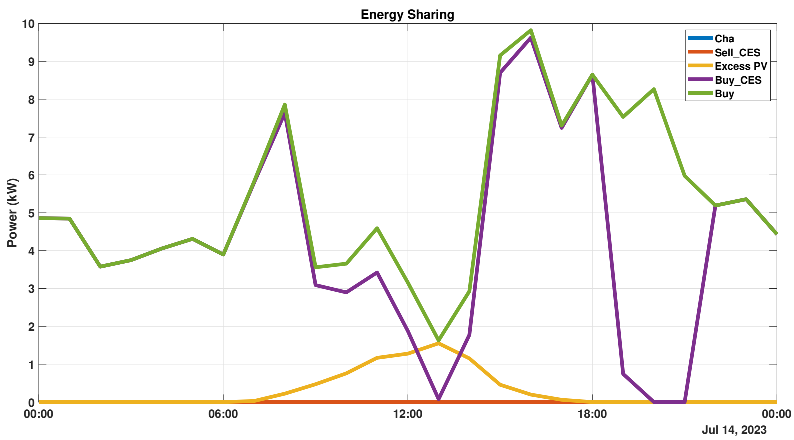

Figure 7.3: Annual grid import, with and without CES

Energy Arbitrage

Another operational mode, evident during winter days like January 4th 2023 shown in figure 7.4, is energy arbitrage. When generation is low, the battery charges from the grid during times of low prices and demand, staying within power constraints to avoid creating load peaks. This increases the energy imported from the grid but ensures that energy bought during high-price periods is minimized, as the battery discharges at these times. This shift in time-of-use ensures that consumers get lower costs.

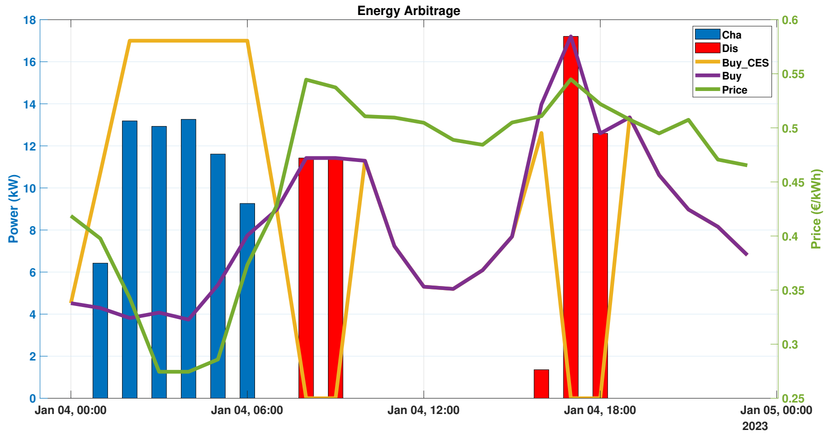

Figure 7.4: Annual grid import, with and without CES

Peak Shaving

Peak shaving is an additional operation mode for the battery. For example, on June 13th 2023 shown in figures 7.5 and 7.6, we observe excess PV generation in the afternoon for several hours. The battery stores some of this energy and manages peak shaving by selling the excess to the grid. Without peak shaving, the battery might store all required energy in the first few hours, failing to reduce subsequent peaks. Peak shaving behavior is driven by profitability maximization for consumers, ensuring that their excess energy is utilized when prices are high instead of being sold to the grid at a lower feed-in tariff. Consumption peak shaving follows the same principle, with the battery gradually discharging during high-peak times to reduce subsequent peaks up to the maximum capacity of $P_{sell,grid,max}$ and $P_{buy,grid,max}$.

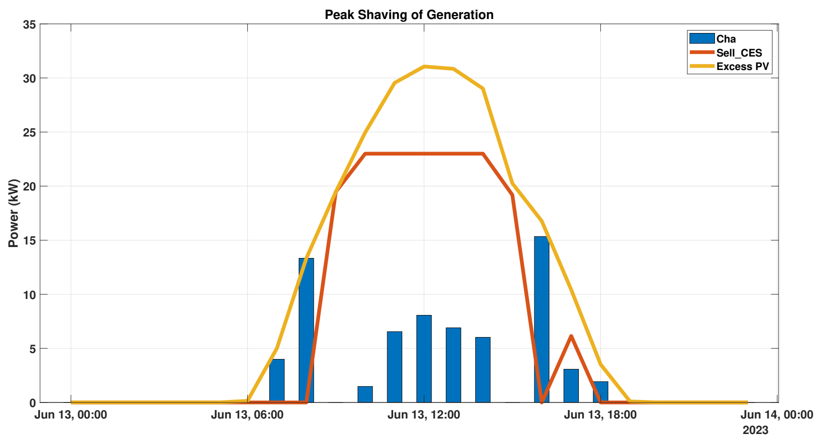

Figure 7.5: Price fluctuations within a summer-day

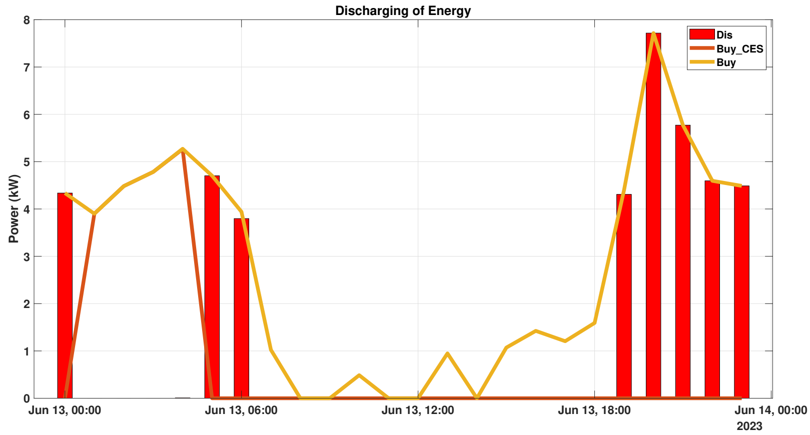

Figure 7.6: Price fluctuations within a winter-day

Partial Operation Days

There are days when operation patterns are less straightforward. For instance, not all excess PV energy can be stored, or the discharged energy is insufficient to cover the load of all houses. In such cases, decisions are made on distributing the energy, which will be discussed in the cost allocation chapter. Two examples illustrate this: one day shown in figure 7.7 when not all excess energy can be stored and some is sold to the grid, and another day shown in figure 7.8 when the discharged energy is insufficient, requiring the community or some households to purchase additional energy.

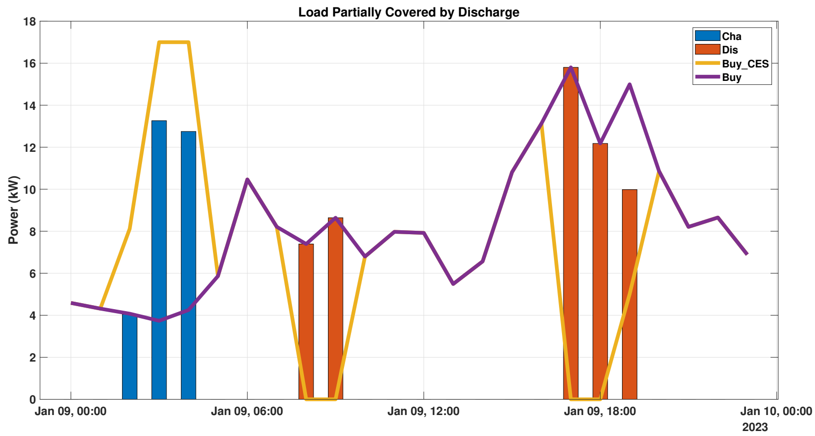

Figure 7.7: Price fluctuations within a summer-day

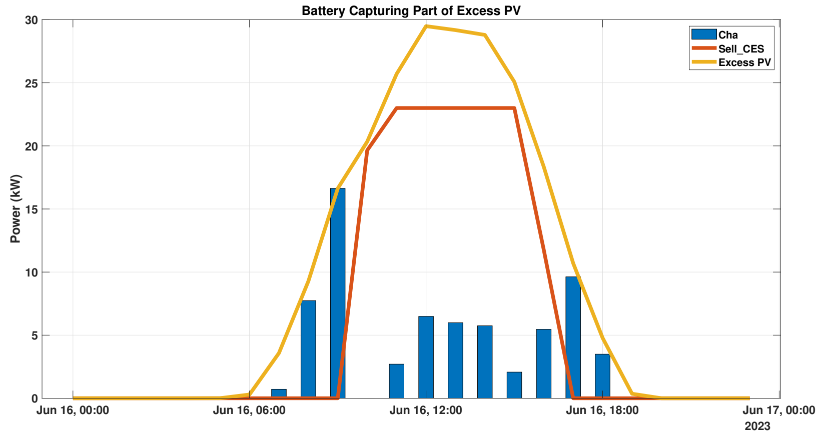

Figure 7.8: Price fluctuations within a winter-day

7.1.5. Energy distribution

The results from the previous chapter show a 23.8% reduction in the total grid import (Net load) for the whole community, including the battery. As illustrated in Figure 7.9, the net grid import by households decreased by 38.5%, amounting to 29.7 MWh compared to the initial 48.2 MWh. However, considering the energy arbitrage operations of the battery, which accounted for an additional import of 7.1 MWh from the grid, the overall grid import with the CES stands at 36.8 MWh."

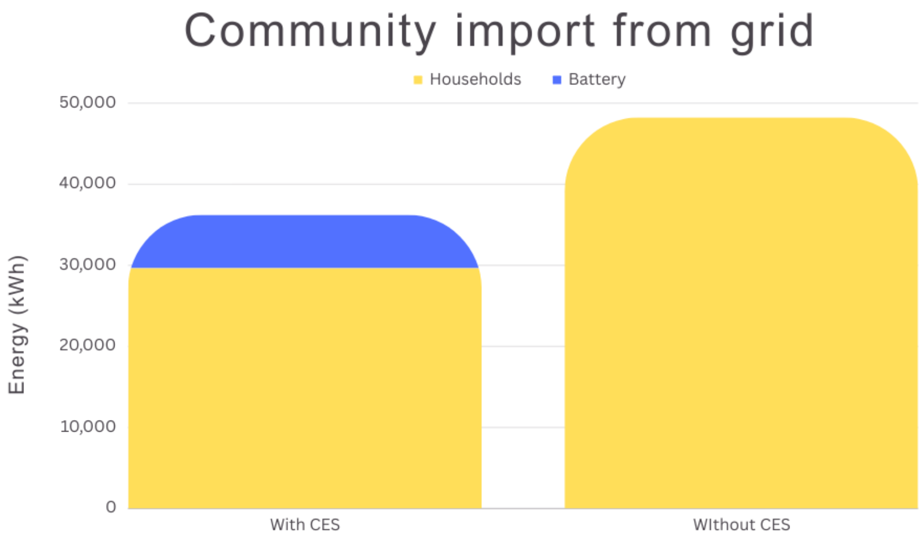

Figure 7.9: Community import from the grid (Net Load) with and without CES

Figure 7.10 illustrates the system's energy balance. It shows that the net demand, not met by the PV generation, is covered by the combined net supply from battery discharge and grid imports. This results in the anticipated energy balance, as dictated by the optimization constraints.

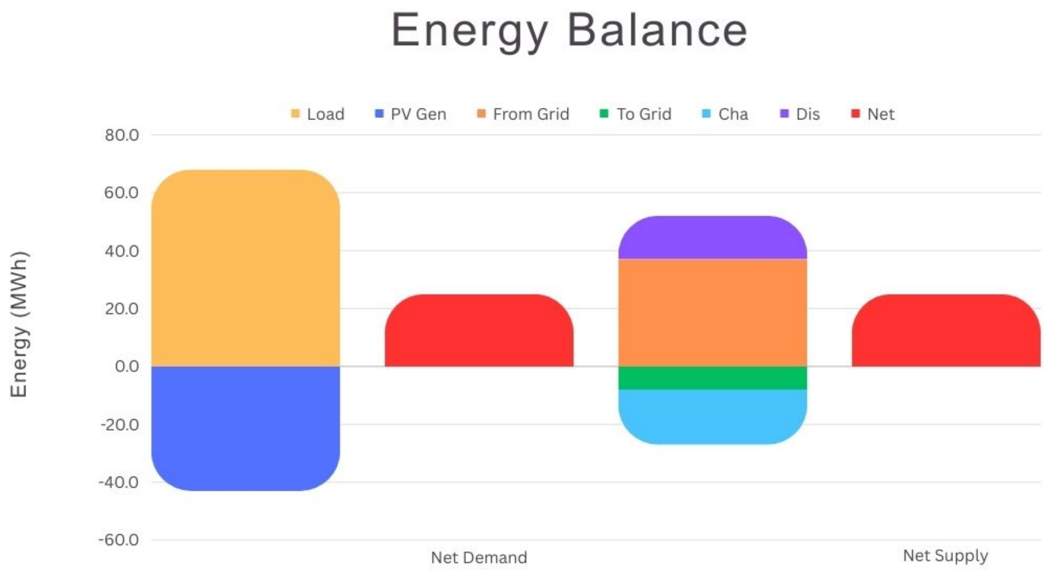

Figure 7.10: Energy balance of the system - MDU Community

Focusing specifically on the net load of the households, and excluding the battery's grid import, a significant decrease is observed. The initial 48.2 MWh imported from the grid without the storage system is now partially met through grid imports, and partially through energy received from the community and the battery. This distribution is illustrated in Figure 7.11.

