Universiteit Utrecht

Techno-economic analysis of self-consumption in the residential sector and the associated effect on the electricity network

A case study of the Netherlands: Policy recommendations for the Dutch government in a time horizon toward 2031 and beyond.

Daan Booij

University	Utrecht University
Course Title	Master Thesis Energy Science
Course Code	GEO4-2510
Programme	Energy Science
ECTS	30
Name	Daan Booij
Contact	d.booij@students.uu.nl (+31 6 18410438)
Supervisor	dr. ir. Ioannis Lampropoulos
Supervision contact	i.lampropoulos@uu.nl
Second reader	dr. Elena M. Fumagalli
Second reader contact	e.m.fumagalli@uu.nl

Acknowledgement

First and foremost, I would like to express my special thanks to my supervisor dr. ir. Ioannis Lampropoulos. He gave me the opportunity to formulate a research topic according to my wishes and provided guidance and feedback during the project.

Secondly, I want to thank my parents who have supported me unconditionally throughout my study period.

Executive summary

Currently, over 600,000 households are equipped with a PV system in the Netherlands. This number is expected to increase in the coming years due to climate targets set by the European Union and the rapid decline in investment costs. To stimulate residential grid-connected PV systems, the Netherlands has currently the net metering policy in force. However, this net metering policy will be gradually abolished between 2023 and 3031. Increased self-consumption or incentives could raise the profitability of PV systems and lower the stress on the electricity grid. In this study, several self-consumption measures are tested in alternative policies. When the net metering system is maintained, the minimum PBP of a 3 kWp PV system is at least 4.0 years in 2020. When the net metering system is abolished this PBP will increase toward 2031. An average household (that consumes annually 2790 kWh) equipped with a 3 kWp PV system (which generates annually 2896 kWh) holds a self-consumption ratio of 29%. The integration of a 7 kWh lithium-ion battery can result in an increase of the self-consumption ratio to 64%. The difference in network impact between a PV system and a PV system with BESS can be seen in winter and summer. In winter most of the overproduction is stored in the BESS which removes most of the power peaks. In summer, however, the overproduction is much larger of which only a part is stored in the BESS to fulfil the demand until the next day. Therefore, BESS's does not affect the amplitude of the power demand peaks in but only the duration in summer. It is recommended to the Dutch government to continue the current policy to encourage prosumers to increase their self-consumption over time as the investment costs of BESS's are expected to decrease. An investment subsidy can be applied when the PBP becomes too long. By changing to a feed-in tariff or net billing policy, the PBP becomes higher but prosumers are immediately incentivised to use the BESS as it is much more cost-effective to store electricity on the BESS and used later than returning electricity to the grid. By stopping the reimbursement for excess electricity in the net metering abolishment policy, households that already have a PV system installed are even more encouraged to invest in a BESS. However, stopping the reimbursement for excess electricity will also increase the PBP of a combined PV system and BESS.

1. Contents

1. INTRODUCTION 7

1.1 BACKGROUND 7
1.2 RESEARCH QUESTION 9
1.3 GOAL AND SCOPE 9

2. THEORETICAL BACKGROUND 10

2.1 SELF-CONSUMPTION 10
2.2 SELF-CONSUMPTION DRIVERS 11
2.3 SELF-CONSUMPTION PARAMETERS 11
2.4 BATTERY ENERGY STORAGE SYSTEMS (BESS) 12
2.4.1 LITHIUM-ION BATTERY 12
2.4.2 VALVE-REGULATED LEAD-ACID BATTERY 13
2.4.3 REDOX FLOW BATTERY 13
2.4.4 MOLTEN SALT BATTERY 13
2.5 TECHNICAL PARAMETERS OF STORAGE TECHNOLOGIES 14
2.6 ECONOMIC PARAMETERS OF STORAGE TECHNOLOGIES 15
2.6.1 LITHIUM-ION BATTERY 16
2.6.2 LEAD-ACID BATTERY 16
2.6.3 REDOX-FLOW BATTERY 17
2.6.4 HIGH-TEMPERATURE BATTERY 18
2.7 OVERVIEW BESS COSTS 18
2.8 DEMAND-SIDE MANAGEMENT (DSM) 19
2.9 DUTCH ENERGY MARKET SYSTEM DESIGN 20
2.10 THE ELECTRICITY PRICE 21

3. METHODOLOGY 23

3.1 PV SYSTEM MODEL 23

3.1.1 PV SYSTEM 23
3.1.2 PV SYSTEM COSTS 24

3.2 RESIDENTIAL LOW VOLTAGE NETWORK MODEL 25

3.3 DEFINITION OF THE ASSESSMENT FRAMEWORK 28
3.3.1 CONSUMER SIDE 28
3.3.2 DSO FRAMEWORK 29
3.3.3 SENSITIVITY ANALYSIS DEVELOPMENT 29
3.4 CASE STUDY 30
3.4.1 ALTERNATIVE POLICIES 30
3.4.2 DEVELOPMENT OF SCENARIOS 31
3.4.3 DATA COLLECTION 31

4. RESULTS 33

4.1 Scenario 1: Reference 33
4.2 Scenario 2: PV 33
4.3 Scenario 3: lithium-ion BESS 35
4.4 Scenario 4: PV & Lithium-ion BESS 36
4.5 Scenario 5: PV system & valve-regulated lead-acid BESS 38
4.6 Scenario 6: PV system & Redox-flow BESS 39
4.7 Scenario 7: PV system & High-temperature BESS 40
4.8 Scenario 8: PV system & DR 41

5. SENSITIVITY ANALYSIS 44

6. DISCUSSION 47

7. CONCLUSION 51

8. REFERENCES 53

APPENDIX 1. ANNUAL LOAD PROFILE 57

APPENDIX 2. INPUT PARAMETERS, COSTS AND PBP'S 58

..... 58

Acronyms

BESS: Battery energy storage system

DR: Demand response

DSM: Demand side management

DSO: Distribution system operator

EMS: Energy management system

PBP: Payback period

PV: Photovoltaic

SoC: State of charge

TSO: Transmission system operator

1. Introduction

1.1 background

One of the most significant challenges humanity is facing these days is anthropogenic climate change. Worldwide are the effects measurable, such as higher (average) temperatures, a rapid decrease of sea-ice and more extinct species than ever (Rockström et al., 2009). Fossil fuel emissions from the energy sector (electricity generation, heat production and petroleum refining) were responsible for 29% of total emissions in 2017 (European Commission, 2018). To mitigate climate change, the European Union has set a key target for 2030 to reduce its greenhouse gas emissions by 40% compared to 1990 levels (Hof et al., 2016). Essential means for contributing to the reduction of greenhouse gas emissions is to increase the share of renewable energy sources and to limit the use of fossil fuels. The Paris Agreement that was adopted in 2015 and signed in 2016 (Michiel & Robert, 2018) included a convention in which all countries pursued their ambitions to mitigate climate change. The primary goal was to keep the temperature rise below 2°C compared to pre-industrial levels (United Nations, 2015) However, still much effort is required to achieve this. In addition to its target to reduce greenhouse gas emissions, the European Union has set itself the goal of having at least 32% renewable energy in the European Union by 2030 (European Council, 2014).

The residential sector is one of the key contributors to greenhouse gas emitters as they account for a quarter of the final energy consumption in the European Union (Nejat et al., 2015). Therefore, the role of the consumer is critical in the mitigation of climate change. As a result of several factors including grid parity, subsidies and customer acceptance is a substantial increase visible in the number of installed PV systems on residential rooftops. Grid parity refers to the point that the cost of PV generated electricity equals the cost of buying power from the grid. The Netherlands has reached this point in 2012 (van Sark et al., 2012). The installed PV in the last decade indicates an exponential growth that equals a worldwide increase of 120 GW in 2019 (Willuhn, 2019).

The Netherlands had a share of 7.4% renewable energy in 2018 and is presumably not going to reach its ambitious target of 14% renewable energy in 2020. Therefore, the Netherlands is falling behind compared to other countries in the European Union (CBS, 2019). Many additional measures are required to fulfil the European goals. Despite this, the generated energy by PV in the Netherlands increased from 3.7 billion kWh in 2018 to 5.2 billion kWh in 2019 (CBS, 2020). All agreements and goals that have been made are stated in the National Climate Agreement (ministry of economic affairs and climate, 2019).

PV generation is characterised by an intermitted generation pattern which can lead to a mismatch between power output and demand. Governmental incentives and policies determine possibilities for consumers to deliver surplus electricity to the grid to stimulate renewable energy. As the share of renewable energy is currently low, the grid managers can manage the energy flows. However, up to a certain point that the energy market becomes saturated with renewable energy, either the DSO must make adjustments to the electricity grid or consumers must adjust their energy management. In Germany, for example, periods occur that electricity market prices fall below zero. Negative energy prices are the result of a market equilibrium. When a high inflexible power supply is combined with a low electricity demand, it can result in negative energy prices to keep the energy system in balance and prevent overloading of the grid. Self-consumption is a solution to this problem, not only to decrease stress on the electricity network, but it also has the potential to increase profit for prosumers (both a consumer and a producer). The gradual abolishment of the net metering policy will decrease the profitability of stand-alone PV systems for prosumers as the cap on the feed-in tariff is lowered from 2023 onwards. It makes it less profitable for prosumers to supply power to the grid and self-consumption becomes more profitable (van Sark et al., 2020). This research is focused on different systems to increase self-consumption and what the development of the profitability will be in response to these changes. Besides, what the effect of self-consumption measures is on the electricity network.

Generally, there are many studies focused on the technical and economical implementation of PV panels(Brown & Wu, 2009; Khatib et al., 2013; Messenger, 2018). The research on self-consumed PV generated electricity is less comprehensive. As the number of studies is limited and there is a variety of specific studies that focusses only on one aspect of self-consumption such as a single storage technology. The lack is in comparative studies on various technologies in different policies. Luthander, Widén, Nilsson & Palm (2015) provides an overview of different studies quantifying increased self-consumption, of which most is focussed on storage technologies (Luthander et al., 2015). Various studies contain optimisations of batteries in households with and without demand-side management (DSM) (Castillo-Cagigal et al., 2011; Schram et al., 2018). Some studies cover a techno-economic analysis of photovoltaic with BESS and the influence of different consumer load profiles on self-consumption. Another study covers the influence of battery storage and PV system design on PV self-consumption and grid interaction (Litjens et al., 2016). In addition, much information is provided on a wide variety of storage technologies. The International Renewable Energy agency provides besides parameters of these storage technologies also learning curves for future predictions (IRENA, 2017). Finally, literature provides alternatives for the current net metering policy for solar PV in the Netherlands (Londo et al., 2019). This published work is highly relevant research as it provides the development of PBP towards 2030 and how this is affected by different financial schemes such as net metering, feed-in tariffs and financial caps.

Although several studies are conducted on self-consumption, there are still gaps for future research. Most research is focused on general self-consumption and not on a specific system or country like the Netherlands. Since financial mechanisms differ a lot per country and have a significant influence on the profitability of PV systems, more research can be done on this aspect. Specifically, the approach of the Dutch government towards and beyond 2031 as a result of decreasing subsidies. Moreover, different storage technologies can be researched as most studies include only a single storage technology; this can be extended with optimisation of PV systems and storage technologies with future expectations on costs. Current research focusses on a single household which is mainly for optimisation of costs in households, whereas fewer studies are focussed on the effect on the electricity network when multiple households or neighbourhoods increase their self-consumption which involves another stakeholder, namely the DSO. A case study is performed to gain new insights into the effect on the electricity network as a result of increased self-consumption in the residential sector, which takes into account the prosumer, DSO and the government.

1.2 Research question

What is the technical and economic potential of self-consumption in the residential sector while taking into account the effect on the electricity network, and what are policy recommendations for the Dutch government in a time horizon toward 2031 and beyond to support self-consumption?

Sub questions:

1. Which parameters affect self-consumption and which technical options can be utilised to increase self-consumption in the residential sector?
2. What is the current and future policy in the Netherlands for financial support on self-consumption and distributed generation and what are alternative policy designs?
3. How can storage technologies and DR in combination with a PV system be tested in a model to optimise self-consumption as well as the corresponding network impact?
4. What is the techno-economic feasibility of different self-consumption scenarios taking into account different policies based on the case study toward 2031 and beyond?
5. What are potential policy recommendations to support self-consumption in the residential sector to make it financially attractive and reduce negative network impact that results in high costs for grid operators?

1.3 Goal and scope

The goal of this research is to identify the technological and economical options to increase self-consumption and consequently analyse the effect on the electricity network to make policy recommendations for the government. The timeframe of the analysis of the research is towards 2031 and beyond, because the net metering subsidy in the Netherlands will be abolished in this timeframe. The inventory analysis takes only the currently available storage technologies and DR options into account, as well as currently available design parameters that extend beyond 2031. The literature review on design parameters takes place in a global context. The case study will be limited to the Dutch legislation. Moreover, the model will be limited to the scenarios that are set up in this research. Finally, the policy recommendations will be based on the outcome of the model and the case study.

2. Theoretical background

Herein, first, a general introduction is provided about self-consumption in section 2.1. This is followed by an overview of drivers of self-consumption in section 2.2. Section 2.3 provides an overview of the parameters that affect self-consumption. Section 2.4 consists of an overview of storage technologies to increase self-consumption, and section 2.5 elaborates on the technical parameters of the technologies described in the previous section. Thereafter, section 2.6 and 0 examines the economic aspects of the storage technologies. Then DR is discussed in section 2.8. Finally, an overview of the Dutch energy market system design is provided in section 2.9.

2.1 Self-consumption

Self-consumption defines the in-situ consumption of PV generated electric energy (Luthander et al., 2015). It can either be partial self-consumption or total self-consumption. In partial self-consumption is a part of the generated power consumed on-site and the surplus is injected into the grid. Total self-consumption means that all the generated electricity is used on-site, and no electricity is injected into the grid. Figure 1 illustrates a simplified demand and production profile. The production profile consists of area B and C combined. Area C is the demand that is directly covered by the production and area B is the excess generated part of electricity. Area C is the part of the demand that is not covered by production. There are two identified self-consumption indicators. The self-consumed part and the self-consumed ratio of which the last term is commonly used when it comes to self-consumption. Firstly, the self-consumed part is the share of directly consumed generated electricity compared to the total demand which is area C divided by area C and A (Equation 1). Secondly, the self-consumption ratio. This is the share of energy that is self-consumed compared to the total generated energy which is area C divided by area B and C (Equation 2) (Dehler et al., 2017). The main difference is that the self-consumption part refers to the self-consumption share in relation to demand while in the self-consumption ratio this is the portion self-consumption in relation to production. In this research is self-consumption ratio used by which the focus lies on maximum use of PV generated electricity.

$$Self consumption\ part = \frac{C}{C + A}$$

Equation 1

$$Self consumption\ ratio\ (SCR) = \frac{C}{B + C}$$

Equation 2

Typical self-consumption ratios in households are in the range of 30% (European Comission, 2015). The self-consumption part depends on many variables such as, household-size, energy consumption and the irradiation profile. It is often the case that production takes place when residential homeowners are not at home. Self-consumption can be increased by energy storage and load management. This last term is also known as DSM (Luthander et al., 2015). Self-consumption can be beneficial for PV system owners by reducing the amount of electricity taken from the grid, but it can also decrease the stress on the electricity network (Lang et al., 2016; Li et al., 2018; Quoilin et al., 2016). Therefore, residential homeowners, as well as the TSO and DSO, can benefit from increased self-consumption.

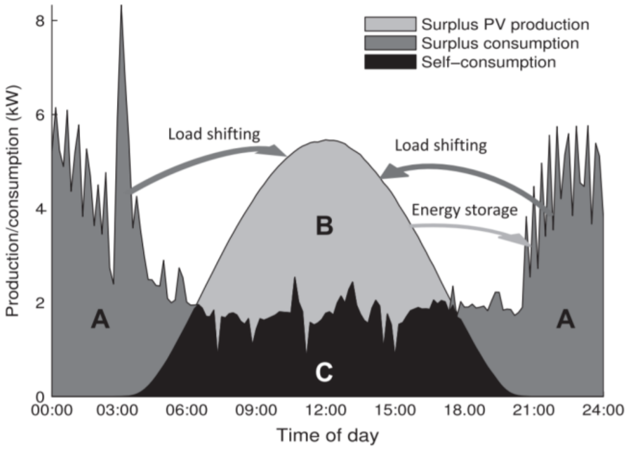


Figure 1: Self-consumption (Luthander et al., 2015).

2.2 Self-consumption drivers

There are different drivers to increase self-consumption (Bertsch et al., 2017). Finance-related drivers are based on financial instruments. As a result of technological developments, the costs of PV systems and storage technologies are reduced, and technical characteristics are improved. This results in more profitable systems and more efficient electricity storage that stimulate consumers to increase self-consumption. Moreover, another financial stimulus can be the expected rise in electricity prices or electricity taxes. For that reason, consumers tend to reduce their energy consumption from the grid to become less dependent on external factors. The political influence to drive self-consumption is probably the most dominant factor. When the net metering system is active or feed-in tariffs are provided, prosumers tend to increase their self-consumption less because they benefit less from it. In contrast, the urge for self-consumption is much higher without financial reimbursement for excess electricity.

In addition to financial drivers, there are quantity-related drivers. When residents have a geographical location or metrological conditions that are suitable for self-consumption, it can be an incentive to increase self-consumption. There can be reasons for both supply and demand for self-consumption dependent on demand and production profiles and amounts of generated electricity. Self-consumption can be incentivised at a higher amount of electricity production, but the load profile is also of importance whether it can be done efficiently.

2.3 Self-consumption parameters

The profitability of self-consumption depends on many variables. In Table 1 several parameters are listed concerning self-consumption. For each design parameter, the options and effects on self-consumption are provided (Masson et al., 2016). Currently, an electricity billing mechanism called net metering policy is active to promote the integration of renewable energy in the Netherland (Ministerie van Algemene Zaken, 2019). Besides the net meter policy, other self-consumption design parameters affect the profitability of self-consumption.

Table 1: Self-consumption parameters, based on (Masson et al., 2016).

Parameter	Options	Effect on self-consumption
Right to self-consume	Yes/No	If self-consumption is not allowed, none of the other parameters are relevant
Revenues from self-consumed PV	Monetary value	Revenues include savings on the electricity bill and possible additional revenues. Self-consumption becomes more profitable when revenues are higher
Charges to finance T&D	Monetary value	Grid costs for self-consumed electricity. Fewer charges for T&D result in more profitable self-consumption
Revenues from excess electricity	Net metering/Feed-in tariff/Green certificates/Fees/Taxes	Self-consumption becomes more profitable when revenues are higher
The maximum timeframe for reimbursement	Days/Months/Years/ Indefinitely	A longer timeframe brings more flexibility for self-consumption.
Geographical compensation	Virtual net metering/ Meter Aggregation/Peer to Peer	Some geographical locations have particular benefits for self-consumption
Regulatory scheme duration	Years	Duration of the reimbursement scheme
Third-party ownership accepted	Yes/No	Structure such as leases is possible in third party ownership.
Grid codes and additional Taxes	Self-consumption fee/Balancing costs/Back up costs	Additional taxes make self-consumption less profitable
Other enables of self-consumption	Demand-side management (ToU, CPP, EDP, RTP, load shifting)	Additional options to make self-consumption attractive
PV size limitations	kWp	Limitations can decrease profitability
Electricity system limitations	-	Setting a maximum PV penetration rate can lead to unapplied regulations

2.4 Battery energy storage systems (BESS)

A BESS is a way to deal with the variability of the intermittent solar energy and to increase self-consumption. BESS is an electrochemical way of storing energy. The BESS includes a bidirectional energy flow that can both absorb and deliver power (Reihani et al., 2016). Currently and for the foreseeable future, lithium-ion batteries are the most promising technology (Terlouw et al., 2019). A variety of different types of lithium-ion batteries are described in section 2.4.1. The valve-regulated lead-acid batteries are described in section 2.4.2, flow batteries in section 2.4.3 and molten salt batteries in section 2.4.4, as all of those technologies are suitable for stationary applications. This section describes the storage technologies with their main characteristics.

2.4.1 Lithium-ion battery

The lithium-ion battery was firstly introduced in 1990 and is currently the most common battery technology for stationary residential storage (Gupta & Paranjape, 2020). The Lithium-ion battery exchange lithium ions between the cathode and the anode (Osha, 2019). The battery is characterised by a high round trip efficiency and a low self-discharge (Johnson & White, 1998). Moreover, it has a high energy density and a long lifetime. There is a variety of different types of lithium-ion batteries which are characterised by different materials. Those different types of lithium-ion batteries intend to optimise for specific purposes and have their specific advantages and disadvantages. A negative aspect of the lithium-ion battery is that the optimal performance is within a tight range of temperature. It means that when the temperature is outside this range, performance drops dramatically. Besides, the battery is sensitive to overload or a too low voltage, and needs therefore a control system to manage the battery charging and discharging, making the BESS more expensive.

2.4.2 Valve-regulated lead-acid battery

The lead-acid battery is one of the oldest batteries and was invented approximately 150 years ago. The lead-acid battery consists of lead plates that hung in the electrolyte, which is a sulphuric-acid solution. When the battery is discharging, it releases the energy by converting lead plates into lead-sulphuric oxide. The opposite happens when the battery is charging and energy is used to convert load-sulphuric oxide into lead plates (Berndt, 2001). The maintenance-free valve-regulated lead-acid battery is taken into account in this research. Advantages of this battery is that it has low cost, low self-discharge, and that is performing at a wide temperature range (IRENA, 2017). Disadvantages are that it has a limited operating range and a shorter lifetime compared to lithium-ion batteries.

2.4.3 Redox flow battery

The redox flow battery differs from the regular batteries. It consists of two separate tanks that contain the positive and negative electrolytes. These are respectively the anode and the cathode (Rodriguez, 2015). When the battery is in use, the two liquids are pumped into the electrochemical cell. The redox flow battery can be designed in any combination where the power and capacity can be sized independently because of the adjustable tank and membrane size. This flexibility of independent energy and power ratio is an advantage of the redox flow battery next to the high number of cycles and the ability of a deep discharge. Disadvantages of the battery are the high costs and lower efficiency compared to the lithium-ion and lead-acid batteries. Moreover, the energy density is relatively low, which results in larger BESS (IRENA, 2017).

2.4.4 Molten salt battery

Molten salt batteries belong among others to the thermal batteries. Molten salt batteries work with a chemical reaction. High temperatures are required to keep the salts in a liquid state. The two most common molten salt batteries are the sodium-nickel-chloride and the sodium-sulfur battery. The sodium-sulfur battery operates between 270°C and 350°C (Ould Amrouche et al., 2016). The disadvantage is that the battery must be kept at high temperatures to keep the materials in a liquid state which also reduces its performance; another disadvantage is that fluctuations can occur in the power output. Advantages of the battery are the long lifetime, low self-discharge and high energy density (IRENA, 2017).

2.5 Technical parameters of storage technologies

In this paragraph, the most relevant parameters of the storage technologies are described with comparative/indicative values for each storage technology. This is done to compare the technologies and provide input for the residential low voltage network model. A summary of the parameters of the technologies is provided in Table 2 and the main advantages and disadvantages are represented in Table 3.

