End-user Economics of PV-coupled Residential Battery Systems in the Netherlands

MASTER'S THESIS – MSC ENERGY SCIENCE

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Abstract

Due to a decline in prices of lithium-ion battery storage systems, a steep growth in photovoltaic installations in the Netherlands, and the announced phasing out of Dutch net metering policy, residential PV-coupled battery electric storage systems (PV-BESS) are attracting more research as well as more interest of the Dutch PV market. In this paper the end-user economics and policy dependencies of PV-BESS in the Netherlands were studied. In addition, an understanding of the Dutch market potential of lithium-ion home storage till 2030 was acquired.

By comparing the legal environment for PV-BESS in the Netherlands with other European countries that have already achieved significant residential PV-BESS capacity, it becomes clear that the Netherlands lacks a clear legal definition for (battery) storage, a matured PV-market and financial benefits for investing in residential battery systems. Subsequently, four regulatory frameworks are considered for analyzing the economics of PV-BESS systems.

A model that optimizes for self-consumption is deployed to determine self-consumption rates for different PV-BESS system sizes installed for an average household. It shows that investing in residential batteries in the Netherlands under current policy will continuously result in longer payback periods (PBP's) than PV-only systems. Nevertheless, PBP's for all considered PV-BESS configurations are in the realm of profitability with PBP's shorter than their respective lifetime of 15 years. When an investment policy of 30% of initial investment costs would be introduced under current policy, however, investments in PV-BESS systems would achieve shorter payback periods than PV-only systems after 2023-2029, depending on the system size and decline in BESS costs.

Consequently, the most optimistic scenario for the battery storage market in the Netherlands (assuming a direct introduction of the aforementioned investment subsidy, linear growth of Dutch residential PV capacity and German-like growth of BESS capacity), would result in €130 million & €778 million of revenue for the energy storage branch in 2025 and 2030, respectively. This indicates an upper limit of what could be expected for the future Dutch battery storage market. Lastly, several implications of this research are discussed, and multiple recommendations for future research are made.

Acknowledgements

At first, I expected that writing my master's thesis during a nationwide lockdown would be a great gift. Whilst writing my bachelor's thesis, I had learnt that I suffered difficulties with undertaking a project of this proportion and guessed that some imposed exclusion of distractions would work extremely beneficial for me.

Later on, I realized that the lockdown brought up some other serious challenges, such as remaining in contact with my scientific peers. I also fell into several of the pitfalls that are often associated with writing a master's thesis. Mainly the magnitude of the chosen subject and possible approaches has often overwhelmed me. Also, the inability of the 'online working environment' to generate creative ideas frustrated me at times. Nevertheless, the process has caused me to learn valuable lessons about the field of energy science and myself.

What kept me going, was my growing affiliation with the subject. Tackling the highly relevant subject of PV-coupled residential battery storage from multiple perspectives, as well as setting my first steps in PV-system modelling have been two things I have thoroughly enjoyed over the past few months. I also realize that my 'generalist' approach and ambition to bring scientific research and a market-research oriented commercial company together, might have resulted in a paper that is less 'niche-focused' than I originally would have wanted. I have, however, attempted to satisfy both the scientific principles and requirements of Libra Energy, the company where I did my internship, to the best of my ability.

I would like to especially thank my university supervisor, Madeleine Gibescu, for allowing me to pursue and formulate my own thesis topic, and my company supervisor, Gijs Stevers, for helping me improve my style of work and supporting me through the process. Additionally, I would like to thank my parents, friends and brother for their continuous support during these strange Corona times, and my colleagues at Libra Energy for the opportunity to gain relevant working experience within the Dutch solar market.

Pieter van Eig,

March 2021.

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1. Introduction

1.1 Societal background of research

Global electricity generation by solar photovoltaics has grown at an almost exponential rate over the past two decades. Although the unprecedented scale of the Covid-19 pandemic has caused predictions for 2020 onwards to be lowered, the overall expectation that strong growth in electricity produced by solar energy will persist (IEA, 2020a). The growth in solar power capacity in the Netherlands matches the global trend; the total capacity of PV-systems in the Netherlands has grown by a record rate of 51% over 2019 and accumulated to 6800 MW by the end of 2019, generating 20 PJ of electricity over the whole year (CBS, 2020a).

The subsequent quantity of solar photovoltaic systems and other fast-growing renewable electricity technologies like on- and offshore wind systems, however, have resulted in immediate grid connection of projects to be less self-evident. Furthermore, concerns about connecting Dutch photovoltaic projects to the grid in time and possible grid congestion are already being expressed (PV magazine, Bellini, 2019), illustrating a considerable threat that is being posed upon the steep growth of solar electricity generation.

In addition, the Dutch government has announced a phasing out of net metering policy (Rijksoverheid, 2020a). Net metering is a policy that allows small energy consumers to deduct self-produced solar electricity fed into the grid from their own electricity consumption. This consequently results in a significant energy bill discount for these small energy consumers. Therefore, net metering not only directly acts as an important incentive for these individuals to invest in solar panels, but also indirectly acts as a great catalyst towards the solar power capacity and generation growth in the Netherlands. Whereas this policy is currently still in place, the Dutch Ministry of Economic Affairs will gradually reduce the compensation for net metering from 2023 till 2030.

Hence, a mix of new solutions are required for tackling these solar-energy-integration challenges and for maintaining the accelerating growth in cumulative solar electricity generation. Electric energy storage (ESS) will be an essential part of this mix of solutions. ESS technologies do not only potentially provide grid relief, but also offer improvements in matching energy demand and supply. Furthermore, EES also contribute to indirectly curbing carbon emissions and subsequently mitigating climate change (Dell & Rand, 2001; Denholm et al., 2010; IPCC 2014).

Besides these direct societal benefits of EES, there also lies a communal interest in researching EES to give guidance and assurance to the Dutch renewable energy industry & markets. In contrast to the long-time recognized potential for combatting global warming, economic benefits of energy storage and case studies for different technologies & applications are still being heavily researched and remain more uncertain. Especially for the Netherlands, the EU member state with the lowest percentage of renewable energy sources in 2018 (Eurostat, 2020), the renewable energy industry still has little grasp on what the future of energy storage in the Netherlands during the upcoming decades will hold.

1.2 Scientific background of research

The potential of electric energy storage for society, however, has already been widely recognised by science for decades. The first pumped hydro storage facility was constructed in the beginning of the 20th century and even lithium-based batteries have been around for more than 40 years (Whittingham, 2012). Despite this awareness, the global realisation of electric energy storage capacity has been very marginal. The cumulative global capacity was estimated to be a total of 8 GWh in 2018, of which ± 96% was conventional pumped hydro storage (WEC, 2019; IEA 2018). Although the global energy storage market had grown almost exponentially for a decade until then, 2019 has shown a slight flattening of this growth, as depicted in Figure 1. Nevertheless, the expectation is that the storage market will soon return to accelerating numbers (WEC, 2019).

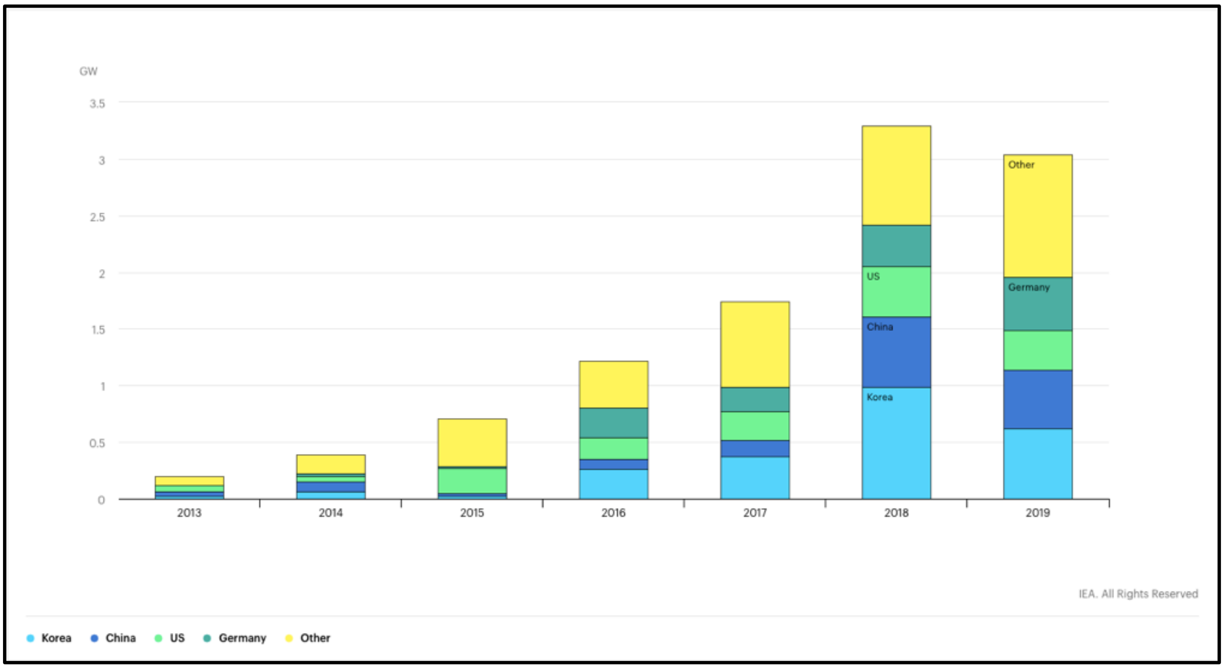

Figure 1 | Annual energy storage deployment by country (IEA, 2020b)

Considering the simultaneous increase in energy storage research (Luo et al., 2015), the marginal amount of storage capacity becomes even more remarkable. Cost trends and projections of the different ESS technologies, however, give insights into the situation; Figure 2 illustrates the experience curves and levels of maturity of the major available technologies for electricity storage. The residential & utility scaled technologies, except for electrolysis, all show to be significantly more expensive than pumped hydro storage and lead-acid, despite the price declines they have experienced throughout the last decades (Schmidt et al., 2017).

In addition to costs, energy storage faces numerous other barriers towards implementation. Firstly, technical features such as round-trip efficiency, charging duration and total rated power often put limitations on where and how these technologies can be used. Secondly, (national) regulatory frameworks are often not adequately adapted to allow for the implementation of energy storage, nor for actively incentivizing it. Thirdly, effective business models for the application of energy storage systems are often absent, partially as a consequence of the inadequate regulatory frameworks (Kooshknow & Davies, 2018; Anuta et al., 2014).

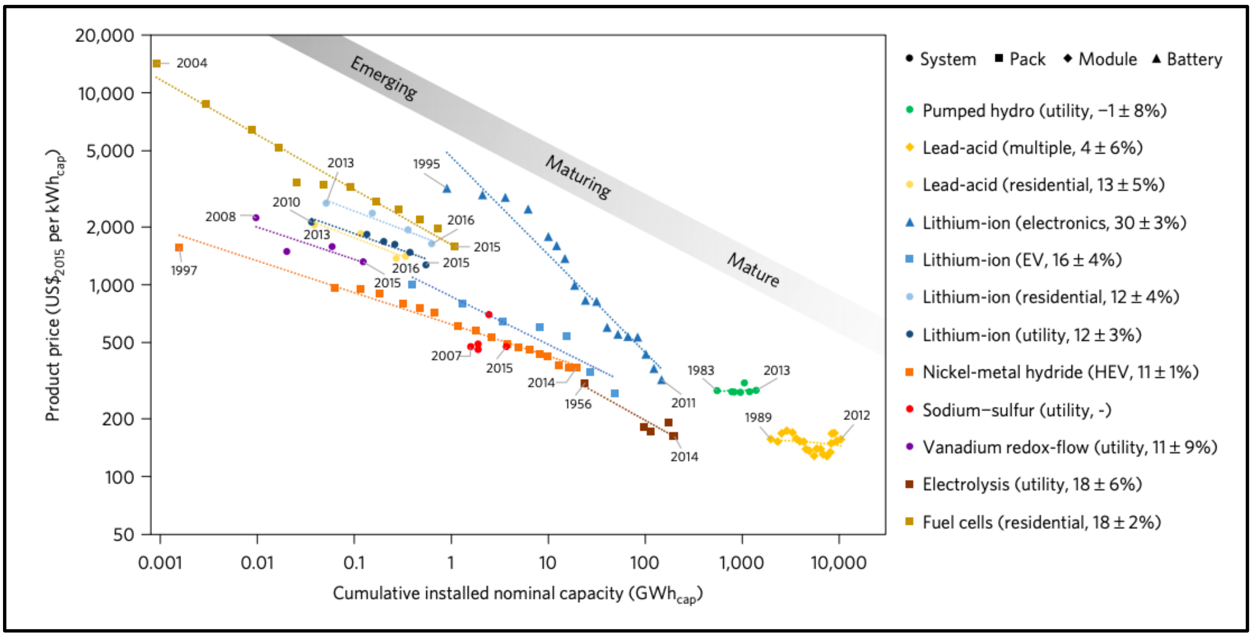

Figure 2 | Experience curves for electrical energy storage technologies (Schmidt et al., 2017). Fuel cells & electrolysis must be considered in combination to form an EES technology.

Although pumped-hydro storage is currently the second-most installed ESS technology, it has the severe disadvantage of having very specific geographical requirements. Only mountainous regions are suitable for pumped hydro storage, and the development of pumped hydro storage facilities can cause social or ecological disputes due to the fact that these areas are potentially located in highly (ecologically) sensitive areas. Furthermore, pumped hydro storage seems less suitable for solving all the challenges of intermittent renewable energy. Its long discharging times will not be able to charge and discharge the variability of solar and wind on a daily basis, nor will the relatively large capacities be able to store all forms of scattered energy generation effectively.

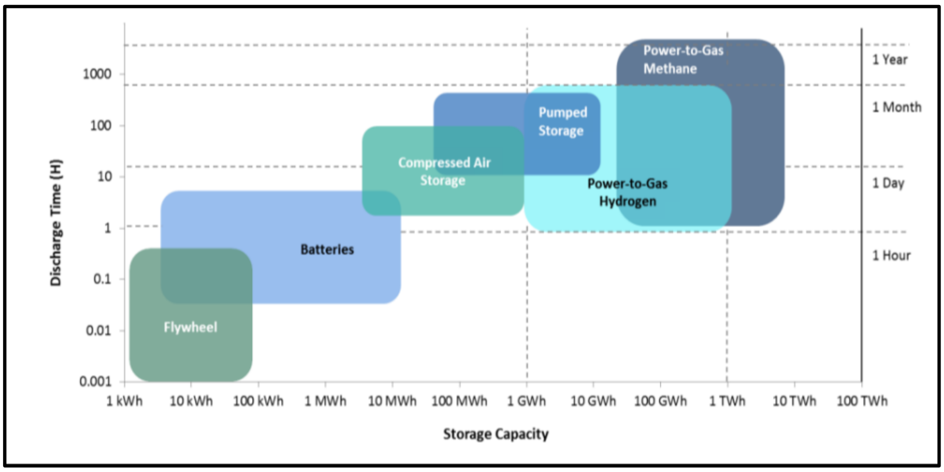

Figure 3 | Comparison between major energy storage technologies in terms of discharging time and storage capacity. (CHBC, 2015)

In contrast, the costlier Battery Electric Storage Systems (BESS) have the advantage of being able to be built in smaller capacity sizes, allow for faster discharging times, and are significantly more energy dense. Figure 3 compares the difference in capacity sizes and discharging times between batteries and pumped hydro accordingly. Moreover, Battery Electric Storage Systems (BESS) have portrayed a remarkable growth in global capacity over the past decades in comparison to other non-pumped technologies. Therefore, they are deemed one of the most promising options within the vast range of storage technologies to address the challenges caused by renewable energy variability (Figgener et al., 2020).

There is, however, a plethora of different battery technologies available for storage applications. These so-called electrochemical storage technologies range from the more classic lead-acid batteries (mainly used for starting fossil-fueled motor vehicles) and nickel-based batteries (mainly use for home appliances to the common lithium-ion batteries. Due to the fact that cost-efficient use of novel technologies like flow batteries and sodium-based batteries is still in its infancy, lithium-ion batteries are more likely becoming the predominant solution for small-scale storage (IRENA, 2017). This corresponds with the trend displayed in Figure 4.