On the other hand, the energy export (feed-in) to the grid decreased by 64%. Out of the total excess energy, 11.7 MWh (representing 50% of the total) was stored in the battery, and 3.4 MWh (14%) was distributed within the community rather than being sold to the grid. The remaining 8.4 MWh, constituting 36% of what would have been exported without CES, was then exported to the grid, as detailed in Figure 7.11

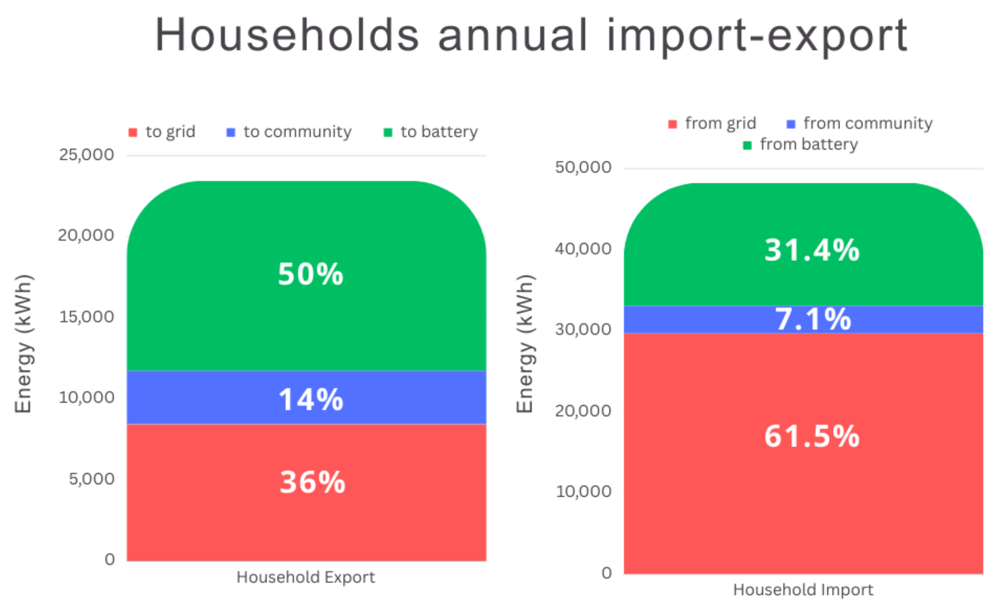

Figure 7.11: Households annual grid import and export

If the focus is now on how each household this energy interaction is further distributed among each household, the following results can be seen:

- The annual **grid import** for households decreased significantly, ranging between 35% and **41%**, with an average decrease of 38%. Figure 7.12 shows the energy imported from the grid without CES and the portion imported when the CES is incorporated. The percentage in the column indicates the relative decrease in grid imports attributable to the CES system.
- The annual **grid export** for households also saw a notable reduction, varying between 58% and 69%, with an average decrease of **64%**. Figure 7.13 shows the energy exported to the grid with CES, without CES and the relative decrease similar to the previous figure.
- The grid **export peak** for households decreased significantly, ranging between 14% and 22%, with an average decrease of **18%**.
- The distribution of grid **import peaks** was **not uniform**, as the primary objective was to shave the aggregated peaks. These peaks were predominantly generated by a limited number of households. While these peaks were successfully damped, households that did not initially have relatively high peaks did not exhibit any significant decrease in their consumption peaks. Seven houses demonstrated a noticeable decrease in import peaks, ranging from 8% to 20%, whereas other households showed no minimum peak decrease.

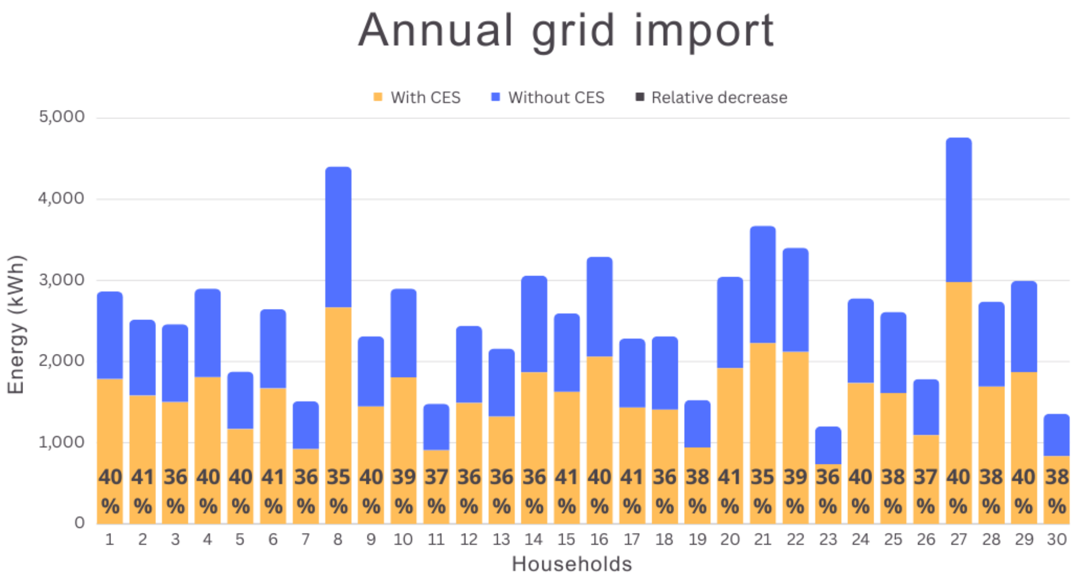

Figure 7.12: Annual grid import per household, with and without CES

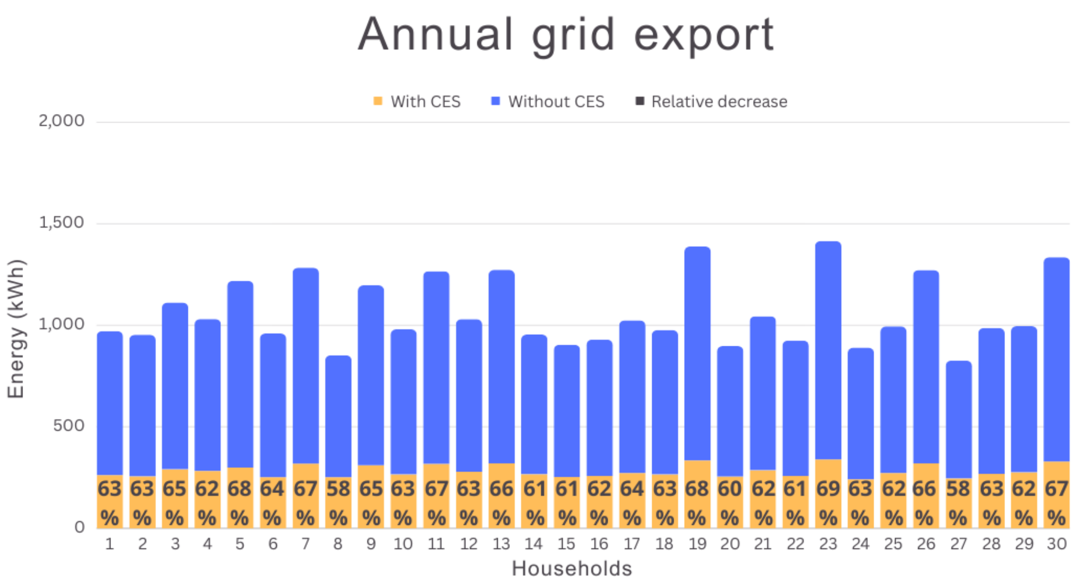

Figure 7.13: Annual grid import per household, with and without CES

Finally, focussing on the peaks from the prespective of the households, we observe a decrease, accordingly, the net-value of the storage system is calculated for each individual household:

$$\text{Net value consumers}_{CES} = \text{Energy Cost}_{WithoutCES} - Energy\ Cost_{WithCES} \tag{7.1}$$

With

$$\text{Energy cost}_{Annual} = \text{Energy Purchase Cost}_{Annual} - \text{Energy Sale Cost}_{Annual} \tag{7.2}$$

Based on this analysis, a net value is derived, ranging between €80.66 and €568.04, with an average of €268.41. Though this range may appear broad for fair cost allocation, it is important to contextualize these values as relative to the original costs of each prosumer, as shown in Table 7.4. The relative decrease in electricity costs for each household exhibits a narrower range, varying between 31% and -43%, with an average decrease of 38%

Household	Cost Old (€)	Cost New (€)	Net-Value (€)	Decrease
1	769.06	462.58	306.48	40%
2	690.10	404.06	286.05	41%
3	638.28	406.73	231.54	36%
4	801.30	477.40	323.91	40%
5	476.49	295.60	180.89	38%
6	721.90	422.84	299.07	41%
7	355.61	239.74	115.87	33%
8	1197.93	764.92	433.01	36%
9	616.01	368.14	247.86	40%
10	790.25	473.73	316.52	40%
11	351.03	231.01	120.02	34%
12	639.97	405.04	234.94	37%
13	567.01	364.42	202.59	36%
14	812.20	509.75	302.45	37%
15	709.26	415.41	293.85	41%
16	916.50	540.77	375.73	41%
17	601.34	356.57	244.77	41%
18	592.99	379.41	213.58	36%
19	362.88	238.21	124.67	34%
20	846.64	484.36	362.28	43%
21	953.24	608.33	344.91	36%
22	947.19	565.98	381.21	40%
23	264.22	183.55	80.66	31%
24	770.40	457.63	312.77	41%
25	688.31	424.17	264.14	38%
26	445.51	288.80	156.71	35%
27	1357.18	789.14	568.04	42%
28	729.32	446.75	282.58	39%
29	837.15	496.84	340.31	41%
30	312.38	207.47	104.90	34%

Table 7.4: Consumers electricity costs, with and without CES

The total net value for all consumers amounts to €8052.32. However, it's important to take into account the role of the battery's energy arbitrage in this calculation. This involves considering the costs incurred when the battery purchases energy at lower prices to supply to consumers later. Factoring in these costs results in a revised total net value of €5748.01, as detailed in Table 7.1.

7.1.6. Financials

Based on the chosen business case of energy sharing the financial for this CES will be presented. The following points summarize the main findings from the operation results of the MDU community:

- The net value (savings) aggregated for all consumers amounts to €8052.32 annually, attributed to reduced electricity bills, with an average cost decrease of 38%.

- The aggregated community's peak grid import is reduced by 22%, and the aggregated peak grid export is decreased by 31%.
- Annually, the community's grid import decreases by 23.8%, and the grid export diminishes by 64%.
- Although individual households' grid-export peaks show an average decrease of 18%, there is no uniformly distributed decrease observed in the load peaks of individual households.

According to Section 5.3, the energy sharing model offers a threefold value proposition, which can be realized through three distinct revenue streams: **(1)** energy trading/sharing between consumers; **(2)** decrease in grid capacity tariffs and **(3)** effective congestion management.
Drawing from the main findings on system operation, it is evident that energy trading offers substantial value for prosumers. However, the grid contracted tariff is linked to consumption peaks, and since a uniform decrease in peaks across individual houses is not observed, this revenue stream is considered less viable. On the other hand, in terms of congestion management, the community successfully lowers consumption and generation peaks significantly. This directly reduces stress on cables and transformers in the low voltage (LV) grid. Moreover, by enhancing local energy utilization and smoothing load and generation profiles, the system potentially alleviates congestion at other points in the LV or medium voltage (MV) grid. However, congestion management payments are currently not available on the LV-grid. Moreover this grid relieve is observed only at a small section of the, namely a community of 30 houses, it is therefore difficult to estimate the financial reward and monetize it.
Based on this, a conclusion can be drawn that the only revenue stream available for this storage system is the energy trade between consumers and prosumers. The costs are represented by the FOM (2.5% yearly of investment cost) and the variable cost representing the battery charging from the grid.

WACC	8%
Investment costs	€ 30,000.00
Revenue	€ 8,052.32
Variable cost	€ 2,303.12
Fixed operational cost (2.5%)	€ 750.00

Table 7.5: Financial Overview

As shown in figure 7.14 the payback period for this system will be 7 years, given that the lifetime of the battery is 15 years. This setup presents an interseting business case.

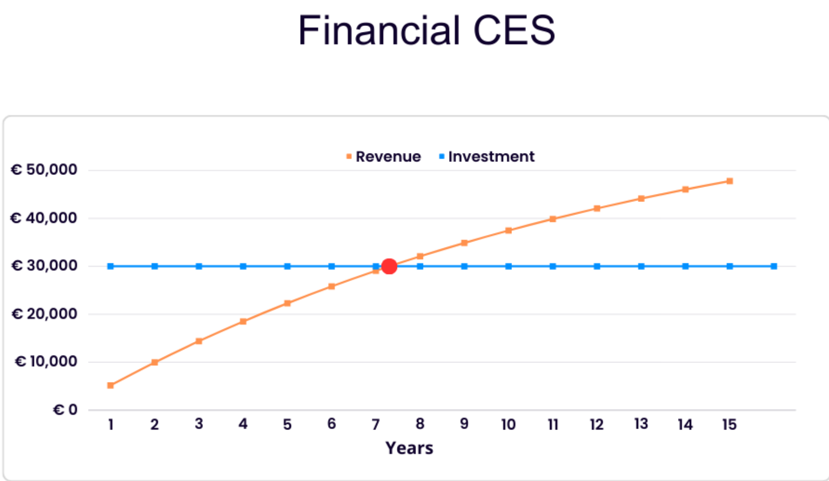

Figure 7.14: Accumulated revenue of the CES system

7.2. Terrace Housing Community

7.2.1. Optimization results

Similar to the approach used for the MDU community, the optimization for the terrace housing community initially focused on minimizing aggregated community costs. As discussed in the previous section, the option without limits on $P_{sell,grid,max}$ and $P_{buy,grid,max}$ resulted in excessively high import peaks, significantly straining the grid. Therefore, this option will be excluded from further consideration. The focus will instead be on the peak-shaving version, as for the success of the CES system, maintaining at least congestion neutrality is crucial. Ideally, to capture additional benefits from energy sharing, the system should contribute to grid relief. The optimization process was conducted by assigning specific values to $P_{sell,grid,max}$ and $P_{buy,grid,max}$, as previously described. For $P_{buy,grid,max}$, the value was set to be 20% lower than its initial value without the CES, and for $P_{sell,grid,max}$, a reduction of 30% was implemented. As highlighted in the general assumptions for the Terrace Housing community in Section 6.1.2, there are notable differences compared to the MDU Community's micro-grid based system. Firstly, **(1)** the storage system in the Terrace Housing (TH) community is not subjected to taxes when purchasing energy from the grid, or from prosumers. The exemption for taxes on energy purchased from prosumers was similarly observed in the MDU Community's system, due to the micro-grid implementation. However, in the MDU case, the storage system's energy purchases are subject to taxation, as it is considered the end-user. Secondly, **(2)** unlike the MDU setup, when consumers in the TH community purchase energy from the battery system, their transactions occur via the grid. As a result, they are subject to the corresponding access costs, which include taxation.

