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The influence of political regulations and market design on energy storage systems

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Abstract

This study examines the profitability of residential storage systems in combination with photovoltaic systems for varying political scenarios and under different market conditions. By comparing the energy flows of a photovoltaic rooftop facility to an average German household's consumption pattern, this thesis calculates the additional self-consumption that can be achieved through a battery storage system and values the resulting savings via a net present value approach. The simulations of this study identify boundaries for specific political regulations and market environments that can enable battery storage systems to be operated in a profitably way. Based on the assumptions of this thesis, current market conditions do not allow battery storage installations to generate positive returns on investment. Nevertheless, there could be lucrative opportunities in battery storage systems for future electricity price movements and sinking system costs.

Keywords: Battery storage, Solar photovoltaic power, Distributed electricity, Energy policy, Market regulation

1. Why energy storage matters

The German energy transition, the so called "Energiewende", heralds a new era in the German power system. With the Japanese reactor meltdown in 2011, the German government passed a law to a shutdown of several nuclear reactors and a nuclear phase-out by 2022, clearing the way for more renewables in the grid.[1] The basis for this energy transition was already planned in the regulations for renewables 'Gesetz für den Vorrang Erneuerbarer Energien' (EEG) in 2000. A huge uptake of renewable energy facilities will substitute current power generation and change the market entirely. The newest targets of the German government include a renewable share of 40-45% of the total electricity generation until 2025 and a share of 55-60% until 2035.[2] The massive addition of renewable energy sources was politically incentivized by regulations to compensate the higher investment costs of renewable facilities.[3] Due to higher scaling and technical improvements, the prices of certain technologies dropped. This decrease of prices, for example for photovoltaic systems, led to a global growth of the corresponding industry.[4] With a share of already 33% of the total German electricity production in 2015, the energy mix of wind, hydro, solar and biomass plants are foreseen to reach the governmental targets.[5] This energy transformation accelerated the renewable energy development, making Germany one of the world leaders in clean power technologies.[6] Since renewable energy technologies are becoming more and more efficient and cheaper, they provide an alternative to diesel power and other fossil plants.[7] The biggest amount of the renewable energy production will come from variable sources like wind and solar power.[8] However, the substitution of dispatchable fossil-fuel plants with intermittent energy resources implies challenges for the grid and the general power supply.

Unlike fossil-fuel generation facilities, photovoltaic power plants and wind generators depend on the current weather conditions and time of day, leading to peak productions on very sunny or windy days while the facilities stand still during windless nights. With about 35 Gigawatts of fluctuating power generating facilities already in 2010, the renewables and their dependency on weather have a major impact on current market situations.[9] Since the demand does not necessarily follow this generation pattern, additional flexibility

[1] International Renewable Energy Agency (2015) p. 35.
[2] Bundesregierung (2017) Ein neues Zeitalter hat begonnen.
[3] Bundestag (2000) Gesetz für den Vorrang Erneuerbarer Energien (EEG 2000).
[4] Mundada et al. (2016) p. 693.
[5] Bundesregierung (2017) Ein neues Zeitalter hat begonnen.
[6] Borden and Schill (2013) p. 2.
[7] Diaf et al. (2008) p. 743.
[8] Borden and Schill (2013) p. 15.
[9] Ehlers (2011) pp. 58-59.

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measures have to assure a stable grid and power supply.[10]

Building more interconnected grids is a way to increase flexibility in the system. Most wind power plants are stationed in the north of Germany whereas photovoltaic technology is more present in the south.[11] If the transmission grid connecting the north and south has enough capacity, one-sided production can be distributed to the other part as well. A windy night in the north might produce enough wind energy to meet the demand of the southern German households as well. In contrast, a windless but sunny day might provide enough solar energy to compensate for the lack of wind if the transmission capacities are sufficient. However, a better interconnection fails when even in other regions or countries the weather conditions are simply not adequate for generation.[12] In addition to that, long transmission grids face high efficiency losses.[13]

Another way to smoothen the grid stress would be a more sophisticated demand management. Demand management measures are seen to have potential in certain circumstances but are not able to shift the demand entirely. By pricing the consumption at times of higher production with lower electricity retail rates, people could be incentivized to consume along with the production patterns of the renewable facilities. However, the daily and nightly patterns of consumption can not be changed entirely. People tend to use lights usually at night when no photovoltaic production is possible, and therefore demand management also fails.[14]

Energy storage systems can tackle these issues by storing excess energy and discharge it at times of higher demand.[15] Energy storage systems provide multiple application possibilities. By storing energy at times when the prices are low and selling the energy when prices are high, storage systems can serve as an arbitrage tool. Quick changes in the production pattern of the renewables due to sudden weather changes can be absorbed by energy storages. Peak production facilities might be obsolete if there is enough storage capacity that is ready to meet peaks in demand.[16] Thus, energy storage has a grid relieving effect by bridging the gaps between production and demand as well as shaving peaks of renewable energy generation.[17] [18]

Depending on where the energy storage system is stationed – behind the meter, the distribution or transmission level – different use cases are possible. According to Fitzgerald et al. (2015), energy storage would unfold its capabilities best, if it is located on site of the customer's residence.[19]

About 80% of the German photovoltaic power generation is placed decentralized in low voltage distribution grids.[20] All photovoltaic systems in a local grid usually produce at the same time due to their regional affiliation. Thus, when the sun stands high, the regional grid might be overburdened by a large number of grid feeding facilities within an area. The electrical equipment, like transformators and power cables, might be harmed by being exposed to too much excess power.[21] [22] To avoid overstressed regional grids, the energy storage systems might as well be decentralized along with the production facilities to handle the issue where it originates and to avoid transmission losses. Batteries are an effective, decentralized energy storage system and a way to increase the self-consumption of the otherwise grid-stressing photovoltaic power.[23]

Due to falling investment costs, battery storage systems become more and more attractive for households with a photovoltaic installation. By increasing the self-consumption rate, the battery lowers the electricity bill and can hedge against rising electricity prices.[24] Battery storage systems can deliver auxiliary services at low costs that may be necessary to integrate more renewable energy facilities in the grid.[25]

Governments, including the United States, Japan, China and Germany, have supported renewables and the implementation of battery storage systems.[26] However, only 3.5% of the declared photovoltaic systems in Germany were equipped with an energy storage system in 2015.[27] As Sioshansi et al. (2012) suggest market and policy issues, as well as incomplete valuation methods of potential benefits and risks, might be strong influencers on energy storage systems.[28] Current market conditions do not provide appropriate measures and incentives that would compensate the battery investment costs.[29] Substantial cost reductions are needed to incentivize storage installations.[30] Governmental interference is necessary to blaze the trail for further cost improvements and further deployment of storage systems.[31] But which political measurements are affecting the economic profitability of energy storage systems and how sensitive is the economic value of battery storage systems towards changes in the market design?

This thesis identifies influencing political measures and evaluates the sensitivity of storage systems to politically affected parameters by simulating different market conditions and regulations. I deal with the interference of taxes on electricity retail rates, feed-in tariffs as well as subsidy regula-

[10] Crossley (2014) pp. 2-3.
[11] Bundesverband der Energie- und Wasserwirtschaft e.V. (2015) pp. 25-26.
[12] Flatley et al. (2016) p. 6.
[13] Cortekar and Groth (2015) p. 14.
[14] Flatley et al. (2016) p. 6.
[15] Crossley (2014) pp. 2-3.
[16] Sioshansi et al. (2012) p. 48.
[17] Crossley (2014) p. 4.
[18] Flatley et al. (2016) p. 5.
[19] Fitzgerald et al. (2015) p. 6.
[20] Kairies et al. (2015c) p. 201.
[21] Kerber (2011) pp. 31-33.
[22] Farrell (2014) p. 3.
[23] Wirth (2017) p. 65.
[24] International Renewable Energy Agency (2015) p. 35.
[25] Fitzgerald et al. (2015) p. 12.
[26] International Renewable Energy Agency (2015) p. 39.
[27] Kairies et al. (2015a) p. 44.
[28] Sioshansi et al. (2012) p. 61.
[29] Truong et al. (2016) p. 1.
[30] De Sisternes et al. (2016) p. 30.
[31] Kempener and de Vivero (2015) p. 4.

tions and feed-in curtailments. My findings include sensitivity analyses showing potential financial opportunities in battery storage systems with minor changes in the electricity prices as well as opportunities if investment subsidies minimize the battery costs. Assuming total system costs of 600€ per Kilowatthour (kWh) of usable battery capacity, a subsidy of 90€ per kWh could be already sufficient to incentivize installations. An electricity price of 31.6 Cents/kWh would lead to a similar result. Feed-in tariffs would have to decrease by 2.70 Cents/kWh to place battery storage systems in a financially profitable position. Current regulations regarding feed-in limitations could not incentivize installations in battery storage systems if they are above 26% of the nominal photovoltaic power installed.

Chapter 2 identifies different political measurements that influence the financial attractiveness of battery storage systems. Chapter 3.1 demonstrates a method to assess the value of a combined photovoltaic and battery storage system with a net present value (NPV) approach. Furthermore, chapter 3.2 deduces the parameters and input data, which are used for the simulation. Chapter 4 presents and discusses the simulation results and shows sensitivity analyses with respect to different political measures. Chapter 5 gives a summary and presents open research questions.

2. Identification of influencing regulatory measures

The grid must be balanced in a way that the current supply equals the current demand at any point in time to prevent system failures.[32] While demand varies with the behavior of the consumers, the renewable production varies with weather conditions. The grid needs to compensate these fluctuations. Since residential energy storage systems can mellow down grid stressing peaks, incentivizing installations can be profitable for the public infrastructure.

There are many influencing parameters to drive or lessen the installations of battery systems. The decision to buy a battery storage system for a photovoltaic rooftop depends on financial aspects as well as the personal attitudes of the investor. In a survey in 2015, batteries were not recognized for being a good investment opportunity and maximizing returns but are known and seen as an option to be more independent from the energy supplier.[33] Sioshansi et al. (2012) point out, that next to manufacturing costs, roundtrip efficiency and technical characteristics, also non-technical aspects influence further implementations. Limited support of the technology, market design, regulatory treatment as well as issues with storage valuation could slow down a storage update.[34] Taylor et al. (2013) emphasize, that a financial lucrative investment, controllability, performance as well as aesthetics are important for a purchase. Without strong incentives, the installations of energy storage systems might be low.[35] According to Gährs et al. (2015), 69% of the surveyed photovoltaic owners are highly willing to invest in a battery storage system. Some owners base their decision on governmental subsidies.[36] This shows that the market for battery systems is driven by economic incentives and thus highly influenced by political decisions, market design and subsidies. Subsidies are therefore a method to stimulate the market of energy storage systems.[37]

Policy and market barriers, however, can prevent storage systems to overcome financial barriers.[38] If rates of remuneration for feed-in electricity are very high, self-consumption makes no sense for an economic perspective. Governments could indirectly catalyze storage installations by lowering feed-in tariffs and rising retail electricity prices. At higher electricity prices, photovoltaic owners will try to increase their self-consumption to reduce their electricity bill, especially when the compensation for selling electricity to the grid is not lucrative. "Market-pull"-incentives through price interference can boost a technology like storage systems.[39] In addition to that, limiting the feed-in energy and promoting a local use of electricity can influence the profitability of storages as well. Curtailments on energy fed to the grid force photovoltaic owners to increase their self-consumption to avoid energy losses. Therefore, curtailments can be an important governmental driver.[40] Another way of supporting technologies could be giving out securities, loan guarantees to investors so that the associated risks of new technologies are covered by governmental programs. Low interest rates on loans for new technology projects may enable an implementation which would otherwise not be possible to finance.[41]

The following chapters present four politically regulated ways to effect further installations of battery storage systems. Each subchapter presents the current state of political regulations or market parameter and lists results of previous studies in this field. Chapter 2.1 deals with investment subsidies as a political influencer on storage systems. The successive chapters handle the more indirect political measurements: Chapter 2.2 focusses on electricity costs. Chapter 2.3 covers feed-in tariffs and chapter 2.4 deals with feed-in curtailments.

2.1. Investment subsidies

If photovoltaic owners are asked for major reasons against storage systems, the high investment costs are ranked first.[42] High system costs are a major barrier for a broad market launch of small stationary battery systems.[43] Taylor et al. (2013) point out, that potential storage owners must face a lucrative, financial investment to effectively convince them to invest.[44] Thus, the probably most obvious way of boosting

[32]Flatley et al. (2016) p. 2.
[33]Gährs et al. (2015) p. 32.
[34]Sioshansi et al. (2012) p. 49.
[35]Taylor et al. (2013) p. 238.
[36]Gährs et al. (2015) p. 31.
[37]Kantor et al. (2015) p. 223.
[38]Kempener and de Vivero (2015) p. 21.
[39]Borden and Schill (2013) p. 3.
[40]International Renewable Energy Agency (2015) p. 40.
[41]Borden and Schill (2013) p. 11.
[42]Gährs et al. (2015) p. 33.
[43]Kairies et al. (2015c) p. 200.
[44]Taylor et al. (2013) p. 238.

households to implement battery storage systems is lowering the investment costs. The tipping point for a storage boom is expected within the next ten years as batteries become cheaper.[45] Susbidies for investment costs could move up this trend even before. Reducing the investment costs with governmental subsidy programs may stimulate energy storage systems.[46] The survey of Gährs et al. (2015) shows, that 66% of 552 questioned German private photovoltaic owners would invest, if there was a 25% reimbursement of the costs of the storage system.[47] In a study of Kantor et al. (2015) regarding used lithium-ion vehicle batteries being repurposed in household applications, the installation of the system would require a subsidy of $29/kWh capacity for the households to gain net-benefits.[48] Naumann et al. (2015) suggest that an additional subsidy of about 50€ /kWh would turn storages for photovoltaic households profitable. In addition to that, due to decreasing battery prices and improvements in battery performance, investment subsidies might be obsolete by 2018.[49] Nevertheless, at the time this thesis was written, incentive programs are still running and might still be important for the storage market in Germany.

The incentive program with the number 275 of the German ministry for economy and energy 'Bundesministerium für Wirtschaft und Energie (BMWi)' and the German public funding bank 'Kreditanstalt für Wiederaufbau' (KfW) stimulated the photovoltaic storage market since 1st May of 2013, leading batteries from a niche-product to the mass market.[50] The program with an initial fund of 25 million Euros promoted the technology and lowered the prices for household-systems by offering low interest loans with a maximum of 30% reimbursement of the eligible cost.[51] Qualification standards for the program assure, that the incentive leads to further development in the technology of the product and that the storage systems provide grid-relieving features and stability.[52] [53] The program is highly appreciated and seems to be a big success. Initially planned until the end of 2015, the program got extended in a second phase with additional 30 million Euros until the end of 2018 for a maximum reimbursement-rate of 25% per battery.[54] The reimbursement rate is now lowered every six months. Since the 1st January of 2017, the reimbursement is limited to 19% of the costs that are eligible for the grants.[55] Nevertheless around 50% of the storage owners did not use the subsidy.[56] Since only batteries for photovoltaic systems which are installed after 31/12/2012 are qualified for the program, most of the batteries are installed together with a new photovoltaic system. Only a relative small percentage of 17% are installed post hoc to an existing photovoltaic system.[57] The budget-limit for storage installations in 2016 was already reached in September.[58]

Why does it come that still only around 3.5-13% of photovoltaic systems are combined with a storage system?[59] At what investment costs do battery storage systems become economically feasible? What further price decreases or alternatively governmental subsidies are necessary to create a lucrative investment opportunity for photovoltaic owners? Simulations with different investment subsidies will answer this questions in chapter 4.1 by presenting the sensitivity analysis of battery price movements.

