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Self-consumption of solar electricity –  
Modelling profitability and market diffusion  
of photovoltaics and battery systems in the  
residential sector



Fraunhofer-Institut für  
System- und Innovationsforschung ISI

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# Self-consumption of solar electricity

Modelling Profitability and Market Diffusion of  
Photovoltaics and Battery Systems in the Residential  
Sector

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## **ABSTRACT**

The transformation of the energy system includes increasingly active market participation by formerly passive consumers via the installation of photovoltaic (PV) systems for decentralized production and on-site consumption of electricity, so-called self-consumption. A holistic understanding of the market diffusion of PV + battery systems for self-consumption requires a technology diffusion model that considers economic, behavioural and technological market drivers.

A model is developed that considers technical restrictions of PV production and flexible electricity consumption as well as sociological data on consumer behaviour and preferences. An individual analysis of 415 real-world household electricity consumption profiles, as well as electric vehicle charging and heat pump operation profiles allows to determine the system configuration that will optimize individual profitability. The profitability of each system is calculated based on its total cost of ownership and the consumers' preferences expressed in a willingness to pay more. The developed method closes an important research gap and allows to attain a profound knowledge on the preconditions for market formation and development, and to assess the potential of PV self-consumption.

The results show that in the early stages of market formation, the diffusion of PV + battery systems is primarily driven by technology and innovation-oriented households who are willing to pay above the financial benefits generated by the system. In the medium- to long-term, the electricity and battery prices as well as the adoption rates are the main driver for the installation of battery enhanced PV self-consumption systems. Under favourable conditions, such as increasing electricity prices or decreasing battery prices, the installation of a PV + battery system will be financially attractive for every households in single- and two-family houses in Germany.

## **KURZFASSUNG**

Die Transformation des Energiesystems beinhaltet eine zunehmend aktive Marktteilnahme von ehemals passiven Verbrauchern durch die Installation von Photovoltaik(PV)-Anlagen zur dezentralen Erzeugung und dem Vor-Ort-Verbrauch von Strom, der so genannten Eigenversorgung. Für ein ganzheitliches Verständnis der Marktdiffusion von PV + Batteriesystemen zur Eigenversorgung ist ein Technologiediffusionsmodell erforderlich, das ökonomische, verhaltensbezogene und technologische Markttreiber berücksichtigt.

Es wird ein Modell entwickelt, das die technischen Restriktionen von PV-Produktion und flexiblem Stromverbrauch abbildet und zusätzlich soziologische Daten zu Nutzerverhalten und -präferenzen berücksichtigt. Eine individuelle Analyse von 415 realen Haushaltslastprofilen, sowie von Profilen die den Ladevorgang von Elektrofahrzeugen und dem Betrieb von Wärmepumpen abbilden, erlaubt es die rentabilitätsoptimale Systemkonfiguration zu ermitteln. Die Rentabilität jedes Systems wird auf der Grundlage seiner Gesamtbetriebskosten und der Nutzerpräferenzen berechnet, welche sich in einer erhöhten Zahlungsbereitschaft ausdrücken. Die entwickelte Methode schließt eine wichtige Forschungslücke und ermöglicht es, fundierte Kenntnisse über die Voraussetzungen der Marktbildung und -entwicklung zu erlangen, sowie die Potenziale von PV-Eigenversorgung abzuschätzen.

Die Modellergebnisse zeigen, dass die Diffusion von PV + Batteriesystemen in der Frühphase der Marktbildung vor allem von technologie- und innovationsaffinen Haushalten getrieben wird, die eine Zahlungsbereitschaft aufweisen, die über den finanziellen Nutzen des Systems hinausgeht. Mittel- bis langfristig sind Strom- und Batteriepreise sowie Adaptionraten die Haupttreiber für die Installation von batteriegestützten PV-Eigenversorgungssystemen. Unter günstigen Bedingungen, wie steigenden Strompreisen oder sinkenden Batteriepreisen, wird die Installation eines PV + Batteriesystems für jeden Haushalt in Ein- und Zweifamilienhäusern in Deutschland rentabel sein.