The efficiency of the lithium-ion battery is the highest at about 95%. The efficiencies of the lead-acid battery and high-temperature battery are relatively lower at 80% and 70% respectively. The redox flow battery has the advantage of a considerably longer lifetime compared to the other batteries. Even a large variation in the number of life cycles can be seen between the different types of lithium-ion batteries. The zinc-bromide battery has a significant high self-discharge of 15% per day. The other batteries have a self-discharge of less than 1% per day. In the residential sector is the self-discharge less important because the timescale in which electricity is stored in the quantities of hours and not multiple days. The size of the storage unit can be of high importance to residential households. A higher energy density means a smaller storage unit. The Redox-flow battery and lead-acid battery have a relative low energy density. Lithium-ion batteries have a relatively high energy density.

Table 2: Parameters of battery technologies [1] (IRENA, 2017) [2] (Battery University, 2017).

Parameters technologies	Lithium-Iron-Phosphate/ Graphite (LFP-C)	NCA/Lithium-Titanite-Oxide (NCA-LTO)	Lithium-Nickel-Cobalt-Aluminium-Oxide/Graphite (NCA-C)	Lithium-Nickel-Manganese-Cobalt-oxide/Graphite (NMC-C	Valve regulated Lead-acid battery	Flow battery-vanadium battery	Flow battery-zinc bromide	High-temperature battery (Nas)
Round trip efficiency [1]	92%	96%	95%	95%	80%	70%	70%	80%
Lifecycle (cycles) [1]	2500	10000	1000	2000	1500	13000	10000	5000
Self-discharge (day) [1]	0.10	0.05	0.20	0.10	0.25	0.15	15	0.05
Energy density (Wh/L)	620	620	620	735	100	70	70	300
C-rate [2]	1	1	1	1	1	1	1	1
Depth of discharge [1]	90%	95%	90%	90%	50%	100%	100%	100%

The c-rate is the measure related to the ratio between power and capacity. Specifically, the rate of which a battery is charged or discharged. The c-rate is often a fixed ratio. The c-rate of lithium-ion batteries and lead-acid batteries is typically between 0.25 and 4. The c-rate of redox flow batteries can be adjusted to any combinations because the power and energy capacity can be adjusted separately. The commonly used c-rate of 1 is used in this analysis. The variety of the depth of discharge is wide between the different battery technologies. The depth of discharge of redox flow batteries is 100% while the depth of discharge of lead-acid batteries is typically around 50%. The lithium-ion batteries have a good performance on this aspect as well with over a 90% depth of discharge.

Table 3: Advantages and disadvantages of storage technologies.

	Lithium-ion batteries (Gupta & Paranjape, 2020; Johnson & White, 1998)	**Valve regulated Lead-acid batteries** (Berndt, 2001; IRENA, 2017)	**Redox-flow batteries**(IRENA, 2017; Rodriguez, 2015)	**High-temperature batteries** (IRENA, 2017; Ould Amrouche et al., 2016)
Advantages	High energy density High ramp rates Long lifetime Low weight	No maintenance Low self-discharge Performs over a wide range of temperatures	High number of cycles Long lifetime Deep discharge Flexible design	Long lifetime Low self-discharge High energy density
Disadvantages	Best performance in a tight temperature range Charge/discharge management needed to prevent overcharging or a too low voltage	Low energy density Low dept of discharge Pollution risks	High costs Low energy density Low efficiency	High operating temperatures High costs

2.6 Economic parameters of storage technologies

A BESS is not just an assembly of battery cells. It includes the balance of system (BOS) components and the battery management system (BMS). The BOS components consist of, among others wiring, switches, a mounting system, a bidirectional inverter and battery thermal management system (B-TMS)(Asian Development Bank, 2018). The BMS manages the energy flows and protects the system from harmful operation. This means remaining an operational voltage and current that is safe for the system. Moreover, it manages the SoC of the BESS for a reliable operation. The B-TMS controls the temperature of the BESS and ensures that the cells do not overheat. The BOS components can be up to 40 % of the total costs for large scale applications (Cone, 2018; Qudrat-Ullah, Hassan, Kayal, 2019). For small scale residential storage those costs can even become higher. This chapter describes the module costs of the storage technologies. Table 4 summarises the set up of the BESS costs. There is a wide variety of EMS's that differs in functionality and costs, in this case, the average of costs of 400 € is assumed.

Table 4: Summary of BESS system costs.

	PV system	Lithium-ion BESS	Lithium-ion BESS & PV system	Valve-regulated lead-acid BESS & PV system	Redox flow BESS & PV system	Molten salt BESS & PV system
PV Investment costs	PV system costs as represented in Table 10 (incl. BOS components)		PV system costs as represented Table 10 (incl. BOS components)			
BOS components PV system costs (Fraunhofer ISE, 2015)						
BESS Investment costs		Table 5 (excl. BOS components)		Table 6 (incl. BOS components)	Table 7 excl. BOS components	Table 8 excl. BOS components
BOS components BESS costs(Cone, 2018; Qudrat-Ullah, Hassan, Kayal, 2019)		40% of the total system			40% of the total system	40% of the total system
EMS costs (Milieu centraal, 2020)		400 €	400 €	400 €	400 €	400 €

2.6.1 *Lithium-ion battery*

The price of lithium-ion batteries is experiencing a significant decline in the past years. From the observed price of the previous decade, a learning rate of 18% is composed (Logan Goldie, 2019). It means that for every doubling of the installed capacity, the price decreases by 18%. If this trend continues the price of lithium-ion batteries will drop to 78€/kWh in 2024 and 42€ in 2030. In Figure 2 and Table 5 this cost development is represented. The prices are converted from $ to €. The price of lithium-ion batteries in 2031 is constructed by continuing the trend.

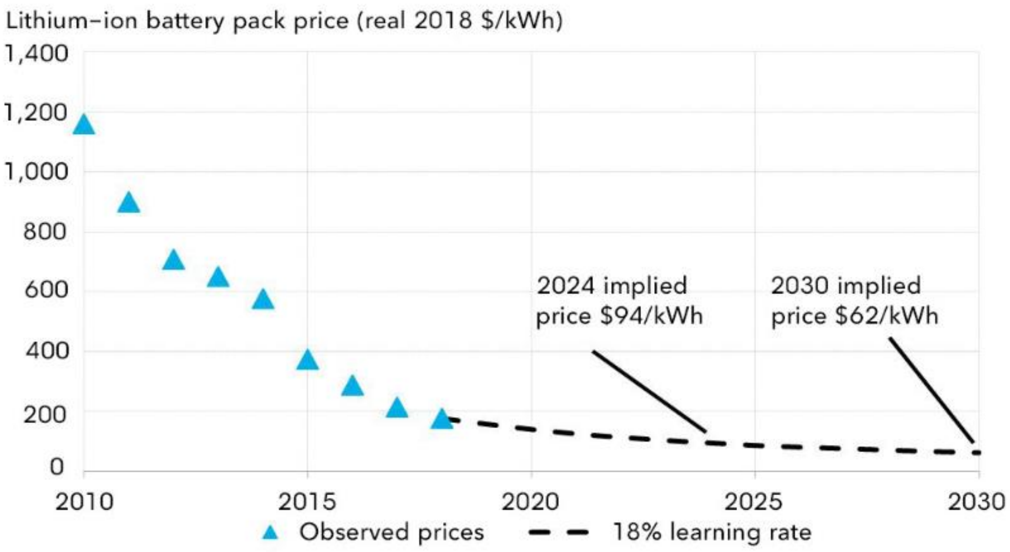


Figure 2: Costs development of the lithium-ion battery (Logan Goldie, 2019).

Table 5: Investment costs lithium-ion battery (Logan Goldie, 2019).

year	*2020*	*2022*	*2024*	*2026*	*2028*	*2030*	*2031*
€/kWh	*125*	*100*	*84*	*70*	*60*	*52*	*50*

The development of lithium-ion batteries goes steadily. A battery company claims a new type of lithium-ion battery technology that will reach $100/kWh in the near future, and that prices can fall even lower than $100/kWh (Alvarez, 2020).

2.6.2 *Lead-acid battery*

The lead-acid battery is already a mature technology with a high installed capacity at low costs. The lead-acid batteries that are used in the residential sector for stationary energy storage is however not yet mature but is expected to increase in the coming years (Schmidt et al., 2017). This increase in installed capacity is accompanied by a reduction of investment cost that is represented in Figure 3 and Table 6.

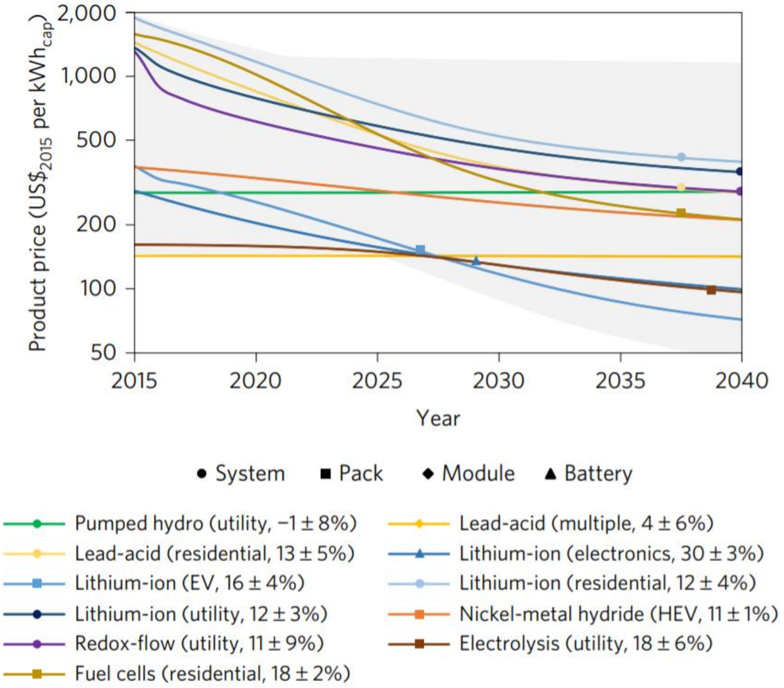


Figure 3: Costs development several battery technologies (Schmidt et al., 2017).

Table 6: Investment costs lead-acid battery (Schmidt et al., 2017).

year	*2020*	*2022*	*2024*	*2026*	*2028*	*2030*	*2031*
€/kWh	*775*	*600*	*500*	*410*	*350*	*310*	*290*

2.6.3 Redox-flow battery

The redox power battery is not yet a mature technology. Therefore, the cumulative installed capacity is still very small. The current costs of zinc-bromide batteries are up to 590€/kWh. It is expected that due to the increased demand for storage technologies, the redox-flow batteries costs will decrease in the coming years. This explains the abrupt decrease in 2021 which is the consequence of an increased installed capacity that has a significant impact on total installed capacity (Figure 4 and Table 7). With an increase in the total installed capacity, the decrease in storage costs will decline.

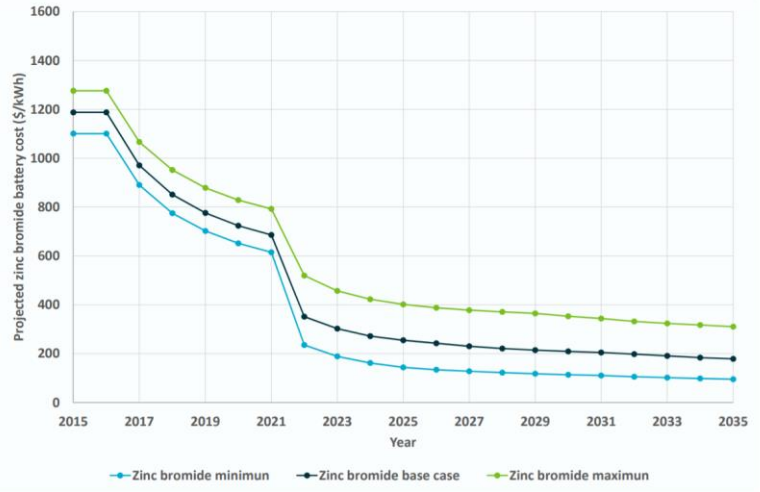


Figure 4: Cost development of the zinc-bromide battery (Brinsmead et al., 2015).

Table 7: Investment costs zinc-bromide battery (Brinsmead et al., 2015).

year	*2020*	*2022*	*2024*	*2026*	*2028*	*2030*	*2031*
€/kwh	*590*	*290*	*225*	*200*	*190*	*185*	*180*

2.6.4 High-temperature battery

Similar to the zinc-bromide battery is the high-temperature battery not yet a mature technology and requires an increase in installed capacity to significantly reduce the investment costs. A steep decline in 2021 is expected that follows up by a declining growth (Figure 5 and Table 8).

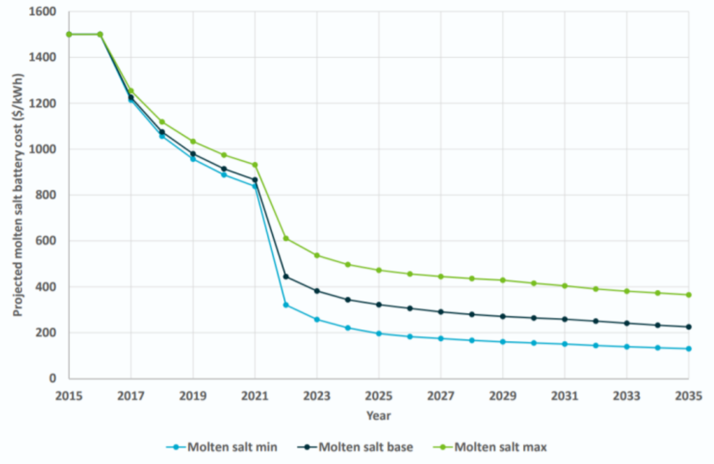


Figure 5: Cost development of the molten salt battery (Brinsmead et al., 2015).

Table 8: Costs molten salt battery (Brinsmead et al., 2015).

year	*2020*	*2022*	*2024*	*2026*	*2028*	*2030*	*2031*
€/kwh	*850*	*560*	*460*	*425*	*405*	*380*	*370*

2.7 Overview BESS costs

The expected investment costs of the BESS are summarised in Figure 6. The lithium-ion battery is the cheapest technology over the entire period and is expected to fall to less than 100 € by 2030. The valve-regulated lead-acid battery is more expensive but has the same trend as the lithium-ion battery. The zinc-bromide and molten salt battery are both characterised by high costs in the early years which is expected to decrease as the total installed capacity increases. The molten salt battery will remain the most expensive storage technology over the whole period. As mentioned before the molten salt battery is the less mature technology of all. It needs a substantial increase in the total installed capacity to be able to drop in price and become competitive with the other technologies.

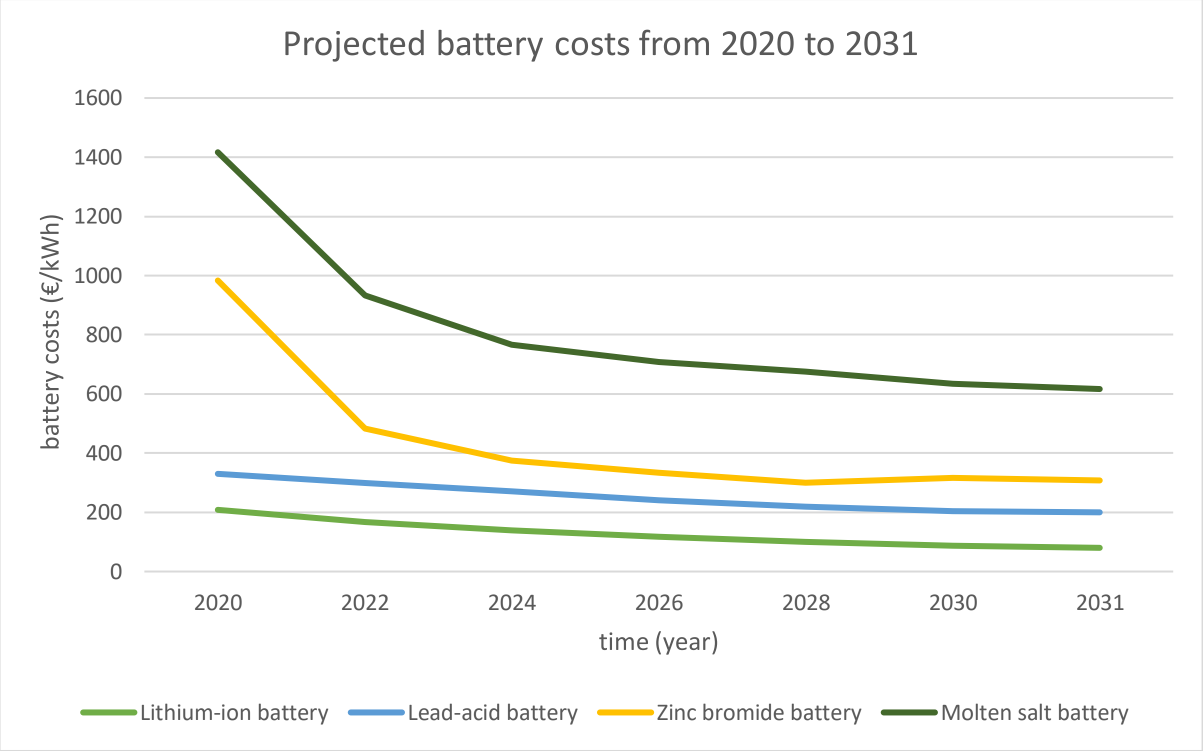


Figure 6: Summary of targeted battery technology costs 2020 – 2031.

2.8 Demand-side management (DSM)

Demand-side management is a mean of flexibility that is used to increase self-consumption. Section 2.8.1 provides a general description on DSM. Then the DR by load shifting is described that will come back in the model (section 2.8.2).

2.8.1 Demand-side management (DSM)

DSM involves the entire range of management functions related to directing activities on the demand side (Lampropoulos et al., 2013). Demand-side management can be accomplished by energy efficiency, which reduces the total energy demand, or by DR. DR incentivises users to change their electricity usage patterns by scheduling their consumption at the short time (Lampropoulos et al., 2013). For DR to work, sensors and smart appliances are required to schedule or shift electricity usage. In addition, smart devices are needed that includes communication and remote control between the appliances. Moreover, the appliances are connected with renewable energy sources (often PV systems and potential BESS) and to a central controller or EMS. This EMS ensures a stable and optimised energy consumption by a two-way communication between customers and utilities. The cost of the EMS is taken into account but the smart devices come with a price as well which is not considered in this research.

DR can be further specified to dispatchable and non-dispatchable DR. In dispatchable DR, the system administrator has gained control over demand through either direct load control or a request to adjust their power consumption (Chai et al., 2019). Examples of this are airconditioning or heating systems at specific times of the year to reduce peak moments.

Interruptible load is another type of dispatchable DR. Consumers receive payments from utilities to reduce their load when required. Decreasing their energy consumption is often done in periods of high demand. The downside compared to storage is that consumers have to adjust their consumption patterns which might reduce the comfort level. Reserves are also means of dispatchable DR. Spinning reserves are already grid-connected and ready to operate can deliver for at least two hours. Non-spinning reserves are not yet connected to the grid and can be online within 10 minutes. Emergencies occur where consumers voluntary adjust their consumption. Regulation service as DR means automatic respond to frequency fluctuations. Non-dispatchable DR is not controlled by the system and consumers choose to change their demand pattern based on price signals from the electrical energy market. Examples of those price schemes are critical peak pricing, time-of-use pricing or real-time pricing.

2.8.2 Load shifting

Load shifting moves the load from one period to another intending to reduce or optimise the energy consumption of the end-user. By shifting consumption from the early morning and late evening hours to moments that PV production is at its highest, increased self-consumption can be accomplished. Prosumers with PV systems exhibit saving behaviour by minimising the use of imported grid electricity and maximising the use of self-generated energy. This can be done by shifting the use of the washing machine and dishwasher to times that PV-production is at its highest. Figure 7 provides a simplified version of load shifting by altering 2.5%, 5%, 7.5%, 10% and 15% of the demand to moments of high PV production. There is a great variation in the types and costs of EMS's. An analysis is carried out with an EMS of 200 € and 400 € (Milieu centraal, 2020).

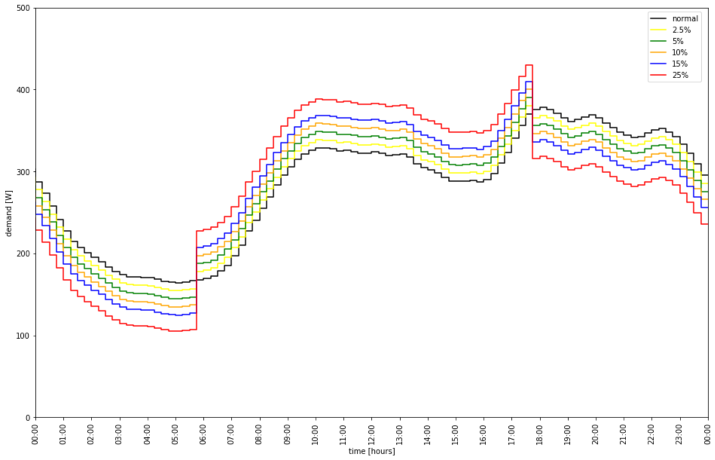


Figure 7: DR by load shifting.

2.9 Dutch energy market system design

Self-consumption is allowed in the Dutch system where the net metering policy is active. The principle of net metering is when the PV production exceeds consumption the electric meter runs backwards. At the end of a billing period, the net electricity taken from the grid is billed to the consumer. In the case that a prosumer generates more electricity than it consumes a price is given for the electricity that is injected into the grid. The feed-in tariff is based on the electricity price per kWh of consumption that energy suppliers charge excluding taxes (Energy tax plus Renewable energy tax plus VAT). The height of this tariff is dependent on the electricity supplier but is approximately 0.07 € per kWh (Yamamoto, 2012). The Ministry of Economic Affairs and Climate establishes a minimum on the feed-in reimbursement of 80% of the electricity supply tariff exclusive Taxes (Energy tax & Renewable energy tax & VAT) from 2023 (Verheij et al., 2020).

The net metering policy for residential PV units is active until 2023 (Ministerie van algemene zaken, 2019). Prosumers can inject into the grid a maximum surplus PV generation of 5 MWh per year but this rule was lifted in 2014, therefore there is no maximum. The feed-in tariff of electricity that is returned above the net metering limit is relatively low. Therefore, above this net metering limit is self-consumption allowed but not incentivised. This subsidy will gradually decrease and phased out between 2023 and 2031. This means that from 2023 the amount of energy that can be delivered to the grid will be reduced each year (van Sark et al., 2020). This will continue until 2031, at which the last 28% is abolished at once. Figure 8 illustrates this abolishment strategy of the net metering policy in an average household with a PV system. On the y-as is the PV production, load, and direct self-consumed part indicated and on the x-as the years. Until 2023 electricity can be returned till the net metering limit that is equal to the demand minus the self-consumption part. Excess electricity is returned to the grid at a feed-in tariff. In the coming years, the net metering limit reduced (red area), and the return of excess energy with an alternative reimbursement is increasing (purple area). Table 9 lists the development of the reduction in percentages.