7.2.2. Community profitability

Based on the initial aggregated community cost minimization the following results are obtained, as shown in table 7.6. The optimal battery size obtained from the optimization is 70 kWh. For this problem the non peak-shaving constraints where not considered, resulting in a single optimal battery size unlike for the MDU community where both options were considered. It's important to note that the energy cost calculations presented here solely account for direct energy savings. They do not include potential revenue from other streams, such as transport capacity reductions or congestion management earnings. Furthermore, the table reveals that the profitability difference between peak shaving and non-peak shaving options is marginal, with both scenarios exhibiting identical payback periods.

Storage Option	Energy cost	Battery size	Energy savings	Payback period
CES peak shaving	€ 12,737080	70	€ 4,009.85	12 years
Without	€ 16,747.65	-	-	-

Table 7.6: Financials of the CES Solution with and without Peak Shaving

7.2.3. Grid relief

In terms of grid relief, the following results are obtained when $P_{sell,grid,max}$ and $P_{buy,grid,max}$ are reduced to 30% and 20% of their values in the absence of the battery. Both the demand and feed-in power peaks decrease significantly, by 21.9% and 30.8% respectively. Furthermore, the total yearly load is smoothed, as evidenced by a substantial decrease in the yearly energy sold and purchased. This effect is also depicted in Figures 7.15 and 7.16.

Storage option	Net Load (kWH)	Net Feed-in (kWh)	Peak load (kW)	Peak feed-in (kW)
Without CES	40674.87	30969.69	20.59	40.39
CES	28274.45	15110.36036	16.5	28.27
Difference (%)	**-30.5%**	**-51.2%**	**-19.9%**	**-30.0%**

Table 7.7: CES Grid Impact without Peak Shaving - Battery Size = 70 kWh

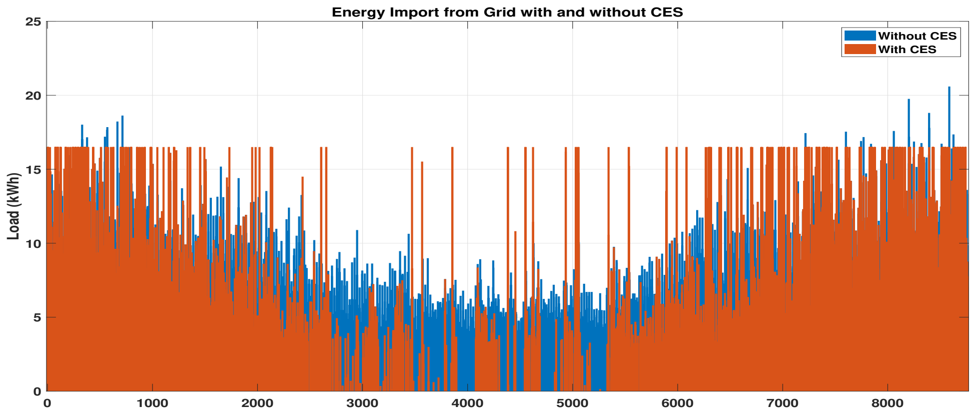

Figure 7.15: Annual grid import per household, with and without CES (peak-shaving)

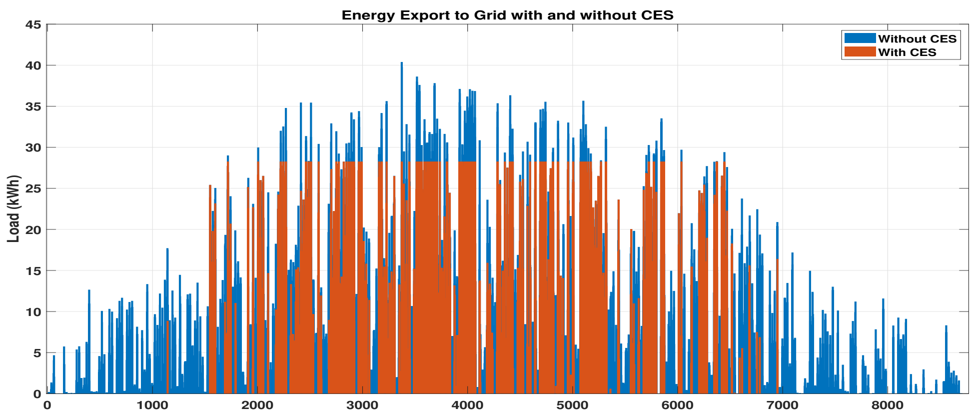

Figure 7.16: Annual grid import per household, with and without CES (peak-shaving)

7.2.4. Operation modes

The various operational modes observed within the MDU communities are also evident in the TH model. Energy arbitrage is showcased in Figure 7.17. On January 6th, in the absence of excess PV generation, the battery is not charged. To make use of the battery's capacity, it is charged from the grid during times of low prices, specifically between 00:00 and 04:00 when prices hover around 0.28 euro/kWh. This energy is then discharged during peak price periods, notably at 08:00 and between 16:00 and 19:00, thereby reducing the energy import from outside the community to zero when the price peaks at 0.68 euro/kWh.

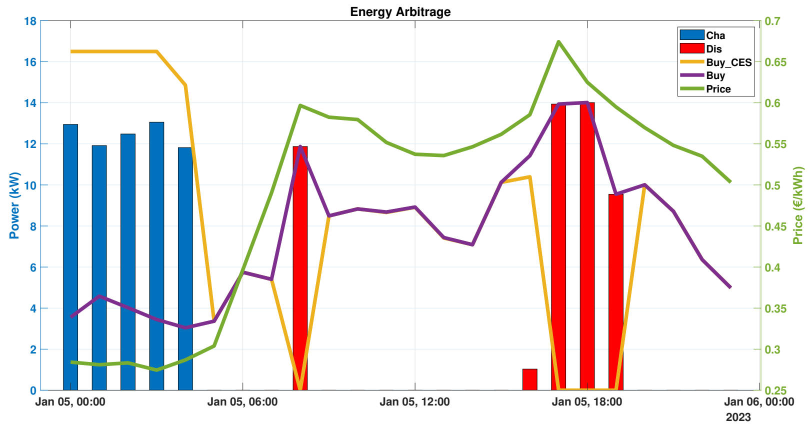

Figure 7.17: Energy arbitrage operation (6-01-2023)

Energy sharing is demonstrated in Figure 7.18. On November 1st, it is clear that some houses have excess PV generation between 09:00 and 14:00, while others have net consumption. Instead of exporting this excess energy to the grid, it is shared within the community, thereby reducing the amount of energy exported, as indicated by the lower value of Buy_CES compared to Buy.

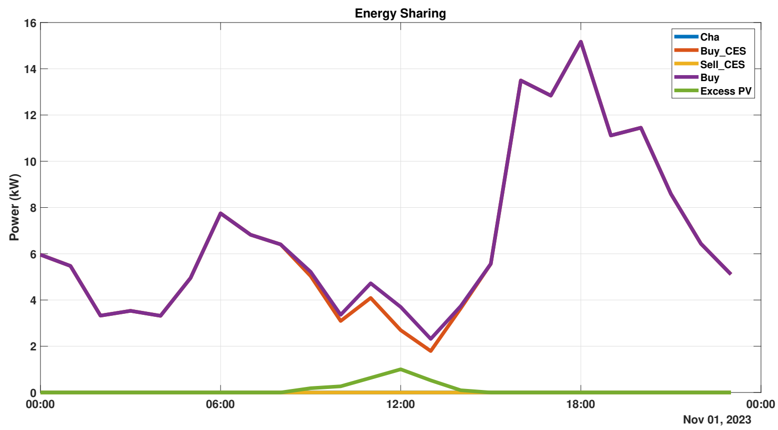

Figure 7.18: Energy sharing operation (01-11-2023)

Peak shaving is depicted in Figure **??**. Here, the peak PV generation at 10:00 and 16:00 exceeds the grid's self-inputted values. In this case, the battery uses a portion of this excess energy for charging, thereby reducing these peaks. It is important to note that the battery capacity is not sufficient to store all the excess PV; hence, it reserves this capacity for peak hours to mitigate peak demands.

The discharge of this stored energy later in the day is shown in Figures 7.19 and 7.20, effectively reducing the grid import from outside the community to zero, as indicated by Buy_CES compared to Buy.

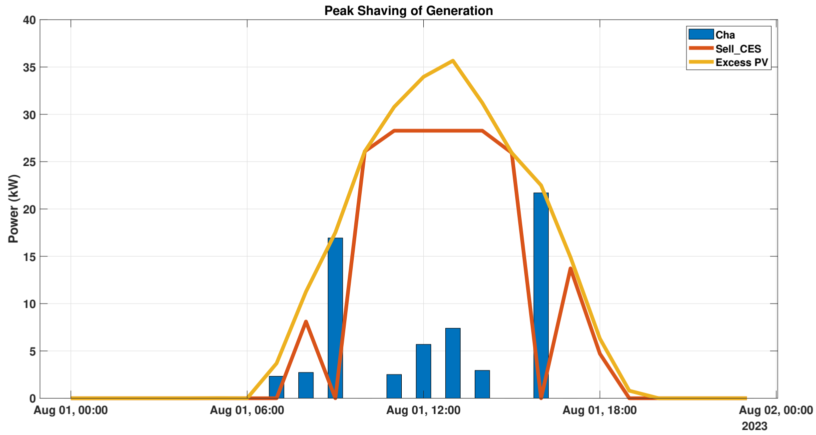

Figure 7.19: Peak shaving operation on August 2nd, 2023

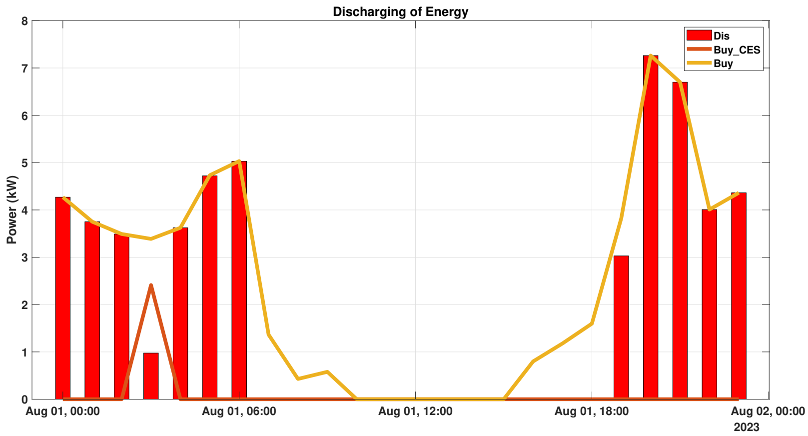

Figure 7.20: Discharging energy, stored through peak shaving on August 2nd, 2023

7.2.5. Energy distribution

The results from the previous chapter show a 30.5% reduction in the total grid import (Net load) for the whole community, including the battery. As illustrated in Figure 7.21, the net grid import by households decreased by 43.9%, amounting to 22.8 MWh compared to the initial 40.67 MWh. However, considering the energy arbitrage operations of the battery, which accounted for an additional import of 5.5 MWh from the grid, the overall grid import with the Community Energy Storage (CES) stands at 28.2 MWh. Figure 7.22 shows the energy balanced similar to 7.10.

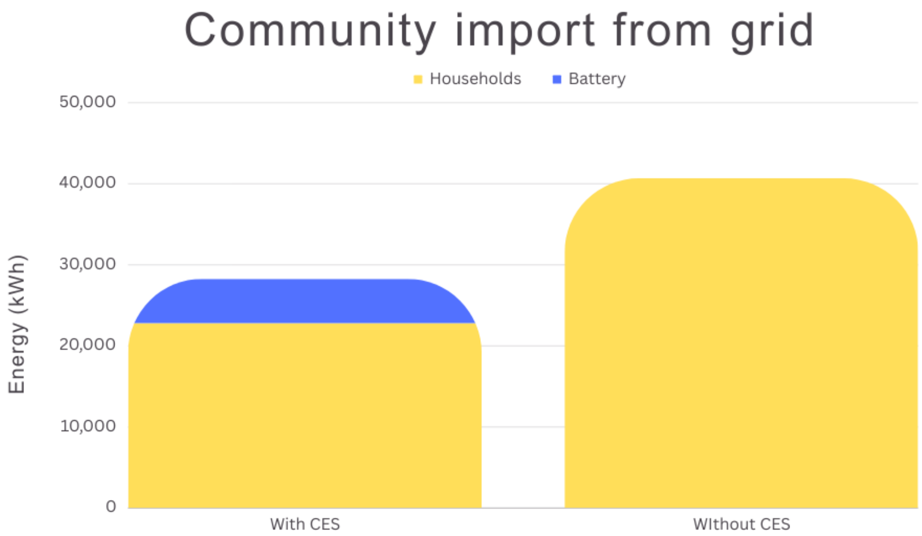

Figure 7.21: Community import from the grid (Net Load) with and without CES

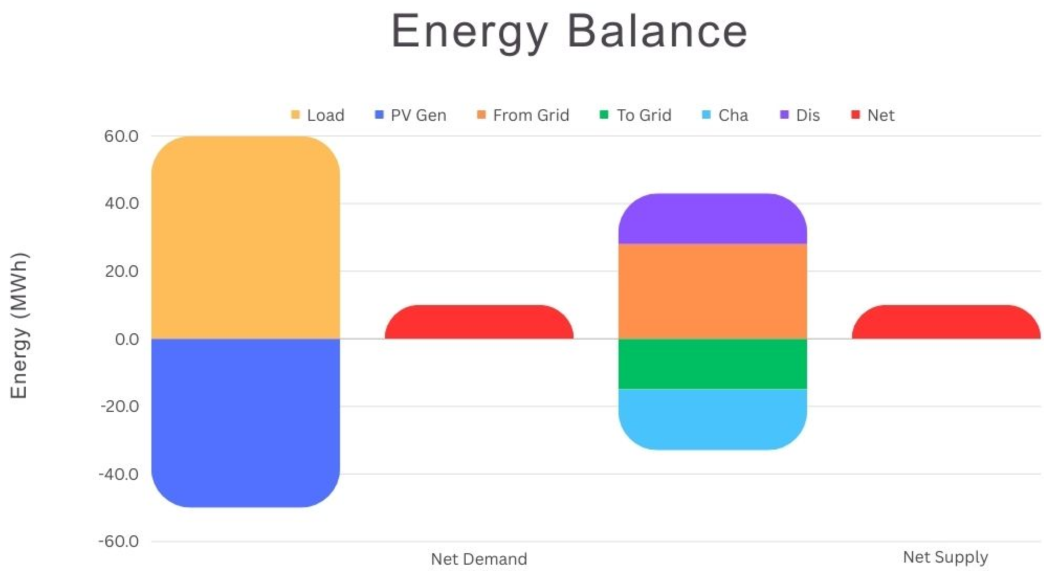

Figure 7.22: Energy balance of the system - TH community

The net load of households, excluding the battery's grid import, showed a significant decrease. Originally, households imported 40.7 MWh from the grid, which has now been reduced due to partial grid imports and energy received from the community and the battery. This is depicted in Figure 7.23.
The energy export to the grid decreased by 51.2%. Specifically:

- 12.89 MWh of the excess energy, representing 51.5% of the total, was stored in the battery.
- 3.0 MWh, or 9.7% of the excess, was distributed within the community instead of being sold to the grid.
- 3.0 MWh, or 9.7% of the excess, was distributed within the community instead of being sold to the grid.
- The remaining 15.1 MWh, which is 48.8% of the potential export without the CES, was exported to the grid. This is further detailed in Figure 7.23.