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## **LIST OF PUBLICATIONS**

This thesis is based on the following publications, which are listed in the following including a summary for each publication and notes on my individual contributions. In the thesis, it is referred to the publications by their Roman numerals.

**Publication I: Klingler, A.-L.,** Schuhmacher, F., 'Residential photovoltaic self-consumption: Identifying representative household groups based on a cluster analysis of hourly smart-meter data', *Energy Efficiency*, Vol. 11, Issue 7, pp. 1689-1701 (2018).

**Summary:** The focus of this publication is the effect of electricity consumption behaviour on self-consumption and self-sufficiency rates. Since the profitability of PV self-consumption systems largely depends on the match of PV electricity production and the household's consumption, it was found that the consumption behaviour affects the consumer's profitability of a self-consumption system significantly. In energy system modelling, a household's consumption behaviour is commonly represented by means of a standard load profile. However, the household sector's heterogeneity is not reflected in one single profile, and the use of only one load profile thus results in a misjudgement of the profitability of self-consumption. In this study, we generated a set of representative household groups based on their electricity consumption structure. These groups better represent the heterogeneous residential consumption behaviour. The household groups were compiled through a cluster analysis of hourly electricity consumption data from a smart-meter study, using household characteristics as explanatory variables. Between the average load profiles of the groups, significant differences were found. Subsequently to the cluster analysis, the electricity supply with a PV and a PV + battery self-consumption system was simulated for each household individually. We found that the achievable level of self-consumption also differs between the groups, which in turn affects the profitability of the PV + battery systems. We conducted a binary logit regression analysis, which revealed that employment and the presence of children are distinguishing factors for the different types of self-consumers. These results suggest that (i) within the heterogeneous household sector, four homogeneous cluster groups could be identified with distinctive electricity consumption characteristics explained by consumer behaviour. Based on this finding, it can be said that the residential sector cannot be well represented by one individual or average consumption profile. (ii) Different self-consumer types can be identified through socio-demographic characteristics: We found that unemployed households achieve the highest self-sufficiency rates with an average of 40% with a 5 kW PV system, the lowest rates with 30% on average occur within households of educated families. When combined with a 7.5 kWh battery, the self-sufficiency rates vary between 56% and 67% over all groups. (iv) Although the discrepancies in consumption behaviour are significant, the effect of these differences on the consumers' profitability is still limited under the current market conditions in Germany.

**My contribution:** I wrote all of the paper, did the statistical analysis and validated the cluster analysis. Further, I modelled the self-consumption with a PV + battery system for the different households, and calculated the self-sufficiency rates.

**Publication II: Klingler, A.-L.** 'The effect of electric vehicles and heat pumps on the market potential of PV + battery systems', *Energy*, Vol. 161, pp. 1064-1073 (2018).

**Summary:** In this publication, the focus is on the effect of electric vehicles and heat pumps on the market potential of stationary batteries for the enhancement of self-consumption until 2040. The study develops a self-consumption model in which 415 individual household consumption, heat pump and vehicle charging profiles are used to address differences in the consumption behaviour between individual households. To assign a charging profile to each individual household, the similarity in socio-demographic characteristics between each household and each charging profile was calculated. Regarding the heat pumps, the individual heat demand of each household was derived based on its living space and number of inhabitants. Since heat pumps are considered to be installed in combination with a thermal storage, i.e. a hot water tank or the thermal mass of the building, its optimal operation is the most economical solution to raise the household's self-consumption. Thus, the load optimization of the heat pump was conducted prior to the determination of the optimal battery load. The charging of electric vehicles is not optimized in this study, all vehicles are charged after the last trip. Most of the vehicles in the sample are not at home during the day, so the possibility to shift charging loads towards midday hours to increase direct self-consumption is limited. Subsequent to the optimal load scheduling of the heat pumps, the battery operation for each household with its individual electricity consumption profile is determined, using different sizes for PV panel and battery, and the self-consumption for each system configuration is calculated. Self-consumption with PV + battery systems is modelled for conventional households, households equipped with an electric vehicle, households with a heat pump, and households with both, an electric vehicle and a heat pump. The results of the self-consumption calculations serve as input to the subsequent analysis of the market potential.