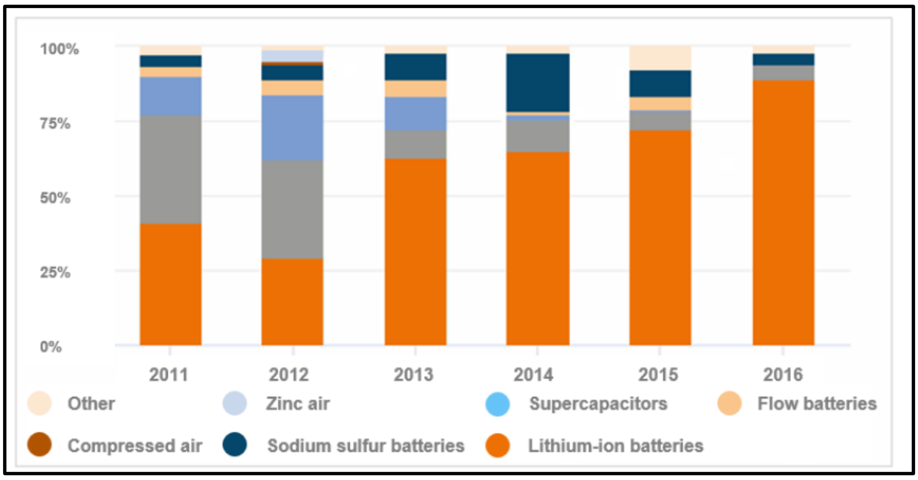

Figure 4 | Mix of technologies for stationary storage applications over time, excluding pumped hydro (IEA, 2019; WEC, 2019). It shows the dominance of lithium-ion batteries. This occurred simultaneously with the decline in flywheel installations (sea blue) after having a ± 25% share in 2012 and the decrease in lead-based batteries (grey) after having a share of ± 40% in 2011.

Besides different technological options, battery storage systems can also provide a wide array of services to different actors within the energy system, as shown in Figure 5. Most of these services, however, are currently obstructed due to regulatory or market barriers. Nevertheless, it nicely depicts the potential added value for BESS in the future. As this study considers end-user economics, the services for utilities & grid operators (ISO/RTO) will be neglected. Moreover, the main service BESS currently can provide for residential end-consumers, is an increased PV self-consumption. Back-up power & Demand charge reduction are more considered indirect services, and Time-of-use bill management by consumers is not yet feasible due to energy market regulations.

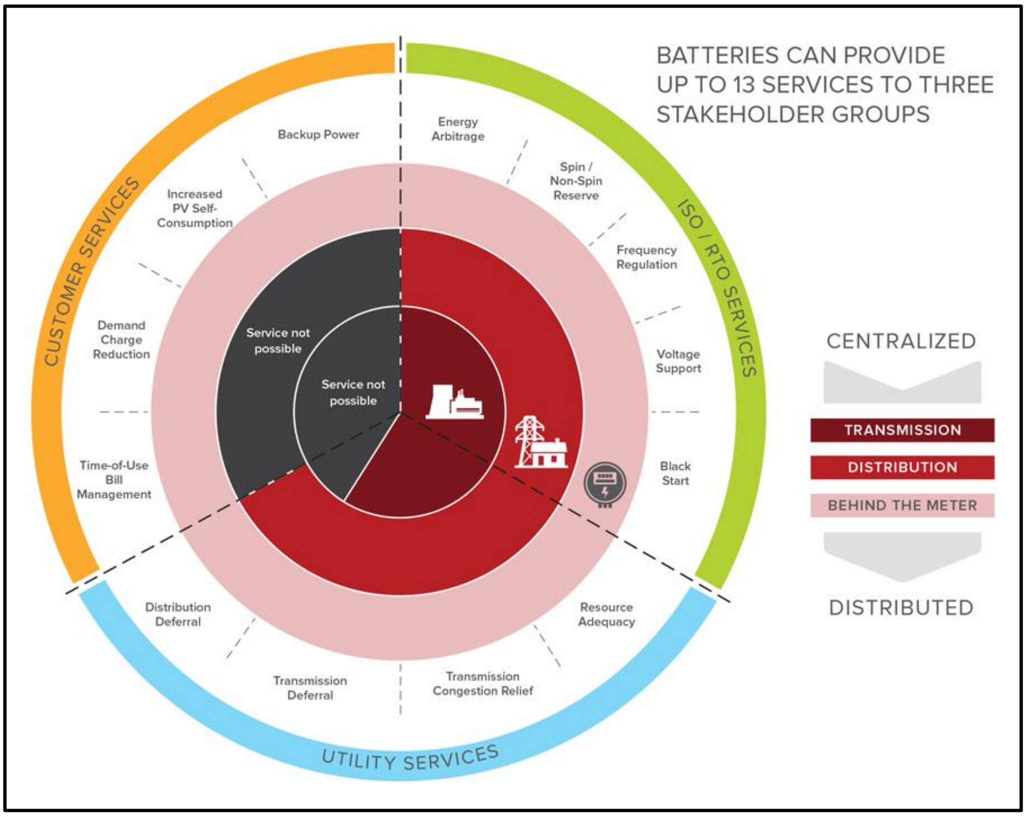

Figure 5 | Classification overview of potential services that can be offered by battery storage systems per stakeholder. In this scheme it is assumed that all regulatory and market barriers that currently exist are cleared. (RMI, 2016)

1.3 Problem definition

The Netherlands aims to remain developing photovoltaic installations at both the residential- and utility scale. Changes in Dutch net metering policy, however, cause lithium-ion battery storage for residential PV systems to be predominantly interesting, because investing in a PV system without a battery might become economically less attractive. Additionally, the stepwise reduction of net metering seems to indirectly incentivize self-consumption, one of the main services battery systems provide at this moment in time.

This thesis therefore aims to research the economics of end-user PV-BESS systems, by analyzing the current Dutch residential electricity storage policy environment and that of its neighboring countries, researching the costs and benefits of a lithium-ion battery residential PV-BESS system, and assessing the subsequent market potential for residential lithium-ion battery systems in the Netherlands till 2030. More specifically, using lithium-ion battery storage to increase effective use of PV installations is already researched for Germany at both the residential level (Braun et al., 2009) and utility scale (Merei et al., 2016), and this paper also aims to add to the existing literature by examining the residential case in the Netherlands and determine if significant differences occur.

Consequently, the following research question has been formulated:

Main research question

What is the economic potential of residential PV-BESS systems for end-users in the Netherlands towards 2030?

Sub-questions

1. How is the economic potential of residential PV-BESS influenced by policy? And how does this relate to the Netherlands?
2. Which factors influence the profitability of a residential PV-BESS system?
3. When and under which regulatory framework(s) will residential PV-BESS systems become more economically attractive than regular PV systems in the Netherlands, and how does this affect the economic potential?
4. What is the potential annual market size for residential BESS systems in the Netherlands in 2025 & 2030?

Chapter 2 intends to explore the legal environments for battery electric storage for both the Netherlands as well as other European countries that have shown to be leaders in installing residential battery capacity. It mainly aims to provide insights for answering sub-question 1.

The methods for analyzing the economics of battery electric storage are discussed in Chapter 3. This includes simulation of a PV profile for a standard residential PV installation in the Netherlands, an optimization for self-consumption, which is hypothesized to be incentivized in the future, and an economic analysis by computing payback periods. Finally, a method for estimating future residential BESS market size is treated.

The results of this methodology are described in Chapter 4 and discussed in Chapter 5. Concurrently, sub-questions 2, 3 and 4 will be answered. Conclusions are drawn in Chapter 6 by answering the proposed research question and the sub-questions.

1.4 Background of Company

Libra Energy is an importer, distributor and full-service wholesaler of products that generate sustainable energy and charging systems for electric vehicles. Since their foundation in 2007, they have had a leading position in the field of solar energy in the Netherlands. Currently, they supply more than 1,500 professional installers, who install both commercial and residential PV projects. Thanks to their many years of experience in sustainable energy solutions, they have an advantage in exploring new possibilities and developments. In close cooperation with their partners and suppliers, they have shown to be the first to introduce new products. Libra Energy was, for example, a member of the team that developed the first hybrid inverters (inverters that can be connected to battery systems) and introduced them in the Netherlands.

Libra Energy intends to accelerate the implementation of renewable energy technologies that boost the growth of solar PV, and therefore aims to understand the main drivers for growth of the battery storage market in the Netherlands.

2. Policy Review

This chapter aims to provide a regulatory context for the rest of this study, by describing the current status of residential battery storage in Dutch policy. Subsequently, it is compared with the policy developments over the last two decades in frontrunning European countries in terms of installed PV-BESS capacity.

2.1 Regulatory environment for residential storage in the Netherlands

The Dutch Climate Agreement and the EU 2020 climate energy package have resulted in several policy targets set for and by the Dutch government to reduce national emissions. Additionally, the Urgenda climate case has led to heightened a sense of urgency for reaching those targets in time. As a consequence, a wide mix of initial plans for stimulating technologies and processes to reach these targets have been drawn up. Battery storage has also been recognized as a promising technology and a national strategy to accelerate battery-use in the Netherlands has been formulated at the beginning of 2020 (Rijksoverheid, 2020b). The so-called 'Nationale Batterijagenda' (national battery agenda) aims to ensure responsible operation of batteries and smart utilization of economic & technological opportunities for their deployment. The first policies to support this national strategy have already been put into place. Nevertheless, multiple regulatory and institutional barriers remain. This section aims to identify these different policies and barriers for battery storage adoption in the Netherlands. Moreover, not only policies that affect residential battery storage are considered, but also those that affect large-scale storage. In this way, a wholesome view of the Dutch policy climate for battery storage is given and potential synergies and/or discrepancies might be spotted.

2.1.1 Phasing out net metering

Net-metering is a great financial incentive and an inherent subsidy for decentralized renewable energy generation by households. The Dutch government has nevertheless reasoned that the steep cost-decline of photovoltaic modules will likely cause investments in photovoltaic installations to also become financially attractive without government subsidies in the near future. Therefore, they have decided to abolish net metering policy, a policy that allows for subtracting locally produced electricity by PV systems from your electricity consumption bill, step by step. The proposed route is depicted in Table 1.

Table 1

Proposed pathway for phasing out net metering for small electricity consumers by the Dutch government (Rijksoverheid, 2020a). The percentage displays how much of the total PV-produced electricity can still be net metered by an individual household.

Year	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Percentage	100%	91%	82%	73%	64%	55%	46%	37%	28%	0%

PV producers still receive financial compensation for the electricity produced that cannot be net metered, albeit significantly less than if it would be net metered (± €0,07/kWh as opposed to the €0,22/kWh when net metering). It should be noted that this already holds for when the annual PV-generation surpasses the total amount of annual electricity consumed. Only this smaller financial compensation is received for the 'overproduced' fraction.

Because net-metering schemes do not take the time of consumption or generation into account (only end-of-year totals are considered), it also acts as a disincentive for behind-the-meter storage. Consequently, the potential benefits of load shifting by implementing residential storage are completely disregarded. As an alternative to regular net-metering, smart metering schemes could be considered to stimulate residential storage in a viable way (Khooshknow & Davis, 2018; DNV GL, 2015). The consideration of smart metering schemes, however, are beyond the scope of this study.

2.1.2 Legal position of BESS & double taxation

In addition, energy storage is not clearly defined under Dutch law and regulations. Currently, energy storage can be categorized as both part of energy production as well as energy consumption. Due to the lack of definition, issues arise in implementing of energy storage because of the need comply to both consumers' and producers' regulation. As a consequence, tax is levied when energy from an energy producer is stored by a storage operator, but also when the storage operator discharges its energy for use by the end-customer. Although the Dutch government already recognized this issue of double taxation in 2019, the issue has still not been resolved anno 2021. The ramifications of the COVID-19 crisis and prospective EU-regulations for storage taxation are stated as the main reasons for postponing further reforms (Rijksoverheid, 2020c).

Whereas this mainly impacts the business case of utility scaled energy storage systems, because larger systems often contain an autonomous storage-operator, it also inhibits innovative small-scale operators to penetrate the storage market. For behind-the-meter storage, on the other hand, double taxation does not occur.

Furthermore, the Dutch subsidy mechanisms, e.g. those for stimulating large-scale renewable energy production (SDE++) and residential energy efficiency and renewable energy production (ISDE), do not include 'energy storage' as one of the potential technologies for financial compensation. Therefore, battery energy storage doesn't benefit from any current Dutch subsidy, whilst its importance for the transition towards renewable energy sources has been widely recognized. Legally defining battery storage as a renewable energy technology, low carbon technology or separate essential storage technology and including it within one of these subsidy schemes would severely improve its uptake in the Netherlands.

2.1.3 Restrictive role for grid operators

Due to strict legal separation of grid operator activities at the European level, transmission system operators (TSO's) and district system operators (DSO's) are prohibited to engage in any form of commercial activity within the European energy markets (Wasowicz et al., 2012). The ambiguous definition of energy storage subsequently results in managing BESS & other storage technologies being forbidden for grid operators, because it involves trading energy. The Dutch cabinet has also recently expressed that it still approves this legislation, stating that 'Grid operators entering the energy storage market would be undesirable' (SSM, 2020).

2.2 Development of residential storage in other EU countries

Despite the promising development of formulating a national battery storage, its effectiveness is still to be measured. Moreover, the Netherlands has achieved very little in terms of battery storage capacity upon 2020 compared to other countries in Europe, as depicted in Figure 6. The European storage market is nevertheless rapidly growing as seen in Figure 7. Therefore, a review of the policy environments of neighboring countries that have achieved significant amounts of residential battery storage capacity can generate valuable insights for the Dutch battery landscape.

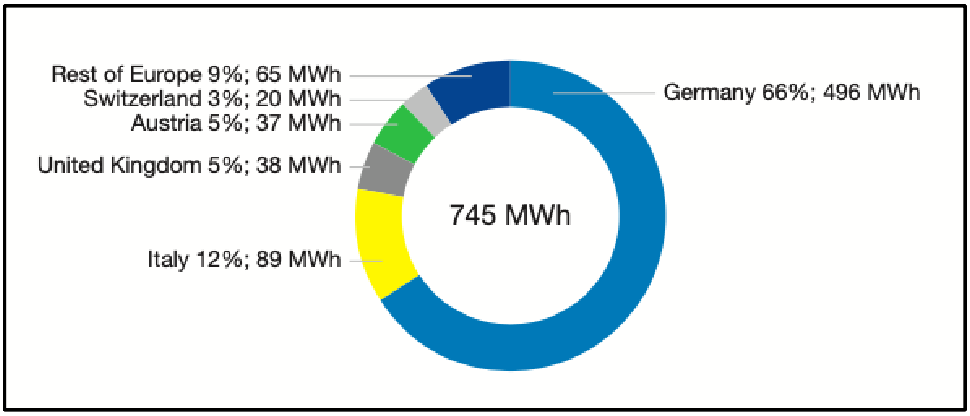

Figure 6 | The top 5 European residential storage markets. The figure depicts the installed capacity of stationary battery storage for European homes in 2019. (SolarPower Europe, 2021)

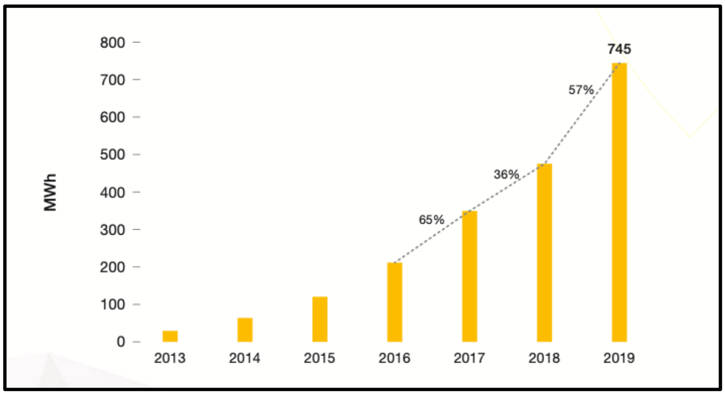

Figure 7 | Annual market for residential BESS systems in Europe, i.e. the amount of capacity that is added each year (SolarPower Europe, 2021).