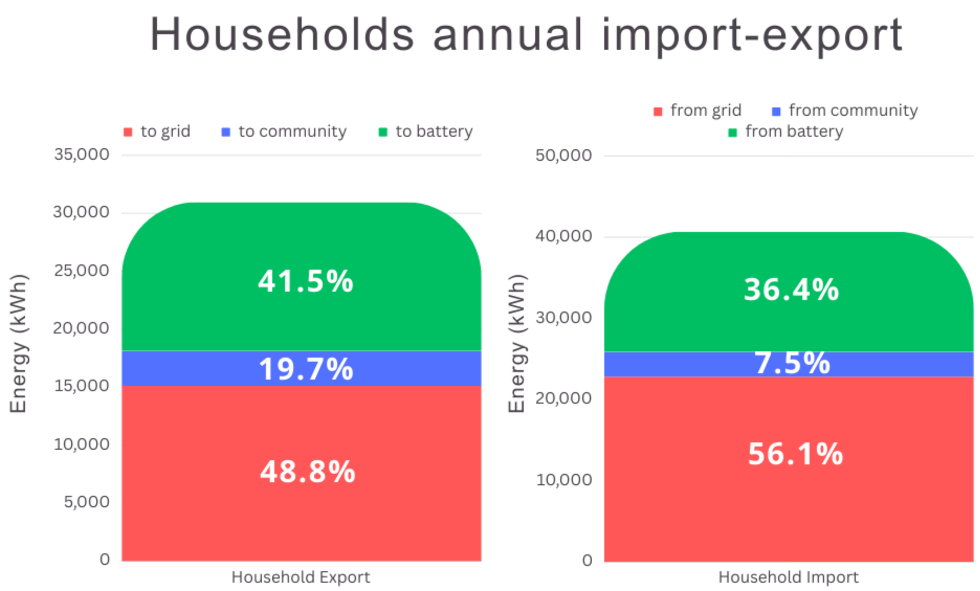

Figure 7.23: Households annual grid import and export

If the focus is now on how each household this energy interaction is further distributed among each household, the following results can be seen:

- The annual **grid import** for households decreased significantly, ranging between 39% and **47%**, with an average decrease of 44%. Figure 7.24 shows the energy imported from the grid with CES without CES and the relative decrease.
- The annual **grid export** for households also saw a notable reduction, varying between 47% and 56%, with an average decrease of **51%**. Figure 7.25 shows the energy exported to the grid with CES, without CES and the relative decrease.
- The grid **export peak** for households decreased significantly, ranging between 14% and 22%, with an average decrease of **18%**.
- The distribution of grid **import peaks** was **not uniform**, as the primary objective was to shave the aggregated peaks. These peaks were predominantly generated by a limited number of households. While

these peaks were successfully damped, households that did not initially have relatively high peaks did not exhibit any significant decrease in their consumption peaks. Seven houses demonstrated a noticeable decrease in import peaks, ranging from 8% to 20%, whereas other households showed no minimum peak decrease.

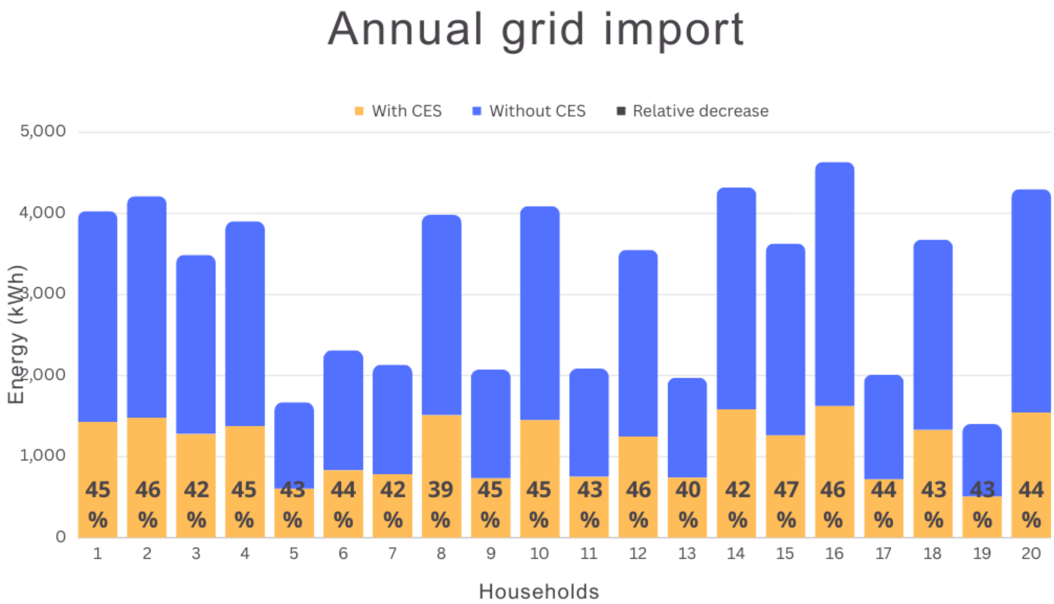

Figure 7.24: Annual grid import per household, with and without CES

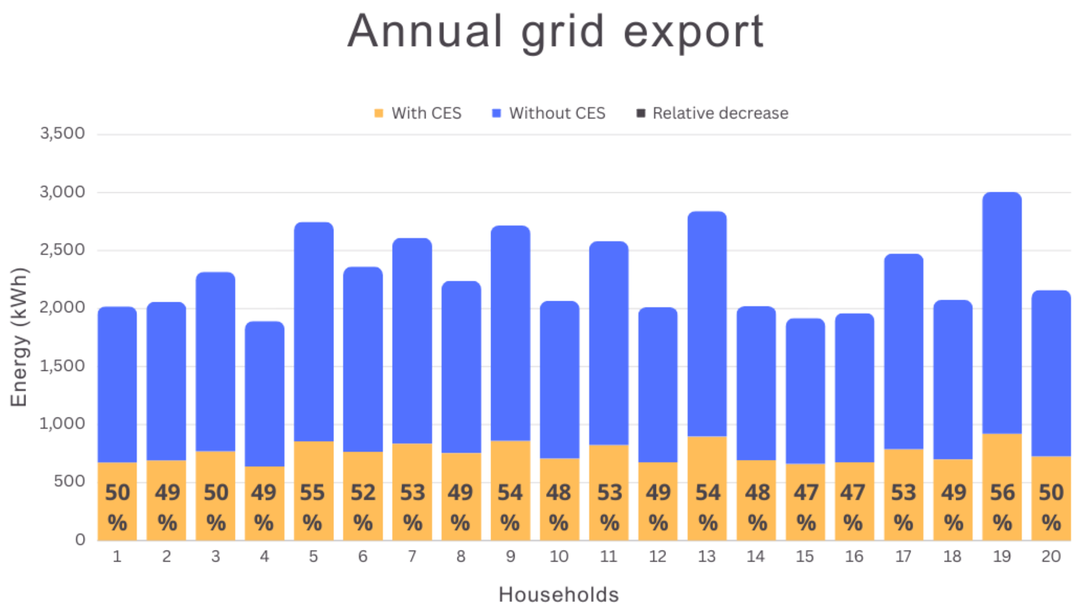

Figure 7.25: Annual grid import per household, with and without CES

Based on calculating the net-value of the storage system for each individual household according to equations 7.2 7.1, a net value is derived, ranging between €46.46 and €419.89, with an average of €244.92. Though this range may appear broad for fair cost allocation, it is important to contextualize these values as relative to the original costs of each prosumer, as shown in Table 7.4. The relative decrease in electricity costs for each household exhibits a narrower range, varying between 32% and -18%, with an average decrease of 28%

The total net value for all consumers amounts to €4898.59. Considering the variable operational cost of the battery of € 888.74, namely the charging from the grid. results in a revised total net value of €4009,85, as detailed in Table 7.1.

7.2.6. Financials

Based on the chosen business case of energy sharing the financial for this CES will be presented. The following points summarize the main findings from the operation results of the MDU community:

- The net value (savings) aggregated for all consumers amounts to €8052.32 annually, attributed to reduced electricity bills, with an average cost decrease of 38%.
- The aggregated community's peak grid import is reduced by 22%, and the aggregated peak grid export is decreased by 31%.
- Annually, the community's grid import decreases by 23.8%, and the grid export diminishes by 64%.
- Although individual households' grid-export peaks show an average decrease of 18%, there is no uniformly distributed decrease observed in the load peaks of individual households.

According to Section 5.3, with regards to the energy sharing business case. A similair conslusion can be drawn about the TH FTM system.

- Energy trading is beneficial for prosumers, however due to the acces cost due to taxation, a large part of the value is lost.

Household	Cost Old (€)	Cost New (€)	Value (€)	Decrease
1	1099.48	765.89	333.59	30%
2	1202.56	817.69	384.87	32%
3	913.97	654.22	259.74	28%
4	1100.10	753.65	346.45	31%
5	358.06	278.01	80.05	22%
6	573.20	416.44	156.76	27%
7	494.34	372.52	121.81	25%
8	1046.23	770.24	275.99	26%
9	494.93	359.99	134.94	27%
10	1133.20	780.85	352.34	31%
11	488.67	360.93	127.74	26%
12	983.11	671.53	311.58	32%
13	452.39	349.81	102.57	23%
14	1168.07	826.08	341.99	29%
15	1008.55	686.60	321.94	32%
16	1318.42	898.53	419.89	32%
17	470.37	347.52	122.85	26%
18	980.92	691.31	289.61	30%
19	264.50	218.05	46.46	18%
20	1196.60	829.20	367.40	31%

Table 7.8: Updated Consumers electricity costs, with and without CES

- While there was no informal distrbuted peak reduction, the total community peak decrease by 20% for import and 30% for export. Through a Groeps-TO this community behaviour can be captured to lower the total grid-tariffs. There are however no estimations about the monetary value added due to this scheme.
- While the system has been beneficial for congestion management,it is challenging to estimate the financial rewards or monetize them effectively. as it is not yet available on the LV-grid

Based on this, a conclusion can be drawn that the only revenue stream available for this storage system is the energy trade between consumers and prosumers. The costs are represented by the FOM (2.5% yearly of investment cost) and the variable cost representing the battery charging from the grid.

WACC	8%
Investment costs	€ 28,000.00
Revenue	€ 4,898.59
Variable cost	€ 888.74
Fixed operational cost (2.5%)	€ 700.00

Table 7.9: Financial Overview

As shown in figure 7.26 the payback period for this system will be 7 years, given that the lifetime of the battery is 15 years. This setup presents an interseting business case.

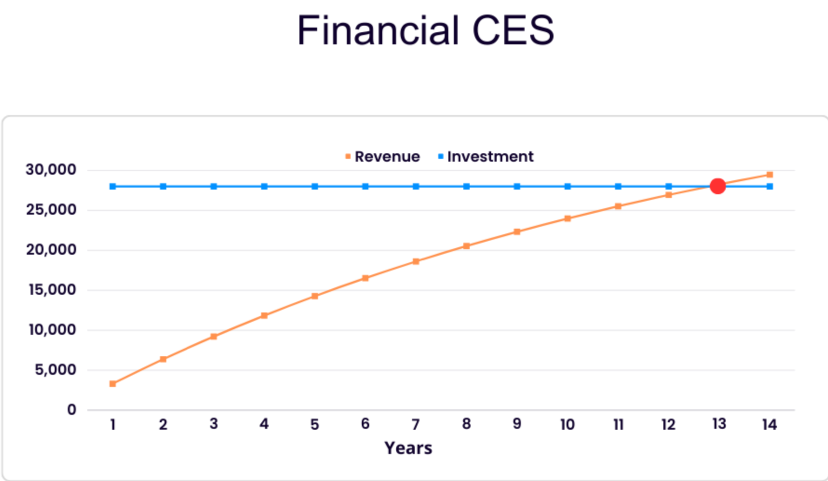

Figure 7.26: Accumulated revenue of the CES system

7.2.7. Case: Optimal community

As highlighted previously, the problem of access costs in Front-of-the-Meter (FTM) solutions poses a challenge to the financial viability of the system. This challenge is evidenced by the FTM terrace housing system, which demonstrates a relatively long payback period of 12 years. To assess the impact of policy adjustments, a case is modeled considering optimal interaction within the community. This case is based on the following assumptions:

Consumers within the community are not subject to energy taxes for energy sourced internally, whether from neighbors or the battery system. This approach is in line with initiatives under discussion by the EU and the Dutch Ministry of Energy, as detailed previously. This exemption leads to a reduction in the tax burden for consumers, amounting to €2723.79, thereby increasing their aggregated annual profit to €7622.38, as opposed to €4898.59 achieved in the earlier simulation.