The results of this study show that the diffusion of electric vehicles can increase the market for stationary batteries to enhance self-consumption by enabling to charge the electric vehicles after their arrival at home in the evening hours with self-produced PV electricity. In contrast, the installation of heat pumps or other forms of electric heating systems increases the direct consumption of PV electricity and thus reduces the profitability of a stationary battery. This is particularly the case, if the heat can be stored and the heating loads can be scheduled for hours with PV production. However, although the diffusion of electric vehicles and heat pumps affects the market for stationary batteries, the market potential of PV + battery systems for the purpose of self-consumption stands and falls with the electricity and equipment prices.

**My contribution:** I wrote the entire paper, connected household consumption profiles with vehicle charging and heat pump profiles. I modelled the self-consumption with a PV + battery system, and analysed the results.

**Publication III: Klingler, A.-L.,** Teichtmann, L., 'Impacts of a forecast-based operation strategy for grid-connected PV storage systems on profitability and the energy system', *Solar Energy*, Vol. 158C, pp. 861-868 (2017).

**Summary:** In this publication, we developed a forecast-based operating strategy for stationary battery systems with dual use: The primary use is the enhancement of PV self-consumption, as a secondary objective the battery is applied to make use of spreads in the electricity price in the case of hourly real-time pricing. The operation strategy of the battery in this study can be considered more system-friendly than a simple relay-based operation: First, electricity is provided to the system at times of high electricity prices, which are typically based on the variable costs of the marginal technology of electricity production. Second, the forecast-based operation reduces the feed-in peaks from the PV system that could otherwise be challenging to the distribution grid. The operation strategy is based on electricity demand and production forecasts and a real-time price function. The focus of the result evaluation is consequently on the effect of forecasting errors on the batteries' economic performance.

PV electricity production and electricity consumption are forecasted on an hourly time-resolution using artificial neural networks (ANN). ANN are particularly suitable for forecasting in the renewable energy field, since they are capable of learning and have the capacity to recognize patterns in data sets, memorize the structure and use the acquired knowledge at a later point in time. In our study, we chose feed-forward networks with three layers and backpropagation as learning rule. The input parameters for the PV production forecasting are hourly *air temperature*, *global irradiance* and *air humidity* data. Residential consumption is forecasted on basis of *load values from the proceeding day*. Regarding PV production and load forecasts, the ANN outperforms a persistence forecast by around 23%. With the forecasted values as input data, the battery charging and discharging is optimized to maximize self-consumption. Additionally, an optimal feed-in schedule is determined to benefit from the variable feed-in tariff. The developed model was applied in a case study for a household with an electricity consumption of 3,300 kWh per year that is equipped with a 5 kW PV system and a 5 kWh battery. For this case, we show that the model enables an intensified battery usage compared with a simple relays-based battery operation strategy that only maximizes self-consumption. However, the inevitable forecasting errors lead to overall lower economic benefits for the consumer in comparison with the simple relays-based strategy. Considering the inaccuracy of forecasting, we conclude that, if a system-friendly integration of PV + battery systems is to be promoted in the future, households should be provided with better forecasting data or offered other incentives to compensate for their lost benefits.

**My contribution:** I wrote parts of the paper (literature review, formal model description, validation of the results) and did the validation of the forecasting results.

**Publication VI: Klingler, A.-L.**, 'Self-consumption with PV + battery systems: A market diffusion model considering individual consumer behaviour and preferences', *Applied Energy*, Vol. 205C, pp. 1560-1570 (2017).