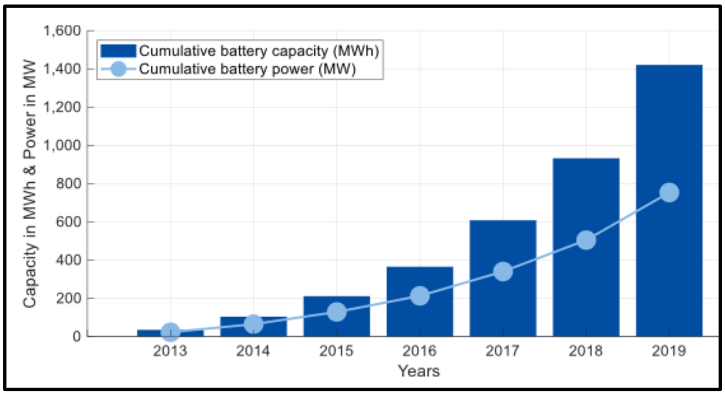

Figure 8 | Estimated cumulative capacity and cumulative power of home storage installations in Germany (Figgener et al., 2021).

2.2.1 Germany

Germany is the clear frontrunner when it comes to realizing residential BESS capacity in Europe. Figure 8 shows the trend of cumulative installation from 2013 onwards, accumulating to a total estimate of 1425 MWh in 2019. Several factors have contributed to successfully achieving this market growth for battery storage since 2013.

Firstly, Germany was the global frontrunner in promoting renewable electricity with a feed-in tariff scheme when introducing this law in 1991 in its first form (Grundinger, 2017). Feed-in tariffs remained the main mechanism to stimulate photovoltaic power production in Germany over the past decades, as opposed to the Dutch net metering policy. Consequently, the German government was also the first to offer a legal incentive for PV-coupled storage by offering a special feed-in tariff for PV owners who could ensure local PV consumption, through amending the German Renewable Energy Sources Act (EEG) in 2009 (Braun et al., 2009). Whilst lithium-ion battery installations remained very little due to high investment costs, the achieved installed PV capacity after the introduction of this bill heavily exceeded expectations, and the feed-in tariff has been often adjusted over time to better align outcomes and expenses (Grundinger, 2017).

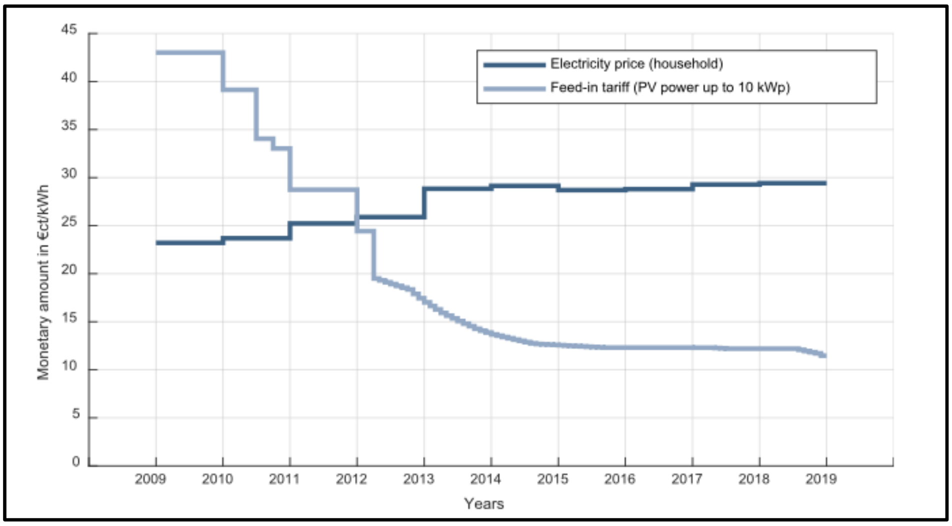

Figure 9 | Course of feed-in tariff for PV installations up to 10 kWp and average household electricity price from 2009-2019 in Germany (Figgener et al., 2020).

Secondly, the electricity price surpassed the feed-in tariff in 2012, generating an additional financial incentive to increase local consumption of PV-produced electricity. This is shown in Figure 9, and displays a correlation with the rise in home storage systems in 2013 depicted in Figure 7 and Figure 8.

Lastly, a market incentive program for residential battery storage systems was issued by the German Government and the state-owned KfW banking group in 2013. The goal of the program was to achieve an accelerated market introduction of PV Battery Systems, which would then increase residential self-consumption and simultaneously relieve the grid. In addition, the development of battery technology and decline of retail prices for small stationary battery systems in the long term would be aided. The premise of the incentive is as follows: the state-owned KfW banking group offers loans for residential BESS at advantageous rates for both PV installation holders as well as consumers interested in installing a new PV-BESS system. The maximum amount of the subsequent repayment grant offered by the German Federal Ministry for Economic Affairs and Energy depends on the year in which the system is installed and ranged from a maximum of 30% of installation costs in 2013 to a maximum of 10% of installation costs in 2018, when the program was discontinued (Kairies et al., 2019; KfW, 2020).

2.2.2 Italy

Similar to Germany, Italy hosted a feed-in tariff incentive program from 2005 till 2012 to promote residential PV installations. Consequently, a significant number of residential PV capacity were achieved over that period of time, culminating to 500,000 installations by July 2013. Whereas

Germany restricted their feed-in policy significantly from 2010 onwards (see Figure 9), Italy discontinued their policy in 2013. However, support remained in a different manner, by offering 50% tax reduction to consumers who invested in either PV or PV-BESS systems to improve their self-consumption (Bayod-Rújula et al., 2017). Also, a policy of net billing, in which the charges and duties included in the electricity price are still compensated when feeding PV electricity into the grid, was maintained instead of the feed-in tariff. Additionally, the region of Lombardia has introduced a subsidy scheme in which up to 50% of the initial investment is covered for PV-BESS systems up to 20 kW for a maximum of €5000 (Cuchiella, D'Adamo & Gastaldi, 2017).

2.2.3 United Kingdom

The UK also made use of a feed-in tariff to achieve renewable energy generation; from 2008 till 2019 the British government maintained this form of policy to promote local production of PV and wind electricity. From 2020 onwards, they introduced a new policy called the Smart Export Guarantee (SEG). This law ensures the provision of an export tariff by energy suppliers for local PV producers.

In contrast to Germany and Italy, the United Kingdom hosted an unfavorable policy landscape for PV-BESS systems till 2017 (Bayod-Rújula et al., 2017). In correspondence, detailed cost/benefit studies for both lithium-ion batteries and lead-acid batteries showed that there was no economic benefit for investing in a PV-BESS system with comparison to a regular PV-system (Uddin et al., 2017; McKenna et al., 2013). To alter this unpromising legislative environment, the British Department for Business, Energy and Industrial Strategy (BEIS) published a concise Smart Systems and Flexibility plan in 2017. Among other things, double taxation and an unclear legal definition for storage were announced to be solved (BEIS, 2017; Winfield et al., 2020). There is nevertheless no financial incentive for promoting PV coupled battery electric storage, and whilst battery storage is eligible for the newly introduced SEG legislation (BEIS, 2019), the new law could even demotivate battery electric storage if the renumeration for exporting energy becomes very high.

Despite the deficiencies in current British law, the United Kingdom has still achieved a certain amount of BESS installations. This is hypothesized to be mainly achieved because of a great gap between the price for electricity and the renumeration for which PV electricity is sold under the current SEG system. Contrary to Germany and Italy, the possibility for energy arbitrage and time-of-use pricing in the UK also offers value for consumers interested in investing into PV-BESS system (SolarPower Europe, 2021)

2.2.4 Flanders

Until recently, the Belgian region of Flanders has supported residential PV production in a similar way as the Netherlands; through net metering policy (a de facto feed in tariff, in which the price for electricity consumed equals the price of electricity produced). In 2019, the regional government also introduced an investment subsidy for BESS systems to support the technology, but it was barely used up until the end of 2020. Since January 2021, however, net metering policy has been abolished for new residential PV installations and effectively also stopped by immediate effect for all existing installations through a court ruling (Vlaanderen, 2021; Vlaamsparlement, 2021). To fill the created gap for financial support, they introduced an additional investment subsidy for PV systems besides the scheme in place for battery storage systems. The incentive programs provide €250/kWh with a maximum of 35% of the investment (or max €3200) for BESS and €300/kWp for PV systems up to 4 kWp, and an additional €150/kWp for 4-6 kWp, mounting to a maximum of €1500. Both schemes will diminish financially over time, anticipating price declines in both technologies (Vlaanderen, 2021). Within one month into 2021, the number of applications for the Flemish BESS subsidy quintupled, whilst the size of the BESS subsidy was still disputed in parliament due to discussion about whether investment would be financially attractive (Vlaamsparlement, 2021).

2.3 Synthesis

Reviewing the legislative environments in both the Netherlands and other relevant EU countries, certain key factors that influence the economic- and market potential of PV-BESS systems can be identified:

- A history in extensive stimulation of residential PV capacity, resulting in a significant pool of installed home PV installations, or in other words, a mature PV market. Especially with expiring feed-in tariff contracts, which will occur soon in Germany, will create a large demand for retrofitted BESS systems.
- Disparity between the electricity price and the export rate for feeding electricity into the grid. The larger the disparity, the larger the incentive for self-consumption and thus, BESS adoption.
- An advantageous legal status for self-consumption (disallowing self-consumption is illegal in all analysed countries) and other policies which stimulate self-consumption, such as export restrictions for local electricity consumption like the 60% maximum in Germany, or special feed-in tariffs for installations that promote self-consumption.
- Generous investment subsidies and/or tax reliefs for (PV-)BESS installations.
- Authorisation for other battery applications, such as energy arbitrage or grid services, such as in the UK.

It is apparent that the Dutch policy climate sustains little of these factors:

- The PV market is young in comparison to Germany, Italy & the UK
- Very little disparity between producing and exporting electricity (none for regular net metering, ±0,02 €/kWh when considering a double tariff (Essent, 2021) (also see Table 3))
- No subsidy program for BESS systems.
- Only the proposed phasing out of net metering will result as an export restriction stimulating self-consumption.

This suggests that BESS systems are probably not economically viable for the Netherlands under the current regulatory framework. To further investigate whether PV-BESS systems are currently financially attractive, and how that might change when other regulations would be put into place, the regulatory scenarios depicted in Table 2 will be considered for the further course of this study.

Table 2

Overview of different regulatory frameworks considered for the economic analysis. These frameworks are based on the policy analysis executed in Chapter 2.

Scenario	Name	Explanation
A	Constant net metering	Portrays a scenario in which net metering would continue like it is currently in place in the Netherlands till 2035.
B	Phasing out of net metering	Illustrates the scenario proposed by the current Dutch government; a gradual phasing out of net metering till 2031 (see Table 1).
C	Feed-in tariff	Displays a scenario in which net metering would have been abolished abruptly in 2020. In this case, prosumers would still receive a small compensation for feeding PV-generated electricity back into the grid (= 0,07 €/kWh in 2020).
D	Investment subsidy	Shows a scenario similar to scenario B with the proposed phasing out of net metering and adds an investment subsidy specifically for the battery system. (subsidy = 30% of total investment of PV-BESS)

3. Methods

The goal of this research is to assess the market uptake of residential lithium-ion batteries under the regulatory frameworks as defined in Chapter 2.3 (See Table 2). The methodology utilized in this study follows three steps. Firstly, the basic dynamics of a residential PV system with and without a battery are modeled for an ordinary Dutch household. The dynamics for the added battery are realized by employing an optimization model in order to simulate the best usage of the installation (See Table 3). Secondly, a techno-economic analysis, showing the costs & benefits of residential PV systems & PV-battery systems over their respective lifetime, is made by making use of Payback Period (PBP) calculations. Thirdly, an assessment of the market potential of residential BESS in the Netherlands is given.

The main assumptions used in this approach and their respective justification are stated in Table 3.

Table 3

Overview of the key assumptions made in this methods section.

Assumption	Explanation / Justification
Best usage of BESS = Maximizing self-consumption (Also, all electricity prices & feed-in tariffs are flat-rate prices & tariffs)	Besides flat-rate electricity prices, smart metering schemes based on time-of-use (TOU) already exist in the Netherlands. These mostly concern a double tariff system, in which the electricity price is slightly lower during nighttime and weekends than during weekdays. In theory, TOU feed-in tariffs and operation on the Day-Ahead spot market (hourly changing electricity prices) could also be introduced in the future. These schemes could all provide several benefits or options for BESS usage. For simplicity, however, they are not considered in this study. The reason for this is twofold. Firstly, the Dutch residential PV market is not yet familiar with any proof of the added value of these other battery strategies. Secondly, maximization of self-consumption is the standard setting for batteries. It is therefore likely that most end-consumers and installers will maintain this.
Standard Household = household with 3300 kWh in De Bilt, NL	De Bilt is located in the middle of the Netherlands hosts the Dutch Meteorological Institute. Therefore, it is determined to represent the average Dutch weather & climate the best. An annual electricity demand of 3300 kWh is chosen, because it is the current demand of an average household (Vattenfall, 2021) & average house (Milieucentraal).
Standard characteristics of residential PV-installation = Southern orientation, tilt of 35°	These are the reference parameters for most studies considering PV installations in the Netherlands (Killinger et al., 2018)
Household profiles = 3x25A distribution profile · Annual household demand	The same distribution profile is scaled by a constant factor to simulate larger annual electricity demands (6500 kWh & 10,000 kWh).
Residential PV installation = matched with household demand	The size of the residential PV installation is always matched with the household demand in a 1:1 manner, e.g. 3300 kWh : 3.3 kWp. Also see Table 5.
Demand Side Management is not considered	It is assumed that no specific policy or incentive is in place or introduced to significantly change demand profiles in the Netherlands

3.1 PV profile simulation & optimization model

This research considers two types of installations: installations that consists of a set of photovoltaic solar panels without a battery, as a benchmark, and installations that include a battery. The PV systems only requires a PV profile for calculating Payback Periods, as controllability in demand or a form of Demand Side Management (DSM) is not considered in this study. The PV-battery systems, however, call for modelling the use of the battery under a certain strategy. Therefore, an optimization model is used for simulating the use of the PV-battery system.

Both installations represent a consumer that has installed his/her PV system (or PV-battery system) with the main purpose of maximizing self-consumption. Both installations are modelled to simulate a residence located in De Bilt, The Netherlands, that generates electricity demand and solar panels installed on the roof that generate electricity. The PV-battery installation encompasses an additional battery energy storage system that mediates electricity exchange between the electricity grid and the system.

3.1.1 Technical input data

This section presents the different inputs that were used for synthesizing the annual PV profile and modelling the dynamics of the battery.

3.1.1.1 Household electricity load profile

To simulate the electricity consumption of a standard household, a combination of the rounded mean annual consumption (3,300 kWh per year) of a new medium-sized residence (Milieucentraal, 2020) and an average load profile for a 3x25 ampère-connection to the grid were used (NEDU, 2020). Consequently, an annual household electricity load profile with a 15-minute time resolution could be synthesized. To address the effect of larger installations, profiles for fictional households with 6,500 kWh per year and 10,000 kWh were created in a similar manner.

3.1.1.2 PV generation & conversion

The performance of the photovoltaic solar panels and inverter in this model are simulated with the open-source tool **pvlib python** provided by Holmgren, Hansen & Mikofski (2018). The required input data and the corresponding values used in this model are depicted in Table 3. The data was mainly obtained by weather measurements executed at weather station De Bilt by the Royal Netherlands Metereological Institute (KNMI, 2020) and a study that researched representative characteristics for PV systems in different nations, including the Netherlands (Killinger et al., 2018).

Subsequently, the use of a set of pvlib formulas developed an annual PV-profile with 15-minute time-resolution from the original irradiation data provided by the KNMI (See Figure 10). Besides the input data given in Table 3, the model makes use of specific PV-module and inverter parameters. These can be retrieved from the System Advisor Model (SAM) database (NREL, 2020). For the results of this research, the Canadian Solar CS6X 300Wp (PV Module) and SolarEdge SE4000 240V (Inverter) were used.