Table 9: feed-in percentage net metering.

year	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
feed-in percentage	100%	91%	82%	73%	64%	55%	46%	37%	28%	0%

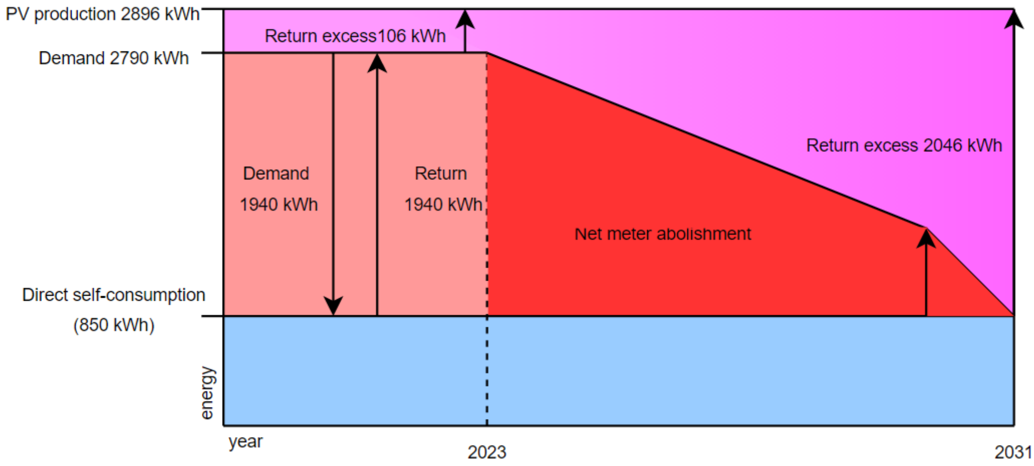


Figure 8: Net metering abolishment (household that consumes 2790 kWh and produces 2896 kWh).

2.10 The electricity price

The electricity price can be broken down into several components. The producer price is the price that the producer pays for the energy production. Compared to the total price this is relatively low, consisting of approximately one-third of the total price. A large part of the total electricity price consists of additional taxes. Three taxes are distinguished. First of all, the VAT, this is the added value tax of 21% of the electricity price. Secondly, the energy tax. The government levies an energy tax to encourage consumers to use energy as efficiently as possible. Due to the energy tax, the energy price is higher, and less energy is consumed. Thirdly, the renewable energy tax. The renewable energy tax was introduced in 2013 by the government to stimulate investment in sustainable energy. The renewable energy tax is an extra tax included in the energy price. This finances the subsidy fund for the Stimulation of Sustainable Energy Production (SDE +)(Essent, 2019). Since 2020, the renewable energy tax has also been used for the energy transition. The energy prices are expected to increase in the coming years, as shown in Figure 9. The energy costs are expected to be 13% higher in 2030 compared to 2020 (Londo et al., 2017).

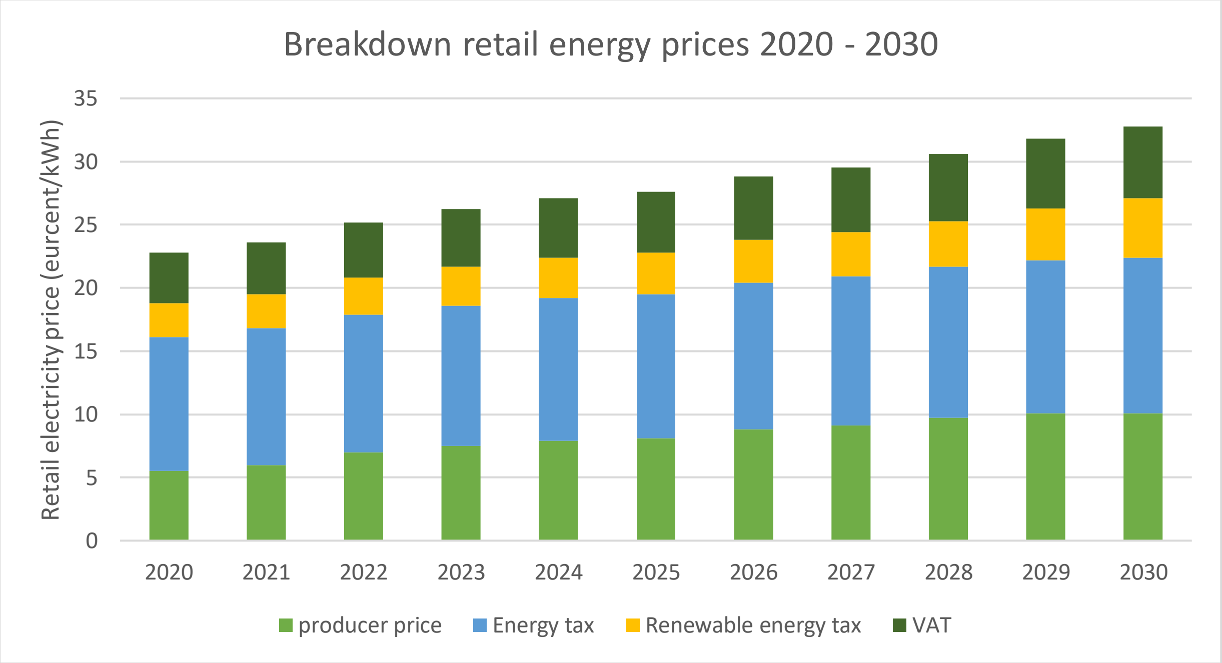


Figure 9: Breakdown of the projected electricity price (Londo et al., 2017).

3. Methodology

A model is developed to calculate the lowest PBP of a series of self-consumption measures based on an optimisation of energy flows in which the point of view of the households is central. The model consists of a PV system model and a residential low voltage network model. In the PV system model is the PV production modelled from the incoming irradiation. The residential low voltage network model addresses the interaction between the PV system and BESS in households and the low voltage network. The inputs and outputs of the PV model and the residential low voltage network model are described in section 3.1 and 3.2 respectively.

The measures for self-consumption are tested in the model in various policies. Besides the current policy in which the net metering is abolished is a set of alternative policies introduced and examined. Those policies and scenarios are part of a case study in the Netherlands. Section 3.4 elaborates on this case study. The alternative policies and scenarios are elaborated in section 3.4.1 and 3.4.2 respectively. The scenarios are compared with the reference case in which all the electricity is bought from the grid. The objective of the household is further specified in section 3.3.1. Moreover, a second objective is set at the DSO side to identify the transformer capacity and to calculate the network costs (section 3.3.2). Based on the power requirement that is associated with the scenarios is the transformer capacity determined. The power capacity of the transformer cannot be customised but consists of fixed capacities. The construction costs of the low-voltage grid are calculated based on the costs of the transformer and cabling/trenches.

The boundaries of the research are that only the households and the low voltage network are taken into account. The medium and high voltage network is left out. The resolution of both models is 15 minutes and the timeframe that is taken into account is from 2020 to 2032. In this way, the whole timeframe of the net metering policy abolishment is considered. Moreover, the types of technologies and input is limited to those identified in the literature review in section 2.4.

3.1 PV system model

The PV system model consists of the technical and financial aspect. The technical aspect consists of a model that generates the energy output of a PV system. In this model adjustments can be made in orientation, tilt, size and location of the PV system. The economic aspect consists of the construction costs of the system which is performed by a literature review. Both of those aspects are described in this section and are used as input for the residential low voltage network model.

3.1.1 PV system

The PV system is modelled by a set of functions from a simulation program called pvlib python (F. Holmgren et al., 2018). The input of the model is the Direct Normal Irradiance (DNI) (W/m²), the Diffuse Horizontal Irradiance (DHI) ((W/m²), the Global Horizontal Irradiance (GHI) (W/m²) and the location (latitude and longitude). Additional input on the PV system is the tilt (°), orientation (azimuth°) and the size (kWp) of the PV system. Based on this input and by the calculations described below is the average power in watts calculated in a time resolution of 15 minutes over a year.

calculate in the first step is the solar position (zenith and azimuth angle) of every timestep calculated from a defined location (latitude and longitude) with the function pvlib.solarposition.ephemeris. In the second step are those zenith and azimuth angles of the sun combined with the surface tilt and azimuth angle of the panel to calculate the angle of incidence of the sun with the function pvlib.irradiance.aoi. The angle of incidence is combined with the DNI, DHI and GHI to calculate the total irradiance that the sun emits on the defined location. Thereafter, the effective irradiance is calculated with function pvlib.pvsystem.sapm_effective_irradiance. The effective irradiance is the adjusted irradiance for the angle of incidence, soiling, and spectral content. This is the available irradiance for the PV system for power conversion. The Advent_Solar_Ventura_210_2008 PV module is used for the calculation(PV Free, 2014). The function pvlib.pvsystem.sapm combines the effective irradiance with the module characteristics to calculate the direct current (DC). The final step is to convert the DC to AC power. This is performed by the function pvlib.pvsystem.snlinverter**.** The ABB__MICRO_0_25_I_OUTD_US_208__208V_ inverter is used for the calculation. The reason this PV system and inverter are chosen is because these were the most recent available technologies in pvlib. Figure 10 shows the efficiency of the inverter (25V). At a power output below 20% of the rated power, the efficiency is significantly reduced. At a power rate between 40% and 60% the efficiency is at its highest and the efficiency reduces slightly as the power output increases to full power.

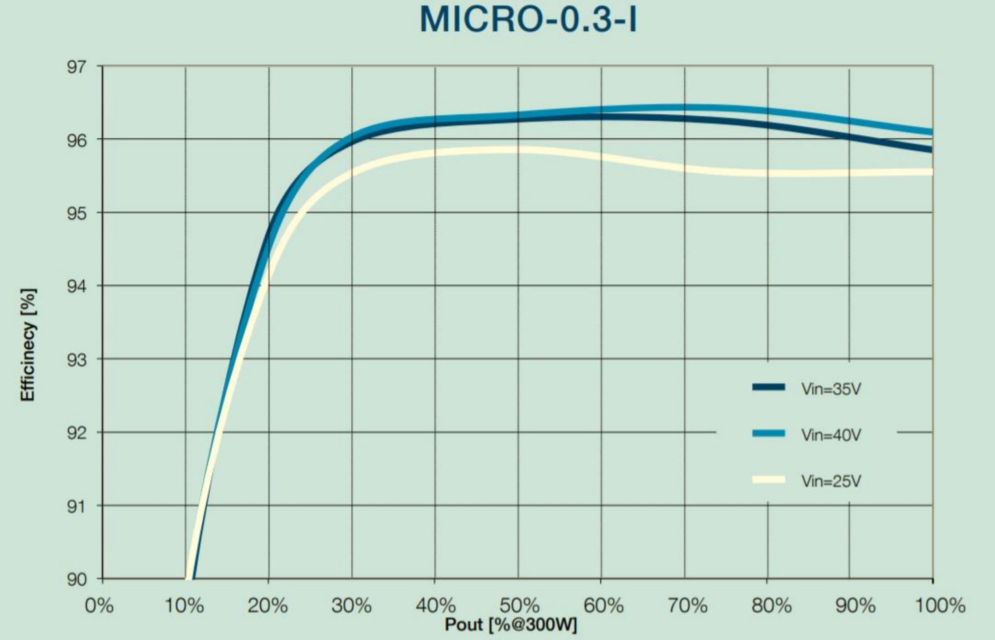


Figure 10: Inverter efficiency(ABB, 2014).

3.1.2 *PV system costs*

Certain costs are associated with the PV system. The increased deployment of PV panels and accelerated technological progress results in significant costs reduction. The components of a PV module can be divided into three parts: the module, the inverter and the BOS components. The BOS components consist of mounting the system, installation, cabling, infrastructure, transformer, grid connection and planning and documentation (Fraunhofer ISE, 2015). The costs of the BOS components and the inverter compared to the total costs of the system is between 40% and 45%. Figure 11 and Table 10 provide an overview of the current and long term projection of crystalline silicon PV modules.

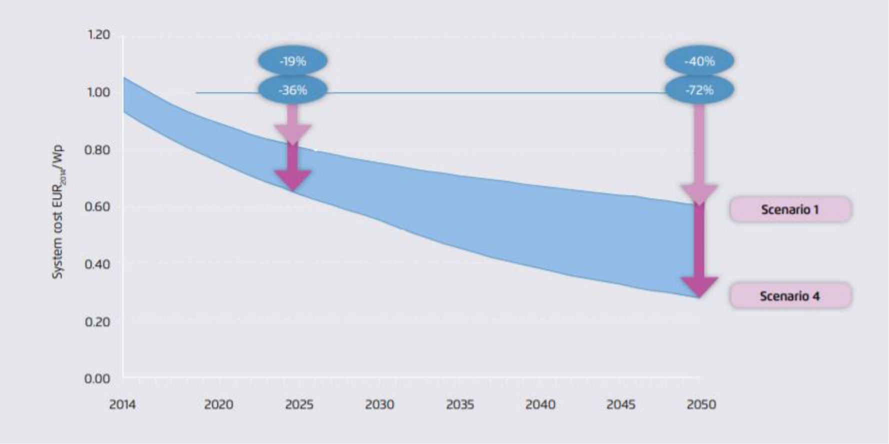


Figure 11: PV module costs outlook (Fraunhofer ISE, 2015).

Table 10: PV system costs (Fraunhofer ISE, 2015).

year	*2020*	*2022*	*2024*	*2026*	*2028*	*2030*	*2031*
€/Wp max	*0.88*	*0.85*	*0.82*	*0.80*	*0.77*	*0.75*	*0.74*
€/Wp	*0.82*	*0.78*	*0.75*	*0.71*	*0.68*	*0.65*	*0.64*
€/Wp min	*0.75*	*0.71*	*0.67*	*0.62*	*0.59*	*0.55*	*0.53*

To summarise the PV system model. The PV power of a certain size is calculated in watts and the costs associated with this system are calculated. This is used as input for the model representing the households equipped with a PV system.

3.2 Residential low voltage network model

The model considers both individual households and the effect of a group of 100 households on the electricity grid. The model represents the interactions between the facets that are represented in Figure 12. The low voltage network is connected to each household. The transformer that connects the low voltage network and the medium voltage network is dependent on the power requirement or return from a combined set of households. The simulation model takes into account the power constraints. Subsequently, an optimisation is performed on which the lowest annual cost is determined based on the electricity consumption from the electricity grid.

The input for the residential low voltage network model is the average PV power production (Watt), the characteristics of a BESS/storage technology (size (kWh), efficiency (%), depth of discharge (%), c-rate (-), self-discharge (%/day)), a power load profile (Watt) and the electricity price (€/kWh). Additional information is required that varies between scenarios which is the net metering limit (%), the feed-in tariff (€/kWh) and additional benefits/costs (€/kWh). The result by optimising for the lowest costs is the average power that is consumed & returned to the grid and the power stored & delivered from the battery all in watts and the SoC of the battery (%). The constrains from the input to output are described in the section below. Based on this output combined with the literature review are the annual costs and benefits calculated and thereafter the PBP.

Zoomed in on one individual household, the first interaction is the physical energy flow (continuous line) that connects the PV system and the inverter with the electricity demand of the household and the grid. The electricity generated from a PV system can be consumed directly or the surplus can be delivered to the electricity grid. Moreover, the BESS is connected to the energy flow as well. The batteries described in section 2.4 are used in the calculation. The battery can either store energy from the PV unit or the electricity grid and can supply when needed. The second interaction is the information flow (dashed line). This consists of the same actors as the physical energy flows because information is required of the PV-unit, demand, battery and electricity grid for the EMS to optimise the costs based on energy flows in the household. It is supplemented with an EMS which is affected by the self-consumption parameters as they determine the optimal energy flows based on the physical ability and costs or profitability of electricity.

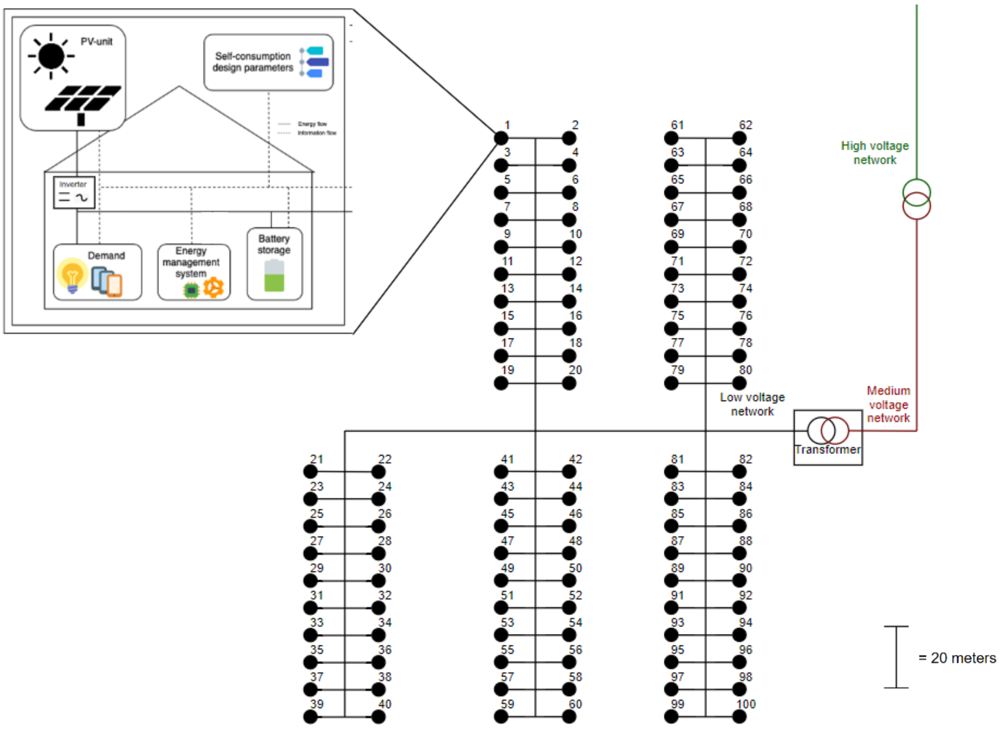


Figure 12: Visualisation of the model that describes the interaction between the PV system, demand, EMS, battery storage, self-consumption design parameters and the low voltage electricity grid, whereas the interactions with the medium and high voltage network are left out of the research scope.

In a household, the following variables are defined (Table 11). The power of the charge and discharge of the battery. The power consumed by the grid and the power injected into the grid. The grid injection is divided into normal injection and injection excess. The normal injection is limited to the net metering cap where electricity can be delivered at the electricity supply tariff. Additional electricity can be returned as excess injection which equals a different feed-in tariff. Finally, the SoC of a battery that defines the level of charge of the battery in percentages.

Table 11: Variables residential low voltage network model.

1	Pbattery charge
2	Pbatery discharge
3	Pgrid consumption
4	Pgrid injection (<= annual demand)
5	Pgrid injection excess (> annual demand)
6	SoC of the battery

The model constraints in the households are as follows. The system needs to be in balance and therefore the electricity demand must be equal to the electricity that is consumed from/injected to the grid plus the electricity consumption of/storage to the battery minus the PV production. The load constraints are defined by Equation 3, Equation 4 and Equation 5. The t indicates the power at a certain time step.

$$P\_dem\,[t] = P\_grid\,[t] + P\_bat[t] - PV\_prod\,[t]\,, \forall\, t \qquad \textit{Equation 3}$$

$$P\_grid\,[t] = (P\_grid, con\,[t] - P\_grid, inj[t] - P\_grid, inje\,)\,, \forall\, t \qquad \textit{Equation 4}$$

$$P\_bat[t] = (P\_bat, dis\,[t] - P\_bat, ch\,\,[t])\,, \forall\, t \qquad \textit{Equation 5}$$

The variables have power flow limits to not violate the power flows. The electricity flows are separated into the flow towards and from the electricity network. Therefore, no negative flows are possible. The flow has to be between the maximum capacity and zero (Equation 6, Equation 7, Equation 8 and Equation 9) (van der Stelt et al., 2018).

$$0 \leq P\_grid, con\,[t] \leq P\_max\,flow\,[t]\,, \forall\, t \qquad \textit{Equation 6}$$

$$0 \leq P\_grid, inj\,[t] \leq P\_max\,flow\,[t]\,, \forall\, t \qquad \textit{Equation 7}$$

$$0 \leq P\_bat, ch\,[t] \leq P\_max\,flow\,[t], \forall\, t \qquad \textit{Equation 8}$$

$$0 \leq P\_bat, dis\,[t] \leq P\_max\,flow\,[t], \forall\, t \qquad \textit{Equation 9}$$

The battery is limited to the capacity that is given to the battery. This ensures that the battery does not perform above its maximum capacity (Equation 10) (van der Stelt et al., 2018).

$$P\_bat, min \leq Pbat\,[t] \leq P\_bat, max\,[t]\,, \forall\, t \qquad \textit{Equation 10}$$

The SoC formula is represented by Equation 11. The SoC formula ensures the SoC of the battery at a certain time. The $\eta dis\ and\ \eta ch$ are respectively the discharging and charging efficiency of the battery. The SoC is limited to the minimum and maximum SoC as represented in Equation 12.

$$SoC\,[\mathrm{t}] = \mathrm{SoC}\,[\mathrm{t}-1] * \mathrm{selfdischarge} - \left(\frac{1}{\eta dis\ *\ Battery\ Capacity}(Pbat, dis\,[t])\Delta t - \frac{\eta ch}{Capacity\ battery}(Pbat, ch\,[t])\Delta t, \forall\ \mathrm{t}\right. \qquad \textit{Equation 11}$$

$$\mathrm{SoCmin}\ \leq\ \mathrm{SoC}\,[\mathrm{t}]\ \leq\ \mathrm{SoCmax}\,, \forall\ \mathrm{t} \qquad \textit{Equation 12}$$

The net metering constraint is guaranteed by the constraint formulated in Equation 13. This is the limit at which electricity can be returned at the electricity supply tariff. Surplus electricity is returned as excess electricity.

$$\mathrm{Pgrid\ injection} <= \ \mathrm{net\ metering\ limit} \qquad \textit{Equation 13}$$

The total power requirement or surplus of all households is calculated with Equation 14. This equation sums the net electricity consumption/return of all households i = 1, … 100.

$$\mathrm{P_{low\ voltage\ network}}[\mathrm{t}]\ = \sum_{i\,=\,1}^{100}(\mathrm{P_{electricity\ consumption_i}}\,[\mathrm{t}] - \ \mathrm{P_{electricity\ return_i}}\,[\mathrm{t}]), \forall\ \mathrm{t} \qquad \textit{Equation 14}$$

Different saturation grades can be applied in the network analysis. The saturation grade is defined as a number of households that is provided with a PV system and/or a BESS. From the power flows in the low voltage network the transformer capacity is calculated. The power factor of the transformer is set at 0.9. Based on this model and the previously described input, different scenarios will be developed and examined. Varieties are applied in the type of storage, the year of instalment and different policies. The year of instalment refers to the year an installation is bought, this is relevant for the investment cost and financial conditions.

3.3 Definition of the assessment framework

3.3.1 Consumer side

The target analysis in those scenarios is to find the lowest PBP by optimising energy flows from the consumers perspective. The LCOE (costs of electricity) is useful for the determination of the costs per kWh of different technologies, but it is less favourable for determine the profitability of different investments. For this reason, the PBP is used as a measure for ranking the different scenarios.