**Summary:** In this paper, a market diffusion model is developed and tested that aims to project future installations of stationary battery systems for the enhancement of PV self-consumption. The model integrates user-specific data to allow for a better evaluation of the technology adoption process. Current studies that address self-consumption, focus mainly on economic aspects and neglect the influence of individual electricity consumption behaviour and consumer preferences on the individual utility of a self-consumption system. Yet, preferences and behaviour have a significant impact on the market uptake of new technologies, as can be seen in the current sales figures of batteries for the purpose of self-consumption enhancement. The technology is purchased, even though it is still far from being economically viable. In this study, a market diffusion model is developed that is based on 415 individual electricity load profiles that define the homeowners' consumption behaviour. Additionally, consumer preferences, which are expressed in varying willingness to pay for a stationary battery for the enhancement of self-consumption, are considered in the developed model. The results of a market survey are used to explicitly model the different adopter groups *Innovators*, *Early Adopters*, *Early Majority*, *Late Majority* and *Laggards*, and map their willingness to pay. The market survey shows that homeowners, who are likely to adopt a self-consumption technology, i.e. have a higher willingness to pay, are on average characterised by higher annual electricity consumption. However, the consumption behaviour is heterogeneous within each user group. Thus, also the individual utility of a battery for self-consumption enhancement differs significantly. Based on the comparison of the actual financial benefit and the willingness to pay for each household, a willingness to pay more of on average 60% for the *Innovators* group could be calculated. The overall results of the market diffusion modelling show that consumer preferences have a significant influence on the market formation in its early stage. The integration of consumer behaviour and preferences in diffusion modelling allowed for better insights into the diffusion of self-consumption technologies. The modelling approach proposed in this study is able to explain the past development of battery installations in private households in Germany. Until 2030, the model simulations suggest a moderate development of battery enhanced self-consumption, resulting in a total capacity of installed batteries of 2 GWh in private households in 2030. However, the model results are highly sensitive to the assumed electricity and technology prices and therefore subject to uncertainties.

**My contribution:** I developed the modelling approach, prepared the load data, modelled self-consumption with PV + battery systems, and wrote all of the paper.

**Publication V: Klingler, A.-L.,** Luthander, R., 'Market diffusion of residential PV + battery systems driven by self-consumption: A comparison of Sweden and Germany', *Working Papers "Sustainability and Innovation"*, Fraunhofer ISI, No. S 18/2018.

**Summary:** In this publication, we evaluate and compare the market diffusion of residential PV systems for detached houses in Germany and Sweden. For this purpose, a hybrid model of the adoption of PV installations driven by self-consumption is applied. We model the profitability and the investment decisions for PV systems in a first step and account for inhibiting factors by introducing an adoption rate. The adoption rate is based on empirical data from the market diffusion of heat pumps in Sweden. Further, we address the market diffusion of battery systems aimed to increase self-consumption. A base case with several sensitivities on long-term trends of different parameters is analysed to examine the variation of the market diffusion until 2040. The results show that self-consumption rates are generally higher in Sweden than in Germany. This is due to the higher electricity consumption in Swedish households that can partly be explained by higher shares of heat pumps and other forms of electricity-based heat provision. However, regarding the current and future market shares of PV systems, we find large difference between Germany and Sweden. Currently we see an estimated 240,000 installed PV systems for self-consumption in Germany compared to less than 10,000 PV systems in Sweden (i.e. 0.6% of households in Germany and 0.2% in Sweden, state as of 2015). In 2040, a base case scenario results in a market share for PV systems of 65% of the German detached houses by 2040, compared to 12% in Sweden. The reason is that direct and indirect support for PV self-consumption is considerably higher in Germany. The main driver for PV self-consumption is a high electricity price. Since the level of the electricity price defines the level of savings through self-consumption. Electricity costs more than twice as much for residential consumers in Germany than in Sweden. Correspondingly, our results show that the market share in Sweden is most sensitive to electricity price changes, whereas the German market is most sensitive to changes in the adoption rate. Since the high electricity price for households in Germany makes PV profitable for most of the households at an early stage, it is mainly the adoption rate that limits the market diffusion in Germany. For Sweden, where the electricity price is much lower, the profitability is the main limiting factor. The market share for battery systems is 5% in Germany and 0% in Sweden in 2040 in the base case scenario. In summary, the results show the influences of several parameters on the market diffusion based on the different initial market conditions, which can be extended to other national markets.