2.2. Electricity costs influenced by taxes, fees and levies

Battery storage systems with focus on increasing self-consumption can shift the supply of the electric power produced by the photovoltaic system to the demand of the household. By increasing the self-consumption, the household requires less energy purchases from the grid, and therefore saves money. These savings depend on the electricity price, which the household would have paid instead, and the remuneration rate, the household would have received, if it sold the produced energy to the grid instead of using it.[60] In this passage I want to focus on political tools to influence the electricity price or the "buying-price" from a household perspective. Assuming that the electricity retail rate is always higher than the rate of remuneration, self-consumption of produced energy must be favored over its selling to the grid. The higher the electricity price is, the more money can then be saved by using self-produced energy instead of purchasing the demanded power. Taxes, fees and levies with an influence on the electricity price have therefore also an indirect influence on the profitability of storage systems. Jülch et al. (2015) expect electricity prices to rise, so that battery storage systems in combination with a photovoltaic production facility will be profitable in less than ten years.[61] Hoppmann et al. (2014) assume scenarios with an increase in the electricity retail rate between 0-2% per year. They find optimal battery capacity sizes between 3-5 kWh, depending on the retail rate.[62] The study of Truong et al. (2016) for electricity prices of constant 28.72 Cents/kWh did result in a neutral return of investment of 0% for a Tesla battery model.[63]

In May 2016, one kWh of residential electrical power cost 28.73 Cents.[64] 54% of the electricity costs of an average German household in 2016 are caused by taxes. Only 21.4%

[45] AECOM (2015) p. 12.
[46] Kantor et al. (2015) p. 223.
[47] Gährs et al. (2015) pp. 30-31.
[48] Kantor et al. (2015) p. 222.
[49] Naumann et al. (2015) p. 45.
[50] Kairies et al. (2016a) p. 1.
[51] International Renewable Energy Agency (2015) p. 36.
[52] Kairies et al. (2015c) p. 201.
[53] Borden and Schill (2013) p. 22.
[54] Kairies et al. (2016b) p. 8.
[55] Kreditanstalt für Wiederaufbau (2017) Erneuerbare Energien – Speicher.
[56] Sterner et al. (2015) p. 24.
[57] Kairies et al. (2015a) p. 51.
[58] Enkhardt (2016) KfW verkündet vorläufigen Stopp der Photovoltaik-Speicherförderung bis Jahresende.
[59] Kairies et al. (2015a) p. 44.
[60] Truong et al. (2016) p. 8.
[61] Jülch et al. (2015) pp. 25-26.
[62] Hoppmann et al. (2014) p. 1111.
[63] Truong et al. (2016) p. 14.
[64] Bundesverband der Energie- und Wasserwirtschaft e.V. (2016b) Energiedaten.

are based on the actual electricity costs for production and sale. The remaining 24.6% of the electricity costs are caused by grid fees.[65] Those taxes can be divided into value added tax, concession levy, EEG reallocation charge, combined heat and power addition, §19 "StromNEV" reallocation charge, offshore liability charge and the electricity tax.[66]

The composition of costs since 1998 show that taxes and levies increased by 281%. The costs of producing energy in the power plants only grew about 1%, giving an indication how big the influence of taxes and levies on the electricity retail rate is in comparison to the costs of production.[67] The EEG reallocation charge is used to distribute the costs of the renewable energy funding and subsidies to the consumers.[68] Introduced as a way to finance the German "Energiewende", the charge has grown rapidly, leading to higher taxes on electricity and therefore higher total electricity retail rates for consumers.[69] The EEG reallocation charges, grown by nearly 600% since 2009, are the biggest public influencer on the electricity price.[70] The taxes on electricity prices, especially the EEG reallocation charge and the combined heat and power addition, are expected to further rise in the next few years, leading to higher electricity prices.[71] It is estimated that the EEG reallocation charge might find its peak 2023 with 7.6 Cents/kWh before going down again.[72] If those taxes are not charged on self-produced and self-consumed energy, self-consumption leads to lower tax payments. Thus, energy storage in form of batteries can take advantage of higher electricity prices.

Storage lacks an individual regulatory and formal definition next to consumption and production.[73] In the EEG regulatory it is handled as a consumer when energy is stored and as a producer when energy is released, which can cause situations where storage owners are forced to pay fees and taxes for storing energy.[74] Since 1st January 2015 generating systems - also when used for self-consumption purposes - underlie EEG reallocation charges whereas renewable energy plants are only obligated to 40% of the charges.[75] As soon as taxes are applied on self-consumed energy, battery storage systems become less attractive since the savings on the electricity bill are diminished by taxes that have to be paid anyway.[76] However, small residential photovoltaic systems being not bigger than 10 Kilowatt-peak (kWp) power, with a maximal yearly production of 10 Megawatt-hours (MWh), which fulfill certain requirements, are freed from EEG charges for 20 years.[77] In cases where the photovoltaic system and the battery storage have not more than 10 kWp power each and the limit of 10 MWh of generated electricity is not exceeded, the whole system is again freed from any EEG charges.[78] Therefore, 10 kWp marks a border as the maximum size of a photovoltaic system for households, with no EEG reallocation charges to be paid.

The value-added tax regulatories do also account for electricity generated by a photovoltaic system. If the photovoltaic system is installed as an investment opportunity to gain revenues, the value-added tax of the system's purchase gets refunded. On the other side, the household is then in the duty to pay taxes on the revenues of selling electricity to the grid and also on self-consumption, where a fictive net electricity price is used to determine the value-added tax.[79] If a household with a photovoltaic system is eligible to choose a so called "small-scale-business"-regularization, the system can be operated without value-added tax. Simplified said, only households with photovoltaic systems that generate less than 17500€ revenues per year are allowed to choose this regularization-method. The downside is that at the time of the purchase, no value-added tax of the investment is reimbursed. In return, selling power to the grid or self-consumption is also free of value-added tax.[80] In most cases, the "small-scale-business"-regularization should be applicable. Photovoltaic systems with battery storage for self-consumption are therefore usually free of value-added tax if this regulation is applied. A battery which is installed after the 04/08/2011 and takes on operation within the next 15 years is free of grid fees for 20 years. Electricity tax costs do not occur when the energy is produced by renewable production facilities.[81]

A combined photovoltaic and battery storage system, which is only used to increase self-consumption and does fulfill the bespoken size limits and the additional requirements, is free of electricity taxes, grid fees, value-added tax and EEG reallocation charges.[82] Assuming no taxes, fees and levies on self-consumption, every kWh of produced energy being consumed, reduces the electricity bill by the complete electricity price per kWh. Likely scenarios of rising electricity prices could make battery storage systems used for increasing self-consumption economically profitable. But which electricity price could now justify the high investment costs of a battery installation? How much would taxes have to rise to make battery storage financially attractive? The simulation results in 4.2 present answers with a sensitivity analysis regarding different electricity prices.

[65] Bundesverband der Energie- und Wasserwirtschaft e.V. (2016a) pp. 33-34.

[66] §19 of the "StromNEV" regulation distributes the costs of discounts for energy intensive industries towards all consumers.

[67] Bundesverband der Energie- und Wasserwirtschaft e.V. (2016a) p. 33.

[68] Bundesverband der Energie- und Wasserwirtschaft e.V. (2015) p. 9.

[69] Bundesverband der Energie- und Wasserwirtschaft e.V. (2016b) Energiedaten.

[70] Deutscher Industrie- und Handelskammertag (2016) p. 29.

[71] Bundesverband Energiespeicher e.V. (2016) p. 8.

[72] Deutscher Industrie- und Handelskammertag (2016) p. 31.

[73] Sterner et al. (2015) p. 25.

[74] Bundesverband Energiespeicher e.V. (2016) p. 7.

[75] Deutscher Industrie- und Handelskammertag (2015) pp. 4-5.

[76] Truong et al. (2016) p. 14.

[77] Deutscher Industrie- und Handelskammertag (2015) p. 6.

[78] Bundesverband Energiespeicher e.V. (2016) pp. 10-11.

[79] Kairies et al. (2016b) p. 70.

[80] Kairies et al. (2015a) p. 69.

[81] Sterner et al. (2015) p. 25.

[82] Borden and Schill (2013) p. 21.

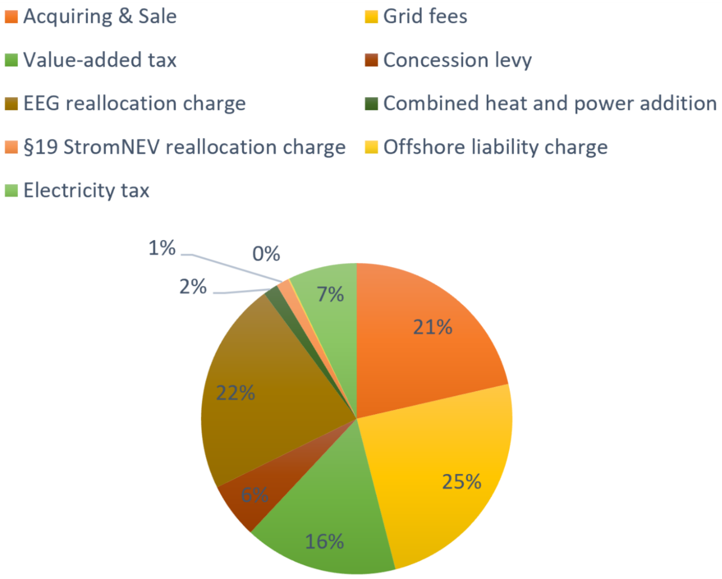


Figure 1: Composition of German electricity costs (in May 2016).
(Based on data of Bundesverband der Energie- und Wasserwirtschaft e.V. (2016b) Energiedaten.)

2.3. Feed-in tariffs

With the regulations of the EEG in 2000, the German government introduced a fixed remuneration rate during a period of 20 years after installation for renewable generation facilities. Per §3, §8 and §9 grid operators are under obligation to purchase all produced photovoltaic energy by a fixed price of initially 45.7 Cents/kWh with additional 11.7 Cents/kWh for systems smaller than 30 Kilowatts (kW) at that time.[83] The rates of remuneration are lowered with respect to the photovoltaic addition in the energy mix.[84] By giving this incentive of fixed compensations, the German government boosted the installation of photovoltaic systems. The fixed rate gives investment security and takes away the risks an energy investor would face otherwise.[85] On the other side, these fixed rates of remuneration have a reverse effect on storage applications.[86] The relatively high and fixed compensation of electricity fed into the grid prevents storage systems to become financially attractive. As long as the rate of remuneration was higher than the electricity retail rate, photovoltaic owners would have lost money if they used the power on their own instead of selling it. Thus, there was no incentive for self-consumption and therefore no financial reason for buying a battery storage system. Current rates of remuneration are lower than the initial compensation and lower than the latest electricity price.[87] [88] If there is lower compensation for selling energy to the grid, the reward of self-consumption rises. Thus, the lower the feed-in tariff, the higher the return of self-consumption. The selling price of produced energy is, therefore, a big driver of the profitability of battery storage systems.[89] Until 2011 the rates of remuneration were higher than the electricity retail rates at that time.[90] [91] But since the rates of remuneration are fixed for 20 years, older photovoltaic systems don't have any incentive to consume the energy rather than selling it to the grid as long as those contracts guarantee the fixed compensation. This will only change if either electricity retail rates rise dramatically or when the production facilities are fading out of the contracts after 20 years. Systems that have lower contracted rates of remuneration might have a theoretical incentive for self-consumption but it is questionable if this financial incentive is big enough to justify the expenses for a battery storage system. However, in 2020, the first installed photovoltaic systems will fall out of the fixed remuneration regulation and therefore face actual market prices. This huge drop in the compensation for the produced energy could actually be incentive enough to switch to self-consumption. Truong et al. (2016) simulated with a retrofitted storage system for a photovoltaic system installed in 2000 with an average remuneration rate of 3.21 Cents/kWh. The scenario for retrofitted installations in 2020 showed big financial potential.[92]

[83] Bundestag (2000) Gesetz für den Vorrang Erneuerbarer Energien (EEG 2000).
[84] Bundesnetzagentur für Elektrizität Gas Telekommunikation Post und Eisenbahnen (2017) Photovoltaikanlagen - Datenmeldungen und EEG-Vergütungssätze.
[85] Ehlers (2011) pp. 58-59.
[86] Kempener and de Vivero (2015) p. 32.
[87] Bundesnetzagentur für Elektrizität Gas Telekommunikation Post und Eisenbahnen (2017) Photovoltaikanlagen - Datenmeldungen und EEG-Vergütungssätze.
[88] Bundesverband der Energie- und Wasserwirtschaft e.V. (2016b) Energiedaten.
[89] Doetsch et al. (2014) pp. 163-164.
[90] Bundesverband der Energie- und Wasserwirtschaft e.V. (2015) p. 48.
[91] Bundesverband der Energie- und Wasserwirtschaft e.V. (2015) p. 63.
[92] Truong et al. (2016) pp. 8-12.

Fitzgerald et al. (2015) assume rates of remuneration around 3.5 Cents/kWh in a scenario in the United States, where net metering is fading out, finding positive returns if the battery storage system is additionally used for secondary services.[93] According to Doetsch et al. (2014) batteries would be profitable in scenarios without any feed-in compensation. In these scenarios self-consumption would be the only way to use produced energy. Under these circumstances, lithium-ion batteries could generate 58 € per kWh capacity on average a year. Lead-acid and redox-flow batteries would earn 40 € and 42 € per kWh capacity a year.[94] The situation for new combined installations together with a photovoltaic system is very different. Current feed-in tariffs are already below the average electricity retail rate for households and thus incentivizing self-consumption.[95] [96] But according to Borden and Schill (2013), the low rates of remuneration could not yet justify the high initial investment costs of a battery storage system in their study carried out in 2013.[97]

With the EEG 2017, the policy makers introduced a new system with investors bidding on feed-in tariffs for photovoltaic facilities of 750 kW or more. The bids with the lowest required feed-in tariffs are eligible for the governmental program. Smaller systems still have a fixed rate.[98]

With decreasing rates of remuneration, battery systems become more and more financially attractive. Is there a specific feed-in tariff where battery storages become profitable together with an installation of a new photovoltaic system? At which rates of remuneration would batteries provide investment opportunities? Chapter 4.3 simulates current and probable future feed-in tariffs and presents the corresponding sensitivity analysis towards the profitability of battery storage systems.

2.4. Feed-in curtailments

The power generation of photovoltaic systems depends on the current weather conditions and the daytime. The supply of these renewables can therefore be very unstable. Due to a high share of solar energy, a very sunny day could lead to a power surplus destabilizing the grid.[99] According to a survey of grid operators, asymmetric load and overload of grid-facilities are the main problems resulting out of the German energy transition.[100] Curtailments are a way to smoothen the feed-in power and assure a stable energy supply.[101] §6 in the German renewable energy regulations of 2012 forces photovoltaic owners with systems not bigger than 30 KW to either partly restrict their feed-in power to 70% of their nominal installed power or install remote controls for shutdowns. Photovoltaic systems above 30 kW must be equipped with technical gear to be controlled and regulated if the grid is overloaded.[102]

These curtailments should secure a stable grid by cutting off solar peaks that could otherwise stress the balance of supply and demand. For the owner of the photovoltaic system, these curtailments can cause financial losses since feed-in power above 70% is simply turned down and is not generating any returns. With a higher self-consumption of the produced energy, the owners can decrease their feed-in power and therefore avoid wasting energy.[103] A battery storage system can support the self-consumption. The subsidy of the "KfW"-bank for storage systems required the corresponding photovoltaic systems to decrease their feed-in power to 60%.[104] Short time after that, the regulation got more restrictive with curtailments above 50% of the nominal power.[105] These limits can enable the grid to deal with a higher share of solar and wind energy. With increasing curtailments, more and more renewables can be installed without overloading the capacities of the grid.[106] The charging strategy thereby is essential to the peak-shaving effect. If batteries are optimized for increasing self-consumption, they will already start storing excess energy in the morning. The simultaneous charging of thousands of batteries in a swarm finds a sudden end in the afternoon when the batteries reach their maximum state of charge. This can cause a massive peak, when excess energy is fed into the grid again.[107] If lots of batteries are charged with a market-driven pattern during low-price hours, this might also harm the stability of local grids.[108] For the financial aspects of a storage owner, this might not be of big importance. Nevertheless, the charging strategy can also have influence on the household's electricity bill by shifting the charging of the battery to peak production times. Weniger et al. (2016) show that a prediction based charging algorithm can decrease the curtailed power from 8% to 2% of the average yearly photovoltaic energy with a 50% curtailment regulatory. By charging with peak power, the battery can operate in a grid-stabilizing mode and enable a higher share of solar power in Germany's energy mix.[109] Since a prediction-based algorithm over multiple years would go beyond the scope of this thesis, I will restrict myself to a self-consumption optimizing algorithm. A previous study of Truong et al. (2016) shows, that a further limitation of feed-in power has noticeable, but small influence on the return of investment with negative effects for the combined photovoltaic and storage system.[110] Kairies et al. (2015b) recommend a dynamic curtailment by grid operators with limits between 40% and 60%

[93] Fitzgerald et al. (2015) pp. 32-34.
[94] Doetsch et al. (2014) pp. 163-164.
[95] Bundesverband der Energie- und Wasserwirtschaft e.V. (2015) p. 48.
[96] Bundesverband der Energie- und Wasserwirtschaft e.V. (2015) p. 63.
[97] Borden and Schill (2013) p. 21.
[98] Bundesministerium für Wirtschaft und Energie (2016) EEG 2017: Start in die nächste Phase der Energiewende.
[99] Weniger et al. (2016) p. 7.
[100] Sterner et al. (2015) p. 4.
[101] Kairies et al. (2015a) p. 13.
[102] Bundestag (2012) Gesetz für den Vorrang Erneuerbarer Energien (EEG 2012).
[103] Weniger et al. (2016) p. 7.
[104] Kairies et al. (2015a) p. 18.
[105] Kairies et al. (2016b) p. 20.
[106] Weniger et al. (2014a) p. 1.
[107] Sterner et al. (2015) p. 5.
[108] Kays et al. (2014) p. 1.
[109] Weniger et al. (2016) p. 3.
[110] Truong et al. (2016) pp. 11-12.

so that the curtailments can be adjusted to the current demand and supply.[111]

It is questionable if the curtailment regulations should only be addressed to systems with storage installations. As soon as newly installed photovoltaic systems would face lower curtailments even without a subsidized storage system, a battery could avoid big losses and offer a lucrative investment opportunity. If the 70% limitation for photovoltaic systems is lowered in the future, new questions will arise. Is there a specific curtailment limit where battery storage systems become profitable? Chapter 4.4 will present a sensitivity analysis regarding different feed-in limitations.