The two key performance indicator that is tested on the consumer side is the self-consumption ratio and the PBP (Equation 15). The PBP indicates the period that is required for the costs of a project to be recovered by relating annual profits. This gives insight into how much risk is involved in the investment. The longer the PBP, the less attractive an investment becomes. The I is the investment at the beginning, B and C are respectively the benefits and the cost. By investing in the PV systems or BESS in different years, the PBP will change because reimbursement for electricity will change and the costs of PV systems and batteries will be reduced.

$$PBP = \frac{\sum_{t=0}^{n} I_t}{\sum_{t=0}^{n} B_t - C_t} \qquad \textit{Equation 15}$$

3.3.2 *DSO framework*

The costs of the DSO side are reflected in the construction costs of the network dependent on the power to be supplied. The costs are limited to the low-voltage grid that includes the transformer and the cabling towards the households. The cable trench costs include excavation and placement of the trench as well as the cable cover and the installation of the cabling. The conduit cable is required for transmitting power and consist of production of the cable including applicable fittings and connectors. Moreover, the required control cable act as agents for different automation processes in line with the conduit cable. The transformer has different fixed capacities as shown in Table 12. The transformer is not optimally sized for the variation in irradiation which could result in grid instability. Therefore, the transformer sizing is important for a reliable electricity network and based on the required power the costs of the system is calculated.

Table 12: DSO costs (MISO, 2019).

Voltage class Transformer	69kV	115kV	138kV	161kV	230kV	345kV	500kV
Transformer (€)	57,219	70,769	82,635	91,785	98,848	124,663	191,738
Cable trench (€/m)	739	739	739	739	739	739	739
Conduit unit (€/m)	16	16	16	16	16	16	16
Control cable (€/m)	13	13	13	13	13	16	16

3.3.3 Sensitivity analysis development

The outcome of the model is dependent on many variables. A sensitivity analysis is performed to check the results when a single parameter is adjusted. In this section are the critical parameters represented. Indicated in green are the non-critical parameters (Table 13). Those parameters have either a certain value is or have a small impact on the result. For the orange parameters is this influence medium or are the parameter values less certain. The red parameter are the critical parameters that significantly influences the results or have an uncertain value.

Table 13: Critical parameters.

Battery efficiency	Transformer power factor
Battery self-discharge	Grid power capacity
Feed-in tariff net metering abolishment	Battery depth of discharge
PV inverter costs	SoC range
Reimbursement excess electricity	Transformer costs
Electricity price	Cabling costs
C-rate battery	Costs BMS
Discount rate	Investment subsidy
PV system size	Orientation of the PV system
PV system costs	Battery size
PV BOS component costs.	Battery investment costs
Battery BOS component costs.	Annual load

3.4 Case study

The case study consists of several policies in which a set of scenarios is examined. The case study is based on Dutch policy and the radiation data from the Netherlands. In section 3.4.1 are the alternative policies represented and section 3.4.2 elaborates on the set of scenarios. Moreover, the data collection is described in section 0.

3.4.1 Alternative policies

Several design scenarios are constructed which are shown in Table 14. In addition to maintaining the net metering policy and the abolishment are a set of alternative policies constructed.

- ***Maintaining net metering:*** Continuing the current policy where the net amount of energy is charged. A price of 80% of the electricity price of the supplier is given for the returned energy that exceeds the net metering limit.
- ***Abolishing net metering with reimbursement for excess electricity:*** The net metering policy is gradually abolished between 2023 and 2031. Excess electricity is injected to the grid at a price that is equal to 80% of the electricity price of the supplier.
- ***Feed-in tariff:*** The feed-in tariff is a fixed price for electricity that is delivered to the grid. In addition to the return of 80% of the production price of the supplier, the feed-in tariff consists of a subsidy that is annually decreasing.
- ***Net billing:*** The net-billing is similar to the feed-in tariff in which different energy flows are assumed that can have different prices. The costs associated with these two flows are netted to calculate the reduction on the electricity bill of the prosumer. The feed-in tariff consists of half of the electricity supply tariff.
- ***Net metering abolishment without reimbursement for excess electricity:*** Self-consumption without reimbursement for excess electricity. The profit consists only of the reduction on the energy bill as a result of generated electricity that is directly consumed. Substantial grid parity or self-consumption measures are required to be profitable.
- ***Net metering abolishment without reimbursement for excess electricity but with investment subsidy:*** Self-consumption without reimbursement for excess electricity. An investment subsidy of 25% of the investment cost is given at the beginning of the investment.

Table 14: Alternative policy scenarios.

	1. Maintaining net metering	2. Abolishing net metering	3. Feed-in tariff	4. Net-billing	5. Net metering abolishment without reimbursement for excess electricity	6. Net metering abolishment without reimbursement for excess electricity, investment subsidy
Revenues from self-consumed PV	Savings on the electricity bill	Savings on the electricity bill	Savings on the electricity bill	Net between revenues and costs	Savings on electricity bill from directly consumed electricity	Savings on the electricity bill from directly consumed electricity
Revenues from excess electricity	Yes, retail energy price	no	Feed-in tariff	Reimbursement <= retail price	No	no
Additional revenues	no	no	no	no	no	yes

3.4.2 Development of scenarios

Various scenarios have been drawn up in which the different policies are investigated through model simulations. Table 15 provides an overview of those scenarios. The reference scenario consists only of the electricity bought by the supplier. In addition, a scenario with only a PV system is developed as well as a scenario with exclusively a BESS. The current amount of households equipped with PV systems in the Netherlands is over 600,000 (Stefan ten Teije, 2019). The PBP of only a BESS is highly relevant to those households. Complementary a combination of a PV system with multiple types of batteries are tested. In the DR scenario is a PV system combined with DR to examine the benefits.

The saturation rate is which in which PV installations and BESS are present is important when looking at the network impact of a combined set of households. When only a few households in a large neighbourhood are equipped with a PV system is the network impact often insignificant. As this number increases, it affects the network to some extent and therefore different degrees of saturation are discussed. The network aspect discussed with the emphasis on a saturation rate of 50%. It is assumed that half of the households have the property of the reference situation and the other half is equipped with a PV system, BESS or DR. In this analysis are different saturation grades installed of PV and storage technologies over time in a neighbourhood. Insight will be gained in what the result is on the electricity network as a result of increased self-consumption in a neighbourhood.

Table 15: Overview of scenarios.

Scenarios 1 - 8					
	PV system capacity	Battery capacity	Design scenarios	DR	Network impact
1. Reference scenario	-	-	-		0%, 25 %, 50%, 75% and 100 % saturation
2. PV scenario	3 kWp PV systems (southern oriented)	-	Maintaining net metering / Abolishment of net metering (with revenues / Without revenues / With investment subsidy / Feed-in tariff / Net-billing		
3. Lithium-ion battery scenario		7 kW / 7 kWh system			50% saturation
4. PV & Lithium-ion battery scenario					
5. PV & Lead acid battery scenario					
6. PV & Redox flow battery scenario					
7. PV & High-temperature battery scenario					
8. PV & DR		-	-	load shifting (15% scenario)	

3.4.3 Data collection

The location of the case study is in the Netherlands at latitude 52.1°N and longitude 5.1°E. A 3 kW PV system is used of which the panels have a tilt of 30° and are oriented southwards at a 180° azimuth angle. The irradiance data is from Utrecht and has a resolution of 5 minutes (KNMI, 2015)(Tsafarakis, 2015). The production data is resampled to a 15-minute time resolution to match the required profile. Figure 13 shows the output of the PV model that generates annually 2896 kWh.

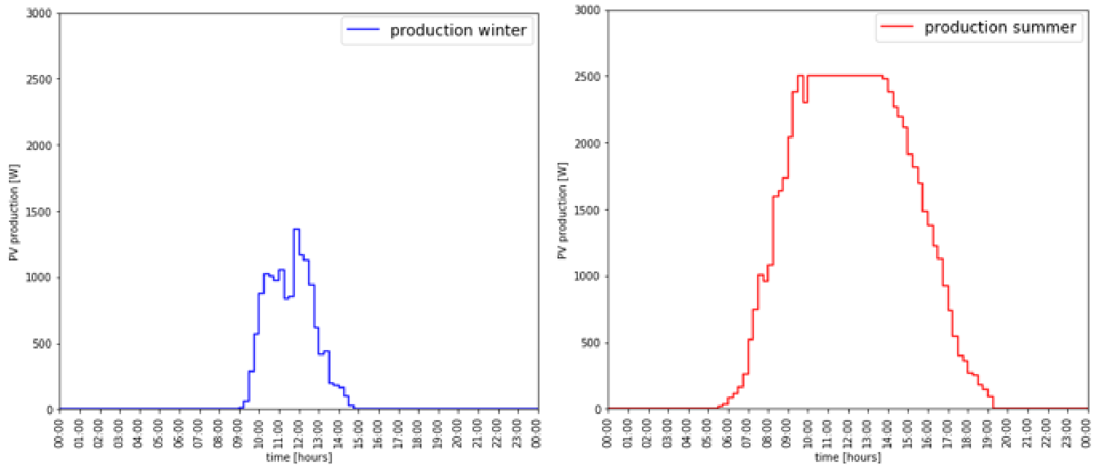


Figure 13: 3 kW PV output on a winter day and summer day with a 15-minute granularity

Additional data for the residential low voltage model consist of battery characteristics that are elaborated in the literature review (section 2.5). The size of the battery that is used is 7 kWh. Electricity prices, feed-in limits and tariffs and additional costs and benefits are represented in Appendix 2. Moreover, for the residential load profile, an average load profile is used based on aggregated historical measurements. This is obtained from the Dutch Energy Data Exchange Association (NEDU, 2019). This data is combined with the average annual electricity consumption per household in the Netherlands, which is 2790 kWh per year (Energie Nederland, 2019). This creates a load profile of an average household over a full year with a resolution of 15 minutes. Appendix 1 provides a representation of the load profile over the full year of 2019. Figure 14 provides a load profile of a summer and winter day with a 15-minute granularity.

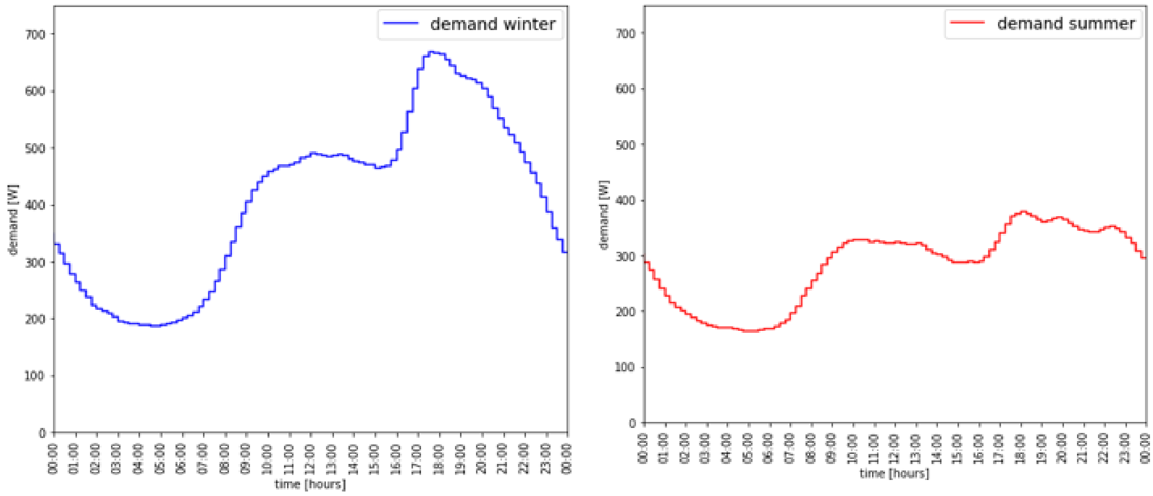


Figure 14: Energy demand on a winter day and summer day with a 15-minute granularity

A cost analysis is performed to cover the network costs corresponding to the scenarios. The network costs are based on one transformer, a trench of 640 meters for the main branches and 1000 meters of conduit and control cable. The network costs are limited to the costs of the materials of the low-voltage network and the trenching. The length of the branches, conduit and control cable are based on the dimensions in Figure 14.

4. Results

In this chapter, the results of the model are represented and described. First, the reference situation is presented in section 4.1. Then the PBP's of the PV systems and various BESS's are discussed in section 4.2 up to and including section 4.7. The DR scenario is discussed in section 4.8.

4.1 Scenario 1: Reference

The reference situation consists of a household with an average electricity consumption of 2790 kWh per year, no PV system or BESS is installed in this household. The annual cost consists only of the electricity that is taken from the grid. Due to the rising costs and taxes for electricity generation (as described in section 2.10 (Londo et al., 2017)), the annual costs are expected to increase in the coming years. Figure 15 shows the development of the costs over the years in €$_{2020}$. The electricity price remains constant after 2031 due to the absence of data on predictions.

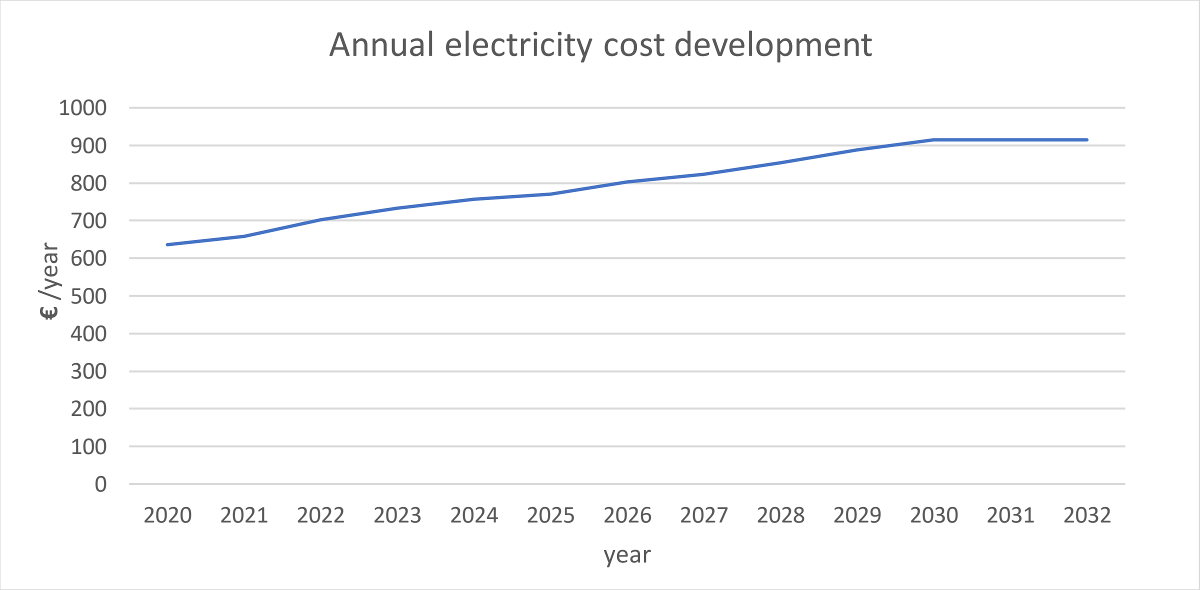


Figure 15: Development of annual cost reference situation.

4.2 Scenario 2: PV

The PV scenario consists of a household with an installed PV system. A total of 2896.3 kWh is annually generated by the 3 kWp PV system of which 850.3 kWh directly is consumed. This is equal to a self-consumption ratio of 29%. The 2046 kWh that is generated when there is no demand for electricity is fed back into the grid. In addition to the self-consumed part is 1939.7 kWh consumed from the grid to satisfy the demand. Figure 16 and Table 16 shows the development of the PBP's between 2020 and 2032 in the different policies.

Maintaining the net metering policy results in a decrease in the PBP from 4 years in 2020 to 2.2 years is 2032. This is due to constant revenues from the government while investment costs are reducing over the years in combination with an increase in the electricity price. The abolishment of the net metering system without compensation for excess electricity, on the other hand, will only increase the PBP in the coming years from 4.1 years in 2020 to 8.9 years in 2032. From 2031 onwards only the direct consumed part of electricity is used and excess electricity is delivered to the grid without any reimbursement. Self-consumption measures are required for this scenario to increase the profitability of a PV system.

The scenario where the net metering is abolished but with a subsidy of 25% of the investment costs results in a reduction of the PBP of approximately a quarter compared to the scenario without subsidy, but the trend of increasing PBP's will continue. The PBP of the current policy in which the net metering policy is abolished but with reimbursement for excess electricity will increase slowly between 2020 and 2032 but will remain under the 5 years. This is a significant difference from the scenario in which the net metering policy is maintained. In the Feed-in tariff and net billing policy, the PBP slowly decreases. In the net billing policy will the PBP decrease slightly more than in the case of the feed-in tariff policy. As of 2026, the PBP of the net billing policy will be lower than that of the current policy.

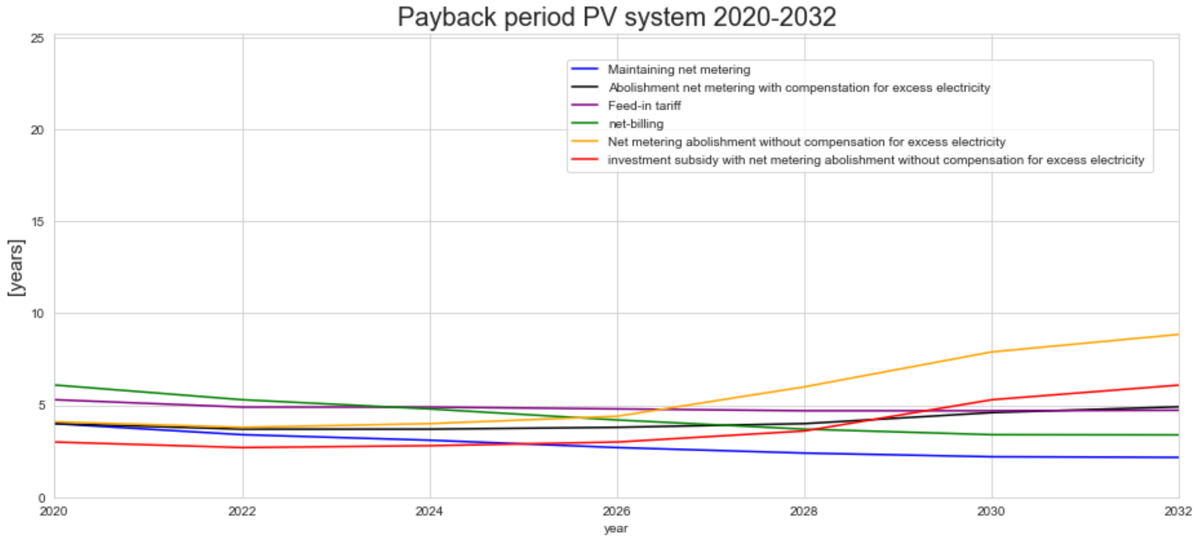


Figure 16: PBP development of a 3 kWp PV system in different policies from 2020 to 2032.

Table 16: PBP's of a 3 kWp PV system in different policies from 2020 to 2032.

2. PV scenario							
year	2020	2022	2024	2026	2028	2030	2032
maintaining net metering	4.0	3.4	3.1	2.7	2.4	2.2	2.2
Abolishment net metering with reimbursement for excess electricity	4.0	3.7	3.7	3.8	4.0	4.6	4.9
Feed-in tariff	5.3	4.9	4.9	4.8	4.7	4.7	4.7
net-billing	6.1	5.3	4.8	4.2	3.7	3.4	3.4
Net metering abolishment without reimbursement for excess electricity	4.1	3.8	4.0	4.4	6.0	7.9	8.9
Investment subsidy with net metering abolishment without reimbursement for excess electricity	3.0	2.7	2.8	3.0	3.6	5.3	6.1
SCR at net metering (abolishment)	0.29	0.29	0.29	0.29	0.29	0.29	0.29

Network aspect

In addition to the PBP, policy decisions can also be stimulated by the network impact. The power capacity of the demand or feed-in to the grid determines the size of the transformer. Higher power flows are accompanied by higher costs. A neighbourhood consists of a variety of different households. There are neighbourhoods where only a few PV systems are installed, but also neighbourhoods where PV systems dominate. A neighbourhood where 25% of the households are equipped with PV system is characterised by different power levels and a different transformer capacity than a neighbourhood where 75% of the houses are installed with a PV system. Figure 17 illustrates the network impact of different saturation rates on 3 winter days and 3 summer days. At a saturation rate of 25%, the network impact is limited compared to the reference scenario because the power production remains mostly within the total consumption and is, therefore, only a decrease in consumption. Where a 115 kV transformer is sufficient for the reference and the 25% scenario is this no longer sufficient for higher saturation rates. At 50% saturation a 138 kV transformer is required, the PV production reaches far higher than the normal consumption pattern in summer. At 75% saturation, a 230 kV transformer is required and at 100% saturation a 345 kV transformer. The total system costs for the reference scenario and the 25% saturation scenario comes down to 572,741 €. For the 50% saturation scenario at 584,607 €. And for the 75% and 100% scenario respectively 600,820 € and 629,523 €.

Figure 17: Network interaction and transformer capacity of the reference PV scenario with different saturation rates of 3 winter days (1,2,3 January) and 3 summer days (3,4,5, Augustus).

4.3 Scenario 3: lithium-ion BESS

In this scenario, the benefits of adding a lithium-ion BESS to an existing PV system are weighed at the expense of a BESS. When the net metering policy is maintained only a very small difference can be made in terms of profit. Only the electricity that exceeds the net metering limit is stored in the BESS which does not lead to a PBP. The highest benefits are accomplished at the abolishment of the net metering system. Most of the excess electricity is now stored and used later instead of returned without reimbursement. The PBP of the lithium-ion BESS in the meter abolishment policy is characterised by long PBP's in the first years which quickly decline. From the results, it can be concluded that regarding the current policy, the PBP declines to 7.1 years in 2026 and 4.7 years in 2032 (Figure 18 & Table 17). If subsidies are granted, the PBP's can be further shortened. The development of the PBP's of the feed-in tariff is comparable to the current policy. The net billing policy has the longest PBP of minimal 8.8 years in 2032. The self-consumption ratio is also reflected in Table 17 which increases as the net metering policy is abolished. This is gradual as the net metering cap is limited and more electricity is stored on the BESS instead of fed-in to the grid (which does not bring losses). In the feed-in tariff and net-billing policy is the self-consumption rate always 64%. This is because storing excess electricity is always more beneficial than returning it to the grid.