Additionally, with consumers being tax-exempt, the battery system is regarded as the final purchaser and is taxed only when buying energy from the grid. Consequently, the cost of charging the battery from the grid rises to €1679.32, compared to the previously calculated €888.74.

Costs	Amount (€)
Battery charging from grid cost	1679.33
Consumers energy cost	9125.27
Total community cost	10804.60

Table 7.10: Financial Data Summary

7.2.8. Financials

The investment and fixed operation costs remain constant, but the revenue due to savings generated by prosumers increases, and the variable cost for charging the battery shows a slight increase. Consequently, this results in a final net value of €5,243.05. When calculated with a WACC of 8%, this leads to a payback period of 6 years.

WACC	8%
Investment costs	€ 28,000.00
Revenue	€ 7,622.38
Variable cost	€ 1,679.32
Fixed operational cost (2.5%)	€ 700.00

Table 7.11: Financial Overview

Storage Option	**Energy savings**	**FOM**	**Net Value**	**Payback period**
CES (optimal community)	€ 5,943.05	€ 700.00	€5,243.05	6 years

Table 7.12: Financials of the CES Solution within an optimal community

8 Discussions

In this chapter, the findings from Chapters 5, 6, and 7 are synthesized within the complete framework of technical, financial, and regulatory aspects. Initially, section 6.1 interprets the results of this research by addressing the previously stated sub-research questions. Section 6.2 then evaluates the research's representation of reality and discusses the assumptions made. Finally, section 6.3 provides a reflection on the research. In this section, suggestions for future work are made based on the remaining gaps, the relevance of this study is discussed, and a personal reflection is offered.

8.1. Interpretation of the results

1. What is the optimal integration approach and its corresponding business model for CES within the residential communities?

Community energy storage in the Dutch residential sector has several possible applications, each associated with different business model design options. The two primary applications are energy inter-trading and energy sharing. These applications can be shaped by diverse business model designs, and there is no single dominant model. While energy trading shows potential for a positive business case, its continuation is uncertain and it does not necessarily support grid relief and may even contribute to grid congestion. Therefore, energy sharing is highlighted as a superior application due to its potential for household energy savings and grid relief. The main community value propositions through energy sharing include increasing self-consumption, reducing energy costs, and providing grid relief. These benefits are captured through various instruments, with the full business model design detailed in Chapter 5.

To obtain large-scale emergence of this business model, the most effective integration strategy is through housing cooperatives or homeowners associations. In this framework, the housing cooperative acts as the community manager, and cooperates with an Energy Service Company (ESCO) which is responsible for setting up and operating the system. The community manager oversees initial investments, while households contribute through variable monthly payments based on usage or a fixed cost included in their service package.

2. What is the optimal system design topology for community storage within each of the defined communities, and what are the associated limitations?

Regarding system connection topology for energy sharing, CES can be integrated as either Behind-The-Meter (BTM) or Front-The-Meter (FTM). The BTM approach involves creating an external micro-grid independent of the main grid, offering more regulatory and transactional freedom, but lacking general frameworks, making it a more ambitious option. The FTM approach utilizes the existing grid infrastructure to connect households within a community. While this method is more realistic, it encounters constraints due to current market designs and regulations that are not yet fully conducive to community formation, potentially reducing profitability.

Both connection methods are tested to evaluate their potential. For Multi-dwelling communities, the CES system implemented BTM. Here the micro-grid infrastructure connecting the households, behind the grid operator meter, is encapsulated within the building. For Terrace Housing communities this external micro-grid formation is less plausible due to the infrastructural challenges, therefore an FTM topology is presented. The detailed system design topology of each community is discussed in detail in Chapter 6.

The main policy and market regulations hindering CES integration include the absence of frameworks for independent micro-grid formation, making BTM solutions challenging to realize under current conditions. For FTM solutions, a significant financial challenge is the taxation of energy traded within the community. Additionally, both solutions are constrained by the lack of tariff designs for flexible transport capacity, limiting the grid relief value capture for prosumers. Finally, there are no existing market instruments on the residential (LV) grid to capitalize on the value of congestion management within general frameworks. However, there is a glimmer of hope on the horizon, as policymakers and stakeholders are actively examining all the identified regulatory and market challenges to foster support for energy communities.

3. How does the chosen CES integration method influence consumer profitability for each of the identified communities?

For Multi-dwelling ommunities, the optimized CES system led to a total energy savings for consumers of 39%. The energy savings for individual households varied between 31% and 43%. Taking into account the variable and fixed operation costs, the net savings for the community amount to 28%. The CES investment in this scenario has a payback period of 8 years.

In the case of Terrace Housing communities, the optimized CES system achieved total energy savings for prosumers of 29%. The energy savings for individual households ranged from 18% to 32%. After considering the variable and fixed operation costs, the net savings for the community amount to 24%, with the CES investment yielding a payback period of 12 years. For the ideal TH community model, assuming an FTM implementation with free-of-charge energy sharing, the energy savings for households reached 46%. However, when operation costs are factored in, the net savings for the entire community are 31%, resulting in a significantly shorter payback period of only 6 years. The detailed financial breakdown of each community is presented in chapter 7.

4. How does the chosen CES integration method impact grid congestion for each of the identified communities?

For Multi-dwelling communities, two variations were tested. The initial variation, with no limits on community import and export from the grid, resulted in a profitable system for households but created consumption peaks due to the battery charging at moments of low prices for energy arbitrage. This led to a load peak increase of 232%. However, since it offered very little added profitability, this approach was discarded. A new variation with limitations on community export and import from the grid was then introduced. In terms of load smoothing, the total community grid import decreased by 23.8%, and the grid export decreased by 64.0%. Regarding peak shaving, the load peaks were reduced by 21.9%, while the feed-in peaks decreased by 30.8%.

The decrease in volume exported or imported to the grid was uniformly distributed among households within a certain range. However, the reduction in grid import peaks was unevenly distributed, primarily in households with initially high peaks, while households with low initial peaks saw no significant change.

For Terrace housing communities, only the peak shaving variant of the model was implemented, resulting in a decrease of 30.5% in community import and a decrease of 51.2% in community export. Similar to the Multi-dwelling communities, the decrease in volume exported or imported to the grid was uniformly distributed among households within a certain range. The reduction in grid import peaks was also unevenly distributed, mainly occurring in households with initially high peaks, whereas households with low initial peaks experienced no significant change.

8.2. Validation and limitations of the results

This section delves into presenting the limitations of of the results obtained based on the assumptions made in this research. Furthermore, it will validate the results and identify the associated uncertainties.

Representation of Communities:

The study primarily focused on specific communities, representing a large segment of the Dutch housing stock. However, the PV capacity data was derived from social housing solar installations, where PV systems typically match household consumption. This does not reflect the general trend in the Netherlands, where, due to the NEM scheme, households often possess PV systems exceeding their electric demand. This is particularly true for larger, standalone houses with ample roof space, which were not included in the defined communities. Consequently, our analysis may underestimate excess generation. The profitability prediction for CES is therefore modest and potential for more added value is present.

Optimization and Distribution Methodology:

The interaction between the grid, households, and battery systems was modeled using an optimization framework. This problem, utilizing full-year data, forecasted optimal solutions for every hour with perfect knowledge of the data of all the other hours in the year. While this represents an ideal control methodology, it diverges from real-world scenarios where future information is imperfect. This research therefor does not present the control algorithm of the Energy Management System of the CES. This gap opens avenues for future exploration. Additionally, a simplified approach is suggested and modeled for energy distribution but not optimized. Although the justifications for this choice are logically presented, they have not been scientifically validated. Thus, they primarily serve to demonstrate the distribution of benefits among community members. The allocation of costs and benefits within residential communities offers numerous possibilities, each contingent upon the chosen business model and local regulations and are of importance for future work.

Data Assumptions:

The optimization was based on data for the year 2023, assuming constant conditions over the battery's lifetime. This approach, necessitated by the lack of long-term, high-resolution data, is conservative. Current trends suggest a significant rise in prosumer electric loads due to electrification, emphasizing the growing importance of storage systems. Furthermore, projections indicate substantial increases in electricity prices up to 92% by 2030, according to a recent study published by PWC (2023), and a decrease in battery costs, deviating from our conservative estimates. These factors suggest that our conservative findings, likely further underrepresent the potential and business viability of CES systems post-2030.

Grid relief and Network effects:

The selected business model identifies grid relief as a key community value and outlines how this can be captured, including an estimation of its monetary value. However, these value capture mechanisms were not included in the final financial calculations for the system. This is due to the fact that certain value capture methods, such as congestion management, are not directly accessible for the Low Voltage (LV) grid. In the context of these projects, project developers often make contracts for flexibility services, but these are challenging to estimate or represent accurately. Therefore, the actual economics of the CES system could be higher if these factors were taken into account.

Additionally, an important dimension of the morphological business model in the context of the proposed system is network effects. The aggregation and coordination of multiple CES systems can significantly enhance the scope and value of these systems' services. However, these benefits depend on large-scale emergence, and due to the current uncertainty in this area, they have not been considered in this phase of research. Nevertheless, these network effects potentially strengthen the business case for the emergence of CES systems.

System Design:

Finally, and most importantly, both system design topologies attempted to navigate the current regulations and market design conditions to offer a feasible solution. However, they both require significant effort, involvement and cooperation of various stakeholders, such as DSOs, governmental bodies, and energy providers or ESCOs. This is particularly pertinent as these solutions represent new complex interventions for the Dutch grid.

Nevertheless, there is growing interest in such solutions in the Netherlands, and the concept of energy cooperatives forming energy communities is rapidly evolving with innovative applications introduced constantly.

8.3. Research reflection

8.3.1. Future Work

This research encompasses a multidisciplinary scope, involving technical, regulatory, economic, social, and environmental dimensions. While it primarily addresses the technical, regulatory, and financial aspects, there remains ample scope for future work across all these disciplines.

Regulatory, future research should concentrate on policy design and the regulatory framework to simulate the development of energy communities within residential settings. This could include examining the impacts of introducing new policy instruments and adjusting current policies on residential communities. Key areas for exploration include regulations related to micro-grid formation, energy sharing transactions, energy taxation and community formation.

Technical studies could delve focus on both micro-grid and central-grid formation and their influence on grid power dynamics. Moreover, it can focus on the high emergnece scenario's of these communities and associated the effect on grid congestion. Another crucial area is optimizing energy distribution and developing control algorithms for energy management systems in storage solutions integrated with residential communities.

Economic studies might explore various models for cost and benefit allocation and ownership within the energy sharing business model. This can help in understanding the financial feasibility and sustainability of such models.

Social research could investigate the dynamics of community formation within residential areas and strategies to enhance household involvement and contribution to future energy systems. This can include studying community engagement models and their effectiveness in promoting sustainable energy practices.

Finally, environmental studies have the potential to assess the impact of energy communities on CO2 reduction targets. By quantifying the environmental benefits of these communities, such studies can provide valuable insights into their role in achieving broader sustainability goals.

8.3.2. Academic and societal relevance

Addition to academic knowledge

This research offered a comprehensive examination of community energy storage, showcasing its potential and evaluating various aspects. It lightly touched upon its regulatory, technical, and economic implications. This was achieved by developing a business model complete with a technical system topology and an integration strategy, while also considering the regulatory challenges and constraints. The study provided new insights into the technical challenges and opportunities associated with central community storage, particularly its role in enhancing consumer profitability and reducing grid congestion in residential areas in the Netherlands. Furthermore, it contributes significantly to the ongoing research in the Dutch government and European directives, specifically concerning the phase-out of the Net Energy Metering (NEM) scheme and the broader formation of energy communities.

Therefore, this work can serve as a foundational reference for future studies in the various disciplines related to community storage systems and post-NEM market solutions. Additionally, the processed data, models, and final assessments presented in this research can be utilized by other researchers for further studies in this field, promoting a deeper understanding and continued exploration of community energy storage solutions.

Impact on society and industry

In the context of Dutch energy networks, one of the main question is the future landscape post-Net Energy Metering. Currently, individual batteries represent the sole market solution, despite their limitations. Alternatives like community storage are being cautiously explored, but there is a noticeable absence of policies, technical and economical frameworks to enable and support such developments. This research contributes to policymakers by demonstrating the potential of Centralized Energy Storage and identifying key policies critical for its emergence. Furthermore, the valuation assessment of CES provided here can serve as a reference point for understanding the solution's potential. Two major policy obstacles are highlighted: the taxation issue as a primary constraint for CES and the lack of frameworks for community grid formation.

For Distribution System Operators, energy providers, Energy Service Companies, housing cooperatives, and other stakeholders in the industry, this research offers a comprehensive overview for consideration in their involvement and cooperation in CES and energy community initiatives. It presents a detailed business model and a case study on how CES can be implemented through housing cooperatives, paving the way for its emergence and adoption. This research lays a piratical foundational basis that can be further expanded upon to develop CES initiatives.

8.3.3. Personal reflection

While this research has not yet been defended or reviewed by my supervisors, I can offer my reflections on the process and experiences during this period. As mentioned in the preface, the genesis of this research initiated from the industry's need for solutions. There was a growing interest within energy networks for diverse answers, and community energy storage emerged as a potential solution in my view. However, initially, this was merely an enthusiastic idea, and I faced considerable challenges in transforming it into a research project grounded in the existing gaps in literature. The field is riddled with numerous gaps, and my initial ambition was to address them all. After some fine-tuning, including revising the research question and methodology, I identified a crucial gap that could be feasibly addressed within the timeframe of this research.

One significant challenge was the lack of collaboration with industry stakeholders, DSOs, companies, or government entities, which left me uncertain about the perspective to focus on. Additionally, since the research did not fall within any defined research trajectory at TU Delft, it was initially unclear where to start and what specific aspects would be of interest. This clarity only emerged midway through the journey, after extensive review of related literature and diving into policy frameworks.