**My contribution:** I did the analysis of the consumption behaviour in Sweden and Germany and wrote it up, I wrote the model description, modelled and analysed the market diffusion of PV + battery systems in Germany and wrote it up.



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# 1 INTRODUCTION

## 1.1 Background and problem definition

The European electricity system is undergoing a profound transformation that will persist for several decades. The transformation includes increasingly active market participation by formerly passive consumers via the installation of photovoltaic (PV) systems for decentralized production and on-site consumption of electricity, so-called self-consumption. Self-consumption is particularly profitable in countries with high electricity purchasing prices and low levelized costs of electricity (LCOE) for PV. The potentially large margin for self-consumed electricity leaves room for owners of a PV system to increase their self-consumption, even if it involves additional costs for technologies such as stationary batteries and active load control (Schill et al. 2017). In the future, falling costs for PV systems and technologies for the enhancement of self-consumption could further drive the market development of decentralized electricity production.

Due to its dynamic development, decentralized self-consumption is now a much debated topic. Some studies stress the benefits of PV self-consumption for the energy system, like the resulting support for the energy transition (Campoccia et al. 2014), (EU Commission 2015), (May and Neuhoff 2016), while others take a more critical view and, amongst others, point to economic inefficiencies (Munoz et al. 2014). Detailed discussions and comparisons of the advantages and disadvantages can be found in (Bird et al. 2013), (CEER 2016), (Schill et al. 2017).

However, irrespective of which side one takes in this ongoing debate, the first question that need to be answered in order to assess potential benefits or adverse consequences, is how many self-consuming households can be expected in the future. More specifically, the question is whether and how the diffusion of PV and PV + battery<sup>1</sup> systems for self-consumption will develop over the next decades.

Besides market actors, such as electricity consumers and retailers, the diffusion of PV or PV + battery self-consumption systems is particularly relevant to policy makers. In Germany, PV self-consumption is still dependent on government subsidies and incentives. It is therefore incumbent upon policy makers to steer the market development towards a sustainable path. To address the possible effects of residential self-consumption, recent studies assess the economic benefits for individual households and different battery systems (Weniger et al. 2014), (Bruch and Müller 2014), (Thygesen and Karlsson 2014), (Kelleher and Ringwood 2009) or load management options (Widén 2014), (Widén and Munkhammar 2013). On a system level, the overall potential of self-

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<sup>1</sup> This thesis explicitly includes the diffusion of stationary battery units, since about every second rooftop PV system in Germany is now installed with a battery: In 2016 45% of new PV installations under 30 kW in Germany included a battery, in 2015 the share of PV systems with a battery was even 53% (Figgner et al. 2017), (Kairies et al. 2016)

consumption has been estimated for Germany (Deutsch and Graichen 2015) and possible paths for market diffusion are assessed (Bardt et al. 2014), (Prognos 2016a). The focus of these studies is on economic aspects. However, consumers do not install self-consumption systems only for economic reasons. On the contrary, recent studies show that, while the installation of a PV self-consumption system is profitable for the consumers under current conditions, the additional installation of a battery for the enhancement of self-consumption does not result in financial gains. Nevertheless, Germany sees an estimated 60,000 installed batteries in 2017 (Figgenger et al. 2017). How can this apparent contradiction be explained?

Studies show that non-economic factors play a key role in shaping private consumer preferences and have a significant influence over investment decisions, in particular for technologies that are perceived as innovative or beneficial to the environment. Achtnicht (2011) for example finds that CO<sub>2</sub> savings influence the choice of heating systems. Borchers et al. (2007) show that residential consumers value solar electricity higher than electricity from other sources, and Peters and Dütschke (2014) find that some people opt for an electric vehicle for non-financial reasons such as innovativeness and environmental benefits. It is reasonable to assume that similar factors may affect the decision over whether to install a self-consumption system. For self-consumption technologies, the ideas of self-sufficiency and the possibility to make a positive contribution to the energy transition are of particular relevance to consumer choice. PV self-consumption is perceived as enabling a decentralized, renewable energy system and as a means of risk provisioning against rising electricity prices due to enhanced self-sufficiency (Balcombe et al. 2014), (Kairies et al. 2015), (Longo et al. 2008), (Oberst and Madlener 2014), (Karakaya et al. 2015). The possibility to participate in the energy system's transition process and hedge against rising electricity prices triggers a relatively high willingness to pay (WTP) (Zerres 2015), (Oberst and Madlener 2014). For some households, the WTP is higher than the financial benefits that self-consumption systems can actually provide.