3. Simulation model

This thesis aims to determine political and market driven influencers on future battery storage installations by calculating their financial value towards the owner. The assumption that all independent variables can be changed in a continuous way, allows multiple options for optimization algorithms e.g. towards an optimal size of the battery system. I simulate a household using a photovoltaic system together with a battery storage system under various market conditions and regulations to determine for which environmental parameters batteries could provide a financial lucrative investment opportunity. The net present value of the combined photovoltaic and battery storage system serves as a reference value to compare different simulations and setups. However, there are multiple ways to operate a battery system. Frequency regulation or backup-power for blackouts are only two of many possible applications that would generate calculative or real revenue streams in a net present value calculation.[112] In this approach, the battery is solely used to increase the self-consumption of the produced photovoltaic power and, by this, reduce the electricity bill of the household.

As it is illustrated in Figure 2, the battery is plugged to the local home alternating current (AC) grid. The battery and the photovoltaic system store or produce the energy in direct current (DC). The inverters transform the energy to be used for the household. The photovoltaic system feeds the home and the battery with energy. In times where the photovoltaic system does not produce enough energy to meet the household‘s demand, the battery takes care of the load. In times where the battery power is not sufficient for the household‘s demand, additional energy can be purchased from the grid. Excess production which cannot be utilized neither within the household nor be stored in the battery at the time is fed into the grid, limited by the curtailment regulations as mentioned in chapter 2.4. Grid power is only used for additional demand in the household and is not allowed to be stored in the battery for later use, since these would cause complex issues regarding renewable and fossil electricity declarations that are not covered in this thesis. Stored energy is solely used to increase the self-consumption and is not used to fed the grid. Thus, the battery is only operated to reduce electricity costs. The reduction in electricity costs in the following years after installation must exceed the initial costs of the system to be economically reasonable.[113] The challenge is to find the battery size that maximizes the net present value. Too big batteries would lead to unnecessarily high investment costs if the capacity cannot be fully utilized. On the other hand, a battery system, which is too small, would not come up for the daily demand shifting. So, for every environmental setup, the algorithm simulates different battery sizes up to the point, where the highest net present value can be achieved and where no further financial improvements are possible by neither decreasing or increasing the battery size. Thus, the optimization with respect to the battery size reveals the environmental states, where battery systems would provide financial benefit to the owner, independently from the net present value of the photovoltaic system. If a stand-alone photovoltaic system without a battery would lead to a higher net present value than a combined system, the simulation algorithm identifies 0 kWh as the optimal battery size.

The following subchapters include a method to calculate the net present value for a combined photovoltaic and battery storage system and deliver values for the input parameters.

3.1. Net present value of a combined photovoltaic and storage system

The net present value serves as an economic performance indicator to evaluate, compare and rank different setups regarding the size of the battery system. The following section describes a way to calculate the net present value of a combined photovoltaic and battery system with a linearized approach. For the basic concept I use a similar approach to Glenk and Reichelstein (2017). I adjust the calculations by adding the battery system and further political and battery-specific technical parameters into the equations. The net present value of the combined system is determined by the present value of future after-tax cash flows subtracted by the system's price of the battery and the photovoltaic system.[114] The revenues and costs are assumed to occur at the end of a year.

$$NPV(k_{PV}, k_{bat}) = -(k_{PV} * SP_{PV} + k_{bat} * SP_{bat}) + \sum_{i=1}^{I} CFL_i * \frac{1}{(1+\gamma)^i} \tag{1}$$

k_{PV}: Size of photovoltaic system in kW
k_{bat}: Usable battery capacity in kWh
CFL_i: After tax cash flow of the system in year i
γ: Discount rate
SP_{PV}: Price of photovoltaic system per kW
SP_{bat}: Price of usable battery capacity per kWh

[111] Kairies et al. (2015c) pp. 4-5.
[112] Lazard (2015) p. 3.
[113] Naumann et al. (2015) p. 38.
[114] Glenk and Reichelstein (2017) p. 20.

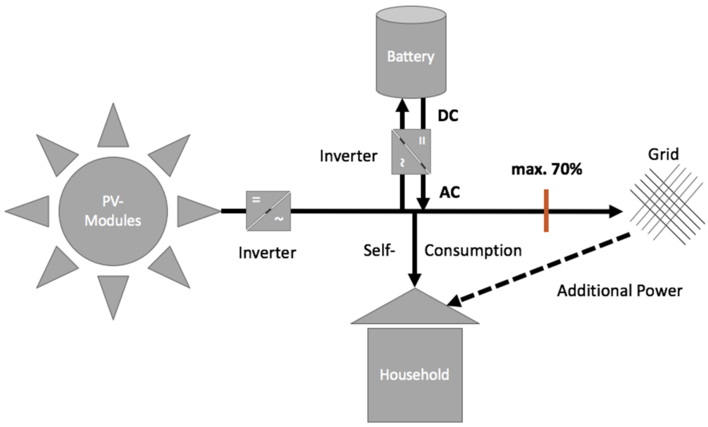


Figure 2: Energy scheme in the simulation.

The after-tax cash flow in year i is calculated by subtracting taxes towards each pre-tax cash-flow with their respective taxable income and the tax rate.[115]

$$CFL_i(k_{PV}, k_{bat}) = CFL_i^{PT}(k_{PV}, k_{bat}) - \alpha * I_i(k_{PV}, k_{bat}) \quad (2)$$

α: Income tax rate
$I_i(k_{PV}, k_{bat})$: The taxable income in year i
$CFL_i^{PT}(k_{PV}, k_{bat})$: Pre-tax cash flow in year i

The taxable income in year i is determined by the pre-tax cash flow minus the depreciation of the battery and photovoltaic system.[116]

$$I_i(k_{PV}, k_{bat}) = CFL_i^{PT}(k_{PV}, k_{bat}) - (k_{PV} * SP_{PV} + k_{bat} * SP_{bat}) * d_i \quad (3)$$

d_i: Allowed deprecation in year I in %

I calculate the pre-tax cash flow in year i as the contribution margin of the system subtracted with its operating costs in the respective year.[117]

$$CFL_i^{PT}(k_{PV}, k_{bat}) = CM_i(k_{PV}, k_{bat}) - (k_{PV} * F_{PV} + k_{bat} * F_{bat}) \quad (4)$$

$CM_i(k_{PV}, k_{bat})$: Contribution margin of the system in year i
F_{PV}: Fixed operating costs per kW of the installed photovoltaic system
F_{bat}: Fixed operating costs per kWh of the installed usable battery capacity

The photovoltaic production data offers information in a frequency of one hour throughout the year. With 365 days per year I consider m = 8.760 as the number of hourly timeframes iterated in the simulation per year.[118] The contribution margin of the system in year i is then given by:

$$CM_i(k_{PV}, k_{bat}) = \int_{t=0}^{m} CM(t|k_{PV}, k_{bat}, i)dt \quad (5)$$

t: Time hour
$CM(t|k_{PV}, k_{bat}, i)$: Optimized contribution margin

I define R_{Buy} as the electricity retail rate or the price for buying energy and $R(t)_{Sell}$ as the rate of remuneration or the price for selling produced energy to the grid at time t. For the revenue of the system I value self-consumed energy with the opportunity costs of alternatively buying it from the grid. Income taxes on returns for self-consumed energy in Germany are usually calculated by assuming a theoretical electricity price.[119] I do not distinguish between the returns of feed-in compensation and the returns of self-consumption, since taxation saving actions, which are individual to specific regions and persons, would distract from the core results. The taxes are calculated on the total return, where the self-consumed energy is valued with the full electricity price. Thus, with this conservative approach, the calculated taxes in the simulations could be higher than in real business cases.

If energy is stored in the battery for later consumption, the electricity is valued with $R(t)_{buy}$ at the time the electricity is used and consumed by the household. The algorithm does not allow storing purchased energy. Thus, the simulation theoretically holds for constant or time-invariant as well as dynamic or time-variant prices if following constraints are valid:

1. $\forall t : R(t)_{Buy} \geq R(t)_{Sell}$ and
2. $\forall t : min(R(t)_{Buy}) \geq max(R(t)_{Sell})$

[115] Glenk and Reichelstein (2017) p. 20.
[116] Glenk and Reichelstein (2017) p. 20.
[117] Glenk and Reichelstein (2017) p. 20.
[118] Glenk and Reichelstein (2017) p. 20.
[119] Bayerisches Landesamt für Steuern (2015) pp. 27-35.

The first restriction simply prevents arbitrage scenarios of endlessly buying and selling energy and assures that there is no point in time where selling produced energy and buying demanded energy is more lucrative than self-consumption. As obvious this might be from a market perspective, this constraint is not fully valid in the German market as I clarified in the previous chapters. Owners of photovoltaic systems usually have signed a price-binding contract, which guarantees them fixed and constant rates of remuneration for 20 years.[120] Due to high feed-in tariffs, energy might better be sold to the grid, even when it could be utilized in the household. The household's demand in this case is then fully satisfied by purchasing the energy from the grid. Simulations with a higher rate of remuneration than electricity retail rate would lead to an optimal battery size of 0 kWh.

In compensation systems where excess power can only be sold to the grid within certain power limits, the charging strategy of the battery can have influence on the profitability of the battery as well. The study of Weniger et al. (2016) with a prediction-based charging strategy in an environment with 50% feed-in curtailments calculates additional revenues of 30c€ per year for their setting by reducing the curtailed energy.[121] However, battery storage systems do not necessarily face these strict regulations as long as they don't use the subsidies of the "KfW"-bank program.[122]

This approach does not consider arbitrage or price-optimized strategies for movements in the spread between the selling and buying price of energy. The simulation assumes that there is no way of earning money by buying energy and selling it later. Hence, the second restriction prohibits scenarios where bought energy could be stored and kept as a speculative option for later selling. The charging-strategy does not consider optimizations for potential higher revenues due to price movements. In some scenarios, it could be economically reasonable to save stored energy and buy electricity from the market to meet the households demand, even if the demand could also be satisfied by the battery. If $R(t+n)_{Buy} > R(t)_{Buy}$, the consumption of stored energy at time t+n leads to higher revenues. If the price movement is substantial, the higher revenues could exceed potential losses of not utilizing the battery in t. The algorithm excludes these speculations. The restrictions towards $R(t)_{Buy}$ and $R(t)_{Sell}$ limit the battery operations to a simple charging strategy, excluding speculations on price movements that would justify additional charging, discharging or preventions of doing so besides of a simple greedy algorithm.

Due to the bespoken restrictions and assumptions, the net present value is maximized by maximizing self-consumption. Similar to the simulations of Truong et al. (2016), this leads to the simple strategy that the battery charges with excess energy as long as there is battery capacity to store it.[123] A higher battery capacity therefore leads to a higher rate of self-consumption.[124] At times where the energy consumption is higher than the production, the energy used is (as far as possible) taken out of the battery. With this approach, the battery usually starts charging in the morning when the photovoltaic production first exceeds the household's demand. On clear days, the battery is usually fully charged at noon and ready to discharge as soon as the sun goes down and the household's demand exceeds the produced photovoltaic power.[125]

To implement the strategy, the optimized contribution margin is then given by:

$$CM(t|k_{PV},k_{bat},i) = P_{SC}(t|k_{PV},k_{bat},i) * R(t)_{Buy} + P_{Grid}(t|k_{PV},k_{bat},i) * R(t)_{Sell} \tag{6}$$

$P_{SC}(t|k_{PV},k_{bat},i)$: Produced power which is consumed by the household in kWh
$P_{Grid}(t|k_{PV},k_{bat},i)$: Produced power which is sold to the grid in kWh
$R(t)_{Buy}$: Revenue of self-consumption / Price of buying energy in € per kWh at time t
$R(t)_{Sell}$: Revenue of feeding energy to the grid / Price of selling energy in € per kWh at time t

The self-consumed energy of the household is the minimum of the load demand of the household and the available energy of the photovoltaic system plus available energy of the battery at time t. Even when the battery is fully charged, the available energy which can be discharged for self-consumption is limited by the maximum discharging power and reduced by efficiency losses of the inverter and the battery:

$$P_{SC}(t|k_{PV},k_{bat},i) = Min[Prod(t|k_{PV},i) + Min[SOC(t-1,i); d_{bat}] * Eff_{bat}; L(t)] \tag{7}$$

$Prod(t|k_{PV},i)$: Production profile / energy produced by the photovoltaic system in kWh
$SOC(t-1,i)$: State of charge / energy available from the battery at time t due to preceding charging in the periods before in kWh
d_{bat}: Maximum capacity that can be discharged within a period t in kWh
$L(t)$: Load profile / energy consumed by the household at time t in kWh
Eff_{bat}: Efficiency of the battery and the corresponding inverter

The production function of the photovoltaic system is given by the current capacity factor of the photovoltaic

[120] Bundestag (2000) Gesetz für den Vorrang Erneuerbarer Energien (EEG 2000).
[121] Weniger et al. (2016) pp. 12-13.
[122] Kairies et al. (2016b) p. 102.
[123] Truong et al. (2016) p. 3.
[124] Naumann et al. (2015) p. 40.
[125] Weniger et al. (2014a) p. 1.

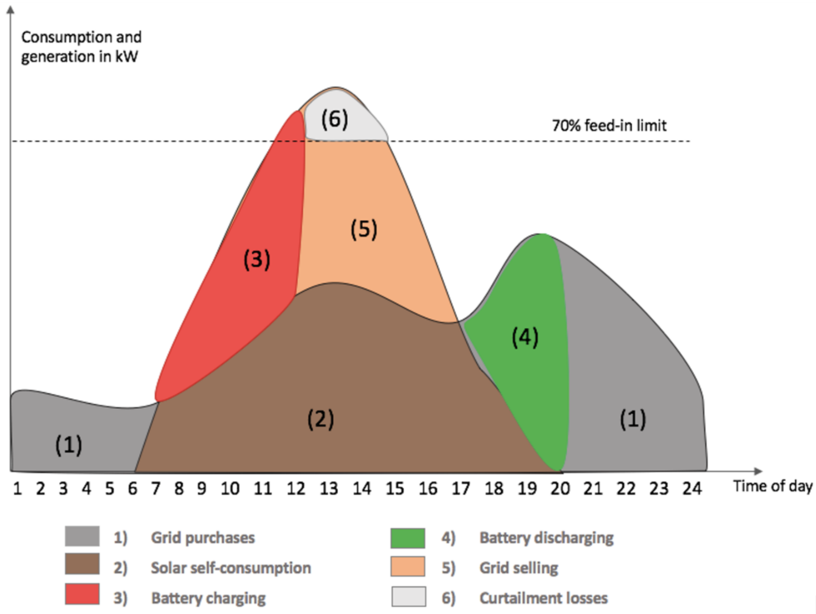


Figure 3: Model for daily pattern of photovoltaic generation and consumption.
(Partly based on similar model of Fitzgerald et al. (2015) pp. 32-33.)

rooftop multiplied by the size of the facility and a factor for losses due to aging of the panels. The production of the system is then given by:

$$Prod(t|k_{PV}, i) = CF(t) * k_{PV} * (1 - x * (i - 1 + \frac{t}{8760})) \quad (8)$$

$CF(t)$: Capacity factor of the photovoltaic system per kW installed for the period t in kWh
x: Factor for capacity losses of the photovoltaic system

The state of charge of the battery system is calculated by taking the state of charge of the previous period and adding charged energy or subtracting discharged energy. The charged or discharged energy is again limited by the maximum charging or discharging power and diminished by efficiency losses of the inverter and battery. The maximal usable capacity of the battery as well as the minimal state of charge limit the energy, which can be stored or taken out of the battery. Battery aging and cyclic fading decreases the maximum capacity.[126] [127] Within this simulations, a battery can never have a state of charge higher than its current usable capacity. On the other hand, a battery can never discharge more energy than it is currently storing. Thus, the battery has a minimum state of charge of 0 kWh in usable capacity.

$$\begin{aligned} SOC(t,i) = & Max[Min[SOC(t-1) \\ & + Max[EE[(t|k_{PV}, i); c_{bat}]; -d_{bat}] \\ & * Eff_{bat}; k_{bat} * (1-\varphi)^{i-1+\frac{t}{8760}}]; 0] \end{aligned} \quad (9)$$

$EE(t|k_{PV}, i)$: Surplus energy or energy deficiency of the household at time t in kWh
c_{bat}: Maximum capacity which can be charged within a period t in kWh
φ: Capacity fading of the battery

The excess energy, if there is an overproduction or deficiency energy at times of higher consumption, is determined simply by:

$$EE(t|k_{PV}, i) = Prod(t|k_{PV}, i) - L(t) \quad (10)$$

The remaining energy which can be sold to the grid is limited by politically determined curtailments.[128] The feed-in power is then given by:

$$\begin{aligned} & P_{Grid}(t|k_{PV}, k_{bat}, i) = \\ & min[Prod(t|k_{PV}, i) - P_{SC}(t|k_{PV}, k_{bat}, i) \\ & -(SOC(t) - SOC(t-1)); k_{PV} * \epsilon] \end{aligned} \quad (11)$$

ϵ: Feed-in limitation

3.2. Input parameters for the simulations

To simulate the energy flows between a photovoltaic facility, the household and a battery, load and production profiles are needed. I compare a photovoltaic production profile located in Munich with a load profile of a representative German household to determine at which times energy can be

[126] Sankarasubramanian and Krishnamurthy (2012) pp. 250-251.
[127] Ecker et al. (2014) p. 842.
[128] Bundestag (2012) Gesetz für den Vorrang Erneuerbarer Energien (EEG 2012).

sent to the battery and when stored energy can be utilized within the household. Battery characteristics, like the maximum capacity or the charging speed, influence the model and are therefore critical values for the simulation. Basic parameters like the project lifetime or interest rates are necessary to evaluate the financial impact of different measures. The following chapters determine these basic parameters in chapter 3.2.1 and give an introduction into the load and production profile in the chapter 3.2.2 and chapter 3.2.3. In addition to that, chapter 3.2.4 declares the basic battery characteristics and input parameters used for the simulations.