This endeavor led to the acquisition of niche information about large-scale storage in the Netherlands, which I believe will bolster my opportunities for further development in this field. Ultimately, I managed to explore the majority of topics that intrigued me, though some areas of curiosity remain open for future research.

9 Conclusions

9.1. Answers to the main research question

This research addresses the question: "*How can centralized community energy storage be implemented to improve the profitability of prosumers and alleviate grid congestion following the NEM-scheme phase out in the solar residential market in the Netherlands?*" Key findings from sub-research questions are synthesized to provide a comprehensive conclusion.

The identified optimal application combines energy sharing combined with energy arbitrage. This model offers prosumers increased value from their surplus photovoltaic (PV) energy, surpassing standard feed-in tariffs and avoiding charges for grid energy feedback. For consumers, this model allows access to shared community energy, potentially more affordable than traditional energy sources. Moreover, for DSO, such energy sharing can mitigate grid congestion, leading to better infrastructure capacity utilization.

Widespread adoption is best achieved through housing cooperatives or homeowner associations, in collaboration with Energy Service Companies (ESCOs). Financially, the community manager oversees initial investments, while households contribute through usage-based or fixed service fees.

The business model's efficacy depends on the grid connection type. Behind-The-Meter (BTM) offers flexibility but lacks standardization, while Front-of-The-Meter (FTM) faces community energy taxation challenges. Testing both types, considering only consumer-prosumer value capture, indicate a total energy savings of 28% for MDU communities, with a 6-year payback period. For Terrace Housing communities, savings are 24%, leading to a 12-year payback period, which could decrease to 6 years in an optimal, tax-free scenario. Load smoothing results show a reduction in total grid import by 23.8% for MDUs and 30.5% for Terrace Housing, while grid exports decreased by 64.0% for MDUs and 51.2% for Terrace Housing. Peak shaving achievements include a 20% reduction in load peaks and around a 30% decrease in feed-in peaks for both community types.

In conclusion, this study demonstrates that centralized CES can significantly enhance prosumer profitability and reduce grid congestion, offering considerable energy savings and improved grid performance in the Dutch solar residential market.

9.2. Recommendations

For Policy Makers:

To facilitate the growth of Community Energy Storage (CES) systems and energy communities, policymakers should focus on adjusting energy taxation policies and developing frameworks to support community grid formation. This includes simplifying regulatory processes and introducing incentives for residential energy community initiatives. Addressing taxation issues as primary constraints for CES and establishing clear guidelines for community grid formation are crucial steps towards fostering a supportive environment for energy community development.

For Researchers:

Researchers should concentrate on a multidisciplinary approach encompassing regulatory, technical, economic, social, and environmental aspects of CES. This includes studying the impact of regulatory frameworks on residential energy communities, exploring grid dynamics with micro-grid integration, investigating cost and benefit allocation models in energy sharing business models, understanding community engagement in sustainable energy practices, and quantifying the environmental benefits of energy communities. Each of these areas offers substantial opportunities for advancing knowledge and practical applications in the field of community energy storage.

For Industry Stakeholders:

Industry stakeholders, including Distribution System Operators, energy providers, Energy Service Companies, and housing cooperatives, should utilize the research findings to guide the development and implementation of CES systems. This involves fostering partnerships and collaborative efforts to explore practical CES initiatives, addressing the technical, economic, and regulatory challenges identified. Additionally, focusing on innovative energy solutions that cater to the market needs in the post-Net Energy Metering landscape is essential for advancing the role of community storage in sustainable energy systems.

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A
Appendix

A.1. Background Information

A.1.1. Solar Energy Market in the Netherlands

The Netherlands represents an important player in the European PV industry. In 2022, the Netherlands had an overall PV capacity installed of 14.3 GW, positioning it as the country with the second largest per capita PV installation worldwide (solar power Europe, 2022), with Australia leading the first place and Germany following in a close third place. According to reports from the International Renewable Energy Agency (IRENA), by 2019 the Netherlands was consuming 8% of its total energy from renewable sources, it was also determined that solar power represented 62% of the renewable capacity of the country by 2021 (IRENA, 2019). Considering that the Netherlands features a Compound Annual Growth Rate (CAGR) of 21%, the growth capacity from 2022 to 2025 will surpass the 4 GW added capacity per year as can be seen in figure 1 (solar power Europe, 2022). In 2015, around 232,000 prosumers were connected to the power grid and delivered solar power, it is expected that by 2025 that number would have more than doubled to 582,000 and reach 785,000 by 2030 (gfk belgium consortium for the european Commission, 2017)

Moreover, the solar energy market of the Netherlands holds a wide variety of key stakeholders in different sectors. Some of the most important ones include PV manufacturers and researchers like Sunrise Energy Co., Ltd, Triple Solar BV, and other companies that produce batteries, PV mounting systems, and many other products. Other important stakeholders include the Authority for Consumers & Markets (ACM), the Dutch government that passes legislations, as well as electric utilities that are affected by the number of prosumers and sell electricity under Solar Power Purchase Agreements (PPAs). Additionally, there are nearly 1.8 million residential prosumers alongside many other commercial and industrial players in the PV market, as well as public and private stakeholders operating in the country (dutch News, 2023;international energy Agency, 2022;Huijben and Verbong, 2013b;solar power Europe, 2022).

Figure A.1: Netherlands Solar PV Market Scenario: Historical and forecast for 2022-2025 (solar power Europe, 2022)

Financial Structure of the Current Solar Residential Market

One of the key factors determining the success of the PV market in the Netherlands has been the evolution of the financial structure in the solar residential sector. The residential solar market in the Netherlands is comprised mostly of grid-tied systems, hence, they are able to take advantage of the NEM scheme, but off-grid PV systems are not entirely uncommon, and several other business models have been explored throughout the years including Community Solar, Solar Shares, Virtual Power Plant, and others. However, the ones that are being kept for experimentation are customer-owned PV systems (gridtied and off-grid), Community Shares, and Third-Party owned PV systems also known as Solar Power Purchase Agreement (PPA) (Huijben and Verbong, 2013b;Londo et al., 2020).

In terms of pricing evolution, the period between 2008 and 2012 saw the largest drop in prices. According to Huijben & Vergong, the cost for PV modules decreased from $4 per Wp in 2008 down to $1 per Wp in 2012, but this drastic cost reduction drove several European PV manufacturers out of the market and into bankruptcy during those years since they could not keep up with the low prices. Van Sark & Schoen confirmed the previous statement by establishing that the PV module price in 2016 would be close to €1 per Wp. Following this study, an average PV system of 5 kWp installed in the Netherlands, would cost around €6,300.00, considering only components before the installation, and would increase to around €7,800 considering the cost after installation for a total system price of €1.56/Wp. Additionally, in a more recent study of 2020, Londo, et al. makes historical and future projections of the full installation cost in a 4.5kWp system as can be seen in Figure 2. Results estimate a similar cost of €1 per Wp for 2024 – 2025, and even a lower one for later years.

Moreover, while PV systems can be paid upfront, most citizens can access a loan scheme with a 1.4% interest rate in a 10-15 year period. (gfk belgium consortium for the european Commission, 2017;Van Sark et al., 2017). The availability for financing options together with lower PV system costs in the Netherlands has allowed the solar market to thrive in the country, however, there is another important market player in the solar industry and that is the policy sector.

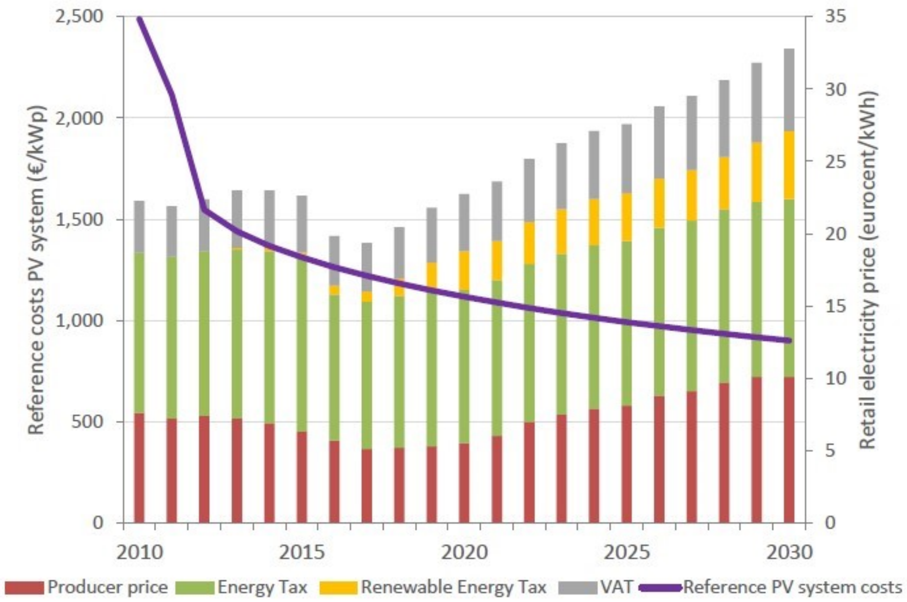

Figure A.2: Cost of a PV system compared to the retail cost of electricity (Londo et al., 2020)

Existing Government Policies and Incentives for Residential Solar Power

The Dutch Government instated various financial incentives in 2008 which were updated in the following years, under the Stimulating the production of Sustainable Energy (SED) program (Kattenberg et al., 2022), partially to comply with the EU target, but also to achieve its target of reducing Greenhouse Gas (GHG) emissions. These policies attempt to incentivize citizens to purchase renewable energy technologies to reduce 49% of GHG emissions by 2030 and 95% of them by 2050, considering as a reference the emissions released in 1990 (Netherlands, 2019). When subsidies began to roll out, Dutch citizens applied for these incentives in large numbers, sending around 15,000 applications after opening in 2008, 2009, and 2010. Applications were collected by the government and a lottery selected the granted applications (Kattenberg et al., 2022).

The main subsidies created by the Netherlands Government to help private households and businesses to increase PV technology acquisition included the Energy Tax Rebate, the Renewable Energy Grant Scheme (SDE+) (only available for companies operating a PV farm), the Crediting electricity supplied to the grid (better known as the NEM scheme), and the Sustainable Energy Investment Grants (ISDE) reducing the cost of solar water heating systems (Government of the Netherlands). The most popular subsidies for residential customers have been the NEM scheme, enjoying high success in the Netherlands, and the Energy Tax Rebate which has reduced the overall expenses of electricity for residential customers (Huijben and Verbong, 2013b). Other subsidies like the SDE+ (later known as SDE++) and the ISDE have also proven to be great tools to incentivize the acquisition of rooftop PV modules and alternative PV technologies (Iskandarova et al., 2021).

A.2. Literature review: Case studies

A.2.1. Bibliography

Low voltage power grid congestion reduction using a community battery: Design principles, control, and experimental validation. *van Westering & Hellendoorn. (2020)*

The paper analyzes the integration of a community battery in the suburban village of Rijenhout, located in the Netherlands. The battery was placed in the low voltage network of Rijenhout by Liander, the Distribution Network Operator (DNO), it features a peak power rating of 55 kW and a capacity of 126 kWh. The authors report on aspects of using a DNO community battery including control strategies for low-voltage network congestion management, control of the voltage and current, and increasing the capacity of the grid. Key findings include the construction of a work model backed by experimental results, providing a solid foundation that residential and community-level batteries can be integrated into low-voltage networks. The work model can accurately stabilize a power network by stabilizing and controlling the loads and is scalable to a large extent.

Energy communities: a Dutch case study *Reijnders, van der Laan, & Dijkstra (2020)*

The authors in the paper analyze the impact of not one single community battery, but a group of batteries installed throughout the community's local grid. The paper simulates the installation of 24 batteries featuring a 5 kWh capacity, the batteries are distributed throughout the local grid in the community of Heeten, and consumers of the local grid are offered dynamic grid tariffs. The project used software to virtually simulate the batteries, providing real-time consumption data and projections on the positive impact on the power grid.

Optimal Management of an Energy Community with PV and Battery-Energy-Storage Systems *Aranzabal, Gomez-Cornejo, Lopez, Zubiria, Mazón, Feijoo-Arostegui, & Gaztañaga (2023)*

A Virtual Power Plant (VPP) was considered by analyzing the data of five prosumers with residential batteries. The information in this paper can be adapted in size to analyze the potential of a terrace housing community with PV systems to install a CES system. The authors analyzed data from different prosumers but modeled it as if they were a community with a shared PV system featuring a CES system for the whole group. The paper analyzes different scenarios considering a PV system and community batteries. The results prove the economic advantages of this configuration on a 15-year basis, assuming that no replacement will be required for the CES system thanks to the moderate use of the battery. The most benefited type of consumers are those with higher energy requirements, while those consuming less than 2,000 kWh per year have increased energy supply expenses.

Community Energy Markets with Battery Energy Storage Systems: A General Modeling with Applications *Guedes, Deotti, Dias, Soares, and de Oliveira (2022)*

The paper illustrates the benefits of installing a BESS or community battery to achieve energy independence in the context of a community and the advantages that it can provide for the local energy market. To deal with the complexity of the energy dynamics, the authors model each of the community agents as a consumer, producer, or prosumer, within this context any of the community agents may be consuming or producing electricity at any given point in time and be perceived as such within the community, but the producer/consumer state of the community may be different as seen from the external market, that perceives the entire community as a single community agent. A linear optimization model was developed by the authors to maximize the revenue from the energy transactions in the studied community. The model developed in the paper is highly adaptable to different types of communities and contingencies. The authors explain that when the battery is seen from the point of view of the community, it provides energy autonomy to its members by reducing dependence on the power grid and therefore from the external energy market, simultaneously when the battery is seen as a single agent or unit from the external market, it also provides advantages to other communities as the battery reduces peak consumption and therefore stabilizes the energy cost consumed from the power grid.