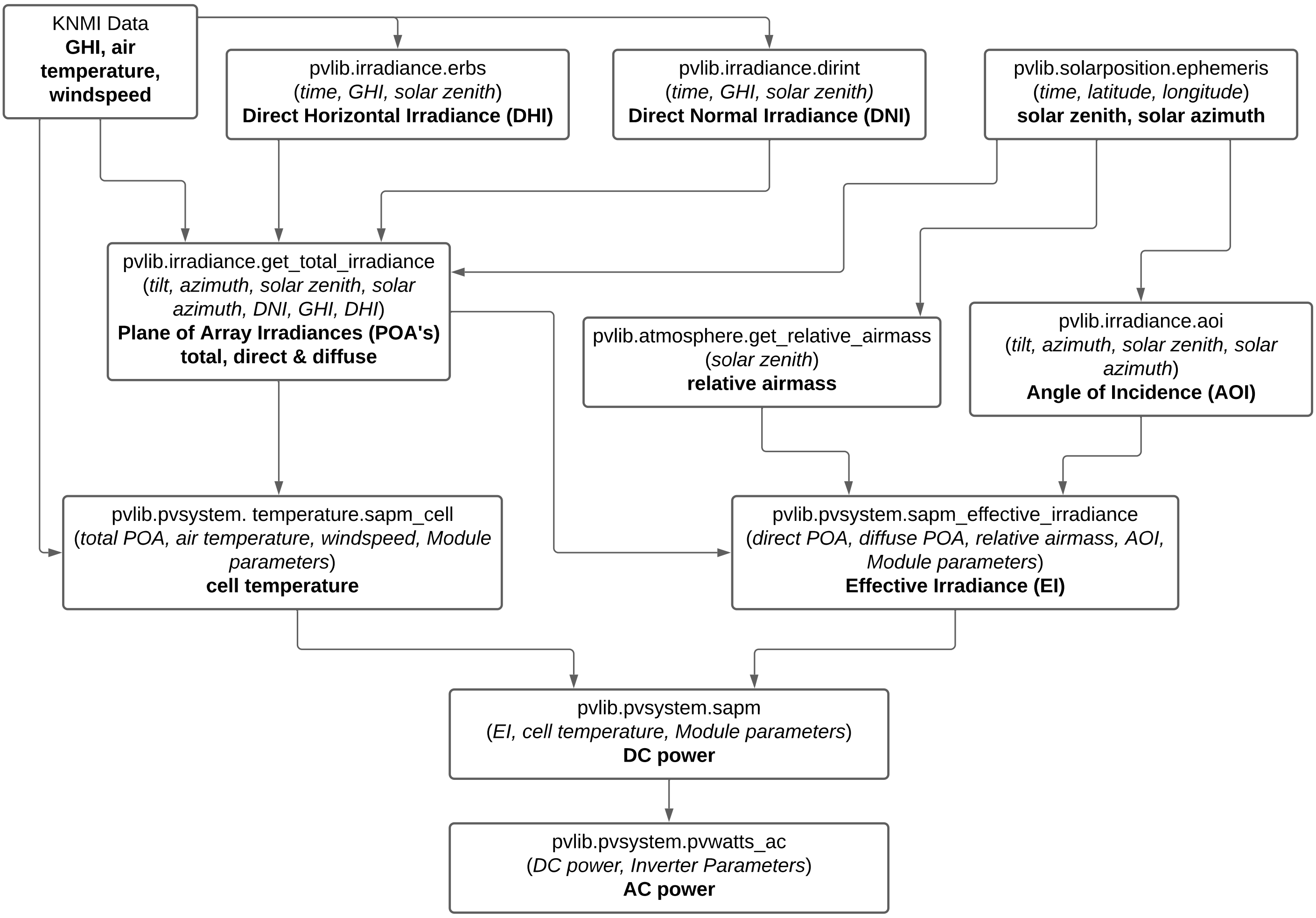

Figure 10 | Flowchart of PV generation profile simulation. The PVlib formula (or measured data) used is depicted in 'normal font', the inputs for the respective formulas are given in '(italics)' and the outputs are given in **bold.** (Inspired by Tsarafakis, 2020)

The resulting household electricity load profile and PV generation profile are depicted in Figure 11.

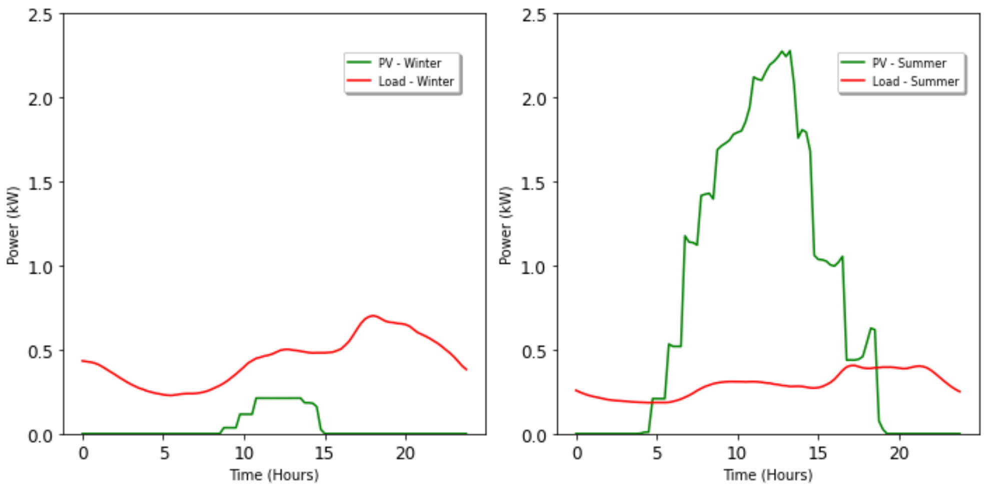

Figure 11 | Household electricity load profile extracted from NEDU and PV generation profile simulated with pvlib depicted for a typical day in winter and summer (NEDU, 2020; Holmgren, Hansen & Mikofski 2018)

3.1.1.3 Lithium-ion battery and grid inputs

The optimization model considers a lithium-ion battery system designed for PV-household applications. The parameters are based on a commercially available range of low-voltage Nickel Manganese Cobalt (NMC) lithium-ion batteries.

Table 3

Input data for simulation of an annual PV profile. PV peak capacity, Tilt angle, Azimuth angle are mean values for PV installations in the Netherlands found by Killinger et al., 2018. Latitude & Longitude represent De Bilt, The Netherlands. GHI, Air Temperature & Windspeed are reformatted data obtained from KNMI (KNMI, 2020). Δt is 15 minutes.

Input parameters PV Generation and Household Demand 'standard household'		
Name	Unit	Value
Household demand for electricity consumption	kWh/yr	3,300-10,000
PV peak capacity	kWp	3.30-10.0
Tilt angle	°	32.5
Azimuth angle	°	0.77
Latitude	°	52.000
Longitude	°	5.180
Total Installed Area of PV Modules	m2/0.3kWp	1.6
Global Horizontal Irradiance (GHI)	W/m2	Varies every Δt
Air temperature	°C	Varies every Δt
Windspeed	m/s	Varies every Δt

Table 4

Additional technical inputs for the optimization model of the PV-battery system. See Equation 1-6 for how these variables are used in the model. 50% as State of Charge at t = 0 is chosen. (t0 = first 15 minutes of January 1st, 2020).

Input parameters Lithium-ion battery & Grid			
Name	Unit	Value	Symbol
Battery capacity	kWh	3.3 – 20	C_{batt}
Maximum rated battery power	kW	0.9 · Batt cap.	$P_{batt.max.}$
(Dis)charging efficiency	-	0.95	$\eta_{batt.ch.}$ / $\eta_{batt.dis..}$
Maximum grid power	kW	3	$P_{grid.max.}$
Minimum State of Charge	%	100	SoC_{min}
Maximum State of Charge	%	0	SoC_{max}
State of Charge at t=0	%	50	SoC^{0}

3.1.2 Modelling the dynamics of a PV-battery system

To study the interaction within a PV-battery system, this research implemented a mixed integer linear programming model. The model was written in python and operated GUROBI as solver to calculate results (Beck et al., 2016; Brinkel, 2020). The annual household electricity demand and PV generation profiles serve as input, for which the model then determines the optimum power streams within the system. The flows to and from the battery, electrical grid interactions, and the state of charge act as variables. All different inputs & variables are defined as positive variables and displayed in Table 6. Additionally, different combinations of PV-system & battery sizes are considered. As baseline configuration, a 1:1 sizing of the PV-system peak power relative to the battery capacity is chosen (Waffenschmidt, 2014). The other considered configurations are defined in Table 5.

Table 5

Overview of analyzed systems. This table shows that it is assumed that the size of the house correlates with the electricity consumption footprint and size of the roof in such a way that the Household demand - PV system ratio is always 1 : 1.

Run	Household demand (kWh)	PV system (kWp)	Battery system (kWh)	PV system : Battery system ratio
0-1	3300	3.30	-	-
0-2	6500	6.50	-	-
0-3	10,000	10.00	-	-
1	3300	3.30	3.30	1 : 1
2	3300	3.30	1.65	1 : 0.5
3	3300	3.30	4.95	1 : 1.5
4	3300	3.30	6.60*	1 : 2
5	6500	6.50	6.50	1 : 1
6	6500	6.50	3.25*	1 : 0.5
7	6500	6.50	9.75*	1 : 1.5
8	6500	6.50	13.00	1:2
9	10,000	10.00	10.00	1 : 1
10	10,000	10.00	5.00	1 : 0.5
11	10,000	10.00	15.00	1 : 1.5
12	10,000	10.00	20.00	1:2

*These battery capacities meet the requirements to analyze linear sizing but are not sizes available on the market by the respective NMC-battery producer considered. Nevertheless, it still gives insights on the relative influence of battery size on payback periods.

Table 6

Variables for the optimization model which vary for every Δt.

Name	Symbol	Unit
Power input battery	${P_{batt.ch.}}^{t}$	kW
Power output battery	${P_{batt.dis.}}^{t}$	kW
Power injected to grid	${P_{PV2grid}}^{t}$	kW
Power subtracted from grid	${P_{grid2load}}^{t}$	kW
Power from PV to load	${P_{PV2load}}^{t}$	kW
State of Charge of the battery	${SOC_{batt}}^{t}$	%

3.1.2.1 Objective function

The main objective of this optimization model is to maximize the self-consumption rate of the system (See 3.2.1 for the explanation of this metric). This is indirectly achieved by taking the minimization of flows towards and from the grid as objective. The formulation of the optimization objective is given in Equation 1.

$$\text{minimize} \sum_{t=1}^{T} ({P_{grid2load}}^{t} + {P_{PV2grid}}^{t}) \Delta t \qquad \text{(Eq. 1)}$$

Effectively, Equation 1 therefore gives the total amount of power that is both extracted from and fed into the grid over one year (T = 1 year). Additionally, the model is constrained through several constraints formulated in the following subsections.

3.1.2.2 Load balance constraints

The load balance constraint is the main constraint of this model. The use of this constraint makes sure that the household electricity demand (${P_{dem}}^t$) is fulfilled at every timestep. The constraint is given in Equation 2.

$$ {P_{dem}}^t = {P_{grid2load}}^t + {P_{PV2load}}^t + {P_{batt.dis.}}^t \cdot \eta_{batt.dis.} - \frac{{P_{batt.ch.}}^t}{\eta_{batt.ch.}} \; \forall \, t \qquad \text{(Eq. 2)} $$

In this model, the household electricity demand is thus satisfied by either the grid (${P_{grid2load}}^t$), PV-system (${P_{PV2load}}^t$) or the battery (${P_{batt.dis.}}^t$). At timesteps where the produced PV power exceeds demand, it can be fed back into the grid or stored in the battery. This set-up represents an AC-coupled PV-battery system. The efficiencies used in this study and referred to in Equation 2 can be found in Table 5. Figure 12 gives a graphical representation of these interactions.

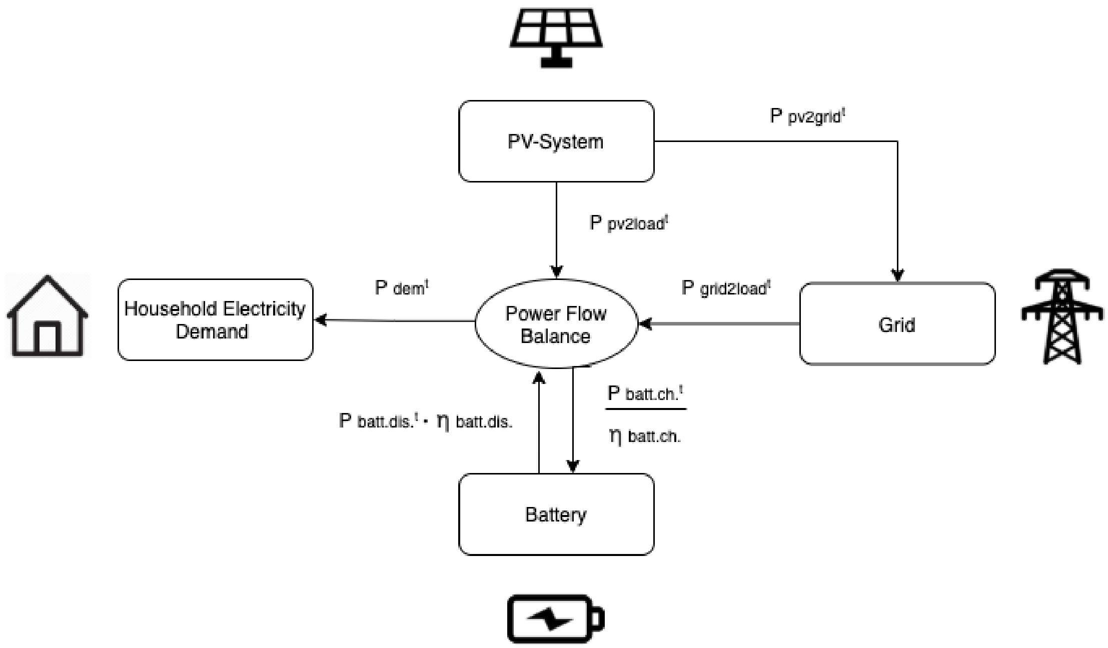

Figure 12 | Overview of power flow dynamics of the PV-Battery system, inspired by Beck et al., 2016.

3.1.2.3 State of charge dynamics

In addition, the storage of electricity in the battery is modeled with the constraint formulated in Equation 3. This constraint ensures that electricity stored in the battery is conserved between the different timesteps. State of Charge (SoC) is therefore defined as the ratio between the maximum storage capacity of the battery and the actual amount of electricity stored at a certain timestep.

$$ {SoC_{batt}}^t = {SoC_{batt}}^{t-1} + \frac{({P_{batt.ch.}}^{t-1} \cdot \Delta t - {P_{batt.dis.}}^{t-1} \cdot \Delta t)}{C_{batt}} \; \forall \, t \qquad \text{(Eq. 3)} $$

The capacity & efficiency of the battery are given in Table 2. Self-discharge is not considered in this model, because of its negligible size (Leadbetter & Swan, 2012). In addition, the state of charge must not cross the limits of usable capacity, which for this battery are set at a minimum of 10% and maximum of 100% (Also see Table 2). The corresponding constraint is formulated in Equation 4.

$$SoC_{min} \leq SoC^t \leq SoC_{max} \quad \text{(Eq. 4)}$$

3.1.2.4 Battery constraints

Additionally, simultaneous charging and discharging of the battery is disallowed in the model through incorporating two binary variables (α and β). Consequently, a constraint is expressed in Equation 5. This constraint ensures that α and β cannot equate to 1 at the same time.

$$\alpha^t + \beta^t \leq 1 \quad \text{(Eq. 5)}$$

Then, the minimum and maximum values for the battery flows can be constrained together with disallowing simultaneous charging and discharging in Equation 6 and Equation 7. Because either α or β, or both are equal to zero, the right term of at least one of Equation 6-7 has to equal zero. Hence, the battery will not charge and discharge at the same time. When α or β is equal to 1 for one of the equations, the (dis)charging power is constrained by the maximum (dis)charging power (See Table 4).

$$P_{batt.dis.}{}^t \leq P_{batt.max.} \cdot \alpha^t \quad \text{(Eq. 6)}$$

$$P_{batt.ch.}{}^t \leq P_{batt.max.} \cdot \beta^t \quad \text{(Eq. 7)}$$

3.1.2.5 Grid constraints

Thereafter, the minimum and maximum of the grid flows must be constrained. Therefore, Equations 8-9 are formulated. The respective maximum values can be found in Table 2.

$$P_{grid2load}{}^t \leq P_{grid.max.} \quad \text{(Eq. 8)}$$

$$P_{PV2grid}{}^t \leq P_{grid.max.} \quad \text{(Eq. 9)}$$

Lastly, the electricity that flows from the PV-system to either the grid or the household cannot exceed the total PV generated electricity. Thus, the system also has to fulfill the constraint formulated in Equation 10.

$$P_{PV2grid}{}^t + P_{PV2load}{}^t \leq P_{PV}{}^t \quad \text{(Eq. 10)}$$

where $P_{PV}{}^t$ equates to the PV profile simulated in 3.1.1.2 with Python pvlib.