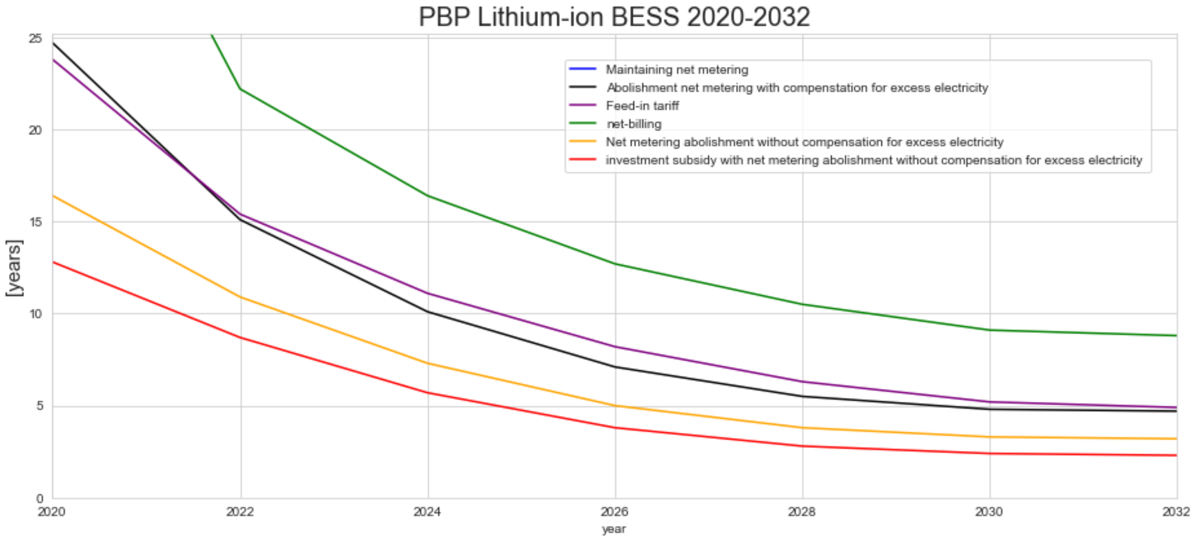


Figure 18: PBP development of a 7-kWh lithium-ion BESS in different policies from 2020 to 2032.

Table 17: PBP's of 7 kWh lithium-ion BESS development in different policies from 2020 to 2032.

7. lithium-ion BESS scenario							
	2020	2022	2024	2026	2028	2030	2032
Maintaining net metering	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Abolishment net metering with reimbursement for excess electricity	24.7	15.1	10.1	7.1	5.5	4.8	4.7
Feed-in tariff	23.8	15.4	11.1	8.2	6.3	5.2	4.9
net-billing	41.5	22.2	16.4	12.7	10.5	9.1	8.8
Net metering abolishment without reimbursement for excess electricity	16.4	10.9	7.3	5.0	3.8	3.3	3.2
Investment subsidy with net metering abolishment without reimbursement for excess electricity	12.8	8.7	5.7	3.8	2.8	2.4	2.3
SCR at net metering (abolishment)	0.33	0.33	0.43	0.54	0.64	0.64	0.64

4.4 Scenario 4: PV & Lithium-ion BESS

In the PV system and lithium-ion BESS scenario, the PBP's decrease over time due to the cost reduction of the PV system and BESS's and the abolishment of the net metering system. Investing in batteries while maintaining the net metering policy does not have compelling benefits. Instead of storing overproduced energy in the BESS, which has losses due to the battery efficiency and the self-discharge of the battery, energy is being injected to the grid until the net metering limit is reached. Excess electricity is stored in the BESS and used at a later moment, avoiding import from the grid and the payment of the full electricity price. In the net metering abolishment policy, the net metering limit is lowered in the coming years and more energy is stored in the BESS. At the net metering abolishment of 46% and lower, the feed-in tariff and the net billing policy is the BESS at its maximal potential. This means that in winter all overproduction is stored and used later, and in summer part of the overproduction is stored to meet the demand until new production starts the next day. At higher abolishment percentages, BESS usage is avoided as this entails losses instead of injection into the grid till the net metering limit. The self-consumption ratio in this case is 64%. From the 2896.3 kWh of generated energy, an amount of 1855.3 kWh is self-consumed. The reason that the self-consumption ratio cannot become higher is due to a relatively low PV production in the winter that cannot supply for a full day, energy from the grid is required or seasonal storage to fulfil the demand in winter.

The current policy of the net metering abolishment with reimbursement for excess electricity holds a PBP of 7.2 years in 2020 and 4.8 years in 2032 (Figure 19 & Table 18). Better options in terms of PBP are found at maintaining the net metering policy and at the abolishment of the net metering policy with an investment subsidy, as well as the net billing policy after 2029. The feed-in tariff and net billing policy have similar PBP's which develops from approximately 9 years in 2020 to 4.3 years in the net billing policy and 4.8 years in the feed-in tariff policy in 2032. Moreover, the investment subsidy with net meter abolishment has the lowest costs for most of the time and holds a PBP of less than 5.5 years in the whole timeframe. This could be a suitable alternative for the current policy to stimulate the investment of PV systems with lithium-ion BESS.

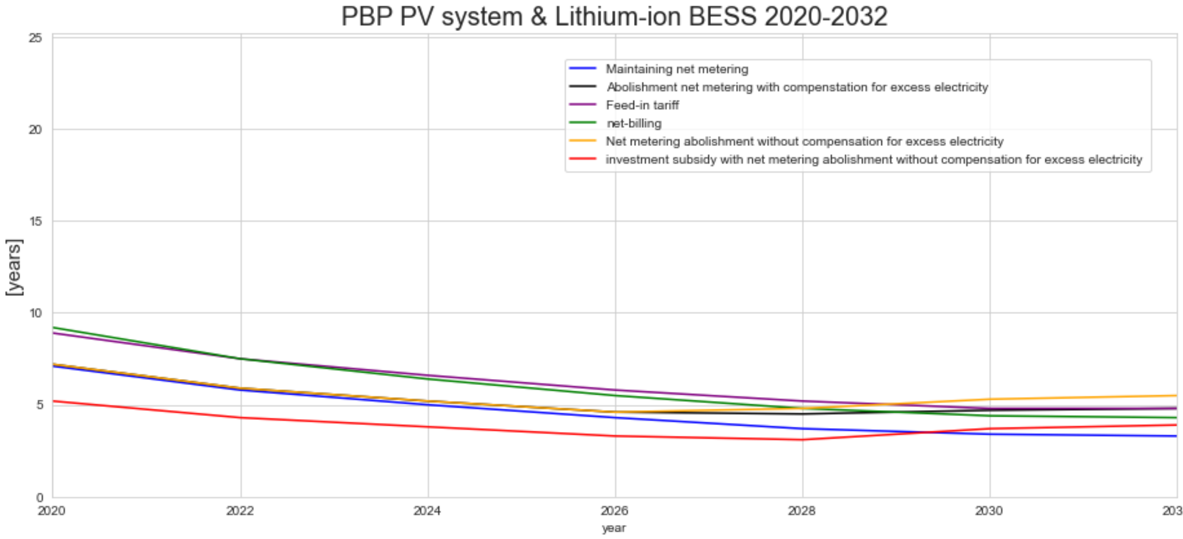


Figure 19: PBP development of a 3 kWp PV system and a 7 kWh Lithium-ion BESS in different policies from 2020 to 2032.

Table 18: PBP's of a 3 kWp PV system and a 7 kWh Lithium-ion BESS in different policies from 2020 to 2032.

3. PV system & lithium-ion BESS scenario							
	2020	2022	2024	2026	2028	2030	2032
maintaining net metering	7.1	5.8	5.0	4.3	3.7	3.4	3.3
Abolishment net metering with reimbursement for excess electricity	7.2	5.9	5.2	4.6	4.5	4.7	4.8
Feed-in tariff	8.9	7.5	6.6	5.8	5.2	4.8	4.8
net-billing	9.2	7.5	6.4	5.5	4.8	4.4	4.3
Net metering abolishment without reimbursement for excess electricity	7.2	5.9	5.2	4.6	4.8	5.3	5.5

investment subsidy with net metering abolishment without reimbursement for excess electricity	5.2	4.3	3.8	3.3	3.1	3.7	3.9
SCR at net metering (abolishment)	0.33	0.33	0.43	0.54	0.64	0.64	0.64

4.5 Scenario 5: PV system & valve-regulated lead-acid BESS

The valve-regulated lead-acid BESS has a significantly longer PBP than the lithium-ion BESS. This is partly due to the performance of the battery that is characterised by a 50% depth of discharge and an 80% round trip efficiency of the battery which reduces the usage of the BESS considerably. This poor performance results in lower self-consumption ratios because a large part of the energy is lost which needs to be bought from the grid to fulfil the demand. Where the highest self-consumption of 64% is achieved at the lithium-ion BESS this is only 56% for the valve-regulated lead-acid BESS. Combined with the relative high instalment costs compared to the lithium-ion BESS makes this the valve-regulated lead-acid BESS an expensive option.

Figure 20 and Table 19 represents the PBP of the installation between 2020 and 2032. Maintaining the net metering policy leads to the highest benefits for the valve-regulated lead-acid BESS in combination with a PV system but holds a low self-consumption ratio and very limited battery usage. The net metering policy without compensation for excess electricity holds a PBP of 12.4 years in 2020 and 7.7 years in 2032. The other scenarios have significantly longer PBP's in the early years and are reduced to the bandwidth of 7.6 and 11.5 in 2032.

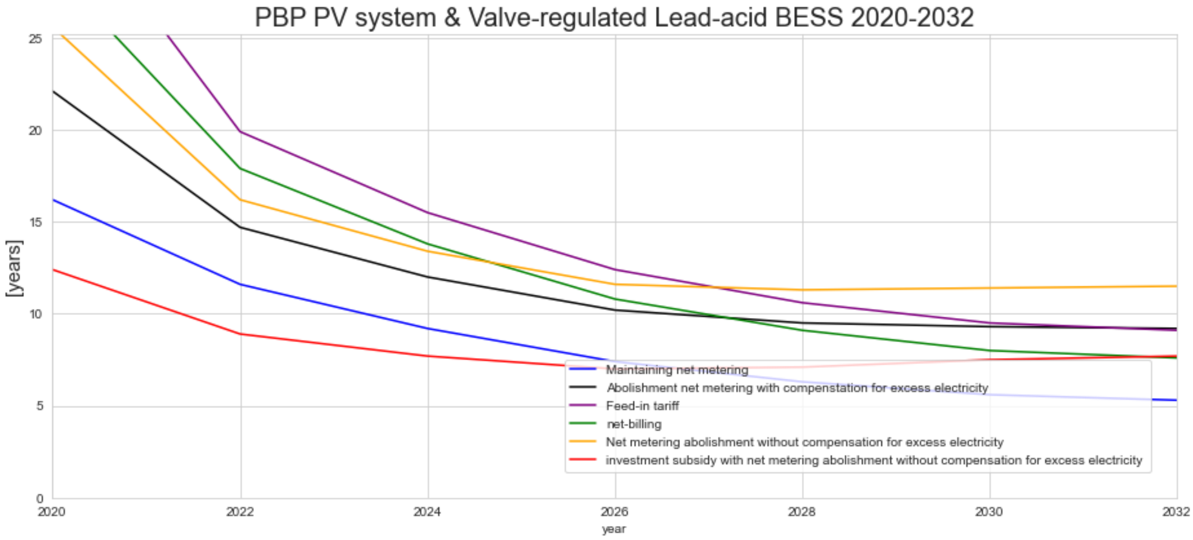


Figure 20: PBP development of a 3 kWp PV system and a 7 kWh Valve-regulated Lead-acid BESS in different policies from 2020 to 2032.

Table 19: PBP's of a 3 kWp PV system and a 7 kWh Valve-regulated Lead-acid BESS in different policies from 2020 to 2032.

4. PV system & valve-regulated lead-acid BESS scenario							
	2020	2022	2024	2026	2028	2030	2032
maintaining net metering	16.2	11.6	9.2	7.4	6.3	5.6	5.3
Abolishment net metering with reimbursement for excess electricity	22.1	14.7	12.0	10.2	9.5	9.3	9.2
Feed-in tariff	33.4	19.9	15.5	12.4	10.6	9.5	9.1
net-billing	28.7	17.9	13.8	10.8	9.1	8.0	7.6

Net metering abolishment without reimbursement for excess electricity	25.6	16.2	13.4	11.6	11.3	11.4	11.5
investment subsidy with net metering abolishment without reimbursement for excess electricity	12.4	8.9	7.7	7.0	7.1	7.5	7.7
SCR at net metering abolishment	0.33	0.33	0.42	0.52	0.56	0.56	0.56

4.6 Scenario 6: PV system & Redox-flow BESS

The benefit of the redox-flow BESS is that it has the highest depth of discharge of all batteries. The full capacity of the battery can be used for charging and discharging. The low round trip efficiency of 70% is however a disadvantage. When the feed-in tariff is higher than 70% of the electricity supply tariff, the model chooses not to use the BESS because profits are higher when electricity is injected into the grid instead of storing the electricity. This is done in the early years for the feed-in tariff and the net billing policy. The early years in those scenarios involve high costs (in 2020 even no PBP) because a BESS is bought while it is not in use, later the feed-in tariff is reduced which results in battery usage.

The self-consumption ratios of the redox-flow BESS is similar to that of the lithium-ion BESS with a maximum self-consumption ratio of 62%. The PBP's at the current policy develops from currently 36.6 years to 8.8 years in 2032. The feed-in tariff, net billing and the abolishment without reimbursement policies have even higher PBP's. Similar to the lithium-ion BESS, maintaining the net metering system and at the investment subsidy, as well as the net billing policy after 2029 holds a lower PBP than the current policy (Figure 21 and Table 20).

Figure 21: PBP development of a 3 kWp PV system and a 7 kWh Redox-flow BESS in different policies from 2020 to 2032

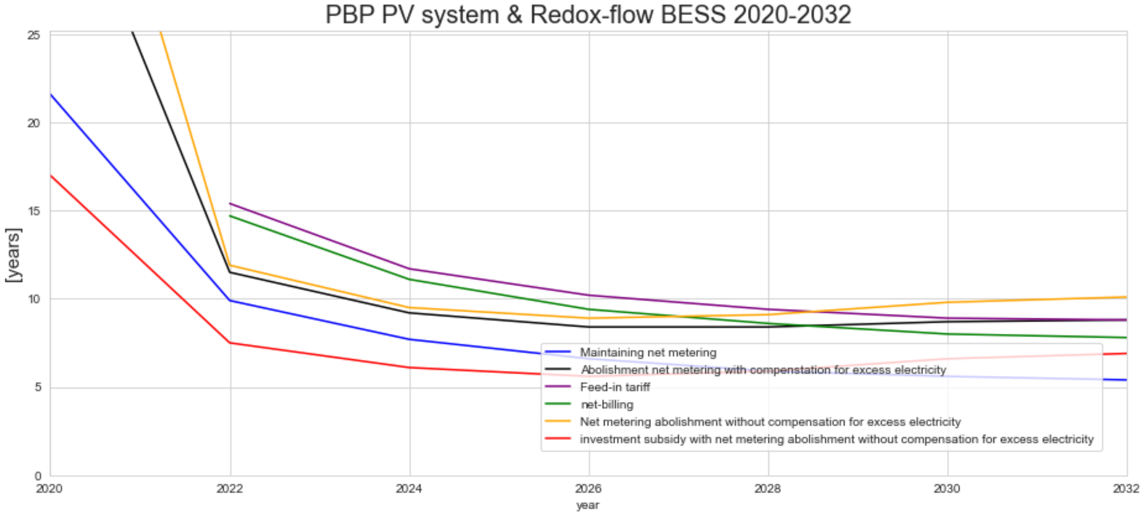


Table 20: PBP's of a 3 kWp PV system and a 7 kWh Redox-flow BESS in different policies from 2020 to 2032

5. PV system & redox flow BESS scenario							
	2020	2022	2024	2026	2028	2030	2032
maintaining net metering	21.6	9.9	7.7	6.6	5.9	5.6	5.4
Abolishment net metering with reimbursement for excess electricity	36.6	11.5	9.2	8.4	8.4	8.7	8.8
Feed-in tariff	n/a	15.4	11.7	10.2	9.4	8.9	8.8
net-billing	n/a	14.7	11.1	9.4	8.6	8.0	7.8

Net metering abolishment without reimbursement for excess electricity	46.2	11.9	9.5	8.9	9.1	9.8	10.1
investment subsidy with net metering abolishment without reimbursement for excess electricity	17.0	7.5	6.1	5.6	5.9	6.6	6.9
SCR at net metering abolishment	0.32	0.32	0.40	0.49	0.57	0.62	0.62

4.7 Scenario 7: PV system & High-temperature BESS

Next to the lithium-ion BESS, the high-temperature BESS holds the best performance with a high efficiency and depth of discharge. The reason for the high PBP's are due to the high investment costs of the high-temperature battery. The battery is still at its development phase which goes hand in hand with high costs. Even in 2032, the costs are expected to be too high for a profitable case in the residential sector as most scenarios ends up above 13 years. However, at the maintenance of the net metering system is the PBP 9.1 years in 2032. The net metering abolishment with subsidy scenario ends up at 11.6 years in 2032 (Figure 22 & Table 21).

Figure 22: PBP development of a 3 kWp PV system and a 7 kWh High-temperature BESS in different policies from 2020 to 2032

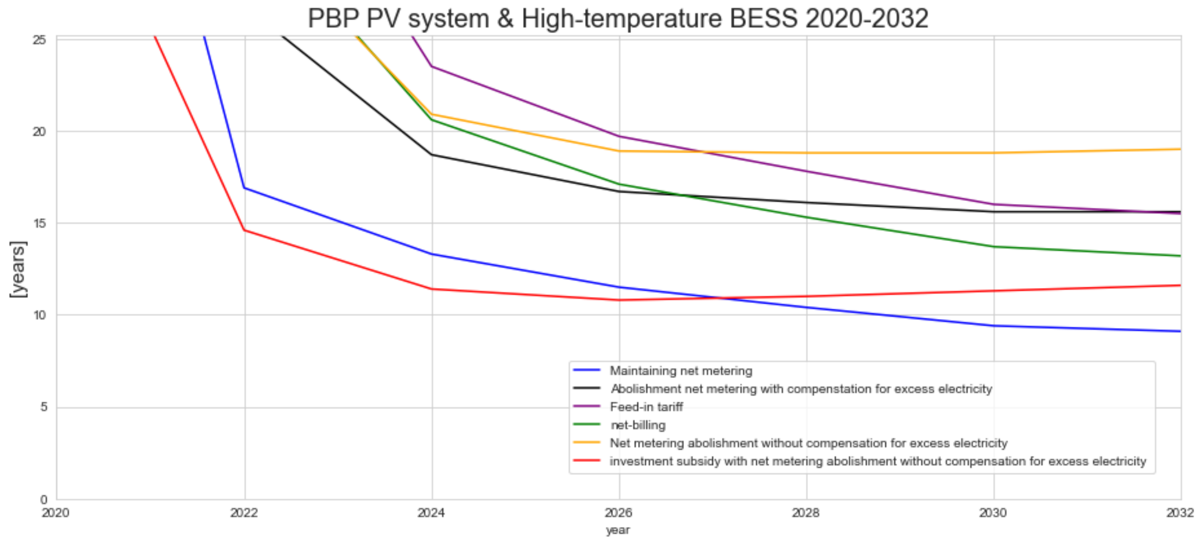


Table 21: PBP's of a 3 kWp PV system and a 7 kWh High-temperature BESS in different policies from 2020 to 2032

6. PV system and high-temperature BESS scenario							
	2020	2022	2024	2026	2028	2030	2032
maintaining net metering	55.5	16.9	13.3	11.5	10.4	9.4	9.1
Abolishment net metering with reimbursement for excess electricity	n/a	26.8	18.7	16.7	16.1	15.6	15.6
Feed-in tariff	n/a	39.5	23.5	19.7	17.8	16.0	15.5
net-billing	n/a	32.1	20.6	17.1	15.3	13.7	13.2

Net metering abolishment without reimbursement for excess electricity	n/a	31.4	20.9	18.9	18.8	18.8	19.0
investment subsidy with net metering abolishment without reimbursement for excess electricity	36.7	14.6	11.4	10.8	11.0	11.3	11.6
SCR at net metering abolishment	0.32	0.32	0.37	0.52	0.61	0.63	0.63

4.8 Scenario 8: PV system & DR

In this scenario, DR is added to the PV system. By adding DR, 15% of the energy consumption has roughly shifted from the early morning and evening /night to the middle of the day (Figure 7). As a result of the shift in energy, the self-consumption ratio will increase from 29% to 32%. Slightly more energy is consumed directly instead of being fed back to the grid, which has the greatest effect on the net metering abolishment without compensation for excess electricity. An EMS of 400 € does not result in PBP's. The PBP's of an EMS of 200 € is shown in Figure 23 and Table 22. The profit that is achieved by the EMS is approximately 15 € per year. It makes this type of DR is not very profitable with high PBP's which is very dependent on the investment costs of the EMS.

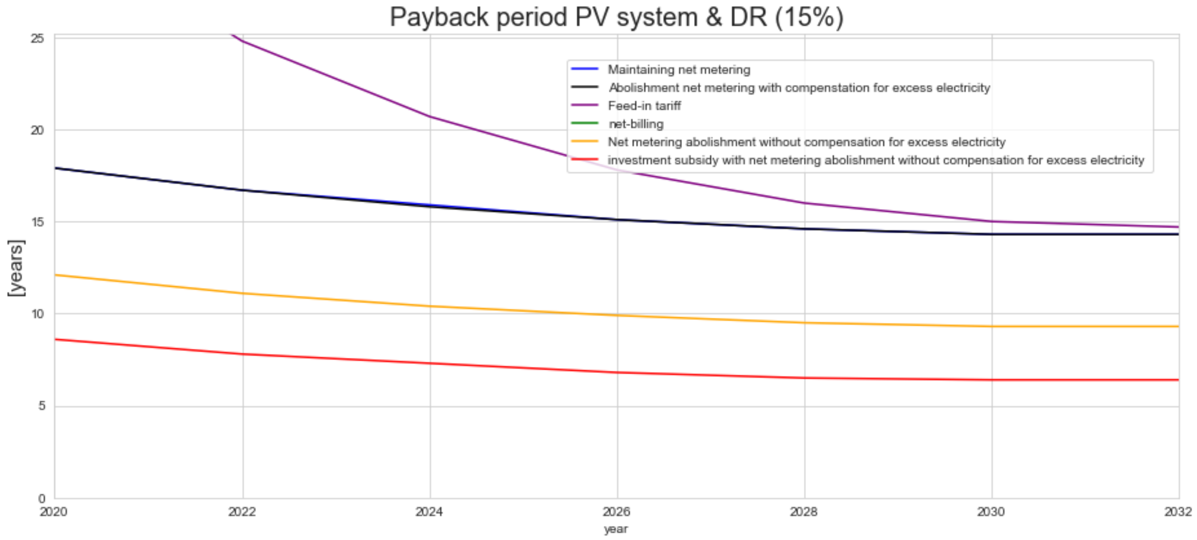


Figure 23: PBP development of a 3 kWp PV system and DR (15%) in different policies from 2020 to 2032

Table 22: PBP's of a 3 kWp PV system and DR (15%) in different policies from 2020 to 2032

7. PV system & DR scenario							
	2020	2022	2024	2026	2028	2030	2032
maintaining net metering	17.9	16.7	15.9	15.1	14.6	14.3	14.3
Abolishment net metering with reimbursement for excess electricity	17.9	16.7	15.8	15.1	14.6	14.3	14.3
Feed-in tariff	31.2	24.8	20.7	17.8	16.0	15.0	14.7
net-billing	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Net metering abolishment without reimbursement for excess electricity	12.1	11.1	10.4	9.9	9.5	9.3	9.3
investment subsidy with net metering abolishment without reimbursement for excess electricity	8.6	7.8	7.3	6.8	6.5	6.4	6.4
SCR at net metering abolishment	0.32	0.32	0.32	0.32	0.32	0.32	0.32

Network impact

Figure 24 illustrates the transformer capacity of the different policies at a 50 % saturation rate of PV system with a lithium-ion BESS. As the net metering policy is abolished, the percentage of self-consumption increases. At a feed-in percentage of 46% and lower as well as the feed-in tariff and net billing policy is the battery at its maximum use.