3.3. Project lifetime, discount factor and taxes

The depreciation period of photovoltaic systems in Germany is 20 years.[129] Batteries installed after 04/08/11 are also free of grid-fees for 20 years.[130] To avoid complicated tax changes within the simulation and to be comparable with previous studies, the simulation stops after 20 years, too. I consider a total project lifetime of 20 years. The end of life of batteries for automotive applications is usually reached, when the discharge capacity falls below 80% of the initial capacity.[131] However, this limit does not exclude repurposing the batteries in a residential stationary environment as presented in the study of Kantor et al. (2015). The following graph shows the expected lifetime for different battery systems of a data collection of the Technical University of Munich. Thus, most battery systems already have a lifetime equal to the considered project lifetime.

In this simulation, I do not consider a replacement of the battery storage system. Even after the capacity reached the limit of 80%, these batteries are usually still working beyond this limit.[132] Thus, the depreciation period of the battery system is analogously to Truong et al. (2016) also set to 20 years.[133] A previous study assumes a lifetime of 18 years for the inverter.[134] For reasons of simplicity, I assume a lifetime of 20 years for the inverter as well. To limit complexity, the simulation does not consider replacements for the inverter. I depreciate the combined photovoltaic and battery storage system linearly over 20 years. Lorenz and Schröder (2014) as well as Jülch et al. (2015) consider a discount rate of 3.5%.[135] [136] The studies of Zerrahn and Schill (2015) and Naumann et al. (2015) choose a discount rate of 4%. [137] [138] I will also simulate with a discount rate of 4%.

Per §6 of the EEG regulations of 2012, photovoltaic owners with systems not bigger than 30 KW must usually partly restrict their feed-in power to 70% of their nominal installed power.[139] This curtailment value is set as a standard regulatory measure for the following simulations.

Profits generated by the facility must be taxed with the owner's income tax rate. This includes virtual profits on self-consumed energy.[140] The income tax rate varies widely depending on the income structure of the photovoltaic owner and can therefore not be determined to match every investors' situation. Comello and Reichelstein (2017) calculate with a corporate tax rate of 30%.[141] I also assume a tax rate of 30%, as it would be accounted in Germany for an unmarried person with a yearly taxable income of 65.000 € .[142]

3.3.1. Load profile of the household

According to an analysis of different datasets in 2011 by Bost et al. (2011), a German single-person-household consumes approximately 1.7 MWh, two persons need 3 MWh, three persons consume 3.9 MWh and four persons would have a demand of 4.5 MWh on average per year.[143] Naumann et al. (2015) use 4.4 MWh as an average consumption for a household with four persons.[144] Truong et al. (2016) simulate with a 4.5 MWh yearly load for an average household and consider 7 MWh for a large household in a second simulation.[145] The installation statistics show, that households with an installed battery have a consumption nearly twice times higher than the average household, leading to the conclusion, that households with higher consumption are more likely to invest into a battery storage system.[146] Households with a higher consumption could make a more frequent and more intense use of a storage system. A higher utilization of the battery system can gain more savings and the system will pay off earlier.[147]

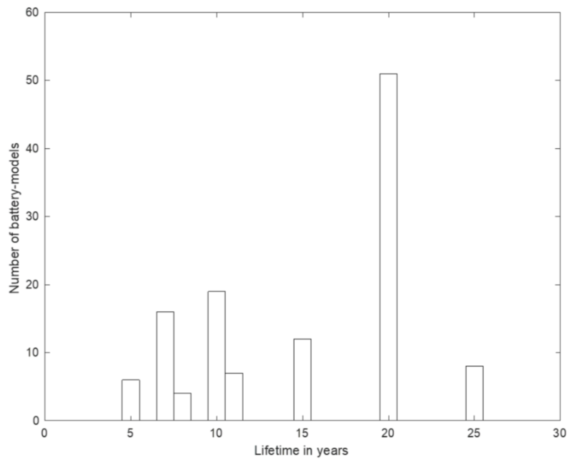
I use the dataset of the "HTW Berlin – University of Applied Science", which published representative load profiles in 2015.[148] The load profiles are based on a dataset of 74 German single family households in 2010 with a frequency of one second.[149] The dataset comes in separated files for idle and effective power in three phases and had to be prepared for the simulation. I sum up all effective power phases and aggregate the data to 8670 hourly loads for each household to have the same periodical time-frames as I have for the photovoltaic production data I will describe in the following chapter. The load profiles of the underlying dataset vary between 1.4 and 8.6 MWh per year with a mean of 4.7 MWh.[150]

[129] Bundesministerium der Finanzen (2000) AfA-Tabelle für die allgemein verwendbaren Anlagegüter (AfA-Tabelle "AV").
[130] Sterner et al. (2015) p. 25.
[131] Schmidt et al. (2015) p. 1231.
[132] Kantor et al. (2015) p. 222.
[133] Truong et al. (2016) p. 5.
[134] Lorenz and Schröder (2014) p. 8.
[135] Lorenz and Schröder (2014) p. 14.
[136] Jülch et al. (2015) p. 21.
[137] Zerrahn and Schill (2015) p. 13.
[138] Naumann et al. (2015) p. 42.
[139] Bundestag (2012) Gesetz für den Vorrang Erneuerbarer Energien (EEG 2012).
[140] Bayerisches Landesamt für Steuern (2015) pp. 27-35.
[141] Comello and Reichelstein (2017) p. 6.
[142] Bundeszentralamt für Steuern (2016) p. 1.
[143] Bost et al. (2011) p. 28.
[144] Naumann et al. (2015) p. 39.
[145] Truong et al. (2016) p. 2.
[146] Kairies et al. (2015a) p. 62.
[147] Kantor et al. (2015) p. 231.
[148] Berlin (2015) Repräsentative elektrische Lastprofile für Einfamilienhäuser in Deutschland auf 1-sekündiger Datenbasis.
[149] Tjaden et al. (2015) p. 2.
[150] Tjaden et al. (2015) p. 3.

Table 1: Overview of input parameter values.

(a) Marked values are not constant over all simulations and may vary for specific scenarios.

Parameter	Description	Value	Unit
d_i	Allowed deprecation in year I in %	5	%
ϕ	Capacity fading of the battery	1.58	%
γ	Discount rate	4	%
Eff_{bat}	Single-sided efficiency of the battery and the corresponding inverter	92.6	%
x	Factor for capacity losses of the photovoltaic system	0.7	%
ϵ	Feed-in limitation	70 (a)	%
F_{bat}	Fixed operating costs of the installed battery	0	€ /kWh
F_{PV}	Fixed operating costs of the installed photovoltaic system	19.05	€ /kW
α	Income tax rate	30	%
c_{bat}	Maximum capacity which can be charged within a period t	0.5	kWh/kWh capacity
d_{bat}	Maximum capacity which can be discharged within a period t	0.5	kWh/kWh capacity
SP_{PV}	Price of PV-system per kW	1270	€ /kW
SP_{bat}	Price of usable battery capacity	600 (a)	€ /kWh
$R(t)_{Sell}$	Revenue of feeding energy to the grid / Price of selling energy at time t	0.1230 (a)	€ /kWh
$R(t)_{Buy}$	Revenue of self-consumption / Price of buying energy at time t	0.2872 (a)	€ /kWh
k_{PV}	Size of photovoltaic system	5.5	kW



Mean	Median	Maximum	Minimum	StdDeviation
14.97	15.00	25.00	5.00	6.06

Figure 4: Lifetime of battery systems.
Based on analysis of Technical University of Munich (2016) Dataset market overview battery storage systems.

Since the electricity profile can have major impact on the self-consumption within the simulation, the profile data should be chosen in a way that it does reflect most households. Households with very specific consumption patterns could distract from the core findings of this thesis. Thus, I take the average of the 74 households' hourly load profiles within the simulations. The simulations are only run on this averaged household's profile-data containing 8670 hourly consumption data values. Since this profile is based on multiple households, the pattern might be more smooth and balanced than an actual household's pattern. Some households might have nearly no consumption at times when the house residents are not at home, but since other households do consume energy within this time, the averaged profile will also show some consumption. Strong peaks in single households will not have that large influence on the simulation, since the other 73 households might have consumed energy as usual. Nevertheless, the averaged data profile is particularly suitable to serve as a general pattern that most households share.

The household consumes a total of 4685.07 kWh over the year. Similar to the data of Kairies et al. (2015a), there is a visible correlation between the season and the consumption of the household. The summer months could require a lower

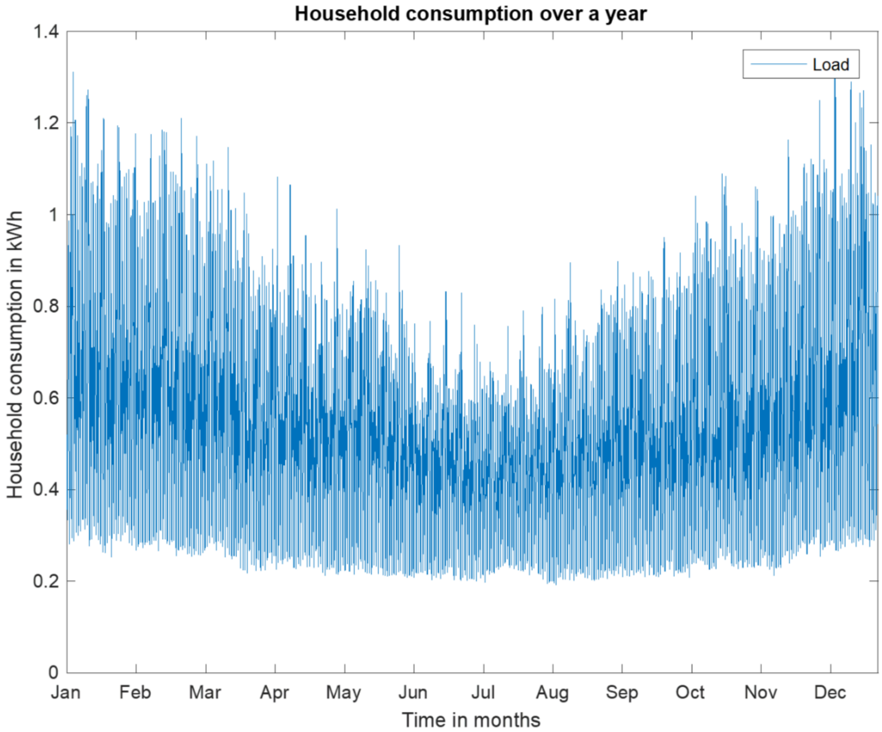


Figure 5: Load profile of an average household in hourly steps over a year.
(Based on analysis of data from Berlin (2015).)

energy consumption due to longer and warmer days.[151] The white zone below the blue line is visualizing the base load of the household that is needed at any time, since the graph does not reach these low areas. Depending on the current season, the base-load is slightly above 0.2 kWh per hour for the summer months and at around 0.3 kWh per hour in the winter. In addition to the base load and a trend towards higher consumption in the winter months, the hourly data can reveal further consumption patterns. I divide the dataset into a "warm" and a "cold" half, whereas the "warm" half covers the summer months from April to September, and the "cold" half consists of the profile-data from October until March. The grouping of the dataset by the time of day, allows a closer look to the actual pattern of the household's demand.

The household shows local maxima at midday and at the evening around 8pm. The consumption drops during night and slightly at the afternoon. The pattern in the winter months is mostly parallel to the summer pattern whereas the winter shows a way higher amplitude between night and day demand. The demand in the winter season peaks at around 7 pm with 1 kWh per hour and a following drop below 0.3 kWh per hour at night.

3.3.2. Photovoltaic system

The simulation requires the capacity factor of a photovoltaic system over a year. The horizontal solar irradiation, the outside air temperature, solar cell temperature and material, azimuth or orientation and tilt angle as well as other performance characteristics of the photovoltaic system have an impact on the energy generation.[152] [153] The website "Renewables.ninja" offers hourly estimated data for wind and photovoltaic systems of the year 2014 based on weather data and satellite observations.[154] [155] As location for the photovoltaic system rooftop I choose Munich with a latitude of 48.13 and longitude of 11.57. The "CM-SAF SARAH"-dataset is chosen as it is said to have higher data quality for Europe.[156] The capacity factor can be generated by choosing one kW as the photovoltaic size. The system is oriented southwards with a 35°tilt. The orientation is chosen to maximize the solar radiation, but not necessarily to optimize self-consumption. The orientation of the facility determines at what time of the day electricity will usually be produced and be available for consumption.[157] Depending on the household's load demand, electricity in the evening or in the morning might be more profitable for self-consumption than a huge production during midday. To maximize self-consumption independently from a battery storage system, the photovoltaic system should be aligned in a way, that the production occurs at the same time as the household's consumption and that the size

[151] Kairies et al. (2015a) p. 61.

[152] Hoppmann et al. (2014) pp. 1105-1106.
[153] Diaf et al. (2008) p. 745.
[154] Pfenninger and Staffell (2016) pp. 1262-1263.
[155] Staffell and Pfenninger (2016) pp. 1237-1238.
[156] Renewables.ninja (2016) Photovoltaic dataset.
[157] Weniger et al. (2014b) p. 82.

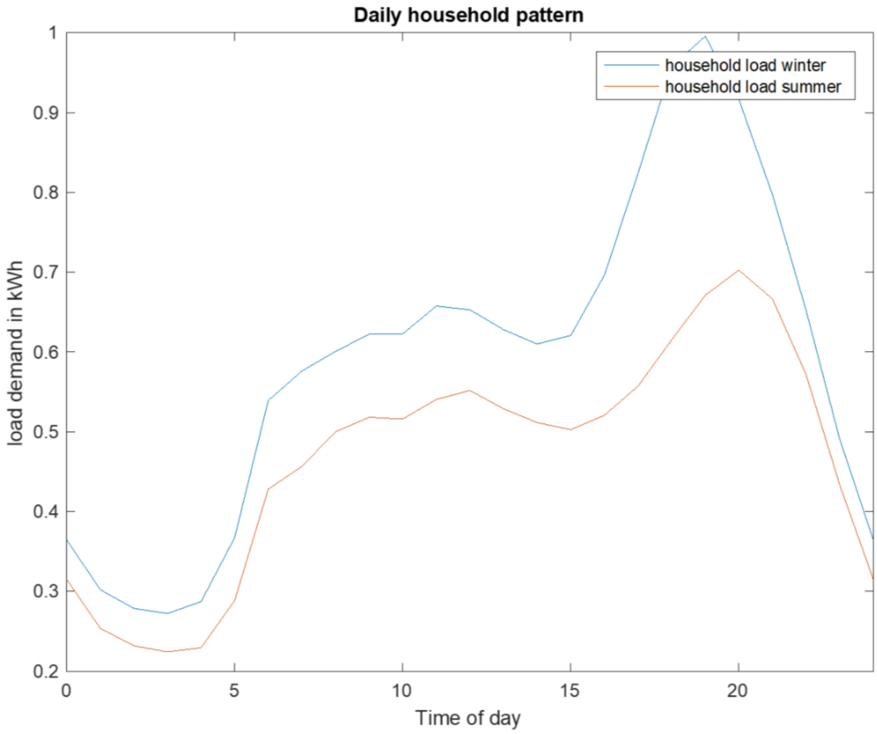


Figure 6: Daily pattern of the household consumption in winter and summer
(Based on analysis of data from Berlin (2015).)

of the system fits the load demand.

Hoppmann et al. (2014) assumed 15% losses in the photovoltaic module electronics generating about 981 kWh/kWp.[158] I use the default value of 10% for system losses as suggested by "Renewables.ninja" leading to an annual production of 1148 kWh/kWp.[159] The estimated production seems to be quite high, but due to ongoing research and development of photovoltaic technology, the facilities have not stopped improving.[160] Newly planned facilities would reach yearly performance ratios of 80% up to 90%.[161] To analyze the capacity degradation by aging, I look at multiple randomly chosen photovoltaic panel data sheets. Specifications of different producers give warranties for 90% of the initial capacity for 10 years and a minimum of 80% remaining capacity after 25 years or promise a maximum linear performance decrease of 0.7% per year.[162] [163] [164] Thus, for the capacity factor of the photovoltaic system in my simulation I assume a continuous yearly linear decrease of 0.7% of the initial production.