3.2 Economic analysis

To subsequently assess & compare different outcomes of the model, an economic analysis is performed. Therefore, two main metrics are used and explained in this section. The self-consumption rates are outcomes of the different runs of the optimization model, whereas payback period calculations act as the main tool for evaluating the different system sizes under several regulatory framework.

3.2.1 Rate of Self-consumption

The definition of self-consumption is the ratio between the amount of electricity generated by your PV-system that is consumed directly by the household and the total electricity produced by the PV-system, as given in Equation 11 & Equation 12. A schematic representation of what is meant, is given in Figure 13.

$$Self - consumption\ (SC)\ PV\ system = \frac{E_{PV,\ direct\ consumed}}{E_{PV,\ generated}} \qquad \text{(Eq. 11)}$$

$$Self - consumption\ (SC)\ PV - BESS\ system = \frac{E_{PV,\ direct\ consumed} + E_{batt.dis} \cdot \eta_{batt.dis.}}{E_{PV,\ generated}} \qquad \text{(Eq. 12)}$$

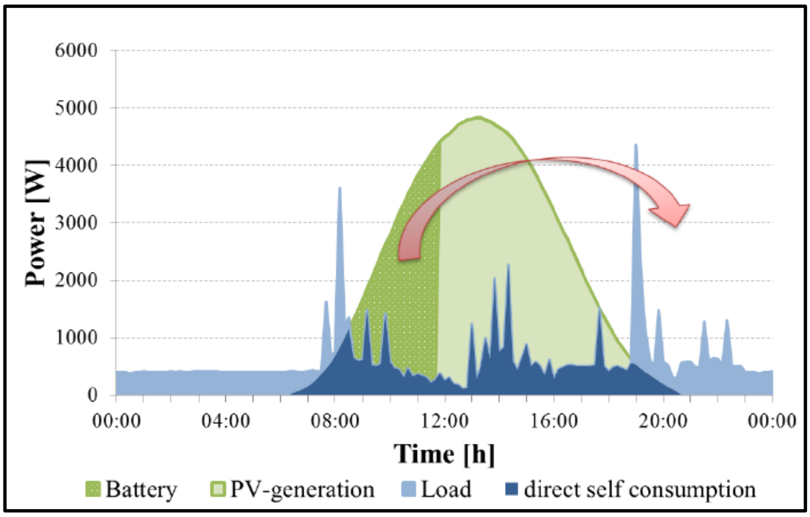

Figure 13 | Self-consumption on an exemplary day (Hirschl et al., 2013)

3.2.2 Payback Period calculations

The general formula for calculating the simple payback period (PBP) is given in Equation 13.

$$PBP = \frac{I}{B - C} \qquad \text{(Eq. 13)}$$

Where the initial investment (I) is divided by the annual benefits (B) minus the annual costs (C) (Blok & Nieuwlaar, 2020). For this specific case, however, changing cashflows (B – C) over time are considered, instead of the constant cash flow in calculating the simple payback period. This translates to the formula stated in Equation 14.

$$PBP = \frac{Initial\ investment\ PV\ /\ PV{-}BESS\ System}{Feed{-}in\ Yields + Avoided\ Grid\ Energy\ costs - (O\&M\ costs\ PV\ \&\ Storage\ system)} \qquad \text{(Eq. 14)}$$

The economic inputs for the PV systems & Battery storage systems are given in Table 7 and Table 8. Furthermore, the PBP's of every analyzed system (see Table 5) are different for every regulatory scenario considered in this study (see Table 2). For regulatory scenarios A-C, the initial investment of a certain configuration is calculated by adding up all relevant inputs from Table 5. For scenario D, 30% of the total investment costs are subtracted to simulate an investment subsidy. Initial investments decrease over time due to the price declines of both PV Modules & BESS systems (See Figure 13 & 14). The feed-in yields are different for every configuration and scenario over time. The avoided grid energy costs, however, are independent of any regulatory scenario. They portray the benefits of a PV or PV-BESS system compared to a reference situation, in which a household consumes the same amount of electricity but does not contain such a system. Lastly, the O&M costs are given in Table 8. The self-consumption rate is assumed to stay the same over time, whereas battery degradation is not considered in this study.

Table 7

Investment costs for PV systems & Battery storage systems. For the PV systems, these are a summation of the 'PV' inputs, whilst for PV-BESS systems they are the sum of all inputs (also see *). These assumptions were formulated through own research of the Dutch & German BESS wholesale market research. The inherent observation was that prices (€/kWh & €/kWp) differ significantly for different system sizes. The prices of both the PV-system as the BESS are assumed to decline over time (see Table 8). The price assumptions are justified in Figure 11 & 12 with (Schmidt et al., 2017), (Naumann et al., 2015) & (Londo et al., 2020).

Name	Assumption
PV – Module costs	210 €/kWp
PV – Inverter costs*	€150 + 75 €/kWp
PV – Installation & Margin costs	€1200 + 400 €/kWp
PV – Mounting material costs	90 €/kWp
BESS – Battery system costs in 2020 (power system, li-ion battery, installation & margin costs)	€1300 + 260 €/kWh
BESS – Hybrid Inverter costs	€650 + 75 €/kWh

*PV – Inverter costs are not considered for PV-BESS systems and replaced by BESS – Hybrid inverter costs.

Table 8

General economic input assumptions. The initial electricity price and initial feed in renumeration were retrieved from the Dutch energy supplier Eneco (Eneco, 2021). The inflation rate is chosen to be similar to other studies (Beck et al., 2016; Bertsch, Geldermann & Lühn, 2017). BESS price decline & calendar lifetime reference is Naumann et al., 2015, which uses 4,96% & 12.5-15.0. years, respectively. Calendar lifetime PV-system & PV system price decline reference is Londo et al., 2020. O&M costs constitute a fixed percentage of the initial investment, paid every year.

Name	Unit	Value
Inflation rate	%	2
Initial electricity price	$€_{2020}$/kWh	0.22
Initial feed-in renumeration	$€_{2020}$/kWh	0.07
PV module capacity degradation	%/yr	1
PV system price decline	%/yr	2
BESS price decline	%/yr	5
Depreciation period	yrs	15
Calendar lifetime BESS	yrs	15
Calendar lifetime PV-system	yrs	25
O&M costs	% of Inv, every year	0.5

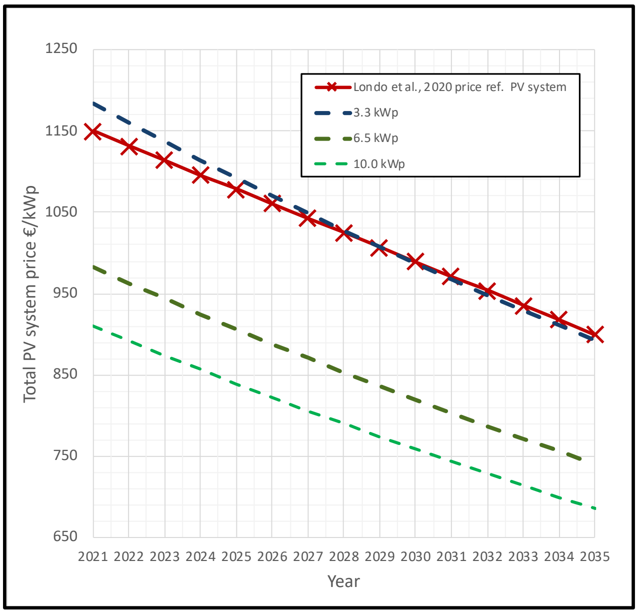

Figure 13 | Price assumptions for different PV system sizes in this study (Aggregate of 4 components listed in Table 7) compared to Londo et al., 2020. It shows that the price assumption for the 'standard' 3.3 kWp system shows close resemblance to the reference price used in Londo et al., 2020. Therefore, this price is deemed a realistic assumption, whereas those for the larger systems might be somewhat optimistic.

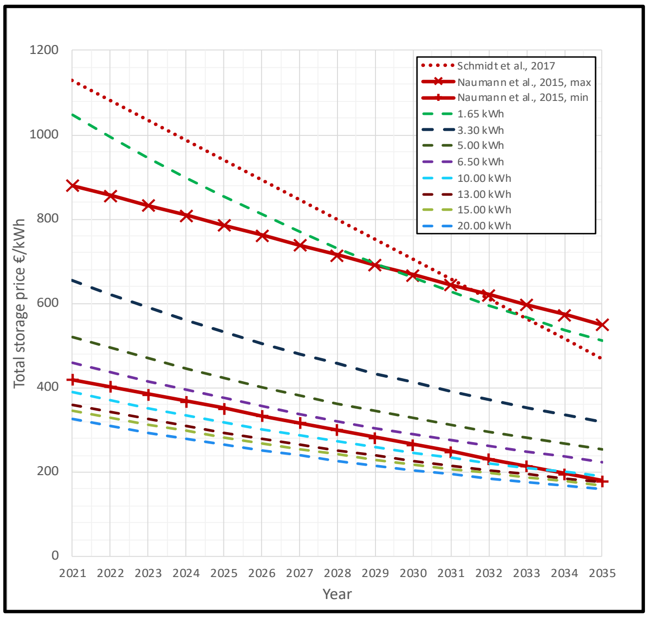

Figure 14 | Price assumptions for different BESS system sizes in this study (excl. PV system & hybrid inverter) compared to the forecasts made by Schmidt et al., 2017 and Naumann et al., 2015. It shows that the price assumption for the 'standard' 3.3 kWh is close to the average between the minimum and maximum prices stated by Naumann et al., 2015. This price is therefore considered a realistic assumption, whereas the prices for the larger systems might be rather optimistic.

3.3 Forecasting market development

Lastly, the size of the future residential BESS-market in the Netherlands is estimated. Market size is defined as the total revenue of the residential energy storage branche, i.e., the aggregated prices end-users pay for BESS systems.

The growth rate cannot be determined based on the current cumulative installed residential battery capacity, because it is not publicly nor centrally registered in the Netherlands. Additionally, the magnitude of the market is still very small. In order to forecast the size of the Dutch market, it is assumed that it will grow similar to the German market did during the last decade once it has achieved the similar profitability of BESS systems. To consequently determine a realistic growth rate, the ratio between the magnitude of the German PV market and the magnitude of residential PV-BESS was considered was chosen as leading factor.

Firstly, the cumulative capacity of residential BESS installations (see Figure 8) and cumulative installed PV capacity data for Germany was used as foundation for this forecast (BMWI, 2021). Additionally, the cumulative installed PV capacity data for the Netherlands was used (CBS, 2021). Residential PV constitutes 40% of the German market (Dharsing, 2017), and the assumption was made that this also holds for the Dutch market. As a result, Table 9 is constructed.

Table 9

Input for Dutch residential BESS market forecast. **Bold figures** constitute real data from other sources, *italic figures* are calculated by the author. German PV capacity and BESS capacity are retrieved from (BMWI, 2021) & (Figgener, 2021), respectively. Dutch installed PV capacity is sourced from (CBS, 2021).

Year	2013	2014	2015	2016	2017	2018	2019
Germany Cumulative installed PV capacity (MWp)	**36,710**	**37,900**	**39,220**	**40,680**	**42,290**	**45,180**	**49,020**
Germany of which 40% = residential PV capacity (MWp)	*14,684*	*15,160*	*15,688*	*16,272*	*16,916*	*18,072*	*19,608*
Germany Cumulative installed BESS capacity (MWh)	**30**	**100**	**210**	**375**	**610**	**950**	**1425**
The Netherlands Cumulative installed PV capacity (MWp)	**650**	**1,007**	**1,526**	**2,135**	**2,911**	**4,608**	**7,177**
The Netherlands of which 40% = residential PV capacity (MWp)	*260*	*403*	*610*	*854*	*1,164*	*1,843*	*2,871*

Secondly, a high, medium & low forecast for the residential PV market in the Netherlands were formulated. All of these PV market forecasts are linear extrapolations towards a set target for 2030. These targets are the full technical potential (European Commission, 2017) of residential solar PV for the high scenario, the expected cumulative (assuming 7 TWh is generated by ± 7700 MWp residential Solar PV) for installed residential PV capacity in the Netherlands, according to the Dutch Environmental Assessment Agency (PBL) and Dutch Climate Agreement, (Rijksoverheid, 2021) for the medium scenario, and 75% of this expectation for the low scenario. This is graphically depicted in Figure 15.

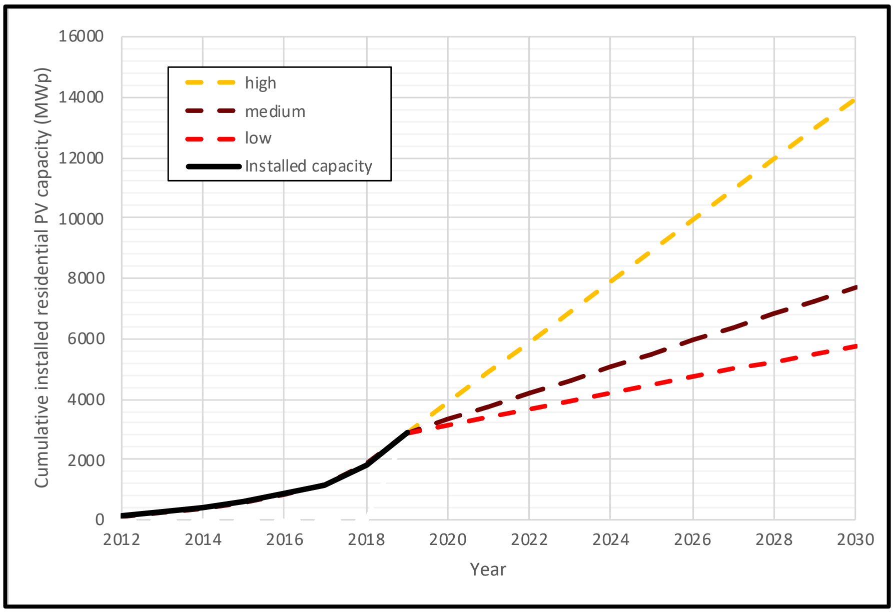

Figure 15 | Linear extrapolation of residential cumulative PV capacity in the Netherlands till 2030. For the (1) high, (2) medium & (3) low scenario, the current capacity is extrapolated to (1) full exploitation of the current technical potential (European Commission, 2017), (2) an expectation formulated by PBL (Rijksoverheid, 2021) and (3) a 75% fulfillment of this expectation.