In winter, this means that the peaks of overproduction are usually stored and used later. However, the production is not enough to meet the demand and extra electricity is needed from the grid. The production in the summer, however, is much higher than the demand. The battery is charged and excess electricity is fed back into the grid. Therefore, no energy from the grid is needed for the households equipped with a PV system and a battery in days of high PV production.

The charge of the battery does not reduce the amplitude of the power peaks in summer but only the length. This difference can be seen between the orange and red line. Therefore an installed battery will not decrease the transformer capacity of the low voltage network. The DR scenario has a slightly different power profile, but not significant that the size of the transformer needs to be changed.

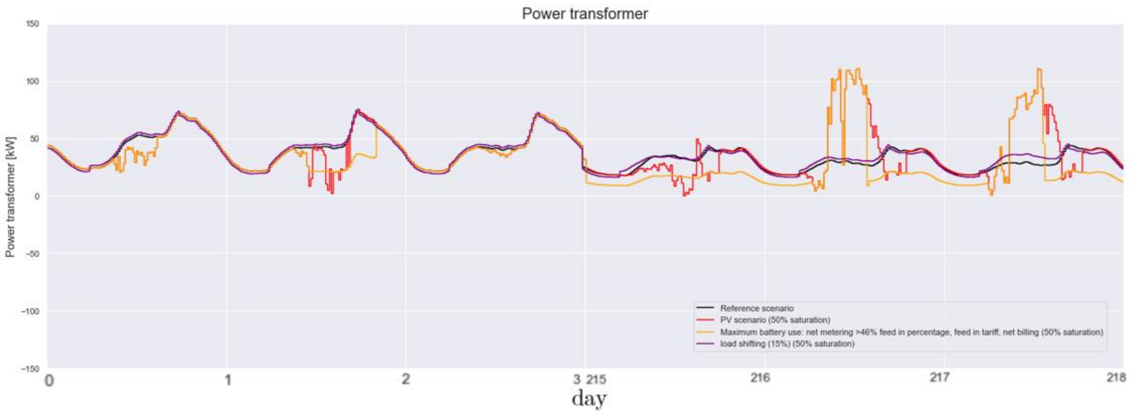


Figure 24: Network interaction and transformer capacity of the reference PV scenario at a 50 % saturation rate of 3 winter days (1,2,3 January) and 3 summer days (3,4,5, Augustus)

It can be summarised from the results that a household (that consumes 2790 kWh annually) equipped with a 3 kWp PV system holds a self-consumption ratio of 29%. If the net metering policy is continued, the expected PBP will decrease from 4.0 years in 2020 to 2.2 years in 2032. When the net metering policy is abolished without compensation for excess electricity, the PBP will increase from 4.1 years in 2020 to 8.9 years in 2032. Several BESS are proposed which increase the self-consumption ratio to a bandwidth of 0.56 (Valve-regulated lead-acid BESS) and 0.64 (lithium-ion BESS) dependent on their characteristics when the battery uses his full potential. The lithium-ion BESS is the best option in terms of performance and costs. The valve-regulated lead-acid battery, high-temperature battery and redox flow battery have all significant higher cost and a lower performance.

Compared to the current policy (in which the net metering policy is abolished with compensation for excess electricity), a lower PBP of a lithium-ion BESS is found at the net metering is abolished without compensation for excess electricity (with investment subsidy) for households that already have installed a PV system. This is because the highest profit can be achieved in this scenario compared to the PV scenario. If the net system continues, the benefits are negligible as most electricity is returned to the grid up to the net metering limit. This is in contrast to the scenarios in which a PV system is combined with a BESS that holds the lowest PBP when the net metering policy is continued even though the battery is hardly used as well as the net metering system abolishment without compensation for excess electricity but with subsidy scenario. In the DR scenario is the self-consumption ratio increased to 32%. The DR scenario is accompanied by high PBP’s in all scenarios.

5. Sensitivity analysis

In this chapter, a sensitivity analysis is performed. The critical parameters that are defined in section 3.3.3 are tested for their effect on the results. The effect on the PBP's are illustrated in Figure 26.

The spread of the discount rates mainly affects the results in the early years. On one hand, a higher discount rate of 9% has a net result of lower profits each year, which extends the PBP, whereas a lower discount rate of 5% results in a shorter PBP. Among the different scenarios, a difference can be observed as well. At the net metering (abolishment) policy only the net electricity is discounted while at the feed-in tariff and net billing policies both energy flows are charged where the discount rate has a larger influence. The spread between a 5% and 9% discount rate in the scenarios is between 0.4 and 1.6 years 2020. This spread is largely reduced in 2032.

The investment subsidy is a useful tool to stimulate the investment of a PV system and BESS. An investment subsidy of 15% and 35% leads to a PBP of respectively 4.5 and 6.0 years in 2032 while without subsidy this is 7.2 years. As an alternative for the net metering policy, the subsidy can be designed to make investments profitable.

The total cost of the system consists of the PV system and the BESS costs with the BOS components of both systems. The costs of the BESS and BOS components of the lithium-ion BESS are simply cheaper than those of the PV installation and have therefore a lower effect on the results. The previous parameters affect only the costs of the investment. The next parameters that are discussed does affect besides the PBP also the energy flows and self-consumption ratios.

The 3 kWp PV system generates 2896 kWh. For comparison: a 2 kWp PV installation generates 1931 kWh per year and a 4 kWp installation generates 3862 kWh. As expected, the self-consumption potential of a 2 kWp system is much higher. When the BESS is at its maximum use the self-consumption ratio is 82%. This is much higher than a 4 kWp system that generates a large amount of excess electricity which result in a lower self-consumption ratio of 52%. In terms of PBP, it can be concluded that the PBP of a 4 kWp system is higher because much excess electricity generated that can only be returned at a lower feed-in tariff, which does not outweigh the investment costs. The PBP of a 2 kWp system is slightly lower but covers less of the total demand. In 2032, the largest spread is attributed to the net metering abolishment policy where the advantage lies with the 2 kWp system. This is because excess electricity is not rewarded and smaller installations will benefit.

The BESS size seems to affect the PBP significantly in 2020 but later, in 2032 is this effect minimal. A larger lithium-ion BESS of 10 kWh will increase the self-consumption to 66% while a BESS of 5 kWh decreases the self-consumption to 61%. Even when larger batteries are used much higher self-consumption ratios are not achievable. the highest self-consumption ratio without seasonal storage is 67% (13 - 20 kWh lithium-ion battery). Therefore, it can be concluded that in terms of costs a 5 kWh system is a better option which reduces the self-consumption ratio only slightly.

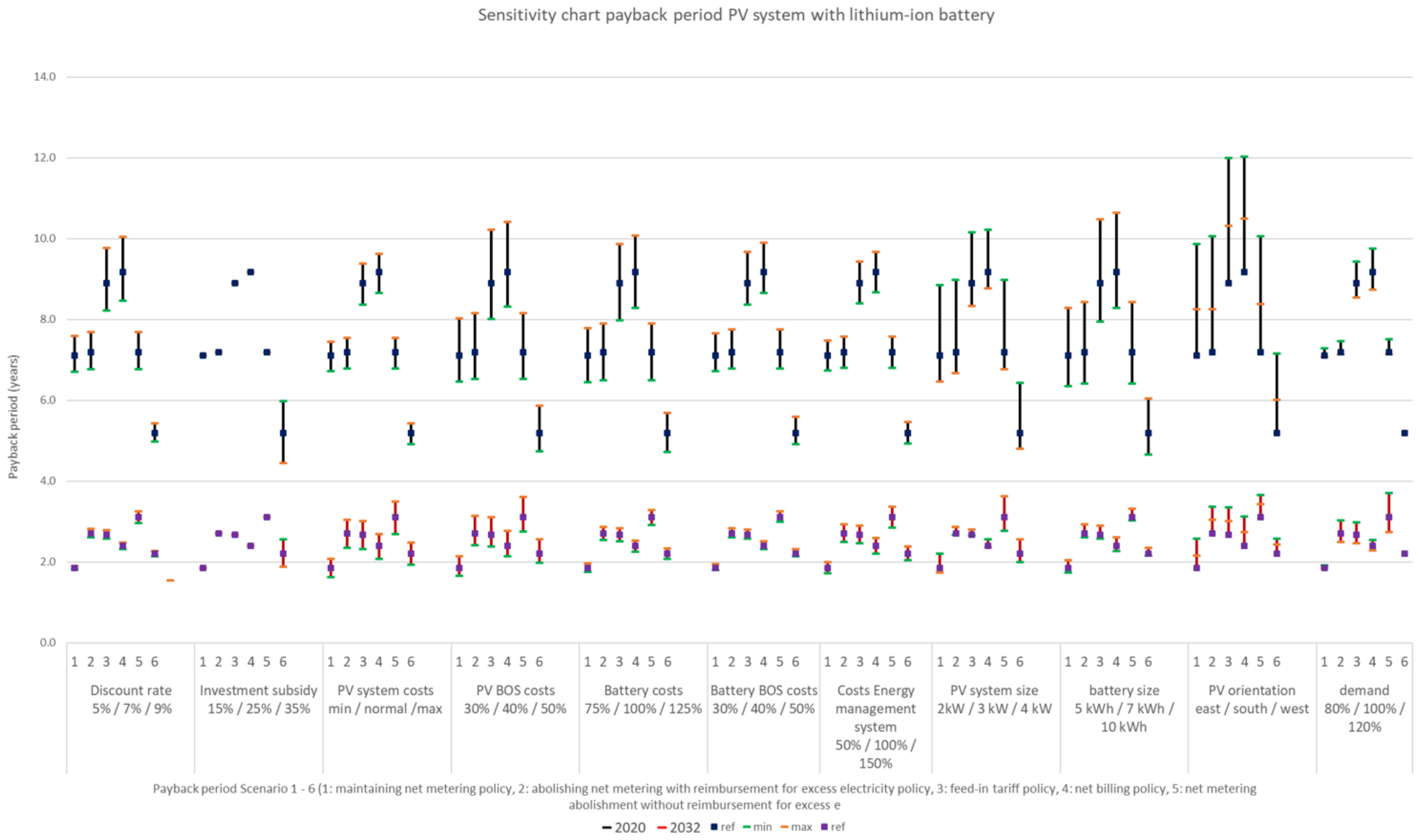
Moreover, the orientation of the PV panels affects the profitability of the installation the most. The costs of the PV system despite of the orientation is the same but the production is highly dependent on the orientation. Eastern oriented PV panels produce annually 2170 kWh and for western orientated panels is this 2529 kWh. This is a significant reduction in production compared to southern oriented PV systems. The self-consumption ratio of eastern and western oriented PV systems is respectively 75% and 66%. A higher self-consumption ratio is observed at eastern and western oriented PV systems, but they have a considerably higher PBP.

Finally, the effect of a changed demand. An average annual demand of 80% is equal to 2232 kWh and 120% of the demand equals 3348 kWh. This means for the reference costs of those alternatives that they are respectively lower and higher. This results in a higher PBP for the 80% scenario and a lower PBP in the 120% scenario. At lower demand, self-consumption is reduced to 55%, while at higher demand, self-consumption increases to 71%. All calculated PBP’s can be found in Appendix 2.

As mentioned earlier, the costs do not affect the energy flows and the associated transformer capacity, but variations in demand, production, battery capacity and orientation do. The variations in demand and battery capacity does not have a significant impact on the result. Increasing the PV system size to 4 kWp will increase the need for a transformer capacity proportionally. A change in the orientation of the PV system will move the power peak to another moment. Figure 25 illustrates the different electricity flows by a change in PV system orientation.

Figure 25: Power flows at PV orientation adjustments

Figure 26: Results sensitivity analysis



6. Discussion

This study shows the potential to increase self-consumption of locally generated electricity from PV systems in households in the residential sector. In this chapter, the results are discussed with the limitations of the research. The policy implications and the scientific relevance are also discussed in this section.

In general, the PBP's of the PV systems are relatively short. The PV costs are based on a literature review where the profit margins are disregarded which can extend the PBP. In combination with optimal results from the model, it is most likely that the PBP will be higher in practice. In line with the hypothesis, the PBP of PV systems will increase when the net metering policy is abolished. This is to a lesser extent when excess electricity is reimbursed with a feed-in tariff. An alternative policy in which a feed-in tariff is applied can be designed to set the PBP to a desired objective. These results build on existing evidence of literature data on technical and economic parameters of PV systems. The generalisability of the PBP is limited by the average load profile. Due to the diversity of residential electricity demand is the PBP depended on individual profiles. This counts as well for the specific PV system yield. The production profile is based on metrological data in the Netherlands. Based on this location and solar intensity is the electricity production modelled over the year 2015 and used over the whole timeframe. In practice, years with high PV production are alternated with low production which affects the PBP.

The extensive variety of sources provides a wide range of prices and characteristics of PV systems and storage technologies. recent sources are used to provide the best estimation on costs and parameters. The BESS costs development towards 2032 however is highly uncertain. Costs are reduced as installed capacity increases. Contrary to expectations, the development of certain types of batteries can go faster than others. Moreover, the technical parameters are kept constant over the whole timeframe which can be improved in the future as well. After 2031 is the electricity price assumed to be constant because of lacked data and uncertainty in the future. It is nonetheless unlikely that the electricity price and taxes will remain constant.

The PBP of a combined PV and a BESS is expected to decrease and will be cost-effective due to technical learning. This in combination with the benefits of storing electricity on the battery instead of injecting it back to the grid at low feed-in prices. The lithium-ion battery holds the lowest cost and best performance and has therefore the lowest PBP's. The network aspect is better suited to the average load profile which gives a good representation of a grouped set of households. The DSO costs on materials, trenching and transformers are defined based on a literature study to provide an estimation on grid costs. Actual prices for DSO's however are unknown.

The DR scenario is a simplified version of displacement of electricity from night-time to daytime. This particular load shifting did not have many additional benefits. Further research that is focused on the smart implementation of DR can lead to additional benefits.

The model is a simplification of the reality and will not fully represent the reality. The model is not performed in real-time but as an optimisation ex-post. This causes the BESS to store the exact amount of energy at the latest moment that the BESS can be charged. Therefore, the self-discharge on the battery is minimised. In reality, the battery stores electricity as soon as overproduction of the PV system occurs because of ignorance whether and how much production follows. The self-discharge of the battery, however, is that low that it does not have a significant effect on the costs.

The sensitivity analysis provides insight into the variations as a result of uncertainty. This is because a difference in, for example, instalment costs, PV system production, load profile, will result in different PBP's. Also, in the several scenarios that are defined are many variations possible, but this was kept to the most general scenarios.

The study of Londo (2019) examines the PBP's of stand-alone PV systems in various policies. The PBP's with the associated trend at the continuation of the net metering policy is very similar to this study. This also applies for the feed-in tariff policy. At the net metering abolishment without compensation policy, a deviation is found in the results. In the study of Londo (2019), the PBP increases from 2000 to 2010, after which it decreases until 2020. It is stated that the decrease in PV system costs and the increase of the electricity price are the reason for this decrease. It is different from this study where the PBP still increases from 2010 to 2020. This is also in line with the expectations because excess electricity is not rewarded and the net metering policy is abolished in this period. The difference may be caused by different PV system investment costs. The other scenarios treated in the research of Londo (2019) are not comparable.

Policy implications

The PBP of only a lithium-ion BESS is characterised by high costs in the early years. All scenarios except of the subsidy scenario holds PBP's over 12.5 years in 2020. This is due to high investment costs and when the net metering policy is still active little profit is achieved as excess electricity is injected into the grid which is not related to battery losses. The PBP is, however, quickly reduced as the net metering system is abolished. The investment costs are reduced as well. In the current policy is the PBP reduced to 4.8 years in 2032. The net metering policy without reimbursement for excess electricity holds a shorter PBP. In this scenario is a BESS more profitable because this scenario holds a high amount of excess electricity that can be used efficiently with a BESS. In combination with investment subsidies, the PBP can be reduced to 3.8 years in 2026 and 2.3 years in 2032.

Moreover. the scenarios that include a PV system and a BESS have diverse PBP's among the different types of batteries. It can be concluded that the lithium-ion battery is the most cost-effective because of the combination of high performance and low costs. In the current policy is the PBP of the system reduced from 7.2 years to 4.8 years. The PBP's in different policies are close together which are all between 3.3 and 5 years in 2032.

The self-consumption ratio on only PV systems is 29%. The remainder is injected into the grid. For the lithium-ion BESS, the self-consumption ratio will increase as the net metering system policy is abolished. For the feed-in tariff and net billing policy, the battery is always at maximum use. At a feed-in percentage of 46% and lower the battery optimal used. This result in a self-consumption ratio of 64%. Among the different batteries, the difference is observed due to the different efficiency and depth of discharge that requires alternative amounts of electricity from the grid. Higher self-consumption ratios are however not possible because the electricity production in winter cannot fulfil the demand. In summer, on the other hand, exceeds the production the demand. Seasonal storage is required for higher self-consumption ratios.

In the sensitivity analysis comes forward that the orientation of the PV panels have a large influence on the PBP. Eastern and Western-oriented panels yield less production while the investment costs remain the same. Despite the PBP becomes is the self-consumption ratio higher at those changed orientations. For eastern and western-oriented panels respectively, 75% and 66%. The demand has also a significant effect on the self-consumption ratio. 80% of the average demand holds a 55% self-consumption ratio while a 120% of the average demand holds a self-consumption ratio of 71%. The costs of the PV system hold a large spread in the PBP because of the high costs. Stagnation or acceleration of installation costs will result in alternative PBP's. Moreover, the size of the PV system is also of importance. Smaller PV installations result in higher self-consumption ratios.

At the abolishment of the net-metering policy, the PBP's of PV systems in the current policy expected to increase in the coming years. The compensation for excess electricity result in a reduced increase compared to the policy in which no reimbursement is given for excess electricity. As a result of this increase are prosumers incentivised to increase their self-consumption. This is reflected in the PBP's of only a lithium-ion battery next to an already existing PV installation, where the net meter abolishment (with compensation for excess electricity) has the lowest PBP. With the feed-in tariff and net billing policy, the PBP is much higher because prosumers are immediately incentivised to use the battery as it is much more cost-effective to store electricity on the battery that is used later than returning electricity to the grid. In the net-metering policy continuation policy, prosumers are not encouraged to add a BESS to an already existing PV installation because the battery is barely used in this scenario which result in significantly low profits and no PBP's. The PBP for the PV system & lithium-ion BESS can only be more incentivised by an investment subsidy or net billing policy after 2029. Therefore, it is advised to continue the current policy. This may be a trade-off between BESS alongside existing PV systems and combined PV systems with a BESS. By stopping the reimbursement of excess electricity, households that already have a PV installation are encouraged to invest in a BESS. However, stopping the refund will also increase the PBP of combined PV systems with a BESS. By stimulating BESS by the government, the development of the systems continues, which also reduces costs.

Scientific relevance and future research

Back to the theoretical implications of the research. To emphasise again the relevance. About 600,000 of the total of 8,000,000 Dutch households, which comes down to 7.5%, is equipped with a PV system. Together with the renewable energy targets and grid parity will this share increase in the coming years. The extend in which PV and BESS systems are bought will depend on policies. Those policies are not only designed towards PBP's but also on potential network impact which can result in network reinforcement. Within a short period is the net metering policy abolished. This means not only that the profitability of new installed PV systems will be reduced but also new investments in PV systems become less profitable which result in decreased investments. This research gives insight into ways to increase self-consumption and consequently alternative ways to use excess electricity that is generated from the PV system as well for a combined PV system and BESS. The PBP is provided for a set of BESS in different policies as well as the network impact.

Further research can be focussed on increased self-consumption by DR as this is not elaborated extensively. Specifically, DR in demand adjustment or pricing schemes, which is not yet extensively researched in literature studies. The model can be expanded in a way it works with real-time data. Moreover, the current or elaborated model can be updated with more recent data when it is available on costs, load profiles, production profiles. Instead of using the irradiation data from one year, data on multiple years from the KNMI can be used(KNMI, 2015).

Research on collective self-consumption at neighbourhood or community level can be part of future research in which electricity share between households is examined. When houses share electricity, higher self-consumption can be accomplished with more efficient use of electricity. The model needs to be extended and additional optimisation steps are required between households. This share of electricity between households can have complicated results in costs for households. With adaptations, the model can even be used for optimisation of PV systems and BESS sizes but specific data irradiation and load is required. Moreover, the network aspect in terms of cabling and transformer costs is based on general data. Future research could examine more specific situations and custom costs. Newly built networks entail different costs than when networks have to be adapted.

7. Conclusion

In conclusion, the parameters that affect self-consumption can largely be brought together to the policy that determines the revenues for excess electricity and the revenues from self-consumed PV systems. Self-consumption can be increased by a BESS and by DR. The current policy in the Netherlands on self-consumption is that it is allowed and while the net metering policy is still active it will be abolished in the coming years. By developing a model and performing simulation studies, the hypothesis is tested that if the net metering policy is abolished, the profitability of stand-alone PV systems is reduced. In the model, self-consumption measures are tested in different policies. Based on average load profiles, the PBP of 3 a kWp PV system in the current policy will increase from 4.0 years in 2020 to 4.9 years in 2032. Alternative policies that result in a reduced PBP is to continue the net metering policy, applying an investment subsidy or a net-billing policy from 2026 onwards. Exclusive investment in lithium-ion BESS's for households that already have a PV system is most profitable in the scenario in which the meter policy is abolished without compensation for excess electricity (with subsidy). In those scenarios, the BESS has the greatest advantage, excess electricity is stored in the battery and used later which otherwise is returned to the grid without profit. The self-consumption is increased in this case from 29% to 64% with a 7 kWh lithium-ion BESS. This scenario is characterised by low profits in the early years which develops to a PBP of 6.8 years in 2032. A 4 kWh BESS, however, only increases self-consumption to 66%. Much higher self-consumption percentages are not possible because the production in winter is not enough to meet the demand. In summer, on the other hand, the demand is far exceeded by the production that results in supply to the electricity grid. The scenarios in which different batteries are tested with a PV system contain a large variation between different batteries. The lithium-ion BESS, valve regulated lead-acid BESS, redox flow BESS and high-temperature BESS are investigated. In terms of cost and performance, the lithium-ion battery is the best option. Under the current policy, the PBP of a PV system with a lithium-ion BESS will decrease from 7.2 in 2020 to 4.8 years in 2032. The other batteries have a longer PBP's. The investment subsidy is an important tool to stimulate investments as they can reduce the PBP to the desired outcome. Higher self-consumption ratios are acquired as the PV system is differently oriented. Eastern oriented panels have a self-consumption ratio of 75% and western-oriented panels 66%. Despite the higher self-consumption ratio is the PBP considerably higher at those scenarios because the same investment costs are accompanied by a lower PV production. When the demand is reduced by 20% compared to the average demand, the self-consumption ratio is 55%, where a 20% increase in demand results in a self-consumption ratio of 71%. With a smaller PV system of 2 kWp,, a higher self-consumption ratio can be achieved of 82%. On the other hand, a 4 kWp PV system has a self-consumption ratio of 52%. Regarding the network impact is the transformer capacity dependent on the production peaks in the summer. Whether a BESS is installed will only change the duration but not the amplitude of the peaks and accordingly the transformer capacity. Additionally, a rough shift in demand in addition to a PV system has no significant benefits. Different orientations of PV systems results in peaks at different periods. The results provide a basis for ways to increase self-consumption and PBP's.