Besides the consumers' preferences, their electricity consumption behaviour has a significant impact on the economics of a PV + battery system: high consumption levels during hours with PV production lead to high direct self-consumption and low usage of a battery to offset the demand, and vice versa. Since individual households differ considerably in their consumption behaviour (Klingler et al. 2016), the financial benefits a PV + battery system will afford them also differs. These differences in consumption behaviour could thus potentially influence the consumer's decision whether to invest in a self-consumption system. This is a particularly relevant aspect, since the introduction of new household equipment, such as electric vehicles and home automation systems, will change households' consumption patterns in the future and therefore greatly influence how profitable self-consumption systems are for consumers (Kaschub 2017).

As has been pointed out in this section, many questions remain unanswered despite a number of recent studies on PV self-consumption. In particular, the market diffusion of self-consumption systems has not yet been fully investigated. A better understanding of the market dynamics will help inform the ongoing debates about the value of self-consumption, and will further help in the design of future support systems for decentralized PV + battery systems.

## 1.2 Objective and Research questions

The objective of this thesis is to systematically investigate the current and future market potential for residential self-consumption with PV + battery systems in Germany. Specifically, the effect of different drivers on the profitability of PV + battery systems is to be modelled, and conclusions about market diffusion are to be drawn. Furthermore, the main drivers at early as well as at medium-term stages of the market uptake are to be identified. A particular focus is thereby on individual households, their behaviour and socio-economic differences.

This objective will be addressed by answering the following research questions:

- i. The profitability of a PV self-consumption system for the individual household largely depends on the temporal match of PV electricity production and the household's consumption. Thus, the consumption behaviour significantly affects the profitability of a self-consumption system. Further, non-financial motivations and barriers are known to influence the perceived utility of a technology. Both aspects are commonly neglected, and no approach to integrate individual consumers into the market diffusion modelling of self-consumption technologies has been presented so far. With respect to behavioural drivers as a key variable for the market diffusion of innovative technologies, the question arises:  
**How do consumer behaviour and preferences influence the profitability of residential PV + battery systems?**
- ii. The diffusion of electric vehicles and heat pumps affects a household's electricity consumption more than other technologies, not only in terms of the total amount of electricity consumed, but also in terms of the temporal distribution. Recent studies address the impact of electric vehicles and heat pumps on PV + battery systems, however, they are limited to individual technologies or a small number of households that cannot represent the entire residential sector. Further, the effect of these new technologies on the market potential for PV + battery systems has not been analysed. The following research question therefore arises:  
**How do electric vehicles and heat pumps influence the profitability of PV + battery systems?**
- iii. A high penetration of grid-connected PV systems can lead to difficulties regarding their integration into the existing electricity system. The necessity of a more system-friendly operation of battery systems for the enhancement of self-

consumption is therefore widely discussed and partly promoted by the government. System-friendly operation strategies require forecast data, such as predictions of PV electricity production and household consumption. The effects of such a system-friendly operation, including potential forecasting errors, on the profitability of the individual PV + battery system has, however, not been investigated. The following question arises:

**How does a system-friendly battery operation influence the profitability of PV + battery systems?**

- iv. The different drivers and aspects addressed in the research questions i) to iii), which influence the profitability of PV + battery systems for the purpose of self-consumption, suggest a variety of factors that potentially affect its market diffusion. To put the individual aspects into perspective, ultimately the following research questions are to be answered:

**What is the market potential of PV + battery systems in Germany? What are the main drivers for market formation and diffusion of PV + battery systems in the short to medium-term?**

Figure 1 connects the posed research questions with the publications that are included in this thesis.