Thirdly, the future cumulative installed capacity of BESS in the Netherlands is estimated. This is done by multiplying the cumulative installed Dutch PV capacity of the year in which BESS market growth is expected to start, with the ratio between the German PV capacity & BESS capacity in the first year of German BESS market growth. Insights for when this BEY might be achieved are gained in the results of the economic analysis and will depend on the policy scenarios (See section 4.2). This is then similarly done for the years that follow:

$$\tilde{C}_{BESS,NL}(BEY_{NL}+t) = \tilde{C}_{PV,NL}\,(BEY_{NL}+t) \cdot \frac{C_{BESS,DE}\,(BEY_{DE}+t)}{C_{PV,DE}\,(BEY_{DE}+t)} \qquad \text{(Eq. 13)}$$

where:

- t = time in years
- $\tilde{C}_{BESS,NL}$ (t) = estimation for cumulative installed residential BESS capacity in the Netherlands in year t
- $\tilde{C}_{PV,NL}$ (t) = forecast for cumulative installed residential BESS capacity in the Netherlands in year t (range between low, medium & high, see Figure 10)
- BEY_{NL} = 'Break Even Year', the year in which market growth for residential BESS in the Netherlands starts. Section 4.2 gives insights in when this might occur, depending on the policy scenario.
- $C_{BESS,DE}$ (t) = Cumulative installed residential PV capacity in Germany in year t,
- $C_{PV,DE}$ (t) = Cumulative installed residential BESS capacity in Germany in year t
- BEY_{DE} = 2013
- All capacities are expressed in MWh

Lastly, the market size is also determined in monetary figures. This is done by making use of German market figures; the German residential BESS market was equivalent to €660 million year in 2018 (Figgener et al., 2020). Table 10 shows that this represents 950 MWh – 610 MWh = ± 340 MWh of installed capacity. The market size is subsequently estimated by:

$$\widetilde{M}_{NL}\,(t) = \tilde{c}_{BESS,NL}\,(t) \cdot \frac{M_{DE}\ \ (2018)}{c_{BESS,DE}\,(2018)} \qquad \text{(Eq. 14)}$$

where:

- t = time in years
- $\widetilde{M}_{NL}$(t) = estimation of residential BESS market size in the Netherlands in year t, expressed in €.
- $\tilde{c}_{BESS,NL}$ (t) = estimation for installed residential BESS capacity in the Netherlands in year t, expressed in MWh.
- $c_{BESS,DE}$ (2018) = installed residential BESS capacity in Germany in 2018, expressed in MWh.
- M_{DE} (2018) = residential BESS market size in Germany, expressed in €.

4. Results

This section displays the results of the modelled optimization of PV & PV-BESS installations, their respective payback periods and a prospective market assessment.

4.1 Self-consumption rates of different PV & PV-BESS configurations

To study the economics of PV-BESS, firstly the maximum self-consumption of different system configurations is determined by optimization, as described in chapter 3.1. The PV profile and Household demand were simulated for the three different PV-system sizes (0-1, 0-2 & 0-3), and subsequently the optimization model was run for all the PV-BESS installations (1-12) and their respective self-consumption rates were calculated. The optimization model was consistently run at a Δt = 15 minutes, for a complete year. The results are shown in Table 8.

Table 8

Results of optimization: self-consumption rates of analyzed configurations

Run	Household demand (kWh)	PV system (kWp)	Battery system (kWh)	Sizing	Initial Investment costs of total system (€$_{2020}$)	**Annual Yield PV system (kWh)**	**Maximized Annual Self-consumption rate (%)****
0-1	3300	3.30	-	-	3048	**3052**	**0.36**
0-2	6500	6.50	-	-	4888	**6012**	**0.36**
0-3	10,000	10.00	-	-	6900	**9428**	**0.36**
1	3300	3.30	3.30	1 : 1	5706	**3052**	**0.59**
2	3300	3.30	1.65*	1 : 0.5	5277	**3052**	**0.49**
3	3300	3.30	4.95*	1 : 1.5	6135	**3052**	**0.62**
4	3300	3.30	6.60*	1 : 2	6564	**3052**	**0.63**
5	6500	6.50	6.50	1 : 1	8378	**6012**	**0.59**
6	6500	6.50	3.25*	1 : 0.5	7533	**6012**	**0.49**
7	6500	6.50	9.75*	1 : 1.5	9223	**6012**	**0.62**
8	6500	6.50	13.00	1:2	10068	**6012**	**0.63**
9	10,000	10.00	10.00	1 : 1	11300	**9428**	**0.59**
10	10,000	10.00	5.00	1 : 0.5	10000	**9428**	**0.49**
11	10,000	10.00	15.00	1 : 1.5	12600	**9428**	**0.62**
12	10,000	10.00	20.00	1:2	13900	**9428**	**0.63**

*These battery capacities meet the requirements to analyze linear sizing but are not realistic sizes available on the market by the respective NMC-battery producer considered.
**Self-Consumption rates of PV-BESS systems with similar ratios are calculated to be the same due to the linearity of the model.

Additionally, the dynamics of the baseline case (3300 kWh Load, 3.3 kWp PV, 3.3 kWh BESS), when optimized for self-consumption, are displayed in Figure 16 and Figure 17 for the different seasons.

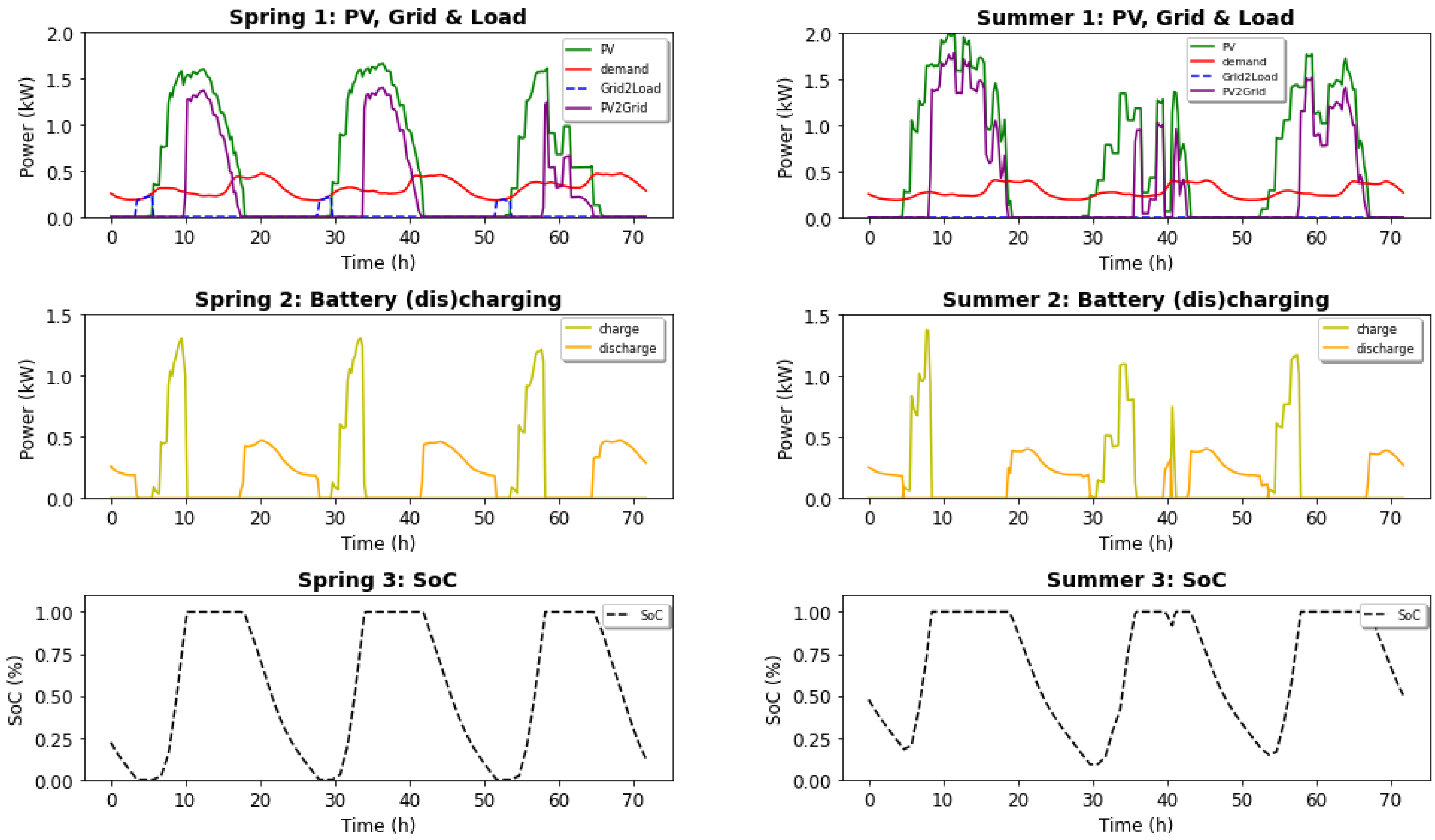

Figure 16 | System operation for three days in spring and three days in summer, when optimizing self-consumption.

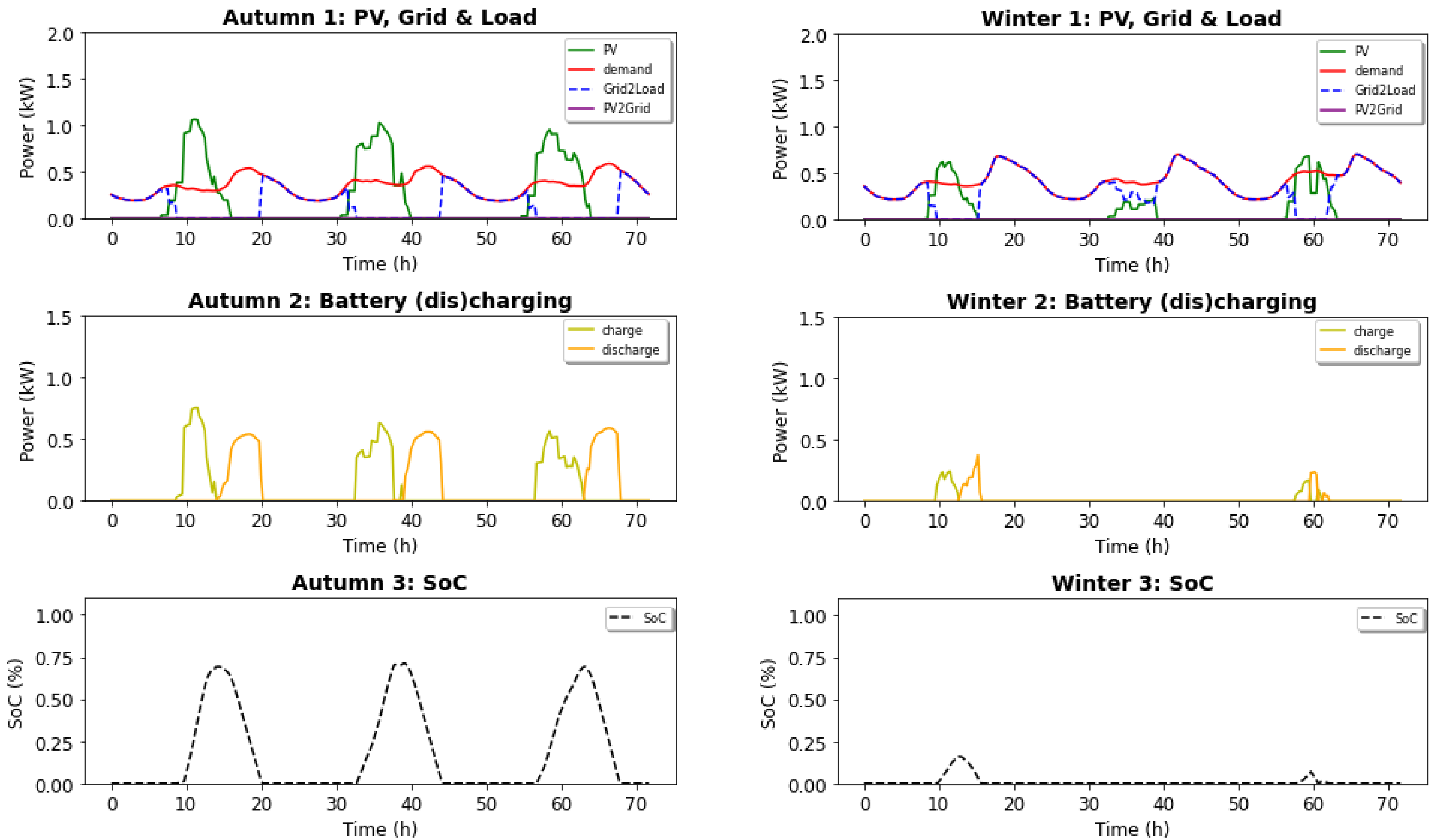

Figure 17 | System operation for three days in autumn and three days in winter, when optimizing self-consumption.

Figure 17 clearly shows that the battery is barely used in winter under this battery strategy, and therefore ages without performing any economic benefit every winter.

4.2 Assessing Payback Periods for PV-BESS systems

The method for calculating payback periods is given in Section 3.2.2. It is assumed that a payback period points out two things:

- If the payback period of an installation is shorter than its calendar lifetime (See Table 8 for PV & BESS lifetimes), it is generally a profitable investment.
- Installations with shorter payback periods are a more attractive investment than installations with longer payback periods.

4.2.1 PV-only system

The payback periods of ordinary PV system's serve as a reference for assessing the profitability of PV-BESS systems. When the PBP of a PV-BESS system is lower than the PBP of a PV-system, it becomes economically more attractive to invest in a PV-BESS system instead of a PV-system. For regulatory frameworks A-C (See Table 2), the PBP's of the 'standard' 3.3 kWp PV-system are depicted in Figure 18. Additionally, the PBP's of the 6.5 kWp & 10.0 kWp PV systems for regulatory framework C are shown.

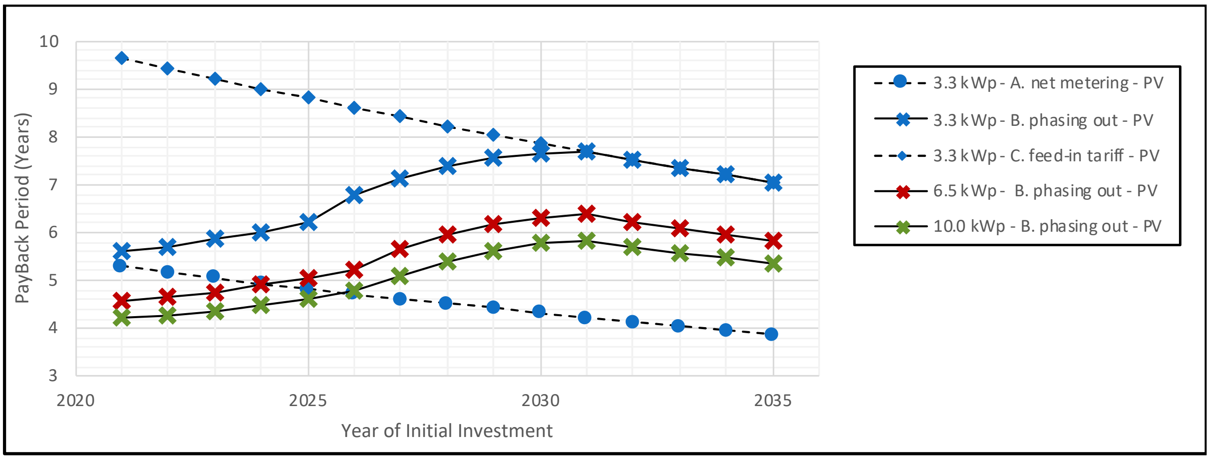

Figure 18 | Payback Periods of different PV system sizes under regulatory frameworks A-C.

The model clearly shows that under current 'phasing out of net metering' policy, the PBP of a 3.3 kWp PV system is 5.6 years in 2021 and will rise to approximately 7.8 years in 2031. Furthermore, Figure 18 shows that larger PV systems are earned back sooner than smaller systems and that the effect increases disproportionally with an increase in capacity.

4.2.2 'Standard' PV-BESS system

Figure 19 displays the PBP's for a 3.3 kWp system with & without BESS system. The PBP's of the PV-BESS system under current Dutch regulation are high; in comparison with the PV only systems, it shows that an installation without battery is economically more attractive in any regulatory scenario than an installation with battery under current governmental policy. In addition, it becomes clear that introducing an extra investment subsidy that covers 30% of the total investment would result in PV-BESS systems becoming economically attractive from ± 2026 onwards.