To determine the size of the photovoltaic system, multiple aspects must be considered. Systems above 10 kWp are excluded, since EEG-reallocations would otherwise have to be billed against the storage owner.[165] Weniger et al. (2014b) find, that depending on the consumption behavior, a self-sufficiency of 30% can be reached by installing one kWp photovoltaic facility per MWh of yearly household's load demand. With oversized photovoltaic systems, the self-sufficiency-rate stagnates since additional surplus can not be consumed at the time when the demand is already satisfied.[166] Looking at the previously bespoken average household data, a system of 4.7 kWp should be a good choice in terms of self-consumption. Nevertheless, many photovoltaic systems might initially not be aiming on increasing self-consumption but focus on maximizing overall production. High fixed compensation at the beginning of the governmental subsidy program might have led multiple households to invest in photovoltaic systems that might be oversized in terms of self-sufficiency but maximize total production for a given rooftop-area. In times where the compensation for feed-in power was higher than the actual electricity price, facilities maximized return by generating as much feed-in power as possible. So, the actual installed photovoltaic sizes might be way bigger than necessary. Thus, I analyze the data of the German grid operators regarding the

[158] Hoppmann et al. (2014) pp. 1105-1106.
[159] Renewables.ninja (2016).
[160] Kairies et al. (2015a) p. 9.
[161] Wirth (2017) p. 74.
[162] SolarWorld AG (2013) Sunmodule Plus SW 265 – 280 mono Product description.
[163] LG Electronics Deutschland GmbH (2015) LG Solarmodule MonoX Product description.
[164] Luxor Solar GmbH (2015) Luxor ECO LINE P60/240 – 260W Product description.

[165] Deutscher Industrie- und Handelskammertag (2015) p. 6.
[166] Weniger et al. (2014b) p. 82.

installed photovoltaic systems.[167] By excluding facilities bigger than 10kW, a system has on average a capacity of 5.95 kW. The analysis contains 589070 reported photovoltaic systems not bigger than 10 kW.

Naumann et al. (2015) follow the suggestions of Weniger et al. (2014b) for an economical ideal size with 4.4 kWp according to their load demand profile.[168] Truong et al. (2016) use with 5 kWp for an annual load of 4.5 MWh and 8 kWp for 7 MWh annual load slightly bigger photovoltaic systems.[169] Kairies et al. (2016b) assume an average photovoltaic system size of 8.1 kWp.[170] Jülch et al. (2015) suggest a self-consumption of 30% with a 5 kWp photovoltaic system in a German household with 4.5 MWh yearly demand.[171] I choose 5.5 kWp as the photovoltaic system size for my simulation, compromising between the recommended size for newly built systems and the actual average installation size.

The total production of the facility with 5.5 kWp system size over the whole year equals 6313.83 kWh. As the photovoltaic profile reveals, the generation facility produces peaks independent from the season. The difference in the summer and winter pattern becomes visible, when the data is grouped to hourly time frames separated by winter and summer months. The production in the winter starts later, ends earlier and is less intensive. Thus, the production pattern behaves contrary to the consumption pattern of the household. In months with higher consumption, the photovoltaic production is limited to a few hours of sunlight. In months with lower consumption, the photovoltaic production is very high. Therefore, the battery will have two different phases of workloads as well.

The prices of photovoltaic systems vary widely depending on material, country produced, manufacturer and further factors. Mundada et al. (2016) find systems between \$0.50/W to \$4.00/W.[172] According to Kairies et al. (2015a), the investment costs of photovoltaic systems are shrinking on average by 13% each year. In the mid of 2015, a price of 1500€ /kWp was on average considered for an investment.[173] In the report of the Fraunhofer Institute 2017, the prices already decreased to 1270€ /kWp.[174] For the simulation, I assume this price of 1270€ /kWp.

In addition to the initial investment, yearly maintenance and operation costs might arise. Diaf et al. (2008) calculate 1% of the investment costs of photovoltaic systems and inverter for maintenance.[175] For the operation costs I go along with the study of Weniger et al. (2014b) and assume 1.5% of the respective investment costs as annual operation and maintenance costs.[176] Since the investment costs are set to 1270€ /kWp the fixed annual operational costs will be 19.05€ /kWp.

3.3.3. Battery system

In addition to the photovoltaic production and the load profile, the battery characteristics are very important for a simulation to be diagnostically conclusive. The used technology as well as efficiency losses, charge rates and aging behavior influence the power flow tremendously. The cost of the battery system is vital for the NPV calculation. Thus, these parameters must be determined as accurately as possible.

I narrow the simulation to AC-coupled lithium-ion systems. According to Kairies et al. (2016b), AC-coupled systems are with 57% in the German market slightly in the majority of the systems installed. AC-coupled systems would be very flexible to be added into a house-grid, especially if they are retrofitted to already installed photovoltaic systems. DC-coupled systems on the other hand would require modifications of the already installed PV-electronics.[177] The storage-technologies for household-applications available on the market are mainly based on lead-acid or lithium-ion. High energy and power densities made lithium-ion batteries the dominant rechargeable system for mobile devices.[178] But the technology also started its triumph in stationary storage applications as the fastest growing storage technology.[179] Already in 2012, this technology showed big potential for future applications in small and large scales.[180] For stationary applications, lead-acid batteries tended to be cheaper per usable kWh of capacity, but in the last years, the price of lithium-ion systems decreased rapidly. Whereas Hoppmann et al. (2014) noted, that lithium-ion systems with a price 3.5 times as expensive as lead-acid models, might be too expensive to be competitive in the market, already a few years later the situation dramatically changed.[181] Lithium-ion systems convince with long lifetime and efficiency and are now affordable. In the first quarter of 2015, about 70% of the new battery installations in Germany were based on lithium-ion technology.[182] In the last quarter year of 2015, lithium-ion batteries had a share of over 90% in new installations in the German market.[183] On average, the lithium-ion battery installations in German households have 5.55 kWh of usable capacity.[184]

To determine suitable input parameter values for the battery characteristics, I mainly use previous literature to verify my parameters and to be comparable to other studies.

[167] Netztransparenz.de (2016) EEG-Anlagenstammdaten Gesamtdeutschland zur Jahresabrechnung 2015.
[168] Naumann et al. (2015) p. 39.
[169] Truong et al. (2016) p. 2.
[170] Kairies et al. (2016b) p. 69.
[171] Jülch et al. (2015) p. 20.
[172] Mundada et al. (2016) p. 694.
[173] Kairies et al. (2015a) p. 9.
[174] Wirth (2017) pp. 8-9.
[175] Diaf et al. (2008) p. 749.
[176] Weniger et al. (2014b) p. 85.
[177] Kairies et al. (2016b) pp. 52-53.
[178] Kassem et al. (2012) p. 296.
[179] Akhil et al. (2013) p. 96.
[180] Simbolotti and Kempener (2012) p. 14.
[181] Hoppmann et al. (2014) pp. 1105-1106.
[182] Kairies et al. (2015a) p. 50.
[183] Kairies et al. (2016b) p. 52.
[184] Kairies et al. (2015a) p. 51.

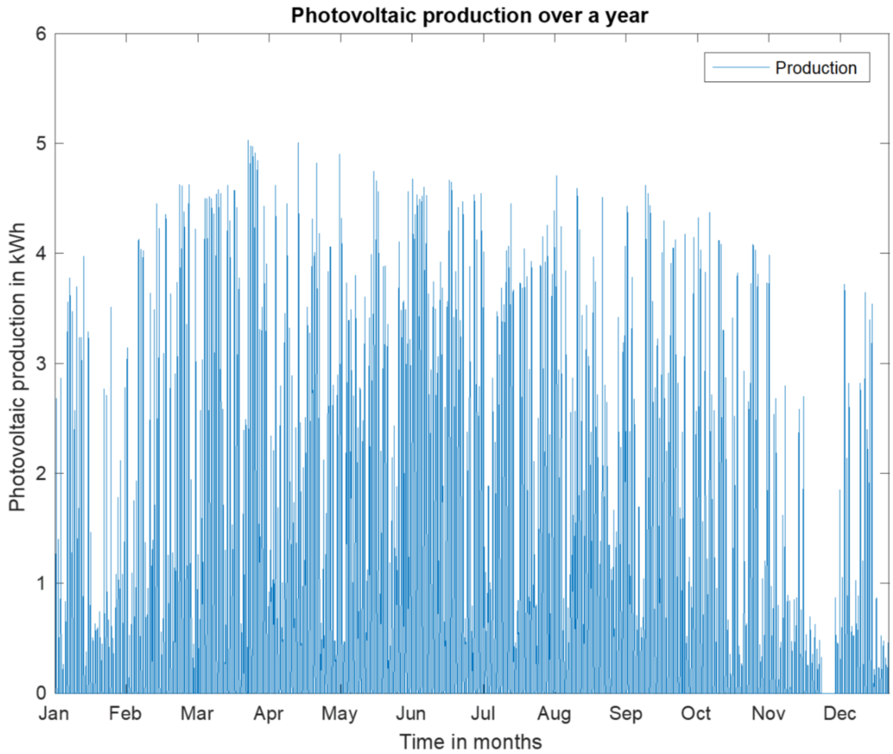


Figure 7: Hourly photovoltaic generation over a year.
(Based on analysis of data from Renewables.ninja (2016).)

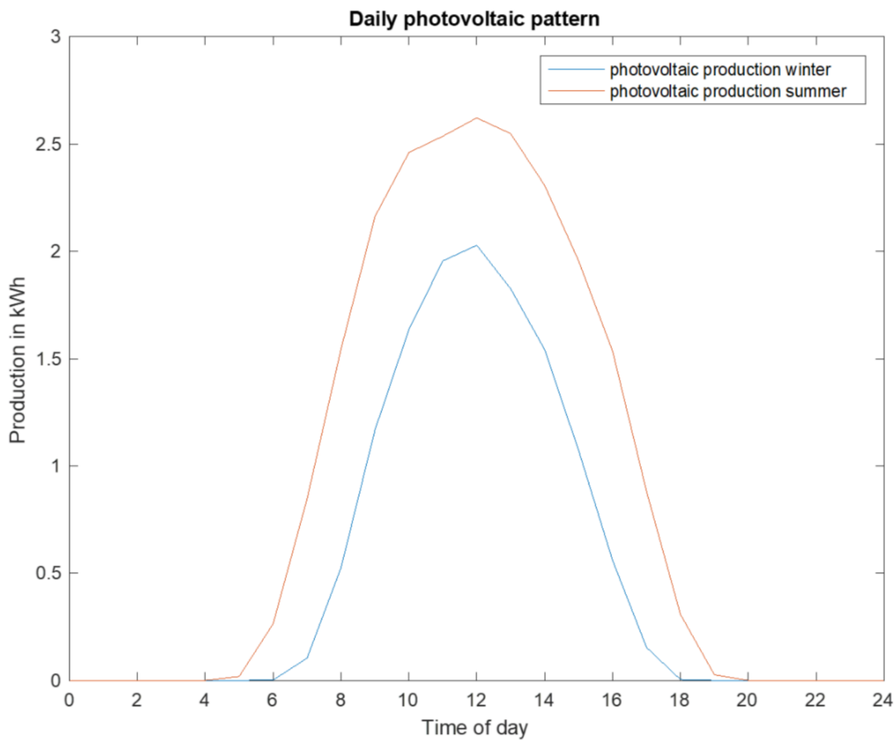


Figure 8: Daily production pattern of the photovoltaic system in winter and summer.
(Based on analysis of data from Renewables.ninja (2016).)

In addition to that, the Technical University of Munich collected market data with currently available battery systems together with their main characteristics.[185] The data set contains 488 battery systems. I filter out all battery systems except of lithium-ion based batteries and exclude systems for industrial purposes and where price, usable capacity or efficiency is missing. The resulting data-set contains 123 battery systems and serves as a reference for the cost of battery systems as well as the efficiency and lifetime parameters.

To gain information regarding common charge- and discharge-rates, further data samples were collected via the database of the "pv-magazin.de"-website.[186] At the time of this study, 140 batteries were listed in this database, after filtering by lithium-ion and AC-systems as well as excluding those with missing or unusable values. Based on previous literature and descriptive analysis of the underlying samples, the following chapters present values for battery parameters used in the optimization simulations.

Cost of lithium-ion battery systems

The simulation considers investment costs as well as fixed costs that arise during the operation of the system. Costs of a battery are a function of multiple qualitative parameters like roundtrip efficiency, depth of discharge, size and lifetime of a system.[187] Therefore, the market offers wide price ranges between different systems. Battery costs are usually given per instantaneous power capacity and potential energy output – also called the usable energy. The potential energy output describes the energy which can be stored in a system at one point in time.[188] The model requires the total costs in potential energy output per usable kWh of battery-capacity installed.

The German market offered lithium-ion batteries in 2015 with an average retail price above 2000 EUR/kWh.[189] An analysis of the underlying battery sample of available batteries offered in the German market shows mean costs above 1900€ /kWh. The cheapest available battery system was already offered at a price of 750€ /kWh.

Battery costs may face a deep price decline in the next years. Customer prices for lithium-ion battery systems are currently shrinking 18% per year.[190] [191] Nykvist and Nilsson (2015) show that price estimates between 2007 and 2014 declined yearly by approximately 14% in automotive applications.[192] Only up to 40% of the total system costs arise out of the energy storing components.[193] Therefore, reducing material costs is only one way to achieve cheaper storage. Lithium-ion batteries as a rather new technology promise big potentials in further price decreases. Economies of scale as well as improvements in the manufacturing process will lead to further cost drops.[194] By producing in a giant factory, Tesla wants to achieve cost reductions in 2017 of 30% compared to costs in 2013.[195] The U.S. Department of Energy for example has also set tough targets in reducing future battery costs.[196] With a short-term drop below $250/kWh and a more long-term target of $150/kWh, lithium-ion battery technology promises further cost advantages.[197] Mundada et al. (2016) assume battery costs between $250-1000 per kWh.[198] Schneider et al. (2015) use 800€ per kWh of storage capacity.[199] Naumann et al. (2015) assume 500 € /kWh.[200] Yet-Ming Chiang, founder of the company 24M, speaks already about producing below $100/kWh for the cells.[201] With these potentials, prognoses and values in mind, I use 600 € /kWh usable capacity for the simulation.

In terms of fixed operational costs, the model allows the consideration of yearly maintenance of the system to keep it running. Beyond maintenance, parts of the system might break over time and cause further costs to repair the damages. The warranty of the system therefore serves as an indicator of quality and the prevention of defects in responsibility of the manufacturer.[202] The warranty of most of the battery systems in the sample is 15 years, giving an indicator from which time on the owner will be in charge for the payment of damages. Thus, defects in the last 5 years of operation would cause additional costs.

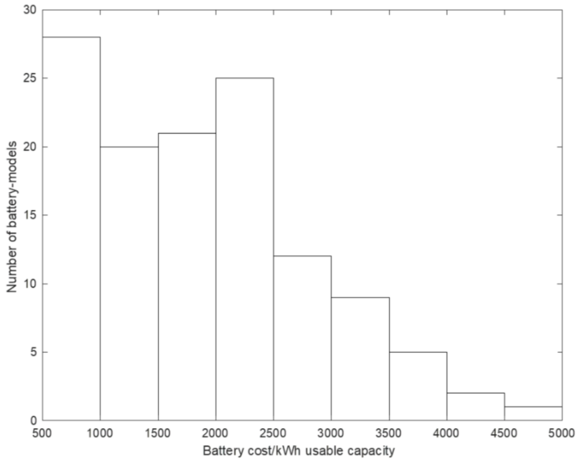
I have no reliable statistical data regarding operational costs and maintenance. Lorenz and Schröder (2014) list various batteries and assume 20 € /kWh per year for maintenance of a battery and 200€ for an exchange of the inverter.[203] Some producers claim that no maintenance is required at all, so that other studies had omitted these costs and so do I.[204] [205]

Efficiency losses of inverter and battery

Power losses appear on multiple steps in the storing process. Storing energy in an AC-system requires an inverter, which converts the power in the house-grid into DC-power for storing in the battery system. When the energy of the battery is used, the inverter must convert the power back to AC for the household's side.[206]

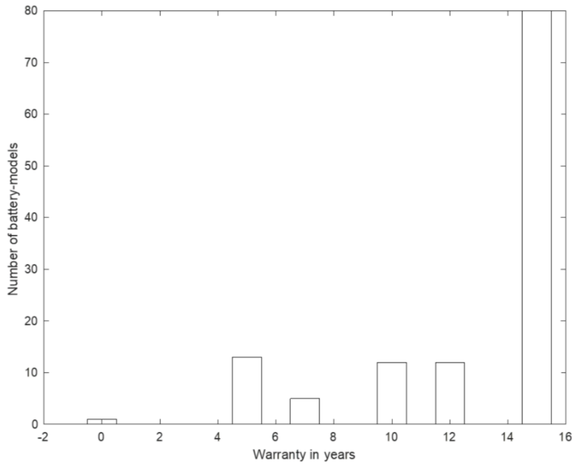
Thus, stored energy underlies efficiency losses of the inverter in both directions. Schneider et al. (2015) use a single-sided conversion efficiency of 0.9.[207] Weniger et al. (2014a)

185 Technical University of Munich (2016).
186 pv-magazin.de (2016) Produktdatenbank Batteriespeichersysteme für Photovoltaikanlagen.
187 Kempener and de Vivero (2015) p. 5.
188 Lazard (2015) p. 1.
189 Kairies et al. (2015a) p. 55.
190 Kairies et al. (2015a) p. 54.
191 Kairies et al. (2016b) p. 56.
192 Nykvist and Nilsson (2015) p. 329.
193 Gyuk et al. (2013) p. 30.
194 Doetsch et al. (2014) pp. 138-139.
195 TESLA p. 1.
196 U.S. Department of Energy (2011) p. 15.
197 Gyuk et al. (2013) p. 33.
198 Mundada et al. (2016) p. 694.
199 Schneider et al. (2015) p. 55.
200 Naumann et al. (2015) p. 43.
201 Fehrenbacher (2015) This startup is looking to revolutionize lithium ion batteries.
202 International Renewable Energy Agency (2015) p. 10.
203 Lorenz and Schröder (2014) p. 13.
204 Truong et al. (2016) p. 2.
205 Diaf et al. (2008) p. 748.
206 Truong et al. (2016) p. 2.
207 Schneider et al. (2015) p. 54.