Assessing the Impacts of Community Energy Storage Systems on the German Electricity Market: An Agent-based Analysis *Safarazi, Deissnroth-Uhrig, and Bertsch (2020)*

Similar to the Netherlands, the German electrical grid is currently suffering from an overproduction of renewable energy, which is why it has to curtail its renewable power production to some degree. The paper Assessing the Impacts of Community Energy Storage Systems on the German Electricity Market: An Agent-based Analysis studies how community batteries would affect the local power grid and if they provide a solution to this energy curtailment. The authors analyze the power grid using an agent-based model called AMIRIS and a single community battery. They study three scenarios: (1) No CES battery, (2) a CES with a profit-maximizing strategy, and (3) a CES with an autonomy-maximizing strategy. The paper determines that while a profitmaximizing strategy or even combining the strategy (2) and (3) may provide benefits, the best solution for energy curtailment is fully adopting an autonomy-maximizing strategy, which also provides profit benefits when the community is producing more energy than it can consume or store.

Establishing the value of community energy storage: a comparative analysis of the UK and Germany *Dong,* *Kremers, Brucoli, Rothman, and Brown (2021)*

The paper by Dong, Kremers, Brucoli, Rothman, and Brown (2021) aims to illustrate the different capabilities of a CES to mitigate PV losses and improve energy independence by promoting solar selfconsumption. The authors analyze three communities of 10 households each with rooftop PV installations, located in Germany and the UK. The same PV system size and battery capacity have been considered in both countries in an attempt to analyze the performance difference in both cases. The result of the paper illustrates that Germany can produce around 30% more savings by installing a CES system as a result of the country featuring a much richer solar resource. Communities in the UK can also save money and reduce their carbon footprint, however, this result illustrates the importance of considering the solar irradiance for the country to estimate the performance of the system. As a result of this performance, the ROI for PV systems and CES is lower in Germany than in the UK.

Homogenising the Design Criteria of a Community Battery Energy Storage for Better Grid Integration *Hayat, Shahnia, Shafiullah, and Samu (2022)*

The paper analyzes a small community to determine the advantages of installing a CES to eliminate the duck curve profile, achieve community self-sufficiency, and shave consumption peaks. For the concept evaluation, the authors considered a community featuring 3 to 10 households with rooftop PV installations with an installed capacity of 10 kWp, and 5 to 50 households that will act exclusively as consumers interested in purchasing energy from the CES under a PPA contract. The storage capacity for the battery ranged from 20 to 600 kWh depending on the initial factors. The authors determine that satisfying all the outlined goals for the study may be more ambitious than initially thought. In most cases it is possible to achieve a high peak shaving and mitigate the duck curve profile, however, according to the data, the duck curve profile becomes more prominent as the design of the entire configuration is more focused on self-sufficiency.

Allocation of Physical Storage Rights in Local Energy Communities *Aprajita, Patwari, and Sharma (2022)*

One of the major setbacks of community batteries is acquiring the storage infrastructure to be shared by all members of a community, usually, the investment cost is too high to be carried out by the community without the intervention of a private or public external agent. In the paper by Aprajita, Patwari, and Sharma (2022), a methodology is proposed to solve this inconvenience with an integration approach that sells day-ahead physical rights to members of the community. The paper proposes that a few members of the community or a third-party company invest in acquiring the battery and make a profit as community members buy storage rights. The storage rights may be to store electricity, consume it, or both. The auction for the physical storage rights is carried out a day-ahead and lasts for 24 hours, the capacity that each community member can reserve depends on its load/generation profile.

Battery Energy Storage Systems to Support the Large-Scale Integration of Renewable Energy *European Commission (2022)*

The European Commission studies several integration approaches for Battery Energy Storage Systems (BESS), which can also be adapted into community batteries. The case study reviews demonstration projects performed by several European companies to support the integration of renewable energy resources such as BESS on a large scale. One of the most important demonstrations is the one performed in the Finnish demonstration by the EU-SysFlex company. This approach aims to integrate effective solutions for industrial-scale and medium-scale batteries, some of which can be easily adapted to CES and provide a working model for the case of the Netherlands

Demonstrators for Flexibility Provision from Decentralized Resources, Common View *EU-SysFlex (2021)*

The paper Demonstrators for Flexibility Provision from Decentralized Resources, Common View, studies different approaches to integrating Renewable Energy Resources (RES) into the power grid to reduce carbon emissions and increase the resiliency of the grid. Some of the demonstrations studied include the integration of medium-scale or industrial-scale batteries such as the specific case of the Finnish demonstrator, which integrates an industrial-scale battery into the local power grid. The integration approach studied in this paper provides an interesting methodology for integrating community batteries into the local power grid. Such an approach can reduce the size of the battery or increase it to accommodate the tailored needs of the community, but it can adapt the smart capabilities studied in the demonstration, which provides a more efficient usage of BESS.

Market Integration of Distributed Energy Resources *IRENA (2019)*

The IRENA (2019) studies the market integration of distributed energy resources to demonstrate some of the benefits such as load shifting, peak shaving, the provision of ancillary services, network congestion management, and improved planning for the generation capacity of a country. The brief introduces enabling technologies, business models, market designs, and system operation recommendations for the integration of such energy resources. This brief also addresses policies and regulatory requirements that will be needed to address the integration of such batteries, providing the necessary documentation that can help not only CES installers but also policymakers attempting to promote the large-scale acquisition of these types of community batteries.

Energy Communities: Tools to Build Them and Make Them Thrive *European Commission (2022)*

The European Commission (2022) presents a number of tools that are designed by companies such as E-LAND, Compile, eNeuron, Hestia, and LocalRES. These tools provide installers with the possibility to create a project with specific information for the individual case of each community. The tools presented in this brief not only provide technical configuration analysis but also business models that can be adapted to each European country and software to operate the community battery long after it has been installed and integrated into the community.

A.2.2. Catalogue of Integration Approaches:

General Model for the Installation of a Community Battery for Consumers, Producers, and Prosumagers

One of the most important integration approaches is the general case that analyzes a community with different agents integrating the group, including the traditional consumer, consumers with a PV system installed, and even prosumers featuring a PV system and a residential battery. The papers that integrate this particular approach show promising results since they feature different configurations and show high adaptability and scalability in each case.
The paper by Guedes, Deotti, Dias, Soares, and de Oliveira (2022) studies a general linearization model that can be adapted to communities of different sizes. Each member of the community is cataloged as a consumer, producer, or prosumer. A community battery is integrated into the local grid of this research group with an individual meter and it is analyzed using two points of view: (1) a point of view from within the community and (2) another point of view seen from the external energy market or other communities. From within the community, the integration approach considers each prosumer as a produce/consumer with the capacity to store energy, consumers as traditional loads, and producers as PV systems integrated into the power grid, each of them fulfilling a role to either produce energy, produce it and consume, or simply produce it. The community can still buy and sell energy from the local power grid when necessary, perceived as a positive influence on the members of the community and the market as it reduces electricity price fluctuations and improves energy quality for the grid.

Safarazi, Deissnroth-Uhrig, and Bertsch (2020) analyze a similar case in the German power grid in an attempt to determine the best business model and approach for CES systems. The authors determine that a CES with a goal of energy autonomy is the recommended course of action, especially in a country that needs to curtail its renewable energy production such as Germany. The similarity of the German case with the Netherlands suggests that the massive adoption of CES in the Netherlands could potentially reduce the congestion of the power grid and reduce the urgency of the Dutch government to phase out the Net Metering system. The paper also highlights the requirement for a proper regulatory framework to incentivize the adoption of community energy systems.

The paper by Hayat, Shahnia, Shafiullah, and Samu (2022) proposes an interesting approach to the general case of installing a CES system with a different business model. The study proposes installing a smart meter at the entryway of each home to measure generated/consumed energy and the creation of a Power Purchase Agreement (PPA) contract between consumers and prosumers, the contract states that consumers will pay prosumers for the generated solar power that is stored in the battery and consumed by homes, instead of consuming electricity directly from the grid. Any excess energy will be extracted from the grid and charged as traditional energy. This approach prioritizes self-sufficiency to reduce CO2 emissions and positively impact the transmission power grid.

Integration of a Community Battery on a Low-Voltage Network Using a Charge Path Optimizer:

A community battery is connected to the low voltage network of the community using a custom battery controller such as a receding horizon charge path optimizer to combine control strategies that will operate the community battery in a real-time grid model, proposing a technical design similar to that of a micro-grid. The community battery with the receding horizon charge path optimizer provides control over the voltage and the current delivered to the load, it also stabilizes energy quality in the power grid.

The integration approach uses the following methodology: calculation of the characteristics of the low voltage network, linearization of the load flow equations using a constant impedance load model, formulation of a battery control problem, and finally application of the model to the specific characteristics of the community, analyzing the accuracy of the result. After the model is created, a battery system is designed with the proper control system to implement in the community.

The paper written by van Westering & Hellendoorn (2020) states that community batteries can be 56% cheaper compared to residential storage systems. While the authors do not specify any business models integrated with the community battery, they explain that this integration approach can be combined with energy trading and energy independence business models.

Installation of 5 kWh batteries distributed throughout a local grid:

The study case of Heeten in the paper by Reijnders, van der Laan, & Dijkstra (2020), provides valuable information on an energy community application that implements several batteries distributed throughout a local grid, implementing a dynamic grid tariff business model. To simulate the project, the open-source Decentralized Energy Management toolkit (DEMkit) was used to model the Heeten community. The software provides control over the batteries and real-time information on the consumption of the users and the impact reduction on the power grid.

The integration approach required an exemption from the law to charge homeowners in Heeten with a dynamic tariff. This law regulation could provide a challenge if the model is adopted large scale until the Dutch government abolishes this law. One of the most important advantages of this integration approach that places batteries in different physical locations of the power grid instead of one single battery is reduced power losses caused by the energy being transferred in small routes, also reducing the congestion of the power grid in peak hours, making better use of the electrical components in the power grid such as the power transformers. Some key findings in the project include the reduction of the peak consumption from 39 kW down to 25 kW (39%), savings of 1,500€ for the entire neighborhood, and less frequency on high peak demands.

Installation of a community PV system + CES system operated as a VPP or micro-grid:

A convenient integration approach combines a community with homes having rooftop PV installations combined with a CES system. These communities create the perfect opportunity to combine a relatively low Return on Investment (ROI) for PV systems while enjoying all the benefits of community batteries. In most cases, the approach involves installing a simple 3 – 5 kWp rooftop PV system and a battery that will allocate 2 kWh up to 4.5 kWh per household with a 20% to 80% Depth of Discharge (DOD) to extend the lifespan of the batteries. A technical approach would recommend installing smart meters to determine the consumption/generation profile for each home regarding the community battery, excess generated solar power is accredited to each home as it is sent from the home to the battery and those credits are consumed when the home requires more energy than it can produce.

One of the most important papers analyzing this integration approach, written by Dong, Kremers, Brucoli, Rothman, and Brown (2021), analyses study cases in the UK and Germany, two countries with different solar profiles. To simplify the linearization of the communities, each household is considered to have a 3 kWp system, while the demand profile is simulated considering the household diversity for each country. The paper illustrates that communities with CES systems in countries with solar irradiance, tariffs, and other similarities to those of German homes can be up to 30% more self-sufficient than countries with the characteristics of the UK.

Another paper that contributes to this integration approach is "Optimal Management of an Energy Community with PV and Battery-Energy-Storage Systems". The authors of this paper gathered data from November 2021 to November 2022, analyzing and modeling five Spanish prosumers and their residential storage systems as if they were a single community with a VPP or a micro-grid, sharing a community PV system with a CES system, which could provide a suitable model for a terrace housing community working with a shared PV and CES system. This model can be scaled for different communities.

The paper proposes an algorithm that aims to maximize PV + BESS energy self-consumption most of the time. An important consideration to extend the lifespan of the batteries was to implement strategies to keep SoC for the system under secure values while maximizing revenue, keeping the battery ideally between 15% and 85%, but setting security limits of 5% and 95% for it.

The CES system does not only provide self-consumption services for the community, but it also aims to work as a Frequency Restoration Reserve (FRR) for DNO under energy market participation bidding successfully thanks to fixed historical data. The business model proposes buying/selling energy considering the deficit or surplus of the energy generated with the community PV system and the energy stored in the CES system regarding the daily load of the community, any excess energy is bid to the market operation in a bidding offer. This work model considers a day-ahead schedule using fixed data, real-time operation considering hourly modifications regarding the fixed data and re-scheduling operations varying on the SoC for the community battery.

Selling Day-Ahead Physical Storage Rights in Local Energy Communities

The paper Allocation of Physical Storage Rights in Local Energy Communities proposes an integration approach where a community battery is installed in a physical location close to the community and it is owned either by members of the community or a private company. The storage owner is not the same entity supervising the operation of the battery, this process is supervised by an impartial agent known as the Community Manage, which mediates between the market and the system operators, to ensure a transparent process. Every 24 hours a periodical competitive auction is held to distribute the storage rights of the community battery to its members, selling the rights for 24 hours. To achieve this a smart metering infrastructure is required to (1) determine the charge/discharge profile of each home, (2) provide active participation for each consumer/prosumer in the bid for rights to use the battery, (3) a control system that limits the power sent/consumed from the home to the battery, sending and consuming the additional energy directly from the grid.

The capacity of the battery installed in the community is sized according to the generation capacity and load profiles of its members. A modular storage capacity is proposed to adapt to contingencies and plan for community growth. The business model used for the allocation of physical storage rights profits solar energy producers by granting them the right to sell electricity at high prices during peak hours or simply to consume it, regular grid customers can also acquire electricity at a profitable price and reduce their carbon footprint, finally DSO may arbitrate between the community market and the distribution system to shift loads or shave peak consumptions in the power grid, acting as an additional member of the community.

Some of the most important benefits of this integration approach include the possibility of having an external agent such as a private company invest in a community battery that will benefit all the members involved, solving one of the most important financial challenges present in the Netherlands for community batteries.

This approach will also provide a financial impact that will benefit prosumers and consumers, alongside reducing grid congestion and reducing peak consumption. This integration approach is mostly designed for communities featuring rooftop PV systems such as terrace housing communities, however, multidwelling units with communal PV systems located in the ground area of the property may also profit from it.