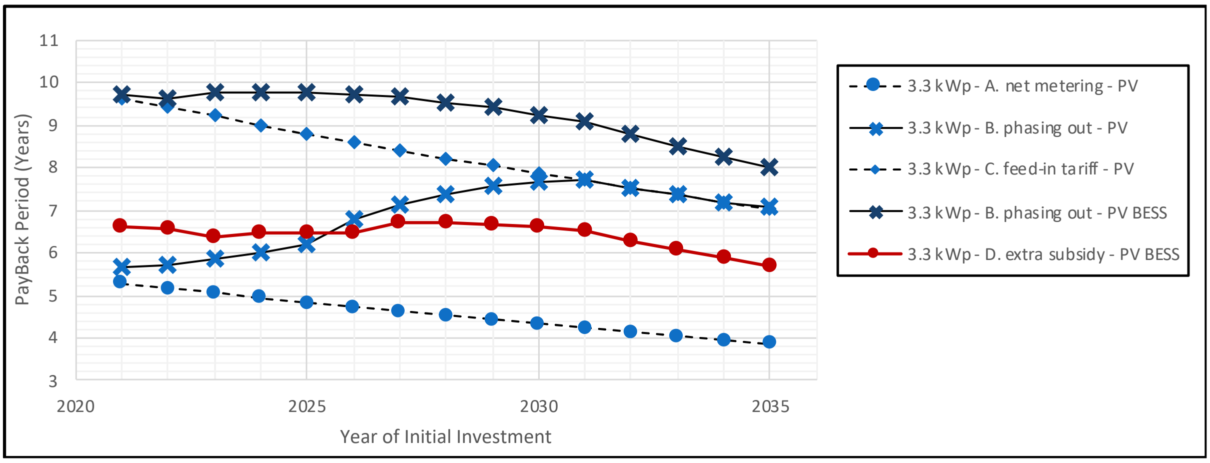

Figure 19 | Payback Periods of 3.3 kWp PV systems under regulatory frameworks A-C and 3.3 kWp/3.3kWh PV-Bess systems under regulatory frameworks B and D.

4.2.3 Influence of BESS size on PBP

Consequently, the model illustrates that altering battery size with respect to the PV system does not severely impact the economic viability; Figure 20 presents that, when considering scenario B, sizing the battery 1 : 1.5 or 1 : 2 is more expensive than 1 : 1, as PBP's stay longer over time than the PBP's of standard 1 : 1 sizing. The PBP's for 1 : 0.5 sizing are initially better than those of standard 1 : 1 sizing, but become higher after 2026, indicating no significant advantages to regular 1 : 1 sizing.

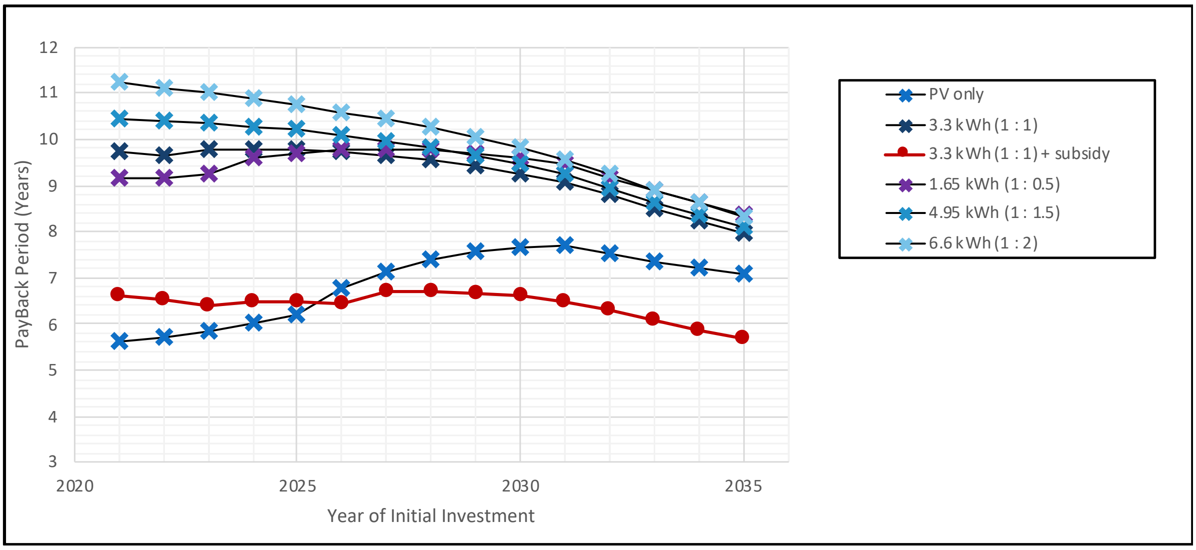

Figure 20 | Payback Periods of 3.3 kWp PV(-BESS) systems for different battery sizes under regulatory framework B. Additionally, a 3.3 kWp/3.3kWh PV-BESS system under regulatory framework D is depicted (denoted as '+ subsidy')

Similar to the reference PV only cases, Figure 21 & 22 show that larger installations result in shorter PBP's. The model illustrates that PV-BESS systems are a more profitable investment for larger household electricity demand, but still maintain longer PBP's than a regular PV system under current

Dutch policy. An extra subsidy covering 30% of the total investment costs, however, shows a more significant effect on economic attractiveness, resulting in standard sized PV-BESS systems having lower PBP's than PV only systems in ± 2024 and ± 2023, for 6.5 kWh and 10.0 kWh systems, respectively. Additionally, it becomes apparent that 1 : 0.5 sizing pays off when installations become bigger. In scenario D, 1 : 0.5 sized PV BESS systems for larger installations would become more economically attractive than 1 : 1 sized PV only systems in the near future. This, however, does not hold for the average household.

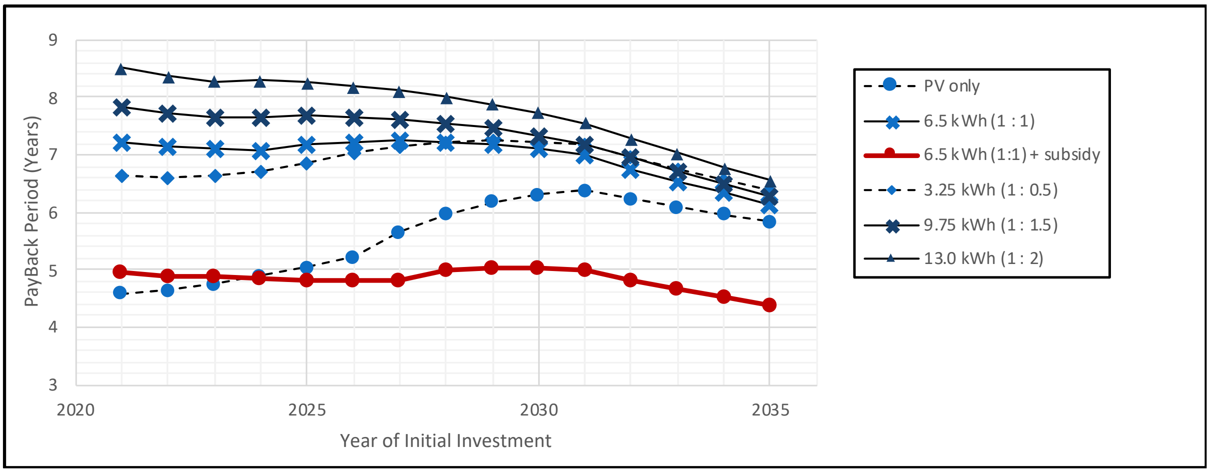

Figure 21 | Payback Periods of 6.5 kWp PV(-BESS) systems for different battery sizes under regulatory framework B. Additionally, a 6.5 kWp/6.5kWh PV-BESS system under regulatory framework D is depicted (denoted as '+ subsidy')

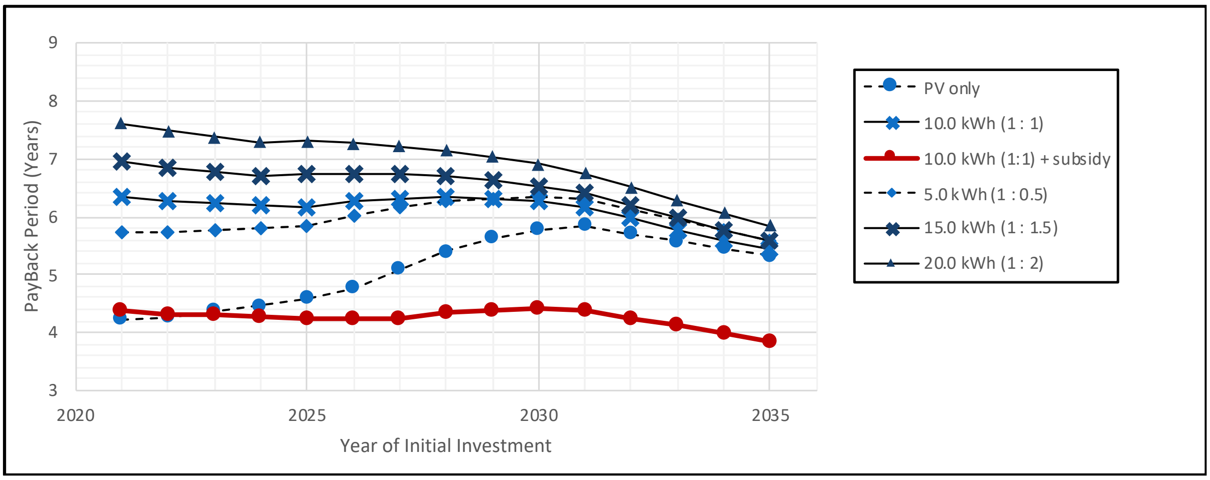

Figure 22 | Payback Periods of 10.0 kWp PV(-BESS) systems for different battery sizes under regulatory framework B. Additionally, a 10.0 kWp/10.0 kWh PV-BESS system under regulatory framework D is depicted (denoted as '+ subsidy')

4.2.4 Influence of BESS Investment costs on PBP

The sensitivity of the BESS investment costs on these results is shown by minimizing and maximizing those costs to match Naumann et al., 2015, in contrast with the 'standard' costs (See Figure 14). The minimized and maximized BESS investment costs are displayed in Figure 23 and 24, respectively. The corresponding results are shown in Figure 25 and 26.

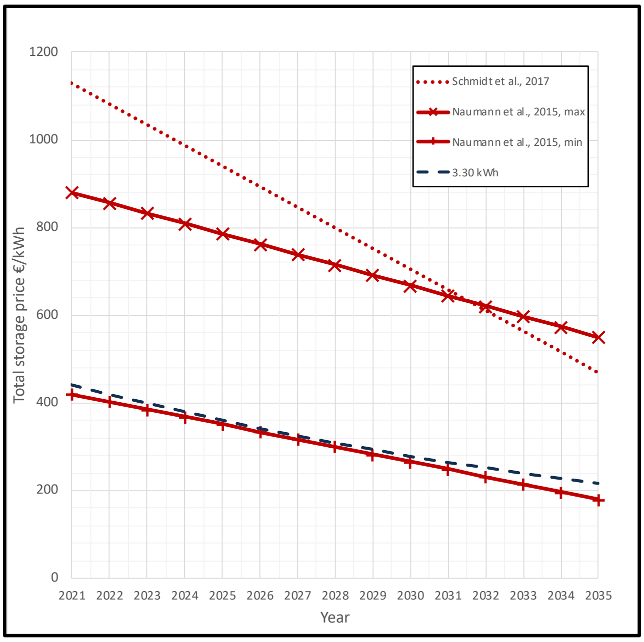

Figure 23 | **Minimized** BESS price for 3.3 kWh system, compared to Naumann et al., 2015 and Schmidt et al., 2017. Also see Figure 14.

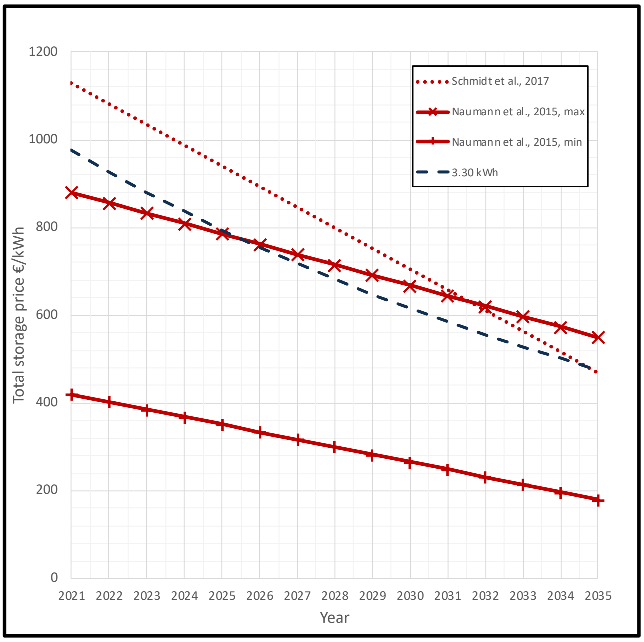

Figure 24 | **Maximized** BESS price for 3.3 kWh system, compared to Naumann et al., 2015 and Schmidt et al., 2017. Also see Figure 14.

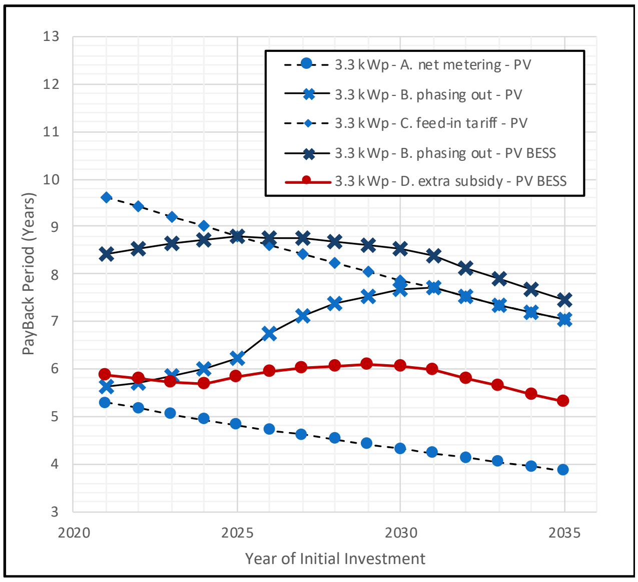

Figure 25 | PBP's of 3.3 kWp PV systems under regulatory frameworks A-C and 3.3 kWp/3.3kWh PV-BESS systems under regulatory frameworks B and D for **minimized** BESS prices.

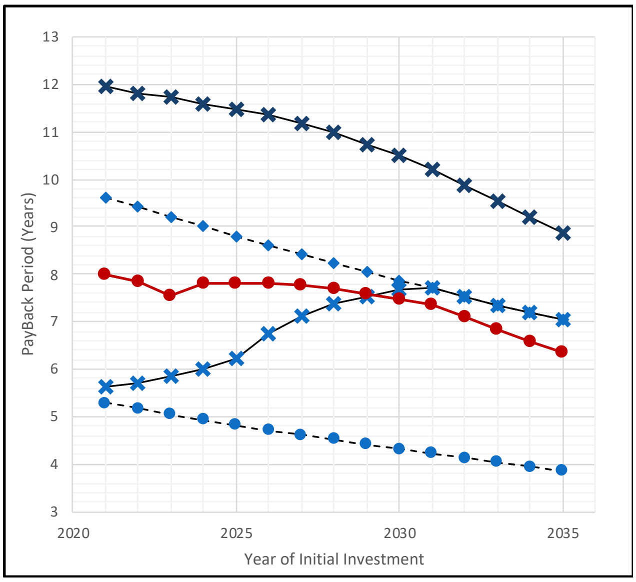

Figure 26 | PBP's of 3.3 kWp PV systems under regulatory frameworks A-C and 3.3 kWp/3.3kWh PV-BESS systems under regulatory frameworks B and D for **maximized** BESS prices. (Same legenda as Figure 25)

The influence of the BESS prices shows to be large. The initial PBP in 2021 ranges from 8.4 year for minimum prices, to 9.8 years for average prices (See Figure 19), to 12 year for maximum prices. In addition, an extra subsidy covering 30% of the total investment costs illustrates that investing in a PV-BESS under this regulatory framework could already become more attractive due to a shorter PBP than a PV-system in 2023 for minimized BESS prices. This happens in 2029 for maximized BESS prices.