Mean	Median	Maximum	Minimum	StdDeviation
1935.47	1852.32	4801.59	750.00	931.51

Figure 9: Histogram of battery costs per kWh usable capacity.
(Based on analysis of data from Technical University of Munich (2016).)



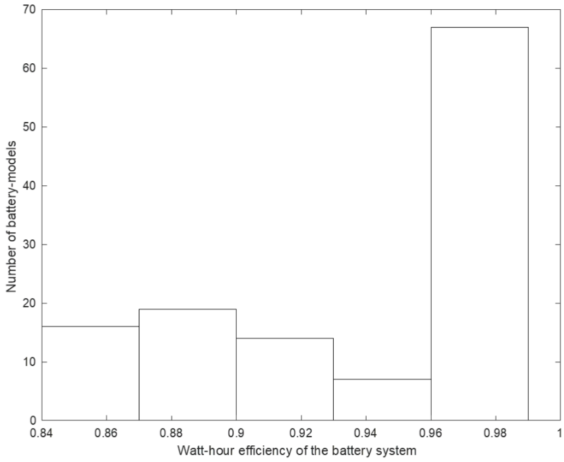
Mean	Median	Maximum	Minimum	StdDeviation
12.72	15.00	15.00	0.00	3.63

Figure 10: System warranty in years based on the battery sample.
(Based on analysis of data from Technical University of Munich (2016).)

assumed the bidirectional battery inverter to have a constant efficiency of 94% and so do I.[208] Battery systems have a very high cycle efficiency compared to other storage methods.[209] Nevertheless, there are differences regarding varying battery systems. The systems of the battery sample have a mean-efficiency of 93%, which is a relatively weak performance resulting out of a few systems with very bad characteristics. Most of the systems already perform with a watt-hour efficiency of 97%, which is also used as the efficiency-parameter for the simulation. Along with Truong et al. (2016), I assume the same efficiency behavior for charging and discharging.[210] With these parameters, the round-trip efficiency of the system is about 0.86. I calculate the losses for a one-directional charging/discharging with $\sqrt{0.97 * 0.94^2} \approx 0.926$, which is used as the single-sided conversion efficiency for the simulation.

Battery systems need energy by themselves to operate their controllers, causing standby-losses. According to

[208] Weniger et al. (2014a) p. 3.
[209] AECOM (2015) p. 10.
[210] Truong et al. (2016) p. 4.



Mean	Median	Maximum	Minimum	StdDeviation
0.93	0.96	0.97	0.85	0.04

Figure 11: Watt-hour efficiency of the battery sample.
(Based on analysis of data from Technical University of Munich (2016).)

Kairies et al. (2016b) these standby-losses add up to 90-350 kWh per year.[211] The simulation in this study ignores these losses. The simulations within this thesis do not consider changes in the operational temperature of the battery system, which might have also effects on the efficiency performance and losses.[212] [213] Lithium-ion batteries usually have a relatively low self-discharge of only some percent per month.[214] Thus, these effects are negligible as well.

Charge and discharge power of the system

The electrical power, which can be charged or discharged from a battery system within a given time span, is limited by the maximum charge or discharge rate. The power which can be directed into the battery is proportional to the number of cells being added to the system.[215] This means that bigger scaled systems can charge or discharge linearly more electricity in each time span than a small system with the same characteristics apart from the size. This aspect is very important for the ability of the battery system to store peak photovoltaic production or handling very high load demands of the household. Since many battery systems for household applications have equal charge- and discharge-rates, the parameters are set to the equal value ($c_{bat} = d_{bat}$).[216] The second sample of batteries offers values for maximal discharge-power in kW and the usable capacity of each system in kWh. By dividing the maximal discharge-power by the total usable capacity, I get the charging-power per usable kWh of capacity, which can be charged or discharged within an hour. If the rate of each battery in the sample is illustrated within a histogram, a big peak in values of around 0.5 kW/kWh can be observed. The median of the sample is positioned to the same value of 0.5 kW/kWh, whereas the mean is with 0.6 kW/kWh slightly above.

Within the simulations, I assume a constant maximal charge and discharge power of 0.5 kW/kWh for the usable capacity installed.

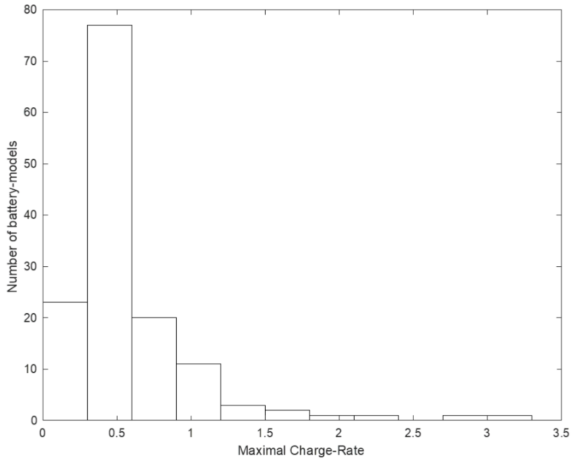
Aging and capacity fade of lithium-ion batteries

Depending on the chemistry, the operation temperature, the number of cycles and other parameters, lithium-ion batteries face irreversible damages in their capability of storing electrical energy.[217] [218] The effects are distinguished between calendar aging with respect to the time and cyclic aging, dependent on the cycles of the system.[219] The loss of cyclable lithium diminishes the capacity of the battery system.[220]

The cyclic aging effect is heavily influenced by the depth of the cycles and the operation temperature of the system.[221] [222] The consideration of these capacity losses is important for the simulation but also very complex to model from a technical perspective. Batteries tend to lose a relatively high percentage of their initial capacity in the first few cycles. This effect slows down after some time and takes on a linear shape of fading before a sudden drop in capacity takes place.[223]

In a study of Wright et al. (2003), lithium-ion cells being tested for 44 weeks with a 25°C operation temperature

[211] Kairies et al. (2016b) p. 67.
[212] Schmidt et al. (2015) p. 1236.
[213] Zhang and White (2008) p. 792.
[214] Schmidt et al. (2015) pp. 1236-1238.
[215] Kairies et al. (2015a) p. 53.
[216] Based on analysis of pv-magazin.de (2016).
[217] Sankarasubramanian and Krishnamurthy (2012) pp. 250-251.
[218] Ecker et al. (2014) p. 842.
[219] Schmidt et al. (2015) p. 1231.
[220] Kassem et al. (2012) p. 304.
[221] Millner (2010) p. 351.
[222] Peterson et al. (2010) p. 2389.
[223] Spotnitz (2003) p. 72.



Mean	Median	Maximum	Minimum	StdDeviation
0.60	0.50	3.15	0.17	0.45

Figure 12: Maximal charge and discharge power per kWh of usable battery capacity.
(Based on analysis of pv-magazin.de (2016).)

showed a nearly linear fade rate. In contrast to that, a nearly square rooted fade rate in function of the time was observable with a 45°C operation temperature.[224] In a calendar life study of lithium-ion pouch cells, Zhang and White (2008) observe a linear capacity fade in low temperatures and nonlinear losses in temperatures above 25°C.[225] Most of the aging curves of Ecker et al. (2014) appear also in a nearly linear shape.[226] The rate of capacity losses decreases over time.[227] Since a complex technical model would go beyond the scope of this economic analysis, I assume a similar fading-behavior and use a simple time-dependent approach to take all capacity losses (cyclical, calendrical or other) into account. The fading-factor is assumed to stay constant over time and is chosen to meet literature observations in capacity tests. Different literature defines the battery end of life by reaching 80% of initial capacity.[228] [229] Truong et al. (2016) observed 80% remaining capacity for lithium-ion cells after 15 years in operation.[230] Thus, to reach the same fading after 15 years, the battery in this simulation continuously loses 1.58 % of the remaining capacity within a year, leading to a decreasing function with a slightly concave slope in the total capacity like shown in the following graph:

The fading-factor is set to 1.58 % to reach 80% remaining capacity after 15 years. Nevertheless, most of the battery systems in the sample are promoted with a life-span of 20 years. For the remaining 5 years of operation, I assume the same fading behavior as before.

[224]Wright et al. (2003) p. 865.
[225]Zhang and White (2008) p. 786.
[226]Ecker et al. (2014) p. 842.
[227]Spotnitz (2003) p. 73.
[228]Millner (2010) p. 350.
[229]Spotnitz (2003) p. 72.
[230]Truong et al. (2016) p. 7.

4. Results and discussion

Before presenting and discussing the results, I want to touch upon some basic problems and limitations of the model and its simulations. The optimization, run in the MATLAB R2016b – version, works with a golden section search and parabolic interpolation.[231] The simulations determine the optimal battery sizes by technically minimizing the negative-inverted net present value. The underlying data allows calculations in hourly steps. Therefore, small battery micro-cycles, for example when clouds prevent solar production for a few minutes, are not considered within these simulations. The optimization is fully linearized, which means that optimal but also continuous battery sizes might arise that are not actually available at the market. All costs are also assumed to be linear, which enables theoretically setup constellations that would not be possible in real business cases, for example a battery installation of just 0.1 kWh. According to Kairies et al. (2015a) installations smaller than 2kWh are usually not profitable since fixed costs for the additional required electrical equipment would be too high.[232]

The simulations in this study assume a fixed photovoltaic system size of 5.5 kW. However, I have to critically mention that an investor, who is interested in buying a photovoltaic system and a battery storage system at once, would try to optimize the sizes of both systems simultaneously, if he had appropriate tools to do so. If a photovoltaic system is not properly sized according to the needs of the household, the over- or underproduction can affect the self-consumption ratios even without storage.[233] The photovoltaic system size

[231]Mathworks Matlab (2017) fminbnd function documentation.
[232]Kairies et al. (2015a) p. 45.
[233]Hoppmann et al. (2014) p. 1104.

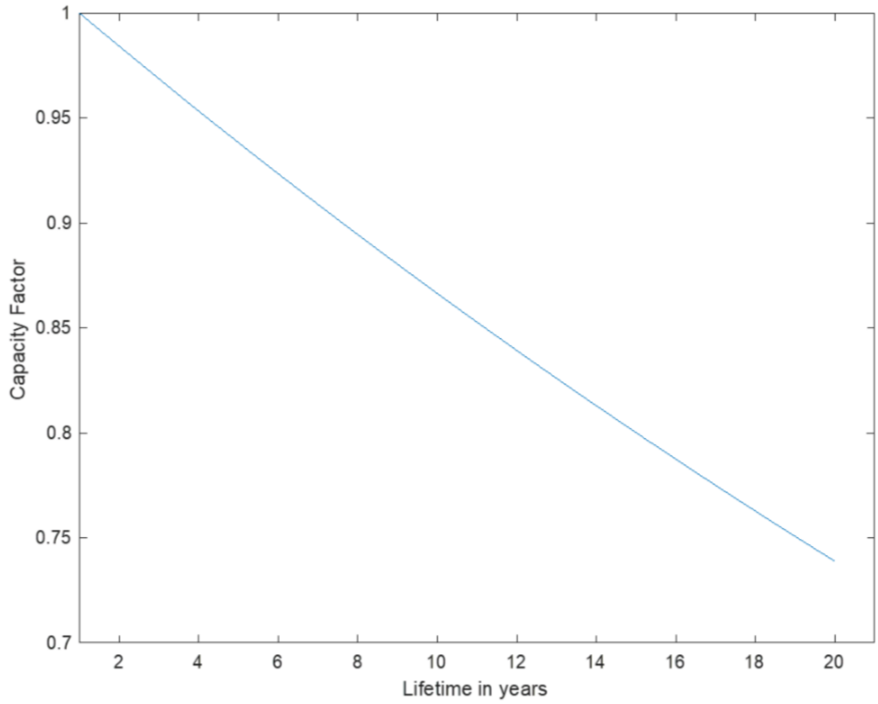


Figure 13: Capacity Factor Function.

for my simulations is set according to the recommendations of previous literature to be well-fitted to the household's load demand without storage.[234] This is important to assure that the results are also meaningful for retrofitting battery installations. Thus, the photovoltaic generation facility might not necessarily be optimally sized for a usage together with a storage system. Therefore, the calculated scenarios could be biased so that battery installations might already be financially lucrative if they were operated together with an appropriately sized corresponding photovoltaic system, even before the simulation results would say so. On the other hand, the battery system could be obsolete if the photovoltaic system would be properly sized and orientated to produce along with the consumption pattern of the household. The total photovoltaic production is with 6313.83 kWh per year theoretically more than enough to cover the 4685.07 kWh of the household's demand. If the energy storage system would work without efficiency losses and had enough charging and discharging power as well as total capacity to store the surplus, the household could live without grid power. Nevertheless, a high autarky in this model can only be achieved by an effective energy storage system that generates more calculative revenues than initial costs. If the production and consumption is grouped in hourly patterns, the intersection of both curves in Figure 14 shows the self-consumed energy without battery storage system. Since a big part of the produced energy can not be utilized immediately, it can either be stored or sold to the grid.

Although this linearized approach underlies multiple assumptions and can only serve as a model framework, the results can give an indication at which boundaries political regulations and market-driven parameters would lead to profitable installations of battery storage systems.

The following graphs show the battery sizes that are optimizing the net present value. The photovoltaic system without battery storage system would generate a net present value of 3268.28€ within 20 years assuming electricity retail rates of 28.72 Cents/kWh and 12.30 Cents/kWh rate of remuneration. A rational investor would only consider projects that have a positive net present value. With 3268.28€ , the photovoltaic modules can generate positive returns on investment and are therefore a profitable investment opportunity.

The following chapters cover five different simulations regarding the bespoken political regulations and market driven parameters. Since every influencing parameter has different consequences to the profitability of battery storage systems, I discuss every parameter separately. For each regulation or market driven parameter, I first present the results of the simulations and then discuss shortly the implication of my findings. Chapter 4.1 outlines the effect of subsidies on battery storage systems. Consequences of changing electricity retail rates and feed-in compensations are presented in chapter 4.2 and 4.3. Chapter 4.4 presents the impact of cuts in feed-in power. The last subchapter plots a possible scenario for an investor in the year 2020.

[234] Weniger et al. (2014b) p. 82.

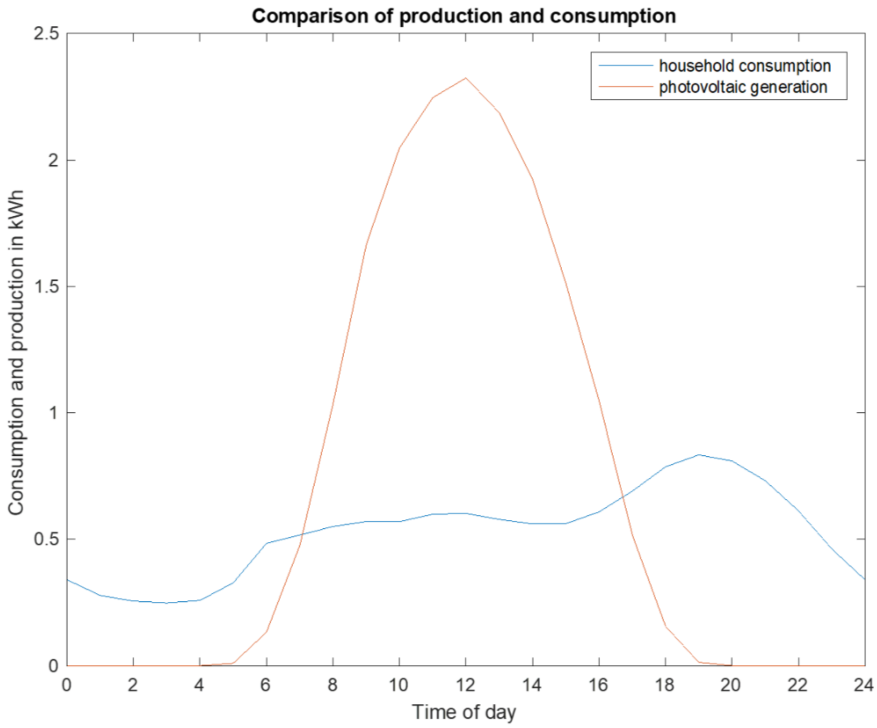


Figure 14: Comparison of the daily consumption and production pattern.
(Based on analysis of data from Renewables.ninja (2016).; Based on analysis of data from Berlin (2015).)