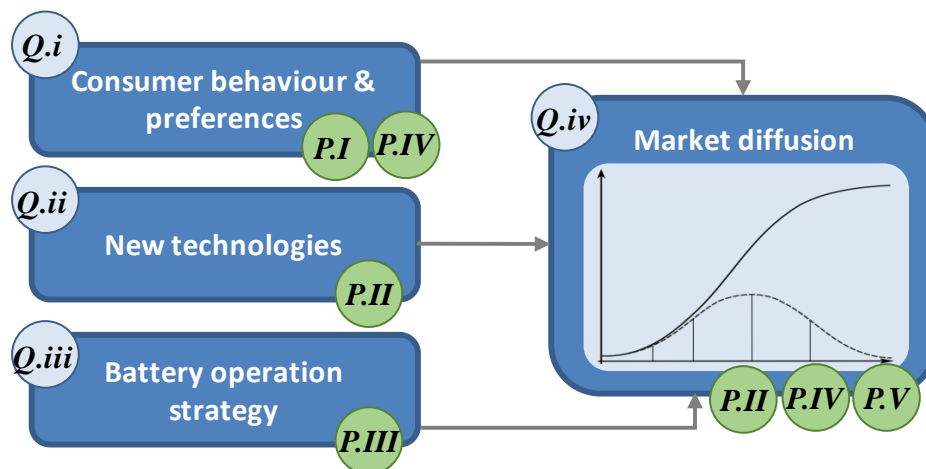


Figure 1: Overview of the research questions (Q.i to Q.iv) and the connected publications (P.I to P.V) that are included in this thesis.

### 1.3 Structure of the thesis

This thesis comprises five chapters, including this introduction. The chapters are based on or structured around articles that have been published in (Publication I, II and IV), or are currently reviewed (Publication III and V) by international peer-reviewed scientific journals.

*Chapter 2: Self-consumption of solar electricity*

This chapter presents the background to self-consumption modelling. The variety of market drivers in the context of PV self-consumption technologies are discussed and the past development of solar self-consumption in Germany is presented. Based on existing studies of the diffusion of innovative technologies and self-consumption, different aspects of self-consumption modelling are discussed.

*Chapter 3: Material and methods*

The requirements that must be met by a suitable methodology to answer the questions posed in this thesis are listed, and based upon these, a methodology is developed. The reasons for the developed methodological approach are given. Furthermore, data requirements are discussed and the applied data is presented.

*Chapter 4: Results*

In this chapter, the major findings from each of this thesis' publications are presented and placed in the broader context as defined by the research questions.

*Chapter 5: Discussion, conclusions and outlook*

This chapter synthesizes the achievements and findings of this thesis for understanding the market for residential PV + battery systems for self-consumption. It critically reflects on the limitations of this thesis and outlines further research needs.



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## **2 SELF-CONSUMPTION OF SOLAR ELECTRICITY**

This section aims to show the need for research in the field of solar self-consumption and serves to point out what can be learnt from earlier works when modelling self-consumption and market diffusion of innovative technologies. It contains two sections: the first Section 2.1 reviews the drivers for the diffusion of self-consumption technologies. These drivers are to be considered in the model developed by this thesis. In addition, the specific support schemes for self-consumption in Germany and its past development are laid out. In the second Section 2.2, a structured literature review of self-consumption models is presented in order to gain insights from existing modelling approaches.

### **2.1 Background of solar self-consumption**

Residential self-consumption is not a new idea. Already in the 1970s and 80s, self-sufficient buildings with respect to electric power were discussed and realized (Leckie et al. 1975), (Voss et al. 1996). However, the necessary technologies for self-consumption at that time were costly, and the few realized installations were mostly part of pilot projects. This has now changed: technology costs have decreased significantly, and we currently see a dynamic development in the adoption of self-consumption technologies. Furthermore, new business models and application possibilities are quickly emerging. In this section, the most important drivers of the current development of self-consumption are discussed. Following Couture et al. (2014), economic, behavioural and technological drivers are distinguished.