4.3 Market size forecast for the residential BESS market in the Netherlands

This section displays the results of future market size estimations of the Dutch residential BESS market. The used break-even years correspond with the maximized BESS prices (low), average BESS prices (medium), minimized BESS prices (high) reviewed in section 4.2.4. Therefore, the results for the market forecast only hold if a 30% investment subsidy (Regulatory Framework D, see Table 2) is introduced before the break-even year. Figure 27 illustrates the outcomes of Equation 13 for three sets of break-even years & residential PV capacity scenarios:

- $\tilde{C}_{BESS,NL}$ for BEY_{NL}= 2023 and the $\tilde{C}_{PV,NL}$ high scenario (corresponding with Figure 25)
- $\tilde{C}_{BESS,NL}$ for BEY_{NL}= 2026 and the $\tilde{C}_{PV,NL}$ medium scenario (corresponding with Figure 19)
- $\tilde{C}_{BESS,NL}$ for BEY_{NL}= 2029 and the $\tilde{C}_{PV,NL}$ low scenario (corresponding with Figure 26)

The large bandwidth in outcomes stands out, which correctly represents the high uncertainty in this approach. It shows that, in the most optimistic scenario, ± 120 MWh of BESS capacity for households will be realized in 2025, and ± 1340 MWh in 2030. The medium scenario gives less than 1 MWh and ± 560 MWh of installed residential BESS capacity in 2025 and 2030, respectively. The most conservative scenario gives less than 1 MWh of battery home storage capacity in 2025, and ± 210 MWh in 2030.

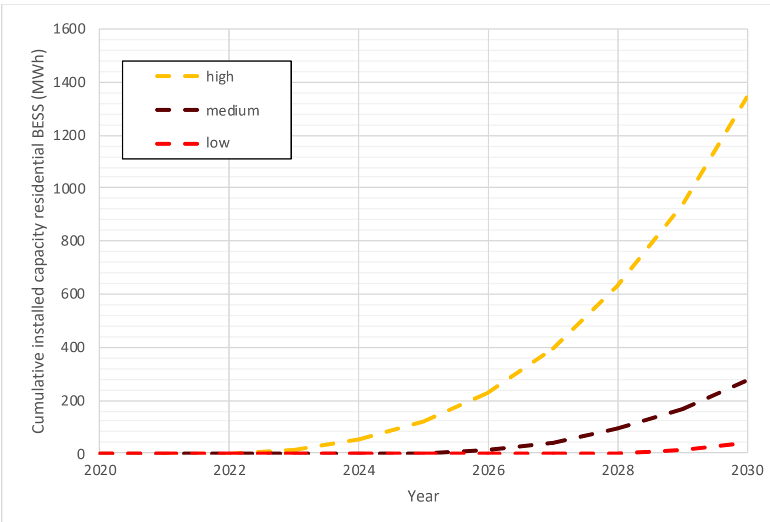

Figure 27 | Potential growth in cumulative installed residential BESS capacity in the Netherlands, if subsidy scheme/tax incentive is introduced and similar growth as in Germany is achieved from 2023 (high), 2026 (medium) or 2029 (low) onwards. The estimated values are shown in Appendix B.

Figure 28 illustrates the results of Equation 14. Similar to Figure 27, this figure shows a high level of uncertainty. The most likely estimates for annual residential BESS market size in the Netherlands in terms of revenue, is less than 1 million euros in 2025, ranging between 0 and €130 million euros. For 2030, the most likely estimate is ± €215 million euros, ranging between €50 and €780 million euros.

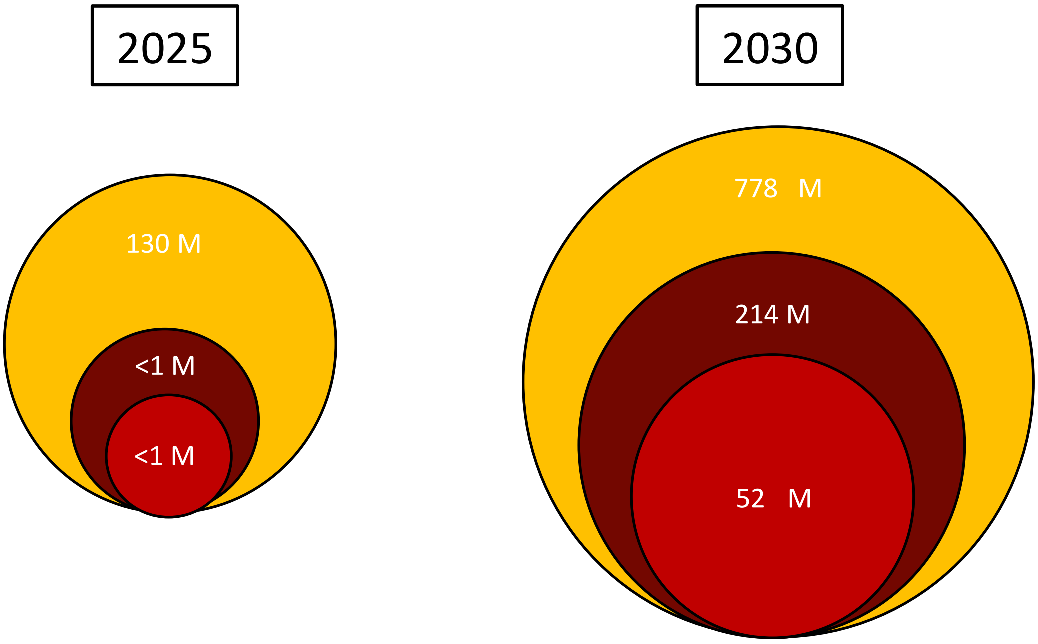

Figure 28 | Estimated market size for the residential BESS market in the Netherlands in 2025 and 2030. (Following assumptions in Figures 15 & 27)

5. Discussion

The aim of this chapter is to examine potential deficiencies of this research. The developed optimization model, economic calculations and market forecast are reviewed. Finally, some implications, of both theoretical & regulatory nature, and several recommendations will be discussed.

In general, it must be noted that a high number of assumptions was made to accomplish this research. Therefore, a larger focus should be maintained on the identified economic factors, interdependencies and their relative influence on the outcomes, than on the numerical results. In other words, every reader should keep the words of the great statistician George E.P. Box (1976) in mind:

"All models are wrong, but some are useful"

5.1 PV profile simulation & Optimization model

The distribution of the household demand profile in this study did not represent a real household demand profile as realistically as desired. This demand profile was retrieved from the Dutch Association for Energy Data Exchange (NEDU) and depicts a smoothed profile due to the averaging of profiles across an entire neighborhood. Subsequently, the steep peaks and deep lows that are characteristic for the load demand profile of a singular household are not optimally presented through making use of NEDU data. This could be improved by making use of a real demand profile of a Dutch household or generating a more distinguished demand profile through alternative sources.

Furthermore, due to the limits of optimization modelling, it is inherently assumed that the battery or management system has perfect information on both future PV generation and household load. The model is also not performed in real-time and is therefore a clear simplification of reality. In reality, more efficiencies would occur because of the absence of future information.

The standardizing of a household also brings up several drawbacks. This model considers the mean tilt and azimuth angles of Dutch PV systems in academic literature, which does not perfectly translate to the average PV system in the Netherlands. The current surface azimuth of 0.77 degrees approximately construes a southern orientation, whereas there are also many east and/or west orientated Dutch solar installations. Similarly, the tilt angle of 32.5 degrees is rather arbitrary, since optimal tilt angles depend on location and time of year. The resulting yields of the PV systems consequently appear to be relatively high: a 3.3 kWp installation which yields 3052 kWh suggests that the installation operates extremely efficient, higher than what would be an expected average yield. The significance of the precision of these inputs, however, fades a little when analyzing policy effectiveness. Therefore, this is determined condonable for this research.

Due to the widespread installation of smart meters in the Netherlands (Every Dutch household will have been offered one by the end of 2022, (NBN, 2021)), the assumption that the optimum strategy for batteries is maximization of self-consumption, overlooks other economic potential. This assumption does reflect, however, how Dutch PV market players currently look at residential storage systems. Therefore, the influence of different (future) battery strategies could be studied. Whereas optimized self-consumption is currently the most obvious strategy for end users, strategies such as cost and emission minimization, or a trade-off between certain objectives, could be considered for both contemporary and future situations (e.g. time-of-use, time-of-export, and real-time trading on the Day Ahead spot market (also see Okur, 2021)). Moreover, it can be argued that effectively communicating this academically identified potential to Dutch companies and stakeholders in the residential solar market would also improve the economic potential of battery storage.

In addition, battery degradation is heavily simplified for both the optimization model and economic assessment in this study. Due to the fact that battery lifetime is also heavily dependent on the number of cycles, a more elaborate manner of modelling this phenomenon would benefit the outcomes of this study.

There are ample other opportunities for deepening this topic and performing future research. The influence of future household demand profiles on PV-BESS economics could be considered, such as profiles that include more electric appliances, an electric car, a heat pump or a combination of those. Similarly, including Demand Side Management strategies could also provide valuable new insights.

5.2 Economic Analysis

For the economic analysis, the relatively short PBP's for PV systems (± 4,5 years in 2021) stand out, as the PBP of a PV system is commonly assessed to be 6-7 years in 2021 (Consumentenbond, 2021; Vattenfall, 2021). This common assessment, however, includes VAT (21% in the Netherlands) in its initial investment, whereas this research excludes VAT of the total investment costs, as this tax can be reclaimed with relative ease from the Dutch tax authorities (Milieucentraal, 2021). Additionally, this research considers changing cashflows over time due to e.g. rising electricity prices & capacity degradation of PV modules, whereas the simplified calculation only looks at costs and benefits during the first year of operation. Lastly, the PBP analysis does not include replacing the inverter, as an average inverter has a lifetime of 10 years. Alternatively, this is attempted to be partially compensated by the yearly O&M costs in the model.

Moreover, it must also be noted that, whilst changing cashflows over time were considered, no discount rate was applied to adjust future costs and benefits for current value. This choice was made by considering the perspective of an end-consumer. In comparison to a professional investor, there is less necessity to receive an immediate return on investment for an end-consumer. Implicitly, discounted value of future cashflow when making an investment decision is also often neglected.

Evidently, a wide range of sources was used to formulate the costs and characteristics of a 'standard' residential PV(-BESS) system in the Netherlands. This amounts to a certain level of uncertainty in the outcomes, where mainly the cost and PBP predictions for PV(-BESS) systems after 2025 become highly uncertain. Especially future electricity prices and the decline in costs for BESS systems and PV modules carry a high level of uncertainty. However, the usage of self-determined assumptions for investment costs through analyzing the contemporary PV & BESS wholesale markets in the Netherlands and Germany can be argued to approach reality better than making use of academic sources, which are often distant to the market, based on forecasts and slightly outdated.

Furthermore, this study profoundly researches the profitability of a complete PV-BESS. However, adding a new storage system to an existing residential PV installation is not considered. Assessing the costs and benefits of this so-called retrofitting (which e.g. requires an additional AC-coupled inverter, instead of a new, hybrid DC-coupled inverter) be of great added value for evaluating the economic potential of residential battery systems.

The relevance of the payback period as metric can also be discussed, despite it being the commonly used economic indicator by PV market players. Alternatively, the closely related Return of Investment (ROI) could be considered. In contrast to the payback period, the metric tells something about how beneficial an investment is, instead of only indicating whether something is profitable or not. In this way, the PV system & PV-BESS system could be compared in a better way when both of their PBP's were shown to be profitable.

5.3 Market forecast

Forecasting studies by definition suffer from high uncertainty. Mainly, the assumption of linear growth of installed PV capacity in the Netherlands heavily simplifies the current trend. The Dutch PV market has experienced exponential growth over the past years due to its juvenility but is expected to slowly level off similar to other countries. Therefore, linear growth probably mainly simplifies the growth for the upcoming 2-4 years.

Also, the assumption that the Dutch BESS market will grow similar to the German BESS market heavily simplifies reality. Chapter 2 identifies the differences between Germany and the Netherlands, suggesting that the Dutch BESS market might grow slower than the German BESS market. It is difficult to quantify how much slower this might be. Nevertheless, due to these optimistic assumptions, this market forecast does give a good upper limit of the potential annual residential BESS market size in the Netherlands for 2025 and 2030.

Lastly, Data availability also lacked for this forecast. Data on current residential BESS installations of the Netherlands are difficult to find or unavailable. Future research could also be focused on keeping up and mapping the BESS developments & installations in the Netherlands.

6. Conclusions

Finally, this chapter harmonizes the outcomes of chapters 2-5. The research questions stated in chapter 1 are revisited and answered, by shortly summarizing the results and concisely discussing additional insights that have been gained throughout this research.

1. **How is the economic potential of residential PV-BESS influenced by policy? And how does this relate to the Netherlands?**

Five main policies were found to drive the economic potential of residential PV-BESS installations: Long-term stimulation of residential PV, a significant difference between the electricity price and feed-in tariff for PV electricity, an advantageous legal status for self-consumption, generous investment subsidies and/or tax reliefs for (PV-)BESS installations & Authorization of other battery applications. Current Dutch policy was found to only fully meet the advantageous legal status. It partially meets the stimulation of residential PV, which is not as long as frontrunning countries when it comes to installed residential BESS capacity, and the difference between electricity- and export price, which is still minor but set to increase by 2023 (see section 2.3).

2. **Which other factors influence the profitability of a residential PV-BESS system?**

A multitude of factors was found to influence the profitability of a residential PV-BESS system, including but not limited to; system orientation; system costs; system degradation & efficiency; system lifetime & ratio between household electricity demand, PV system and Battery size. The battery strategy was also found to have an influence, as optimization of self-consumption showed that the battery was not used in winter (See sections 3.1, 3.2 & 4.1).

3. **When and under which regulatory framework(s) will residential PV-BESS systems become more economically attractive than regular PV systems in the Netherlands, and how does this affect the economic potential?**

PV-BESS installations are profitable investments for all considered configurations and regulatory frameworks. However, their PBP's remain significantly longer than those of regular PV systems in the short term under regulatory frameworks A-C. This would most likely result in very little market uptake. Under regulatory framework D, in which a 30% subsidy is introduced next to the phasing out of net metering, the PBP's of PV-BESS will become shorter than those of PV only systems between 2023 and 2029 (See section 4.2).

4. **What is the potential annual market size for residential BESS systems in the Netherlands in 2025 & 2030?**

The upper limit of the annual residential BESS market in the Netherlands is ±780 million in 2030. In addition, it seems most likely that the annual market size for residential BESS system will remain very small till 2025 (See section 4.3).

Consequently, the main research question could be answered:

"What is the economic potential of residential PV-BESS systems for end-users in the Netherlands towards 2030?"

The economic potential of residential PV-BESS systems for the Netherlands towards 2030 is small in the short term. This study strongly suggests that residential battery storage will not become a more attractive investment for the end-consumer than a regular PV system under current Dutch policy within the next 5 years. Whilst the Dutch PV market matures, however, PV-BESS systems are more likely to become an attractive option for increasing self-consumption in the Netherlands during the second half of this decade, considering the phasing out of net metering and a possible additional incentive for residential BESS market uptake. Furthermore, this study highlights the sensitivity of BESS sizes and prices on the PBP's for PV-BESS systems. Lastly, the inclusion of aspects like different battery operation strategies, battery degradation & the case for retrofitted battery systems are discussed as possible future research.

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Appendices

Appendix A

Table 12

Extrapolation & Forecast values for the Dutch residential BESS market size estimation

Year	Unit	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
High scenario Extrapolated installed PV capacity	MWp	*2871*	*3310*	*3749*	*4188*	*4627*	*5066*	*5505*	*5944*	*6383*	*6822*	*7261*	*7700*
Medium scenario Extrapolated installed PV capacity	MWp	*2871*	*3878*	*4884*	*5891*	*6898*	*7905*	*8911*	*9918*	*10925*	*11932*	*12938*	*13945*
Low scenario Extrapolated installed PV capacity	MWp	*2871*	*3135*	*3399*	*3663*	*3927*	*4191*	*4455*	*4719*	*4983*	*5247*	*5511*	*5775*
High scenario Forecasted installed BESS capacity	MWh	*0*	*0*	*0*	*0*	*14*	*52*	*119*	*229*	*394*	*627*	*940*	*1341*
Medium scenario Forecasted installed BESS capacity	MWh	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*12*	*42*	*91*	*167*	*278*
Low scenario Forecasted installed BESS capacity	MWh	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*11*	*38*