4.1. Sensitivity towards battery subsidies

This first simulation tries to identify a breakpoint of subsidies or alternative drops in battery prices that would lead to profitable battery storage installations. Thereby, I determine the optimal battery sizes with respect to investment costs between 100 € /kWh and 600 € /kWh of usable capacity. Since a subsidy is only in the interest of investors that consider a new installation, I use current market values. For the rates of remuneration I assume the latest feed-in compensation of 12.30 Cents/kWh for January 2017.[235] Similar to Truong et al. (2016), I assume a constant electricity price of 28.72 Cents/kWh over the whole lifetime.[236] The battery price is set to 600 € /kWh of usable storage capacity. The simulation with battery prices from 100 € /kWh to 600 € /kWh leads to the same results as calculating with subsidies between 0 € /kWh to 500 € /kWh. From a financial perspective, subsidizing the battery system does only affect the investment costs of the battery system. Therefore, varying battery costs and subsidies results in the same optimal system setups. Figure 15 shows the return-maximizing battery sizes for different initial investment costs for the battery system.

Battery costs above 510 € /kWh lead to a relative sudden drop in the optimal battery size. With costs above 530 € /kWh the optimal battery size tends to null. The net present value of the overall investment is positive for all battery costs. The photovoltaic system, as I already stated, has a net present value of 3268.28€ . Since the battery size is only bigger than 0 kWh when the net present value of the overall investment can be increased, the net present value is rising with the battery size.

The simulation confirms the results of Kantor et al. (2015), according to which the investment costs would prevent the profitable implementation of batteries under the current environmental circumstances.[237] With prices for lithium-ion systems around 600€ /kWh, a battery storage system does not provide financial benefit and has therefore an optimal battery size of 0 kWh. From another point of view, 525€ /kWh marks a barrier, at which the optimal battery sizes start to become financially lucrative. Assuming market prices of 600€ /kWh, battery costs must either decrease by more than 75€ /kWh or governmental subsidies would have to partly come up for these costs to give a financial incentive for the investor. The difference of the optimal battery size between costs of 510 € /kWh with 2.27 kWh and 530 € /kWh with 0.31 kWh is quite extreme. If future battery prices come down to 530 € /kWh, policy makers could boost further installations of battery storage systems rapidly by subsidizing with rather minor costs to overcome the small gap. The subsidy of the German "kfW"-bank with the program number 275 currently gives a reimbursement for a maximum of 19% of the costs that are eligible for the

[235] Bundesnetzagentur für Elektrizität Gas Telekommunikation Post und Eisenbahnen (2017) Photovoltaikanlagen - Datenmeldungen und EEG-Vergütungssätze.
[236] Truong et al. (2016) p. 6.
[237] Kantor et al. (2015) pp. 222-223.

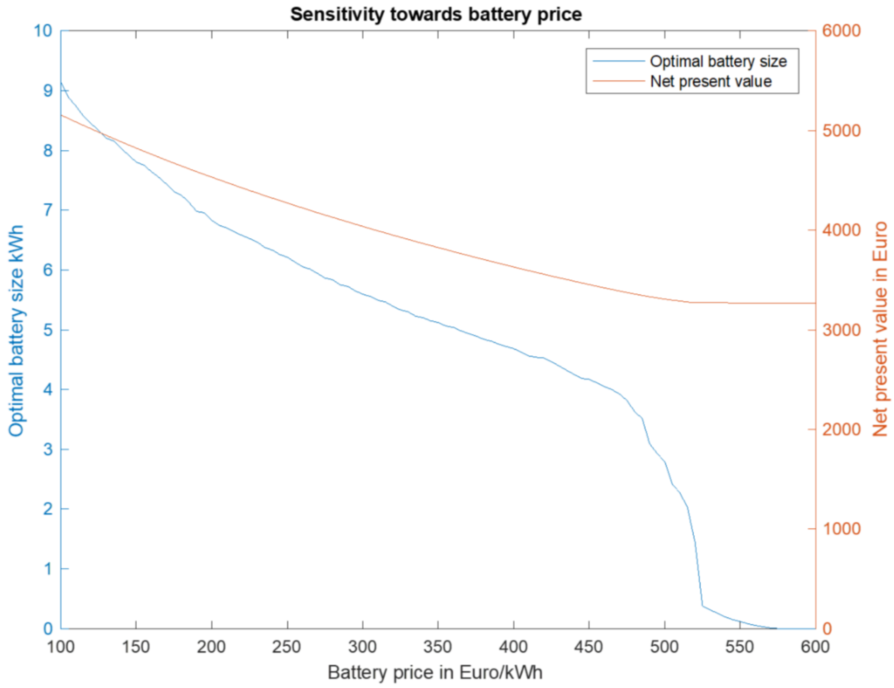


Figure 15: Return-maximizing battery sizes for different battery costs.

grant.[238] Assuming a price of 600 € /kWh of usable storage capacity, the subsidy would add up to 114 € /kWh and could therefore decrease the battery investment costs to 486 € /kWh. Looking at the results of the simulation, the battery storage systems should already be profitable together with this subsidy. However, around 50% of the storage owners did not even use the subsidy.[239] The reasons that this subsidy is not beneficial for every investor are hidden in the requirements of the grant. The reimbursements are calculated upon the eligible costs. The eligible battery costs can differ extremely from the actual system costs. As the calculation tool on the website of the bank reveals, the eligible costs are calculated by taking the total costs of the combined system and subtracting 1.600 € /kWp of photovoltaic power.[240] The remaining costs are considered as the costs of the battery system and tolerated for grant repayments. Since newer photovoltaic modules are already available for prices around 1270€ /kWp and therefore way cheaper than 1600€ /kWh, the calculated eligible costs are way lower than the actual battery costs.[241] To clarify this problem, I will make a simple calculation. Let us assume that a 5kWp photovoltaic rooftop costs 6350€ and the battery with 5 kWh capacity is priced at 3000€ . This adds up to total system costs of 9350€ . Since the grant regulations subtract 1600€ for each kWp of photovoltaic power, the remaining costs that are considered for the storage system are 1350€ . The calculative costs in this example would be way lower than the actual costs of 3000€ for the battery system. With a reimbursement of 19% of 1350€ eligible costs, the grant would only come up for 256.50€ . Thus, the effective subsidy does only add up to 51.30 € /kWh of usable battery capacity. As shown in the simulation results, the subsidy would have to be at least higher than 75 € /kWh to have an impact on the optimal battery size. In addition to that, by making use of the grant, the corresponding facility is additionally forced to limit the feed-in power to 50% of the installed photovoltaic capacity.[242] Since this subsidy comes along with some drawbacks and does not provide enough financial support, the program does not effectively incentivize a battery installation in every business case.

To sum up, I can say that under current market conditions a subsidy program would be elemental for an installation of a battery storage system. To incentivize residential storages, the program would have to be designed in a way that its requirements do not discriminate storage owners towards photovoltaic owners without storage system. Furthermore, depending on the assumptions, the program would have to come up for at least 75 € /kWh to trespass the identified boundary.

[238] Kreditanstalt für Wiederaufbau (2017) Erneuerbare Energien – Speicher.

[239] Sterner et al. (2015) p. 24.

[240] The 1600€ /kWp subtractions are based on the "Tilgungszuschussrechner"-application on the website of the "KfW"-bank, accessed on the 18/02/17: Kreditanstalt für Wiederaufbau (2017) Erneuerbare Energien – Speicher.

[241] Wirth (2017) pp. 8-9.

[242] Kairies et al. (2016b) p. 20.

4.2. Sensitivity towards taxes, fees and levies

Taxes, fees and levies are a governmental tool to influence the electricity price and thereby supporting or preventing further installations of battery storage systems. To measure the effect of changes in electricity tax and fees regulations, the second simulation optimizes the battery size at different electricity prices. This simulation now considers 600€ initial investment costs per kWh usable capacity of the battery storage system. The rate of remuneration is still set to 12.30 Cents/kWh.[243] I simulate constant electricity prices over the whole project lifetime with electricity retail rates between 20 Cents/kWh and 40 Cents/kWh.

The battery size curve in Figure 16 shows a major incline above 31.20 Cents/kWh. The optimization algorithm with 31.20 Cents/kWh calculates an optimal size of 0.43 kWh usable battery capacity. With 2 Cents/kWh more, the simulation finds the optimum battery size at 3.91 kWh for electricity prices of 33.20 Cents/kWh. Since self-consumed energy is valued with the electricity retail rates, the NPV-curve of the system is increasing with the retail rate. Even when the household does not operate any battery system, the photovoltaic power is favorably consumed before the excess energy is fed into the public grid. Nevertheless, within the price of 20-40 Cents/kWh and a rate of remuneration of 12.30 Cents/kWh, the net present value of the overall system is positive. Assuming prices of 28.72 Cents/kWh, an increase of 3 Cents/kWh would lead to an instant investment opportunity in battery storage systems ceteris paribus. A 3 Cents/kWh price increase could occur naturally by market movements, which might for example be triggered by the nuclear phase out. A rise of taxes would lead to the same effect. A rise of the EEG reallocation charges to 7.6 Cents/kWh, assumed to be reached in the year 2023, could already lead to an overall electricity price increase of around 1.3 Cents/kWh.[244] [245]

Even if the electricity price would only grow in a marginal rate, every price increase can have influence on the overall profitability of the battery system. Whether the influence is enough to justify installations, depends on the other influencing parameters as well.

4.3. Sensitivity towards changing feed-in tariffs

Analogously to the price of electricity, also the feed-in tariff influences the profitability of energy storage systems. With a fixed rate of remuneration for a 20-year-period for renewable generation facilities, the German government secured a stable compensation for photovoltaic facilities.[246] If photovoltaic owners can take big profits on selling energy to the grid, there is a lack on a sufficient incentive to increase the self-consumption with a battery storage system. The feed-in tariffs have already decreased to 12.30 Cents/kWh.[247] This simulation should now identify how far the compensation would have to decline to make battery storage systems financially attractive, if all other parameters stay constant. For this simulation, I consider two different kinds of investors and photovoltaic profiles:

- Investor A: The investor purchases a new combined photovoltaic and battery storage system in January 2017. Thus, the new owner contracts an EEG feed-in tariff which guarantees him a fixed compensation for the energy that is fed into the grid. The panels of the photovoltaic system are new and do not show losses due to wear or aging at the beginning of the simulation. The production profile of the solar modules as well as the battery system start with full capacity in all systems. Due to the EEG regulations of 2012, the newly installed photovoltaic systems cut of feed-in power above 70% of the nominal installed capacity.[248]
- Investor B: The scenario is settled in 2020 when the first photovoltaic systems will fade out of the remuneration contracts. I assume that the investor purchased a photovoltaic system 20 years ago and could now install a retrofitted battery storage system to increase self-consumption. The EEG-contract faded out, so the remuneration rate is way lower. The production profile has losses due to 20 years of aging. Since the photovoltaic facility was installed before 2012, no feed-in limits reduce the feed-in power of the system. All other parameters stay constant as in the simulations of investor A.

I simulate each profile with feed-in tariffs between 0 Cents/kWh and 20 Cents/kWh. Thus, this simulation covers the interests of new investors facing the current remuneration rate of 12.30 Cents/kWh as well as photovoltaic owners at the end of the EEG-program facing rates around 3 Cents/kWh.

Figure 17 shows a steep downfall in the optimal battery size for rates of remuneration above 9.6 Cents/kWh for investor A. The optimal battery size at a feed-in tariff of 9.6 Cents/kWh is 2.02 kWh. With an increase of only 0.2 Cents, the optimal battery size already declines to 0.44 kWh. The simulation for investor B shows a similar curve. The optimal battery size is slightly below the line of Investor A due to the lower production efficiencies of the aged photovoltaic system. Since the photovoltaic modules are simulated with 20 years of efficiency degradation, the production profile values are assumed to be lower than for new facilities. The aged photovoltaic rooftop does not produce that much energy. So, the battery does not require that much capacity to store all

[243] Bundesnetzagentur für Elektrizität Gas Telekommunikation Post und Eisenbahnen (2017) Photovoltaikanlagen - Datenmeldungen und EEG-Vergütungssätze.

[244] Deutscher Industrie- und Handelskammertag (2016) p. 31.

[245] Based on data of Bundesverband der Energie- und Wasserwirtschaft e.V. (2016b) Energiedaten.

[246] Bundestag (2000) Gesetz für den Vorrang Erneuerbarer Energien (EEG 2000).

[247] Bundesnetzagentur für Elektrizität Gas Telekommunikation Post und Eisenbahnen (2017) Photovoltaikanlagen - Datenmeldungen und EEG-Vergütungssätze.

[248] Bundestag (2012) Gesetz für den Vorrang Erneuerbarer Energien (EEG 2012).

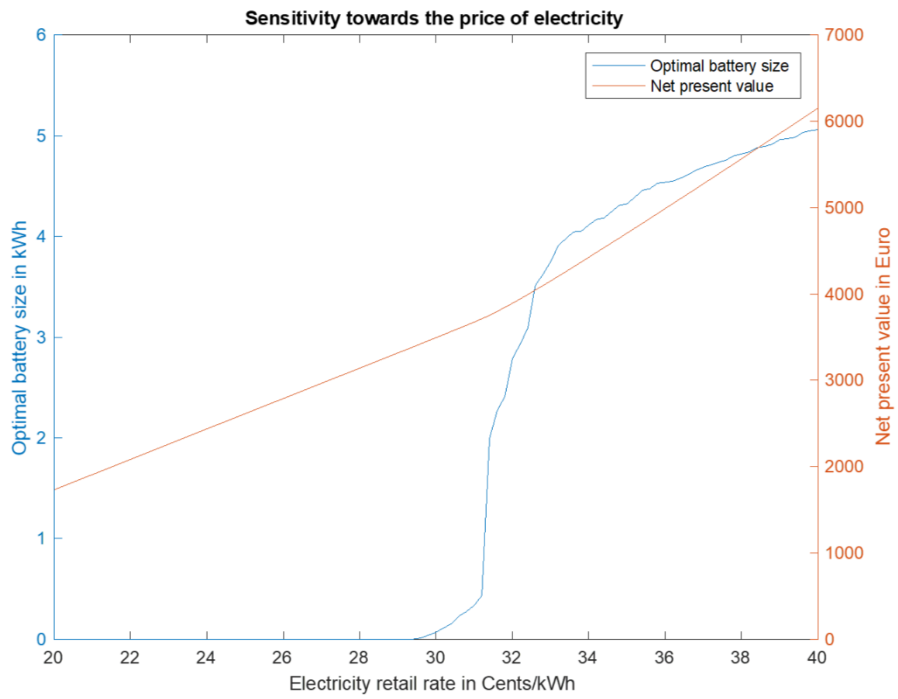


Figure 16: Return maximizing battery sizes at different electricity retail rates.

excess energy for the later consumption. Consequently, also the size of the battery shrinks. The lower photovoltaic power can lead to smaller optimal-sized batteries that do have lower charging and discharging rates. The line of Investor B shows a parallel behavior, but it tends to drop slightly earlier with less steepness. The NPV curve is only shown for investor A since the photovoltaic costs of investor B are already sunk and therefore not relevant for the overall buying decision. The overall project has a negative NPV for rates of remuneration below 1.8 Cents/kWh.

A fall of the current feed-in tariff of 12.30 Cents/kWh to 9.60 Cents/kWh would place battery storage systems in the position of a financially attractive investment opportunity. At rates of 9.60 Cents/kWh, investor A would have a recommended optimal battery size of 2.02 kWh. Battery sizes bigger than 0 kWh already occur at rates of 11.40 Cents/kWh but those battery sizes are very small and probably not yet economic in a real business case. The feed-in tariffs are coupled to the total photovoltaic addition.[249] If the rate of remuneration decreases, also the profitability sinks, which should lead to a slower photovoltaic addition ceteris paribus. Not surprisingly, the net present value grows for higher rates of remuneration or sinks with decreasing feed-in compensation. However, since the battery is increasing the NPV, the NPV for rates below 10 Cents/kWh does not decrease as fast as for rates where no battery storage system would be profitable. The curve shows a salient point at this rate, since the sudden uptake of the battery storage system breaks the constant linear sinking. The NPV curve sinks with 387.37 € per Cent of the rate of remuneration if the system does not include a battery storage system. At rates of remuneration below 9 Cents/kWh, an optimally sized battery storage system can lower the shrinking of the NPV to values between 266 and 305 € per Cent. Assuming that investor A acts rational and according return-maximization, A will not invest for negative NPVs. A rational and profit maximizing investor would only invest, if the net present value is positive. However, in some constellations and scenarios the photovoltaic costs are sunk and battery storage systems can minimize the losses for investments that would otherwise have negative returns. For investor A, the rates of remuneration can only incentivize a battery installation if they are settled between 1.8 Cents/kWh and 9.6 Cents/kWh. If the rates are higher, investor A would only install a photovoltaic rooftop without battery storage system. If the rates are lower than 1.8 Cents, investor A should neither invest in the photovoltaic system nor the battery.