Market-Based Integration of Distributed Resources in Transmission System Operation

The integration approach demonstrated in the Finnish demo by EU-SysFlex (2021) and further explained in the document Battery Energy Storage Systems to Support the Large-Scale Integration of Renewable Energy by the European Commission (2022) provides a large-scale integration of multiple resources such as a 1.2MW/0.6MWh industrial-scale battery, 0.1MW/0.13MWh medium-scale battery, a conglomerate of 40kW in residential batteries, and a load equivalent to 22kW EV in charging points and 20 MW in residential heating. This approach aims to integrate the assets into Virtual Power Plants that will operate in the transmission and distribution network. Installing a community battery under this approach would provide low and medium voltage aggregation processes with flexible assets that could provide ancillary services such as frequency stabilization, and others.

The industrial-scale battery is connected to the 10 kV level in the power grid and operated by the DSO. Each customer in the community must include an AMR meter and access to information on its consumption, while simultaneously DSO has the technical ability to control the electric storage heating system of some residential customers via the AMR meters. The technical integration of this approach provides flexibility to the power grid in case of contingencies and further improves the development of the grid as a smart grid, the size of the battery can be adapted to smaller sized requirements to fit the needs of a community with PV capacity such as terrace housing community with rooftop PV systems or a multidwelling community with a communal PV array.

The IRENA (2019) studies a similar approach in its brief Market Integration of Distributed Energy Resources. The approach proposes the adoption of not only smart meters such as AMR meters but also home gateways and smart appliances that connect to this smart metering, providing control over certain loads through the IoT. This integration approach also implements an Aggregation and Integration Forecasting Software that provides real-time communication between all smart devices to shift the load and make good use of the community battery.

There are several advantages to this integration approach such as the implementation of a smart infrastructure that provides more control over the load, generation equipment such as a PV solar array, and the battery that is to power the load. This integration further promotes the transition to a smart grid and provides benefits to the local grid such as voltage regulation, frequency stabilization, and other ancillary services. It is important to highlight that supportive policies have to be adopted by the Dutch Government in an attempt to create functioning markets, reduce grid costs through the usage of these distributed energy resources, and deploy these smart technologies.

A.3. Electricity price composition

Construction of kWh Price in the Electricity Bill The price per kWh on the electricity bill in the Netherlands is constructed from several elements:

Supply Rate (*Leveringstarief*): This is the basic cost for the electricity used, which fluctuates based on the energy contract and the chosen supplier.

Fixed Supply Costs (*Vaste leveringskosten*): These consistent, fixed charges are levied by the energy supplier to cover administrative expenses.

Network Management Costs (*Netbeheerkosten*): This fee, set by the regional network operator, is for the use of the electricity network infrastructure and may differ by region.

Energy Tax, ODE, and VAT (*Energiebelasting, ODE, btw*): Taxes applied to every kWh of electricity consumed include the energy tax, the Sustainable Energy Supply levy (ODE), and a 21% VAT on all energy-related expenses. The energy supplier collects these taxes and remits them to the Tax Authority.

The sum of these components constitutes the final price per kWh presented on consumers' electricity bills, as shown in Table A.1. Notably, the energy tax rates are adjusted annually and have a significant influence on the overall kWh cost. Moreover, temporary policy changes, such as a VAT reduction for a designated period, also play a role in shaping the final price per kWh.

Cost Item	**Electricity (per kWh)**
Base energy price	€0.1959
Energy tax	€0.1525
VAT	€0.0732
Total	**€0.4216**

Table A.1: Cost overview of Electricity

A.4. Energy distribution calculation

Case 1: For each household h at time step t:

$$\begin{aligned}&buy_h^t = P^t_{h,buy,grid}, \quad sell_h^t = 0, \quad to\_com_h^t = 0,\\ &from\_com_h^t = 0, \quad to\_bat_h^t = 0, \quad from\_bat_h^t = 0\end{aligned}$$

Case 2:

$$a = \frac{\sum_{h=1}^{H} P^t_{h,sell,grid}}{\sum_{h=1}^{H} P^t_{h,buy,grid}} \text{ if } \sum_{h=1}^{H} P^t_{h,sell,grid} \neq 0 \text{ else } 0$$

For each household h at time step t:

$$\begin{aligned}&\text{If } P^t_{h,sell,grid} > 0 : buy_h^t = 0, \quad sell_h^t = 0, \quad to\_com_h^t = P^t_{h,sell,grid},\\ &from\_com_h^t = 0, \quad to\_bat_h^t = 0, \quad from\_bat_h^t = 0\\ &\text{Else if } P^t_{h,sell,grid} = 0 : buy_h^t = P^t_{h,buy,grid} \cdot (1-a), \quad sell_h^t = 0,\\ &to\_com_h^t = 0, \quad from\_com_h^t = P^t_{h,buy,grid} \cdot a, \quad to\_bat_h^t = 0, \quad from\_bat_h^t = 0\end{aligned}$$

Case 3:

For each household h at time step t:

$$\begin{aligned}&buy_h^t = 0, \quad sell_h^t = 0, \quad to\_com_h^t = 0,\\ &from\_com_h^t = 0, \quad to\_bat_h^t = 0, \quad from\_bat_h^t = P^t_{h,buy,grid}\end{aligned}$$

Case 4:

$$b = \frac{\text{dis}[t]}{\sum_{h=1}^{H} P^t_{h,buy,grid}} \text{ if } \sum_{h=1}^{H} P^t_{h,buy,grid} \neq 0 \text{ else } 0$$

For each household h at time step t:

$$\begin{aligned}&buy_h^t = P^t_{h,buy,grid} \cdot (1-b), \quad sell_h^t = 0,\\ &to\_com_h^t = 0, \quad from\_com_h^t = 0, \quad to\_bat_h^t = 0, \quad from\_bat_h^t = P^t_{h,buy,grid} \cdot b\end{aligned}$$

Case 5:

For each household h at time step t:

$$
\begin{aligned}
&\text{If } \sum_{h=1}^{H} P_{h,sell,grid}^t = 0:\\
&\quad buy_h^t = 0, \quad sell_h^t = 0, \quad to\_com_h^t = 0,\\
&\quad from\_com_h^t = 0, \quad to\_bat_h^t = 0, \quad from\_bat_h^t = P_{h,buy,grid}^t\\
&\text{Else if } \sum_{h=1}^{H} P_{h,sell,grid}^t > 0:\\
&\quad c = \frac{\sum_{h=1}^{H} P_{h,sell,grid}^t}{\sum_{h=1}^{H} P_{h,buy,grid}^t} \text{ if } \sum_{h=1}^{H} P_{h,buy,grid}^t \neq 0 \text{ else } 0\\
&\quad \text{If } P_{h,sell,grid}^t > 0:\\
&\qquad buy_h^t = 0, \quad sell_h^t = 0, \quad to\_com_h^t = P_{h,sell,grid}^t,\\
&\qquad from\_com_h^t = 0, \quad to\_bat_h^t = 0, \quad from\_bat_h^t = 0\\
&\quad \text{Else if } P_{h,sell,grid}^t = 0:\\
&\qquad buy_h^t = 0, \quad sell_h^t = 0, \quad to\_com_h^t = 0,\\
&\qquad from\_com_h^t = P_{h,buy,grid}^t \cdot c, \quad to\_bat_h^t = 0, \quad from\_bat_h^t = P_{h,buy,grid}^t \cdot (1-c)
\end{aligned}
$$

Case 6: For each household h at time step t:

$$
\begin{aligned}
&\text{If } \sum_{h=1}^{H} P_{h,sell,grid}^t = 0:\\
&\quad d = \frac{\text{dis}[t]}{\sum_{h=1}^{H} P_{h,buy,grid}^t} \text{ if } \sum_{h=1}^{H} P_{h,buy,grid}^t \neq 0 \text{ else } 0\\
&\quad \text{For each } h:\\
&\qquad buy_h^t = P_{h,buy,grid}^t \cdot (1-d), \quad sell_h^t = 0, \quad to\_com_h^t = 0,\\
&\qquad from\_com_h^t = 0, \quad to\_bat_h^t = 0, \quad from\_bat_h^t = P_{h,buy,grid}^t \cdot d\\
&\text{Else if } \sum_{h=1}^{H} P_{h,sell,grid}^t > 0:\\
&\quad e = \frac{\sum_{h=1}^{H} P_{h,sell,grid}^t}{\sum_{h=1}^{H} P_{h,buy,grid}^t}, \quad f = \frac{\text{dis}[t]}{\sum_{h=1}^{H} P_{h,buy,grid}^t}\\
&\quad \text{For each } h:\\
&\qquad \text{If } P_{h,sell,grid}^t > 0:\\
&\qquad\quad buy_h^t = 0, \quad sell_h^t = 0, \quad to\_com_h^t = P_{h,sell,grid}^t,\\
&\qquad\quad from\_com_h^t = 0, \quad to\_bat_h^t = 0, \quad from\_bat_h^t = 0\\
&\qquad \text{Else if } P_{h,sell,grid}^t = 0:\\
&\qquad\quad buy_h^t = P_{h,buy,grid}^t \cdot (1-e-f), \quad sell_h^t = 0,\\
&\qquad\quad to\_com_h^t = 0, \quad from\_com_h^t = P_{h,buy,grid}^t \cdot e, \quad to\_bat_h^t = 0, \quad from\_bat_h^t = P_{h,buy,grid}^t \cdot f
\end{aligned}
$$

Case 7:
For each household h at time step t:

If $P^t_{h,sell,grid} > 0$:

$$h_{ratio} = \frac{\sum_{h=1}^{H} P^t_{h,buy,grid}}{\sum_{h=1}^{H} P^t_{h,sell,grid}} \text{ if } \sum_{h=1}^{H} P^t_{h,sell,grid} \neq 0 \text{ else } 0$$

$$buy^t_h = 0, \quad sell^t_h = 0, \quad to\_com^t_h = P^t_{h,sell,grid} \cdot h_{ratio},$$

$$from\_com^t_h = 0, \quad to\_bat^t_h = P^t_{h,sell,grid} \cdot (1 - h_{ratio}), \quad from\_bat^t_h = 0$$

Else if $P^t_{h,sell,grid} = 0$:

$$buy^t_h = 0, \quad sell^t_h = 0, \quad to\_com^t_h = 0,$$

$$from\_com^t_h = P^t_{h,buy,grid}, \quad to\_bat^t_h = 0, \quad from\_bat^t_h = 0$$

Case 8:

$$j = \frac{\sum_{h=1}^{H} P^t_{h,buy,grid}}{\sum_{h=1}^{H} P^t_{h,sell,grid}} \text{ if } \sum_{h=1}^{H} P^t_{h,sell,grid} \neq 0 \text{ else } 0$$

For each household h at time step t :

If $P^t_{h,sell,grid} > 0 : buy^t_h = 0, \quad sell^t_h = P^t_{h,sell,grid} \cdot (1 - j),$

$to\_com^t_h = P^t_{h,sell,grid} \cdot j, \quad from\_com^t_h = 0, \quad to\_bat^t_h = 0, \quad from\_bat^t_h = 0$

Else if $P^t_{h,sell,grid} = 0 : buy^t_h = 0, \quad sell^t_h = 0,$

$to\_com^t_h = 0, \quad from\_com^t_h = P^t_{h,buy,grid}, \quad to\_bat^t_h = 0, \quad from\_bat^t_h = 0$

Case 9:

$$x = \frac{\sum_{h=1}^{H} P^t_{h,buy,grid}}{\sum_{h=1}^{H} P^t_{h,sell,grid}} \text{ if } \sum_{h=1}^{H} P^t_{h,sell,grid} \neq 0 \text{ else } 0$$

$$y = \frac{\text{cha}[t]}{\sum_{h=1}^{H} P^t_{h,sell,grid}} \text{ if } \sum_{h=1}^{H} P^t_{h,sell,grid} \neq 0 \text{ else } 0$$

For each household h at time step t :

If $P^t_{h,sell,grid} > 0 : buy^t_h = 0, \quad sell^t_h = P^t_{h,sell,grid} \cdot (1 - x - y),$

$to\_com^t_h = P^t_{h,sell,grid} \cdot x, \quad from\_com^t_h = 0, \quad to\_bat^t_h = P^t_{h,sell,grid} \cdot y, \quad from\_bat^t_h = 0$

Else if $P^t_{h,sell,grid} = 0 : buy^t_h = 0, \quad sell^t_h = 0,$

$to\_com^t_h = 0, \quad from\_com^t_h = P^t_{h,buy,grid}, \quad to\_bat^t_h = 0, \quad from\_bat^t_h = 0$

1. **Battery State of Charge Limits:**

$$SOC_{min} \times C_B \leq E_{bat}^t \leq SOC_{max} \times C_B$$

2. **Battery Charging Power Limits:**

$$0 \leq P_{char}^t \leq P_{bat,max}$$

3. **Battery Discharging Power Limits:**

$$0 \leq P_{dis}^t \leq P_{bat,max}$$

4. **Grid Selling Power Limits:**
$P_{sell,grid}^{max}$, can further be adjusted for peak shaving.

$$0 \leq P_{sell,grid}^t \leq P_{sell,grid,max}$$

5. **Grid Buying Power Limits:**

$$0 \leq P_{buy,grid}^t \leq P_{buy,grid,max}$$

6. **Battery Capacity Decision Variable:**

$$C_B \in \{C_{B_1}, C_{B_2}, \ldots, C_{B_n}\}$$

1. **Energy Balance of the System:**

$$P_{sell,grid}^t - P_{buy,grid}^t = P_{PV}^t - E_{comm}^t - P_{char}^t + P_{dis}^t$$

2. **Initial Battery State of Charge:**

$$E_{bat}^1 = C_B \times SOC_{init} + (\eta_{Bat} \times P_{char}^1) - \left(\frac{P_{dis}^1}{\eta_{Bat}}\right)$$

3. **Battery State of Charge for Subsequent Time Periods:**

$$E_{bat}^t = E_{bat}^{t-1} + (\eta_{Bat} \times P_{char}^t) - \left(\frac{P_{dis}^t}{\eta_{Bat}}\right)$$