It is recommended to continue the net measurement policy, in which consumers and prosumers are encouraged to invest in a BESS (in combination with a PV system). In the net billing and the feed-in tariff policies are prosumers immediately stimulated to increase their self-consumption, as the feed-in of electricity to the grid becomes less profitable but the investment costs becomes significantly higher. The investment subsidy is a useful tool to shorten the PBP of a BESS. A recommendation for further research is to expand the model, after which it can be used for different types of homes or community storage or even for optimisations on PV or battery systems sizes.

8. References

ABB. (2014). *ABB micro inverter system*. https://www.solaris-shop.com/content/MICRO0.25IOUTDUS Specs.pdf

Alvarez, S. (2020). *Tesla's zero-cobalt battery goes beyond price parity, it's a strike to gas cars' jugular*. https://www.teslarati.com/tesla-zero-cobalt-battery-goes-for-gas-jugular/

Asian Development Bank. (2018). *Handbook on battery energy storage system*. https://www.adb.org/sites/default/files/publication/479891/handbook-battery-energy-storage-system.pdf

Battery University. (2017). *BU-402: What Is C-rate?* https://batteryuniversity.com/learn/article/what_is_the_c_rate

Berndt, D. (2001). Valve-regulated lead-acid batteries. *Journal of Power Sources*. https://doi.org/10.1016/S0378-7753(01)00881-3

Bertsch, V., Geldermann, J., & Lühn, T. (2017). What drives the profitability of household PV investments, self-consumption and self-sufficiency? *Applied Energy*. https://doi.org/10.1016/j.apenergy.2017.06.055

Brinsmead, T. S., Graham, P., Hayward, J., Ratnam, E. L., & Reedman, L. (2015). Future energy storage trends: An assessment of the economic viability, potential uptake and impacts of electrical energy storage on the NEM 2015–2035. In *CSIRO*.

Brown, G. F., & Wu, J. (2009). Third generation photovoltaics. *Laser and Photonics Reviews*. https://doi.org/10.1002/lpor.200810039

Castillo-Cagigal, M., Caamaño-Martín, E., Matallanas, E., Masa-Bote, D., Gutiérrez, A., Monasterio-Huelin, F., & Jiménez-Leube, J. (2011). PV self-consumption optimization with storage and Active DSM for the residential sector. *Solar Energy*. https://doi.org/10.1016/j.solener.2011.06.028

CBS. (2019). *Share of renewable energy up to 7.4 percent*. https://www.cbs.nl/en-gb/news/2019/22/share-of-renewable-energy-up-to-7-4-percent

CBS. (2020). *Sharp rise in green electricity production*. Sharp Rise in Green Electricity Production. https://www.cbs.nl/en-gb/news/2020/10/sharp-rise-in-green-electricity-production

Cone, C. (2018). *Battery Energy Storage Systems (BESS) – Worthwhile Investment?* Renewable Energy World. https://www.renewableenergyworld.com/2018/08/23/battery-energy-storage-systems-bess-worthwhile-investment/#gref

Dehler, J., Keles, D., Telsnig, T., Fleischer, B., Baumann, M., Fraboulet, D., Faure-Schuyer, A., & Fichtner, W. (2017). Self-Consumption of Electricity from Renewable Sources. In *Europe's Energy Transition: Insights for Policy Making*. https://doi.org/10.1016/B978-0-12-809806-6.00027-4

Essent. (2019). *Informatie over de opslag duurzame energie- en klimaattransitie (ODE)*. https://www.essent.nl/kennisbank/stroom-en-gas/energierekening/informatie-over-de-opslag-duurzame-energie

European Comission. (2015). Best practices on Renewable Energy Self-consumption. In *European Commission*. https://ec.europa.eu/energy/sites/ener/files/documents/1_EN_autre_document_travail_service_part1_v6.pdf

European Commission. (2018). Shedding light on energy in the EU. *Consulting-Specifying Engineer*. https://op.europa.eu/en/publication-detail/-/publication/d45cb3e2-4444-11e8-a9f4-01aa75ed71a1

European Council. (2014). Conclusions on the 2030 framework for climate and energy policies. *European Union*, *October*. http://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/ec/145397.pdf

F. Holmgren, W., W. Hansen, C., & A. Mikofski, M. (2018). pvlib python: a python package for modeling solar energy systems. *Journal of Open Source Software*. https://doi.org/10.21105/joss.00884

Fraunhofer ISE. (2015). Current and Future Cost of Photovoltaics. *Agora Energiewende*. https://doi.org/059/01-S-2015/EN

Gupta, A., & Paranjape, N. (2020). *Stationary Battery Storage Market Forecast 2030*. https://www.gminsights.com/industry-analysis/stationary-battery-storage-market

Hof, A. F., den Elzen, M. G. J., & Mendoza Beltran, A. (2016). The EU 40 % greenhouse gas emission reduction target by 2030 in perspective. *International Environmental Agreements: Politics, Law and Economics*. https://doi.org/10.1007/s10784-016-9317-x

IRENA. (2017). Electricity storage and renewables: Costs and markets to 2030. In *Electricity-storage-and-renewables-costs-and-markets*. https://doi.org/ISBN 978-92-9260-038-9 (PDF)

Johnson, B. A., & White, R. E. (1998). Characterization of commercially available lithium-ion batteries. *Journal of Power Sources*. https://doi.org/10.1016/S0378-7753(97)02659-1

Khatib, T., Mohamed, A., & Sopian, K. (2013). A review of photovoltaic systems size optimization techniques. In *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2013.02.023

KNMI. (2015). *Daggegevens van het weer in Nederland*. http://projects.knmi.nl/klimatologie/daggegevens/selectie.cgi

Lampropoulos, I., Kling, W. L., Ribeiro, P. F., & Van Den Berg, J. (2013). History of demand side management and classification of demand response control schemes. *IEEE Power and Energy Society General Meeting*. https://doi.org/10.1109/PESMG.2013.6672715

Lang, T., Ammann, D., & Girod, B. (2016). Profitability in absence of subsidies: A techno-economic analysis of rooftop photovoltaic self-consumption in residential and commercial buildings. *Renewable Energy*. https://doi.org/10.1016/j.renene.2015.09.059

Li, Y., Gao, W., & Ruan, Y. (2018). Performance investigation of grid-connected residential PV-battery system focusing on enhancing self-consumption and peak shaving in Kyushu, Japan. *Renewable Energy*. https://doi.org/10.1016/j.renene.2018.04.074

Litjens, G., Van Sark, W., & Worrell, E. (2016). On the influence of electricity demand patterns, battery storage and PV system design on PV self-consumption and grid interaction. *Conference Record of the IEEE Photovoltaic Specialists Conference*. https://doi.org/10.1109/PVSC.2016.7749983

Logan Goldie, S. (2019). A Behind the Scenes Take on Lithium-ion Battery Prices | BloombergNEF. *BloombergNEF*. https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/

Londo, M., Matton, R., Usmani, O., Klaveren, M. van, & Tigchelaar, C. (2017). *De salderingsregeling: Effecten van een aantal hervormingsopties*. https://www.narcis.nl/publication/RecordID/oai:tudelft.nl:uuid%3Afe0cbffe-0bbb-4a31-b9a0-74d35c64d5f5

Londo, M., Matton, R., Usmani, O., van Klaveren, M., Tigchelaar, C., & Brunsting, S. (2019). Alternatives for current net metering policy for solar PV in the Netherlands: A comparison of impacts on business case and purchasing behaviour of private homeowners, and on governmental costs. *Renewable Energy*.

https://doi.org/10.1016/j.renene.2019.09.062

Luthander, R., Widén, J., Nilsson, D., & Palm, J. (2015). Photovoltaic self-consumption in buildings: A review. In *Applied Energy*. https://doi.org/10.1016/j.apenergy.2014.12.028

Masson, G., Briano, J. I., & Baez, M. J. (2016). Review and Analysis of Self-consumption Policies. In *Report IEA-PVPS T1-28:2016*.

Messenger, R. A. (2018). Photovoltaic Systems Engineering. In *Photovoltaic Systems Engineering*. https://doi.org/10.1201/9781315218397

Michiel, H., & Robert, K. (2018). *Analyse van het voorstel voor hoofdlijnen van het klimaatakkoord*. https://www.pbl.nl/sites/default/files/downloads/pbl-2018-analyse-van-het-voorstel-voor-hoofdlijnen-van-het-klimaatakkoord-3380.pdf

Milieu centraal. (2020). *Energieverbruiksmanagers*. https://www.energieverbruiksmanagers.nl/overzicht-energieverbruiksmanagers/

Ministerie van algemene zaken. (2019). *Omvorming salderen*. https://www.rijksoverheid.nl/documenten/kamerstukken/2019/04/25/kamerbrief-over-omvorming-salderen

ministry of economic affairs and climate. (2019). *Climate Agreement*. https://www.klimaatakkoord.nl/documenten/publicaties/2019/06/28/national-climate-agreement-the-netherlands

MISO. (2019). *Transmission Cost Estimation Guide*. https://cdn.misoenergy.org/20190212 PSC Item 05a Transmission Cost Estimation Guide for MTEP 2019_for review317692.pdf

NEDU. (2019). *Verbruiksprofielen*. https://www.nedu.nl/documenten/verbruiksprofielen/

Nejat, P., Jomehzadeh, F., Taheri, M. M., Gohari, M., & Muhd, M. Z. (2015). A global review of energy consumption, CO2 emissions and policy in the residential sector (with an overview of the top ten CO2 emitting countries). In *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2014.11.066

Osha. (2019). *Preventing Fire and/or Explosion Injury from Small and Wearable Lithium Battery Powered Devices*. https://www.osha.gov/dts/shib/shib011819.html

Ould Amrouche, S., Rekioua, D., Rekioua, T., & Bacha, S. (2016). Overview of energy storage in renewable energy systems. *International Journal of Hydrogen Energy*. https://doi.org/10.1016/j.ijhydene.2016.06.243

PV Free. (2014). *Advent Solar Ventura 210*. https://pvfree.herokuapp.com/pvmodules/1048/

Qudrat-Ullah, Hassan, Kayal, A. A. (2019). *Climate Change and Energy Dynamics in the Middle East*. https://www.springer.com/gp/book/9783030112011

Quoilin, S., Kavvadias, K., Mercier, A., Pappone, I., & Zucker, A. (2016). Quantifying self-consumption linked to solar home battery systems: Statistical analysis and economic assessment. *Applied Energy*. https://doi.org/10.1016/j.apenergy.2016.08.077

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., … Foley, J. (2009). Planetary boundaries: Exploring the safe operating space for humanity. *Ecology and Society*. https://doi.org/10.5751/ES-03180-140232

Rodriguez, J. (2015). Going with the flow: An introduction to redox flow batteries. *Solar Choice Pty Ltd*. https://www.solarchoice.net.au/blog/news/an-introduction-to-flow-batteries-030315

Schmidt, O., Hawkes, A., Gambhir, A., & Staffell, I. (2017). The future cost of electrical energy storage based on experience rates. *Nature Energy*. https://doi.org/10.1038/nenergy.2017.110

Schram, W. L., Lampropoulos, I., & van Sark, W. G. J. H. M. (2018). Photovoltaic systems coupled with batteries that are optimally sized for household self-consumption: Assessment of peak shaving potential. *Applied Energy*. https://doi.org/10.1016/j.apenergy.2018.04.023

Stefan ten Teije. (2019). *Zonnepanelen worden nu echt zichtbaar in de samenleving*. https://www.ad.nl/wonen/zonnepanelen-worden-nu-echt-zichtbaar-in-de-samenleving~aab95be3/

United Nations. (2015). Summary of the Paris Agreement. *United Nations Framework Convention on Climate Change*.

van Sark, W., Muizebelt, P., Cace, J., De Vries, A., & De Rijk, P. (2012). Grid parity reached for consumers in the Netherlands. *Conference Record of the IEEE Photovoltaic Specialists Conference*. https://doi.org/10.1109/PVSC.2012.6318094

van Sark, W., Schram, W., & Lampropoulos, I. (2020). *Prosumer Policy Advisory Paper*. https://www.pvp4grid.eu/wp-content/uploads/2020/04/D4.3-National-Policy-Paper-Netherlands.pdf

Verheij, F. J., Menkveld, M., & Usmani, O. (2020). *Effect afbouw salderingsregeling op de terugverdientijd van investeringen in zonnepanelen*. https://www.rvo.nl/sites/default/files/2020/03/TNO-2019-P11928-Afbouw-regeling-salderen-eindversie-25mrt2020.pdf

Willuhn, M. (2019, July). Global PV market: 114 GW to be installed in 2019, with continued growth onwards. *Global PV Market: 114 GW to Be Installed in 2019, with Continued Growth Onwards*. https://www.pv-magazine.com/2019/07/25/global-pv-market-114-gw-to-be-installed-in-2019-with-continued-growth-onwards/

Yamamoto, Y. (2012). Pricing electricity from residential photovoltaic systems: A comparison of feed-in tariffs, net metering, and net purchase and sale. *Solar Energy*. https://doi.org/10.1016/j.solener.2012.06.001

Appendix 1. Annual load profile

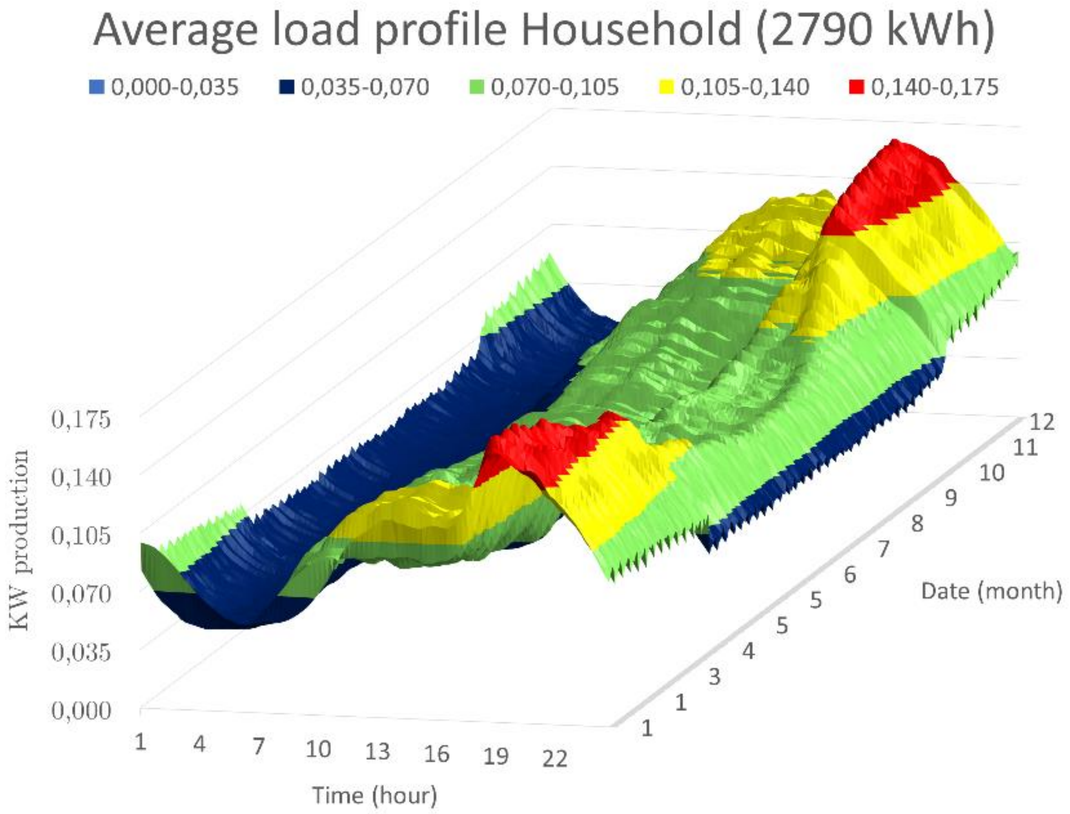


Figure 27: Average load profile household

Appendix 2. Input parameters, costs and PBP’s

Table 23: Input parameters on policies

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2036
producer price (€cent/kWh)	5.50	6.00	7.00	7.50	7.90	8.10	8.80	9.10	9.70	10.10	10.10	10.10	10.10	10.10	10.10	10.10	10.10	10.10
Energy tax (€cent/kWh)	10.60	10.80	10.90	11.10	11.30	11.40	11.60	11.80	12.00	12.10	12.30	12.30	12.30	12.30	12.30	12.30	12.30	12.30
Renewable energy tax (€cent/kWh)	2.70	2.70	2.90	3.10	3.20	3.30	3.40	3.50	3.60	4.10	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70
VAT (€cent/kWh)	4.00	4.10	4.37	4.56	4.70	4.79	5.00	5.12	5.31	5.52	5.69	5.69	5.69	5.69	5.69	5.69	5.69	5.69
Electricity price (€cent/kWh)	22.80	23.60	25.17	26.26	27.10	27.59	28.80	29.52	30.61	31.82	32.79	32.79	32.79	32.79	32.80	32.79	32.79	32.79
net metering (feed in percentage)	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
price for excess electricity (€cent/kWh)	4.40	4.80	5.60	6.00	6.32	6.48	7.04	7.28	7.76	8.08	8.08	8.08	8.08	8.08	8.08	8.08	8.08	8.08
net metering with abolishment (feed in percentage)	100%	100%	100%	91%	82%	73%	64%	55%	46%	37%	28%	0%	0%	0%	0%	0%	0%	0%
price for excess electricity (€cent/kWh)	4.40	4.80	5.60	6.00	6.32	6.48	7.04	7.28	7.76	8.08	8.08	8.08	8.08	8.08	8.08	8.08	8.08	8.08
Feed in tariff subsidy (€cent/kWh)	12.00	11.00	10.00	10.00	9.00	8.00	7.00	5.00	4.00	3.00	2.00	1.67	1.33	1.00	0.67	0.33	0.00	0.00
Feed in tariff producer (€cent/kWh)	4.40	4.80	5.60	6.00	6.32	6.48	7.04	7.28	7.76	8.08	8.08	8.08	8.08	8.08	8.08	8.08	8.08	8.08
feed in tariff total (€cent/kWh)	16.40	15.80	15.60	16.00	15.32	14.48	14.04	12.28	11.76	11.08	10.08	9.75	9.41	9.08	8.75	8.41	8.08	8.08
net billing consumption (€cent/kWh)	22.80	23.60	25.17	26.26	27.10	27.59	28.80	29.52	30.61	31.82	32.79	32.79	32.79	32.79	32.80	32.79	32.79	32.79
net billing production (€cent/kWh)	11.40	11.80	12.58	13.13	13.55	13.79	14.40	14.76	15.31	15.91	16.40	16.40	16.40	16.40	16.40	16.40	16.40	16.40
no compensation (feed in percentage)	100%	100%	100%	91%	82%	73%	64%	55%	46%	37%	28%	0%	0%	0%	0%	0%	0%	0%

Table 24: Annual costs PV system only

year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037
Reference scenario (€/year)	636.1	658.3	702.2	732.6	756.2	769.7	803.5	823.7	854.1	887.9	914.9	914.9	914.9	914.9	914.9	914.9	914.9	914.9
maintaining net metering (€/year)	-4.7	-5.1	-6.0	-6.4	-6.7	-6.9	-7.5	-7.7	-8.2	-8.6	-8.6	-8.6	-8.6	-8.6	-8.6	-8.6	-8.6	-8.6
Abolishment net metering with compensation for excess electricity (€/year)	-4.7	-5.1	-6.0	29.0	65.9	103.7	144.5	186.4	231.1	281.6	336.5	470.7	470.7	470.7	470.7	470.7	470.7	470.7
Feed-in tariff (€/year)	106.7	134.4	169.0	182.0	212.3	238.9	271.3	321.4	353.2	390.6	429.8	436.6	443.5	450.3	457.1	463.9	470.7	470.7
net-billing (€/year)	209.0	216.3	230.7	240.7	248.5	252.9	264.0	270.7	280.6	291.7	300.6	300.6	300.6	300.6	300.6	300.6	300.6	300.6
Net metering abolishment without compensation for excess electricity (€/year)	0.0	0.0	0.0	45.8	94.6	144.5	201.1	257.7	320.7	388.9	458.0	636.1	636.1	636.1	636.1	636.1	636.1	636.1
Investment subsidy with net metering abolishment without compensation for excess electricity (€/year)	0.0	0.0	0.0	45.8	94.6	144.5	201.1	257.7	320.7	388.9	458.0	636.1	636.1	636.1	636.1	636.1	636.1	636.1

Table 25: Annual costs PV system & Lithium-ion BESS

year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037
maintaining net metering (€/year)	-21.41	-22.15	-23.63	-24.65	-25.45	-25.90	-27.04	-27.72	-28.74	-29.88	-30.79	-30.79	-30.79	-30.79	-30.79	-30.79	-30.79	-30.79
Abolishment net metering with compensation for excess electricity (€/year)	-21.41	-22.16	-23.63	-19.32	-14.43	-9.08	-3.63	2.28	11.72	55.73	98.86	233.07	233.07	233.07	233.07	233.07	233.07	233.07
Self-consumption ratio at the net meting abolishment	0.33	0.33	0.33	0.38	0.43	0.49	0.54	0.59	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64
Feed-in tariff (€/year)	64.11	76.99	93.51	100.06	114.15	126.31	141.61	164.39	179.29	196.78	214.91	217.94	220.97	224.00	227.02	230.05	233.08	233.08
net-billing (€/year)	109.54	113.36	120.91	126.14	130.21	132.54	138.35	141.84	147.07	152.88	157.54	157.54	157.54	157.54	157.54	157.54	157.54	157.54
Net metering abolishment without compensation for excess electricity (€/year)	-21.41	-22.16	-23.63	-19.32	-14.43	-9.08	-3.63	2.28	12.98	69.04	128.39	306.48	306.48	306.48	306.48	306.48	306.48	306.48
Investment subsidy with net metering abolishment without compensation for excess electricity (€/year)	-21.41	-22.16	-23.63	-19.32	-14.43	-9.08	-3.63	2.28	12.98	69.04	128.39	306.48	306.48	306.48	306.48	306.48	306.48	306.48