The picture looks completely different for investor B, who is already owning a photovoltaic system. For photovoltaic owners, who are fading out of the EEG-program, a battery would be a good way to increase self-consumption and therefore avoid selling energy to the grid for a very low compensation. Those investors face a selling price of around 3 Cents/kWh at which the optimal usable battery capacity would be above 4 kWh. There is no need in changing any feed-in tariffs for investors of type B to generate an investment opportunity. These findings go in hand with the recommendations of the German storage association "Bundesver-

[249] Bundesnetzagentur für Elektrizität Gas Telekommunikation Post und Eisenbahnen (2017) Photovoltaikanlagen - Datenmeldungen und EEG-Vergütungssätze.

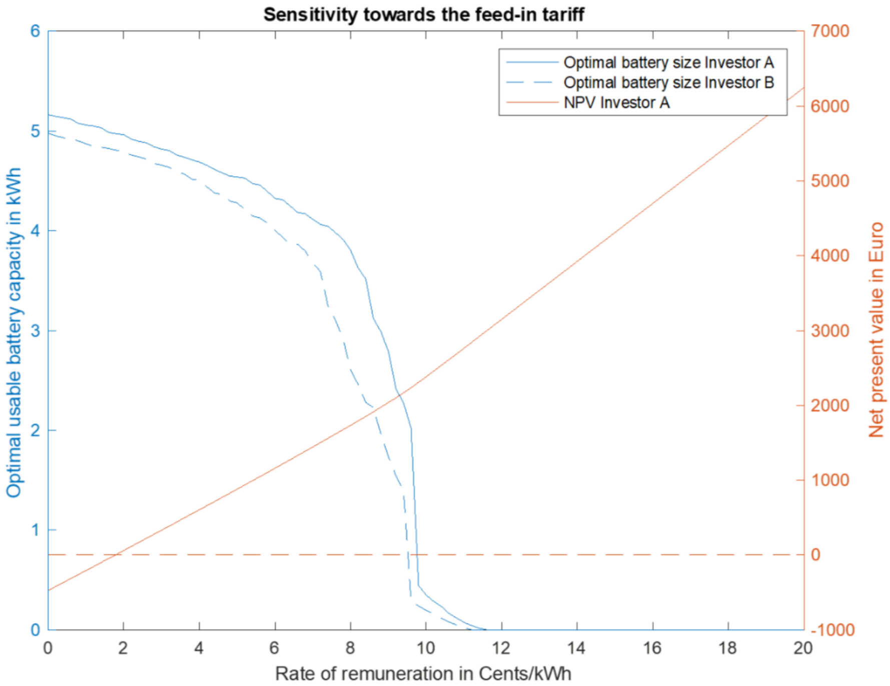


Figure 17: Return-maximizing battery sizes for different feed-in tariffs.

band Energiespeicher e.V. Berlin" regarding the retrofit of storage systems for photovoltaic facilities fading out of the fixed remuneration rates.[250] However, due to the lack of a production profile of an old facility, I have to critically mention, that this simulation is also based on the photovoltaic production profile of the website "Renewables.ninja" of the year 2014.[251] The production profile is simulated with previous linear capacity losses for 20 years due to aging of the facility, but the fading of older photovoltaic systems from the year 2000 might be completely different after 20 years. It is questionable, if the production profile would still have a linear efficiency fading.

4.4. Sensitivity towards curtailments

Curtailment regulations should incentivize photovoltaic owners to increase their self-consumption to avoid losses due to curtailments. In times of very high solar radiation, the feed-in energy is cut if the power exceeds the curtailment limit. Thus, there is no compensation for this energy. The current feed-in limit for photovoltaic systems is 70%.[252] The curve in Figure 18 shows an optimal battery size of 3.93 kWh for a curtailment above 20% of the nominal power. At a feed-in limit of 30% the optimal battery size already dropped to nearly 0 kWh. The first optimal battery size that could be realistically operated in a profitable way for a real business case is at a feed-in limit of 26%. For this feed-in limit, the calculated optimal battery size would be 1.96 kWh. The NPV-curve of the overall project is negative at feed-in limits below 5%. The net present value without battery storage system is already negative at around 10% feed-in power.

Thinking of the current feed-in limit for photovoltaic systems of 70%, a radical political interference would be needed to incentivize a battery storage uptake only via curtailments. There are already lower feed-in limits for EEG-subsidized battery storage systems. To receive an investment subsidy for a new battery system, the photovoltaic system must not feed-in more than 50 % of its nominal power.[253] However, these limits are not incentivizing a battery storage installation since these regulations do not apply on systems without battery storage. The limit that is applied to all photovoltaic systems and that could promote a battery storage installation, is currently set to 70% and is therefore not influencing the optimal battery size at all. If the rational investor is only investing in projects with a positive net present value, curtailments could prevent an investment in a photovoltaic system only at feed-in limits below 10%. If the investor additionally installs a battery storage system, the project generates a positive NPV until a feed-in limit of 5%. An investment in a combined photovoltaic rooftop and residential storage system would therefore only be profitable and financially beneficial for feed-in limits between 5% and 26%. For all feed-in limits above 26% the investor would only purchase a photovoltaic system without installing a battery storage system. At feed-in limits below 5% the investor would neither invest in the photovoltaic modules nor in a battery. The current feed-in limit that is

[250] Bundesverband Energiespeicher e.V. (2016) p. 20.
[251] Renewables.ninja (2016).
[252] Bundestag (2012) Gesetz für den Vorrang Erneuerbarer Energien (EEG 2012).
[253] Kairies et al. (2016b) p. 20.

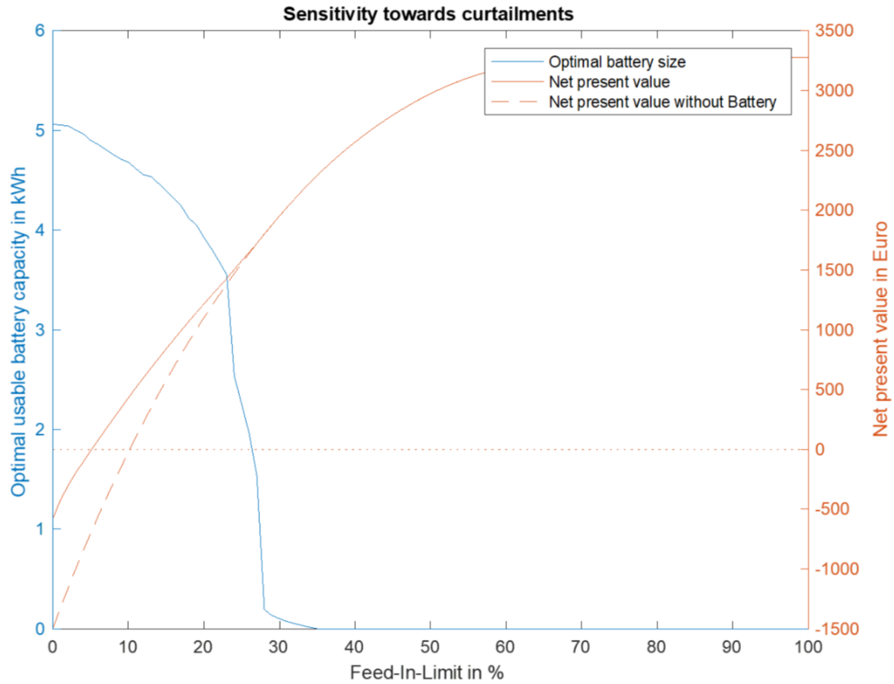


Figure 18: Return-maximizing battery sizes at different feed-in limit regulations.

applied towards photovoltaic installations would have to decrease from 70% by 44% to incentivize battery storage installations.

4.5. Simulation of a likely future scenario

By now, I determined the optimal battery sizes for different battery costs, electricity prices, feed-in tariffs and curtailment regulations. Every parameter includes values, at which it could incentivize a battery storage installation. However, none of the parameters shows an imminent investment opportunity if it is changed alone without adjusting also other parameters. It might be not possible for any parameter to change as much as needed to create a financially lucrative investment in battery storages while the other parameters stay constant. Thus, I simulate a possible future scenario for the year 2020 changing multiple parameters. In contrast to the simulation of investor B in chapter 4.3, this is a speculative scenario changing multiple parameters according to previous historic movements. The changes in rates of remuneration are assumed to continue linearly over the next three years until 2020. The rates of remuneration decreased from 12.95 Cents/kWh in January 2015 to 12.30 Cents/kWh in January 2017 leading to a yearly decline of approximately 0.325 Cents/kWh.[254] I assume a similar decrease until 2020, therefore using a feed-in tariff of 11.325 Cents/kWh. The simulation works with constant electricity retail rates over 20 years. Therefore, the chosen price should be an average value for the years 2020 until 2040. Looking at the electricity costs since 1998, total electricity costs increased by 68% until 2016 whereas taxes, fees and levies increased by 281% and the retail rates are still expected to rise.[255] [256] Even if the prices might currently not be rising in a constant linear manner, I assume an increase in the electricity retail rates in the next years and calculate with an electricity price of 31 Cents/kWh. Curtailment regulations did not change in the last years and are still set to the current rate of 70%.[257] Thus, I keep this and all other parameters as they were already applied in the previous simulations. The estimations for future battery costs vary widely. Some experts expect the total costs to sink to very low levels of 100$/kWh.[258] Thus, I take the initial investment costs of the battery system for the x-axis and calculate the optimal battery sizes with the new parameters and battery costs between 100-600 € /kWh.

Figure 19 shows a slowly decreasing curve of the optimal battery size. In the range between 100-600 € /kWh battery system costs, the optimal battery size is always positive and higher than 2.78 kWh. The NPV is always positive and decreasing with increasing battery costs. Thus, assuming the bespoken parameters, there could be a clear financially lucrative investment opportunity in battery storage systems in 2020.

[254] Bundesnetzagentur für Elektrizität Gas Telekommunikation Post und Eisenbahnen (2017) Photovoltaikanlagen - Datenmeldungen und EEG-Vergütungssätze.

[255] Bundesverband der Energie- und Wasserwirtschaft e.V. (2016a) p. 33.

[256] International Renewable Energy Agency (2015) p. 35.

[257] Bundestag (2012) Gesetz für den Vorrang Erneuerbarer Energien (EEG 2012).

[258] Fehrenbacher (2015) This startup is looking to revolutionize lithium ion batteries.

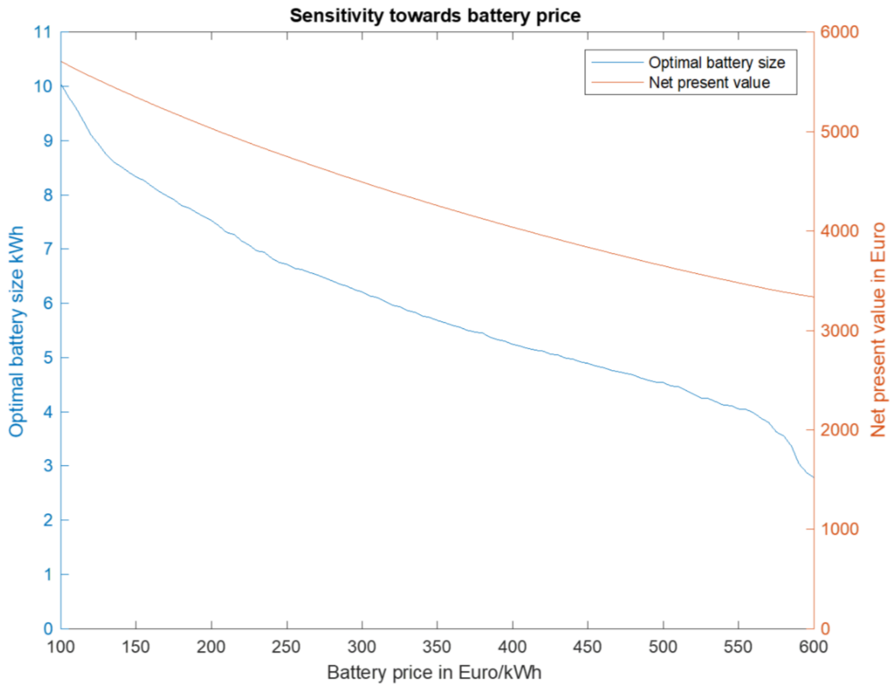


Figure 19: Return-maximizing battery sizes in a "2020 scenario".

5. Summary and further research

This thesis determines the net present value-maximizing battery sizes in different market scenarios and varying political regulations for a German photovoltaic owner. By comparing the production profile of a residential photovoltaic rooftop facility with an average household's energy demand in hourly steps, I simulated energy shifts with a battery storage system to compute the financial value of residential storage applications. This thesis identifies boundaries in political and market driven parameters that have a crucial influence on the financial value of the battery storage system. This is done by varying initial costs of the battery storage system, electricity retail prices and rates of remuneration as well as feed-in limiting regulations.

Investment costs of a battery system above 510€ /kWh lead to a steep drop in the net present value-optimizing battery size. Subsidies could help overcome the high initial investment costs of a battery installation. However, current subsidy regulations do not provide profitable opportunities for every photovoltaic owner. Rising electricity retail rates or lower rates of remuneration could have a similar effect on the profitability of battery storage systems ceteris paribus. The higher the price of electricity, the higher the incentive to increase the self-consumption to avoid paying for the expensive energy. Electricity costs below 31.6 Cents/kWh lead to a decrease in the optimal battery size so that a storage system would not be profitable. Thus, taxes, fees and levies like the EEG-charges that are influencing the electricity retail rate could have a high influence on the profitability of battery storage systems. If the compensation of selling energy to the grid is low, photovoltaic owners will try to increase their self-consumption with a battery system. Rates of remuneration above 9.6 Cents/kWh diminish the calculative revenues of self-consumption such that battery systems become unprofitable. The current rates of remuneration are at 12.30 Cents/kWh.[259] Thus, the compensation is too high to allow a battery storage system (that is operated for increasing self-consumption) to be financially lucrative. For the 20-year-period the EEG-contracts guarantee these rates of remuneration, photovoltaic installations that have already been built will not have financial opportunities in retrofitting storage systems under the assumption of constant electricity retail prices. Regulations that limit the power that can be sold to the grid could deliver a similar incentive for self-consumption. Current regulations regarding feed-in limitations on photovoltaic facilities however do not show any impact on the optimal battery size. To incentivize battery installations via feed-in curtailments, every residential photovoltaic owner would have to be forced to cut feed-in power above 26% of the installed capacity.

The one-dimensional simulations of every influencing parameter have revealed that at the currently assumed market situations no parameter could solely financially justify the high investment costs of a battery installation. The only scenario where a battery storage system shows immediate profitability is for photovoltaic owners that are fading out of the fixed EEG-compensations. These investors could be facing rates of remuneration at around 3 Cents/kWh. However,

[259] Bundesnetzagentur für Elektrizität Gas Telekommunikation Post und Eisenbahnen (2017) Photovoltaikanlagen - Datenmeldungen und EEG-Vergütungssätze.

battery installations on new residential photovoltaic systems might be profitable in the near future. The experimental simulation with presumable parameters for the year 2020 already shows financial opportunity in battery storage systems.

Finally, it should be critically highlighted that all simulations using this linearized approach are based on multiple assumptions and therefore not meant to be used on calculations regarding a specific business case. The optimal battery sizes calculated in this thesis are usually not available at the market. The results depend on the assumed parameters and are not suitable to draw conclusions about an optimal investment for a specific household's consumption pattern. Every household faces different solar radiation and has an individual consumption behavior, causing big deviations from the results of this study. The simulations of this paper instead focus on the general connections and impacts of various political- and market-driven parameters on the profitability of residential storage. The key results of this paper are heavily based on the input values and can thus be improved by using more accurate data or more precise parameter values. Production and consumption profiles in a frequency resolution higher than the current hourly pattern can improve the accuracy. In addition, there is plenty of room for further research in similar variations for different application purposes.

Since these one-dimensional simulations assume multiple fixed parameters, for example the size of the photovoltaic system, future research could focus on optimizing the system setup in a multidimensional approach in order to calculate political boundaries and necessary subsidies. As increasing photovoltaic self-consumption is only one way to operate battery storage systems, follow-up studies could integrate additional operation modes into the net present value calculations and clarify how political regulations and market design influence the profitability of investments in stacked battery storage systems. As Gährs et al. (2015) already mentioned, it is complex to operate residential storage that is usually used for storing photovoltaic rooftop power, in peak-shaving applications or use it for balancing the grid. If battery capacity is used for auxiliary services, the available capacity for self-consumption is lowered, which could lead to economic losses.[260] Further work on this topic could develop a storing and capacity partitioning mechanism that works in a revenue optimizing way. Similar to the algorithm of this paper, an advanced optimization algorithm could continuously switch to the currently most profitable application. This paper focuses on residential usage of battery storage systems in combination with a rooftop photovoltaic facility. By switching the perspectives, similar simulations on an aggregated level could determine critical boundaries for the grid operators. Since multiple storage installations affect the energy flows in the grid, a simulation of energy streams could compare the results of changing profitability of residential storage with alternative costs for peak-shaving facilities on grid-side at different market and regulatory environments.

Battery storage systems in combination with residential solar plants might be one of the key elements to path the way for a transition towards a fully renewable energy supply. The boundaries of a supporting political environment are only one small part of a complex energy system. There are many open questions that can be important for the valuation of battery storage systems and for the identification of necessary political measures towards a greener future.

[260] Gährs et al. (2015) pp. 29-30.

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