Table 26: Annual costs PV system & Valve-regulated lead-acid BESS

year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037
maintaining net metering (€/year)	-19.4	-20.1	-21.4	-22.3	-23.1	-23.5	-24.5	-25.1	-26.0	-27.1	-27.9	-27.9	-27.9	-27.9	-27.9	-27.9	-27.9	-27.9
Abolishment net metering with compensation for excess electricity (€/year)	-19.4	-20.1	-21.4	-13.2	-4.2	5.3	15.6	31.6	72.6	116.9	164.6	298.8	298.8	298.8	298.8	298.8	298.8	298.8
Self-consumption ratio at the net meting abolishment	0.33	0.33	0.33	0.37	0.42	0.47	0.52	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56
Feed-in tariff (€/year)	89.2	105.2	126.0	134.4	151.9	166.9	186.0	214.0	232.6	254.3	276.8	280.4	284.1	287.8	291.4	295.1	298.8	298.8
net-billing (€/year)	144.2	149.2	159.1	166.0	171.4	174.4	182.1	186.7	193.6	201.2	207.3	207.3	207.3	207.3	207.3	207.3	207.3	207.3
Net metering abolishment without compensation for excess electricity (€/year)	-19.4	-20.1	-21.4	-13.2	-4.2	5.3	15.6	34.0	88.7	147.8	209.5	387.6	387.6	387.6	387.6	387.6	387.6	387.6
Investment subsidy with net metering abolishment without compensation for excess electricity (€/year)	-19.4	-20.1	-21.4	-13.2	-4.2	5.3	15.6	34.0	88.7	147.8	209.5	387.6	387.6	387.6	387.6	387.6	387.6	387.6

Table 27: Annual costs PV system & Redox flow BESS

year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037
maintaining net metering (€/year)	-17.1	-17.7	-18.9	-19.7	-20.3	-20.7	-21.6	-22.1	-23.0	-23.9	-24.6	-24.6	-24.6	-24.6	-24.6	-24.6	-24.6	-24.6
Abolishment net metering with compensation for excess electricity (€/year)	-17.1	-17.7	-18.9	-6.2	7.5	21.9	37.6	53.7	71.4	91.4	137.3	271.5	271.5	271.5	271.5	271.5	271.5	271.5
Self-consumption ratio at the net meting abolishment	0.32	0.32	0.32	0.36	0.40	0.45	0.49	0.53	0.57	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62
Feed-in tariff (€/year)	106.7	123.2	140.5	148.5	162.0	172.9	188.3	208.3	223.0	240.1	257.1	259.5	261.9	264.3	266.7	269.1	271.5	271.5
net-billing (€/year)	147.0	152.1	162.3	169.3	174.7	177.9	185.7	190.3	197.4	205.2	211.4	211.4	211.4	211.4	211.4	211.4	211.4	211.4
Net metering abolishment without compensation for excess electricity (€/year)	-17.1	-17.7	-18.9	-6.2	7.5	21.9	37.6	53.7	71.4	91.8	151.8	329.9	329.9	329.9	329.9	329.9	329.9	329.9
Investment subsidy with net metering abolishment without compensation for excess electricity (€/year)	-17.1	-17.7	-18.9	-6.2	7.5	21.9	37.6	53.7	71.4	91.8	151.8	329.9	329.9	329.9	329.9	329.9	329.9	329.9

Table 28: Annual costs PV system & high-temperature BESS

year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037
maintaining net metering (€/year)	-19.4	-20.1	-21.4	-22.3	-23.1	-23.5	-24.5	-25.1	-26.1	-27.1	-27.9	-27.9	-27.9	-27.9	-27.9	-27.9	-27.9	-27.9
Abolishment net metering with compensation for excess electricity (€/year)	-19.4	-20.1	-21.4	-13.2	-4.2	5.3	15.5	26.1	37.7	68.6	114.1	248.3	248.3	248.3	248.3	248.3	248.3	248.3
Self-consumption ratio at the net meting abolishment	0.32	0.32	0.32	0.37	0.42	0.47	0.52	0.56	0.61	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63
Feed-in tariff (€/year)	83.9	96.5	113.2	120.4	134.1	145.7	160.9	182.4	197.1	214.3	231.9	234.6	237.3	240.1	242.8	245.6	248.3	248.3
net-billing (€/year)	125.1	129.4	138.1	144.0	148.7	151.3	158.0	162.0	167.9	174.6	179.9	179.9	179.9	179.9	179.9	179.9	179.9	179.9
Net metering abolishment without compensation for excess electricity (€/year)	-19.4	-20.1	-21.4	-13.2	-4.2	5.3	15.5	26.1	37.7	77.1	136.7	314.8	314.8	314.8	314.8	314.8	314.8	314.8
Investment subsidy with net metering abolishment without compensation for excess electricity (€/year)	-19.4	-20.1	-21.4	-13.2	-4.2	5.3	15.5	26.1	37.7	77.1	136.7	314.8	314.8	314.8	314.8	314.8	314.8	314.8

Table 29: Annual costs PV system & DR

year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037
maintaining net metering (€/year)	-20.4	-21.1	-22.6	-23.7	-24.4	-24.9	-26.0	-26.7	-27.7	-28.8	-29.7	-29.7	-29.7	-29.7	-29.7	-29.7	-29.7	-29.7
Abolishment net metering with compensation for excess electricity (€/year)	-20.4	-21.1	-22.6	11.7	48.1	85.7	125.9	167.4	211.6	261.3	315.4	449.6	449.6	449.6	449.6	449.6	449.6	449.6
Self-consumption ratio at the net meting abolishment	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
Feed-in tariff (€/year)	101.3	127.8	160.9	173.2	202.3	227.7	258.8	306.7	337.1	372.9	410.5	417.0	423.5	430.1	436.6	443.1	449.7	449.7
net-billing (€/year)	199.3	206.3	220.0	229.5	236.9	241.2	251.7	258.1	267.6	278.2	286.6	286.6	286.6	286.6	286.6	286.6	286.6	286.6
Net metering abolishment without compensation for excess electricity (€/year)	-19.4	-19.4	-21.5	23.4	71.5	121.0	176.5	232.5	294.5	361.7	430.0	608.0	608.0	608.0	608.0	608.0	608.0	608.0
Investment subsidy with net metering abolishment without compensation for excess electricity (€/year)	-19.4	-19.4	-21.5	23.4	71.5	121.0	176.5	232.5	294.5	361.7	430.0	608.0	608.0	608.0	608.0	608.0	608.0	608.0

Table 30: Annual costs sensitivity analysis 2 kWp PV system

year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037
maintaining net metering (€/year)	195.9	202.7	216.2	225.6	232.9	237.0	247.4	253.7	263.0	273.4	281.7	281.7	281.7	281.7	281.7	281.7	281.7	281.7
Abolishment net metering with compensation for excess electricity (€/year)	195.9	202.7	216.2	228.8	239.4	247.1	261.4	271.5	285.2	300.4	313.5	375.4	375.4	375.4	375.4	375.4	375.4	375.4
Self-consumption ratio at the net meting abolishment	0.40	0.40	0.40	0.45	0.50	0.54	0.59	0.64	0.69	0.73	0.78	0.82	0.82	0.82	0.82	0.82	0.82	0.82
Feed-in tariff (€/year)	235.5	246.4	265.8	278.0	289.8	297.6	313.2	326.2	340.5	356.7	370.7	371.5	372.3	373.1	373.9	374.7	375.4	375.4
net-billing (€/year)	247.3	255.9	273.0	284.8	294.0	299.3	312.4	320.3	332.1	345.2	355.7	355.7	355.7	355.7	355.7	355.7	355.7	355.7
Net metering abolishment without compensation for excess electricity (€/year)	195.9	202.7	216.2	228.8	239.4	247.1	261.4	271.5	285.2	300.4	313.5	394.6	394.6	394.6	394.6	394.6	394.6	394.6
Investment subsidy with net metering abolishment without compensation for excess electricity (€/year)	195.9	202.7	216.2	228.8	239.4	247.1	261.4	271.5	285.2	300.4	313.5	394.6	394.6	394.6	394.6	394.6	394.6	394.6

Table 31: Annual costs sensitivity analysis 4 kWp PV system

year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037
maintaining net metering (€/year)	-215.9	-223.4	-238.3	-248.6	-256.7	-261.2	-272.7	-279.6	-289.9	-301.3	-310.5	-310.5	-310.5	-310.5	-310.5	-310.5	-310.5	-310.5
Abolishment net metering with compensation for excess electricity (€/year)	-215.9	-223.4	-238.3	-243.5	-216.2	-184.2	-156.1	-122.4	-89.4	-52.6	-9.6	121.5	121.5	121.5	121.5	121.5	121.5	121.5
Self-consumption ratio at the net meting abolishment	0.48	0.48	0.48	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
Feed-in tariff (€/year)	-101.1	-84.5	-68.5	-66.8	-48.3	-30.0	-12.8	23.2	40.8	62.2	87.1	92.8	98.5	104.3	110.0	115.8	121.5	121.5
net-billing (€/year)	-15.1	-15.6	-16.6	-17.3	-17.9	-18.2	-19.0	-19.5	-20.2	-21.0	-21.7	-21.7	-21.7	-21.7	-21.7	-21.7	-21.7	-21.7
Net metering abolishment without compensation for excess electricity (€/year)	-215.9	-223.4	-238.3	-211.4	-199.2	-162.3	-120.3	-73.0	-23.5	29.9	86.7	260.6	260.6	260.6	260.6	260.6	260.6	260.6
Investment subsidy with net metering abolishment without compensation for excess electricity (€/year)	-215.9	-223.4	-238.3	-211.4	-199.2	-162.3	-120.3	-73.0	-23.5	29.9	86.7	260.6	260.6	260.6	260.6	260.6	260.6	260.6

Table 32: Annual costs sensitivity analysis 5 kWh battery

year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037
maintaining net metering (€/year)	-21.4	-22.2	-23.6	-24.7	-25.4	-25.9	-27.0	-27.7	-28.7	-29.9	-30.8	-30.8	-30.8	-30.8	-30.8	-30.8	-30.8	-30.8
Abolishment net metering with compensation for excess electricity (€/year)	-21.4	-21.4	-21.4	-19.3	-14.4	-9.1	-3.6	2.3	28.2	70.7	116.7	250.9	250.9	250.9	250.9	250.9	250.9	250.9
Self-consumption ratio at the net meting abolishment	0.33	0.33	0.33	0.38	0.43	0.49	0.54	0.59	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61
Feed-in tariff (€/year)	67.3	81.3	99.2	106.2	121.5	134.8	151.4	176.2	192.3	211.3	231.0	234.4	237.7	241.0	244.3	247.6	250.9	250.9
net-billing (€/year)	117.0	121.1	129.2	134.7	139.1	141.6	147.8	151.5	157.1	163.3	168.3	168.3	168.3	168.3	168.3	168.3	168.3	168.3
Net metering abolishment without compensation for excess electricity (€/year)	-21.4	-21.4	-21.4	-19.3	-14.4	-9.1	-3.6	2.3	36.1	93.1	153.1	331.2	331.2	331.2	331.2	331.2	331.2	331.2
Investment subsidy with net metering abolishment without compensation for excess electricity (€/year)	-21.4	-22.2	-23.6	-19.3	-14.4	-9.1	-3.6	2.3	8.6	53.1	112.0	290.1	290.1	290.1	290.1	290.1	290.1	290.1

Table 33: Annual costs sensitivity analysis 10 kWh battery

year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037
maintaining net metering (€/year)	-21.4	-22.2	-23.6	-24.7	-25.4	-25.9	-27.0	-27.7	-28.7	-29.9	-30.8	-30.8	-30.8	-30.8	-30.8	-30.8	-30.8	-30.8
Abolishment net metering with compensation for excess electricity (€/year)	-21.4	-22.2	-23.6	-19.3	-14.4	-9.1	-3.6	2.3	8.6	42.3	87.0	221.2	221.2	221.2	221.2	221.2	221.2	221.2
Self-consumption ratio at the net meting abolishment	0.33	0.33	0.33	0.38	0.43	0.49	0.54	0.59	0.65	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66
Feed-in tariff (€/year)	62.0	74.1	89.8	96.0	109.3	120.7	135.2	156.6	170.6	187.1	204.2	207.1	209.9	212.7	215.6	218.4	221.2	221.2
net-billing (€/year)	104.6	108.2	115.4	120.4	124.3	126.5	132.1	135.4	140.4	146.0	150.4	150.4	150.4	150.4	150.4	150.4	150.4	150.4
Net metering abolishment without compensation for excess electricity (€/year)	-21.4	-22.2	-23.6	-19.3	-14.4	-9.1	-3.6	2.3	8.6	53.1	112.0	290.1	290.1	290.1	290.1	290.1	290.1	290.1
Investment subsidy with net metering abolishment without compensation for excess electricity (€/year)	-21.4	-22.2	-23.6	-19.3	-14.4	-9.1	-3.6	2.3	8.6	53.1	112.0	290.1	290.1	290.1	290.1	290.1	290.1	290.1

Table 34: Annual costs sensitivity analysis Eastern-oriented PV system

year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037
maintaining net metering (€/year)	141.4	146.4	156.1	162.9	168.1	171.1	178.6	183.1	189.9	197.4	203.4	203.4	203.4	203.4	203.4	203.4	203.4	203.4
Abolishment net metering with compensation for excess electricity (€/year)	141.4	146.4	156.1	166.6	175.7	182.8	194.9	203.9	215.7	228.7	253.6	346.5	346.5	346.5	346.5	346.5	346.5	346.5
Self-consumption ratio at the net meting abolishment	0.38	0.38	0.38	0.43	0.48	0.53	0.58	0.63	0.68	0.73	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Feed-in tariff (€/year)	193.5	205.4	224.6	235.6	248.4	257.8	273.8	290.0	305.0	322.1	337.7	339.2	340.7	342.1	343.6	345.1	346.5	346.5
net-billing (€/year)	215.5	223.0	237.9	248.2	256.2	260.8	272.2	279.1	289.4	300.8	310.0	310.0	310.0	310.0	310.0	310.0	310.0	310.0
Net metering abolishment without compensation for excess electricity (€/year)	141.4	146.4	156.1	166.6	175.7	182.8	194.9	203.9	215.7	228.7	258.8	382.0	382.0	382.0	382.0	382.0	382.0	382.0
Investment subsidy with net metering abolishment without compensation for excess electricity (€/year)	141.4	146.4	156.1	166.6	175.7	182.8	194.9	203.9	215.7	228.7	258.8	382.0	382.0	382.0	382.0	382.0	382.0	382.0

Table 35: Annual costs sensitivity analysis Western-oriented PV system

year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037
maintaining net metering (€/year)	59.4	61.5	65.6	68.4	70.6	71.9	75.0	76.9	79.8	82.9	85.5	85.5	85.5	85.5	85.5	85.5	85.5	85.5
Abolishment net metering with compensation for excess electricity (€/year)	59.4	61.5	65.6	73.1	80.3	86.7	95.6	103.2	112.5	137.6	179.9	297.6	297.6	297.6	297.6	297.6	297.6	297.6
Self-consumption ratio at the net meting abolishment	0.33	0.33	0.33	0.38	0.43	0.49	0.54	0.59	0.65	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68
Feed-in tariff (€/year)	131.0	143.8	162.2	171.2	185.1	196.3	212.5	232.7	248.2	266.0	283.5	285.9	288.2	290.6	292.9	295.3	297.6	297.6
net-billing (€/year)	166.2	172.0	183.5	191.4	197.6	201.1	209.9	215.2	223.2	232.0	239.0	239.0	239.0	239.0	239.0	239.0	239.0	239.0
Net metering abolishment without compensation for excess electricity (€/year)	59.4	61.5	65.6	73.1	80.3	86.7	95.6	103.2	112.5	143.7	198.3	354.6	354.6	354.6	354.6	354.6	354.6	354.6
Investment subsidy with net metering abolishment without compensation for excess electricity (€/year)	59.4	61.5	65.6	73.1	80.3	86.7	95.6	103.2	112.5	143.7	198.3	354.6	354.6	354.6	354.6	354.6	354.6	354.6

Table 36: Annual costs sensitivity analysis 80% demand

year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037
maintaining net metering (€/year)	-133.8	-138.5	-147.7	-154.1	-159.1	-161.9	-169.0	-173.3	-179.7	-186.8	-192.5	-192.5	-192.5	-192.5	-192.5	-192.5	-192.5	-192.5
Abolishment net metering with compensation for excess electricity (€/year)	-133.8	-138.5	-147.7	-149.9	-150.4	-137.7	-114.1	-86.5	-59.1	-29.0	5.5	110.9	110.9	110.9	110.9	110.9	110.9	110.9
Self-consumption ratio at the net meting abolishment	0.45	0.45	0.45	0.49	0.53	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55
Feed-in tariff (€/year)	-49.4	-37.4	-25.2	-23.0	-9.8	3.1	15.9	41.1	54.0	69.6	87.4	91.3	95.3	99.2	103.1	107.0	110.9	110.9
net-billing (€/year)	9.3	9.6	10.2	10.7	11.0	11.2	11.7	12.0	12.4	12.9	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3
Net metering abolishment without compensation for excess electricity (€/year)	-133.8	-138.5	-147.7	-149.9	-150.4	-133.7	-100.1	-62.1	-22.4	20.3	65.9	205.7	205.7	205.7	205.7	205.7	205.7	205.7
Investment subsidy with net metering abolishment without compensation for excess electricity (€/year)	-133.8	-138.5	-147.7	-149.9	-150.4	-133.7	-100.1	-62.1	-22.4	20.3	65.9	205.7	205.7	205.7	205.7	205.7	205.7	205.7

Table 37: Annual costs sensitivity analysis 120% demand

year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037
maintaining net metering (€/year)	103.0	106.6	113.7	118.6	122.4	124.6	130.1	133.4	138.3	143.8	148.1	148.1	148.1	148.1	148.1	148.1	148.1	148.1
Abolishment net metering with compensation for excess electricity (€/year)	103.0	106.6	113.7	123.9	133.3	141.2	153.2	163.0	175.1	188.4	234.3	366.7	366.7	366.7	366.7	366.7	366.7	366.7
Self-consumption ratio at the net meting abolishment	0.34	0.34	0.34	0.39	0.44	0.50	0.55	0.60	0.65	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71
Feed-in tariff (€/year)	179.9	194.3	216.0	227.3	243.0	255.1	273.7	295.4	313.0	333.4	352.8	355.1	357.5	359.8	362.1	364.4	366.8	366.8
net-billing (€/year)	214.7	222.2	237.0	247.3	255.3	259.8	271.2	278.1	288.3	299.7	308.8	308.8	308.8	308.8	308.8	308.8	308.8	308.8
Net metering abolishment without compensation for excess electricity (€/year)	103.0	106.6	113.7	123.9	133.3	141.2	153.2	163.0	175.1	188.4	247.2	423.0	423.0	423.0	423.0	423.0	423.0	423.0
Investment subsidy with net metering abolishment without compensation for excess electricity (€/year)	103.0	106.6	113.7	123.9	133.3	141.2	153.2	163.0	175.1	188.4	247.2	423.0	423.0	423.0	423.0	423.0	423.0	423.0

Table 38: Payback periods sensitivity analysis

		2020			2032		
	scenario	min	max	ref	min	max	ref
Discount rate 5% / 7% / 9%	1	6.7	7.6	7.1	3.2	3.4	3.3
	2	6.8	7.7	7.2	4.7	5.0	4.8
	3	8.2	9.8	8.9	4.6	5.0	4.8
	4	8.5	10.0	9.2	4.1	4.4	4.3
	5	6.8	7.7	7.2	5.3	5.8	5.5
	6	5.0	5.4	5.2	3.8	4.1	3.9
Investment subsidy 15% / 25% / 35%	1	7.1	7.1	7.1	3.3	3.3	3.3
	2	7.2	7.2	7.2	4.8	4.8	4.8
	3	8.9	8.9	8.9	4.8	4.8	4.8
	4	9.2	9.2	9.2	4.3	4.3	4.3
	5	7.2	7.2	7.2	5.5	5.5	5.5
	6	6.0	4.5	5.2	4.6	3.4	3.9
PV system costs min / normal /max	1	6.7	7.4	7.1	2.9	3.7	3.3
	2	6.8	7.5	7.2	4.2	5.4	4.8
	3	8.4	9.4	8.9	4.1	5.4	4.8
	4	8.7	9.6	9.2	3.7	4.8	4.3
	5	6.8	7.5	7.2	4.8	6.2	5.5
	6	4.9	5.4	5.2	3.4	4.4	3.9
PV BOS costs 30% / 40% / 50%	1	6.5	8.0	7.1	3.0	3.8	3.3
	2	6.5	8.2	7.2	4.3	5.6	4.8
	3	8.0	10.2	8.9	4.2	5.6	4.8
	4	8.3	10.4	9.2	3.8	4.9	4.3
	5	6.5	8.2	7.2	4.9	6.5	5.5
	6	4.7	5.9	5.2	3.5	4.6	3.9
Battery costs 75% / 100% / 125%	1	6.4	7.8	7.1	3.1	3.5	3.3
	2	6.5	7.9	7.2	4.6	5.1	4.8
	3	8.0	9.9	8.9	4.5	5.1	4.8
	4	8.3	10.1	9.2	4.0	4.5	4.3
	5	6.5	7.9	7.2	5.2	5.9	5.5
	6	4.7	5.7	5.2	3.7	4.2	3.9
Battery BOS costs 30% / 40% / 50%	1	6.7	7.7	7.1	3.2	3.5	3.3
	2	6.8	7.8	7.2	4.7	5.1	4.8
	3	8.4	9.7	8.9	4.6	5.0	4.8
	4	8.7	9.9	9.2	4.1	4.5	4.3
	5	6.8	7.8	7.2	5.3	5.8	5.5
	6	4.9	5.6	5.2	3.8	4.1	3.9

		2020			2032		
	scenario	min	max	ref	min	max	ref
Costs Energy management system 50% / 100% / 150%	1	6.7	7.5	7.1	3.1	3.6	3.3
	2	6.8	7.6	7.2	4.4	5.2	4.8
	3	8.4	9.4	8.9	4.4	5.2	4.8
	4	8.7	9.7	9.2	3.9	4.6	4.3
	5	6.8	7.6	7.2	5.1	6.0	5.5
	6	4.9	5.5	5.2	3.6	4.3	3.9
PV system size 2kW / 3 kW / 4 kW	1	8.8	6.5	7.1	3.9	3.1	3.3
	2	9.0	6.7	7.2	4.7	5.1	4.8
	3	10.2	8.3	8.9	4.7	5.0	4.8
	4	10.2	8.8	9.2	4.6	4.2	4.3
	5	9.0	6.8	7.2	5.0	6.5	5.5
	6	6.4	4.8	5.2	3.6	4.6	3.9
battery size 5 kWh / 7 kWh / 10 kWh	1	6.3	8.3	7.1	3.1	3.6	3.3
	2	6.4	8.4	7.2	4.7	5.2	4.8
	3	8.0	10.5	8.9	4.6	5.2	4.8
	4	8.3	10.6	9.2	4.1	4.7	4.3
	5	6.4	8.4	7.2	5.4	5.9	5.5
	6	4.7	6.0	5.2	3.9	4.2	3.9
PV orientation east / south / west	1	9.9	8.3	7.1	4.6	3.8	3.3
	2	10.1	8.2	7.2	6.0	5.4	4.8
	3	12.0	10.3	8.9	6.0	5.4	4.8
	4	12.0	10.5	9.2	5.6	4.9	4.3
	5	10.1	8.4	7.2	6.5	6.1	5.5
	6	7.2	6.0	5.2	4.6	4.3	3.9
demand 80% / 100% / 120%	1	7.3	7.1	7.1	3.4	3.3	3.3
	2	7.5	7.2	7.2	5.4	4.5	4.8
	3	9.4	8.5	8.9	5.3	4.4	4.8
	4	9.8	8.7	9.2	4.5	4.1	4.3
	5	7.5	7.2	7.2	6.6	4.9	5.5
	6	5.3	5.2	5.2	4.7	3.5	3.9