#### **2.1.1 Drivers of self-consumption**

##### **2.1.1.1 Economic drivers**

For the vast majority of households, the decision to invest in PV systems is primarily driven by its expected economic performance (Claudy et al. 2010), (Peter et al. 2002), (Scarpa and Willis 2010). The economic performance is mainly determined by the PV system costs, end-consumer electricity prices, the regulatory regime, insolation, and the ratio of self-consumption.

##### **Cost of PV electricity**

The levelized cost of electricity includes investment in PV system components, such as modules and inverters, as well as labour costs. Modules generally account for the largest share of the system costs in small-scale PV systems (Bortolini et al. 2013), amounting to about 40% of the total cost in Germany (Kelm et al. 2014). Between 2010 and 2015, PV

modules from China have seen a price drop of more than 60%, from 1.5 to 0.5 EUR/W<sup>2</sup>. Accordingly, the system costs have also decreased rapidly, by about 20% per year (Fraunhofer ISE 2015), (Schleicher-Tappeser 2012), and range currently between 1 and 1.68 EUR/W for small-scale systems in Germany (state of 2014, (Bruch and Müller 2014), (Fraunhofer ISE 2015)). Even though the development is not expected to continue at the same pace for the next decades, recent studies anticipate further declining PV system costs (Breyer and Gerlach 2013), (Breyer et al. 2015), (EPIA 2012), (Fraunhofer ISE 2015). For the long-term perspective, findings go as low as 0.28 EUR/W in Germany (Fraunhofer ISE 2015). Self-evidently, lower costs for PV modules will improve the LCOE and thus the economics of solar self-consumption.

Furthermore, the LCOE is determined by module efficiency and solar insolation. It therefore varies between countries or even within one country.

### **End-consumer electricity prices**

End-consumer electricity prices include the costs to produce electricity, the costs for the electricity transmission and distribution system, additional taxes and surcharges levied by the government, and a profit margin. High end-consumer prices generally increase the value of savings from self-consumption and therefore improve the return on investment. Another factor in the economic outcome of PV self-consumption is the pricing policy applied. Electricity prices for end-consumers can include both volumetric and non-volumetric charges. Volumetric charges are paid for every kWh of electricity consumed and thus vary with the amount of electricity purchased. Non-volumetric (or fixed) tariffs are charged independently of the amount of electricity purchased and can include for example charges based on the size of the connection to the grid, so-called capacity-based network fees.<sup>3</sup> Volumetric and non-volumetric charges can also be combined in one tariff.<sup>4</sup> Volumetric tariffs encourage self-consumption of electricity, since every unit of electricity produced and consumed onsite will generate savings equal to the full end-consumer electricity price.

Volumetric tariffs can also be time-based. Time-variable tariffs are introduced to reflect the dynamics in the underlying costs of electricity production due to changes in demand over time (U.S. Department of Energy 2006). Different time-based tariffs are currently used in Europe and elsewhere<sup>5</sup>, for example in the form of so-called real-time pricing

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<sup>2</sup> pvXchange price index <http://www.pvxchange.com/priceindex>

<sup>3</sup> Capacity based-network fees exist for example in France (Couture et al. 2014) or the Netherlands (EU Commission 2015).

<sup>4</sup> For instance in Spain or Italy the electricity grid tariff consists of a flat component (EUR/household), a component billing the connected load (EUR/kW), and a progressive volumetric component (EUR/kWh) (EU Commission 2015)

<sup>5</sup> In Sweden every household has the right to a RTP tariff, but it is not mandatory. The electricity supplier pays for the necessary metering equipment (Vesterberg et al. 2014).

(RTP). RTP is a tariff scheme that reflects the variations in electricity costs over short time intervals, typically hourly. The effect of a time-based electricity tariff on the economics of PV self-consumption is not clear. Ong et al. (2012) point out that time-based rates do not always result in a net benefit for self-consuming households.

### **Feed-in remuneration**

To promote renewable electricity production, many countries have introduced a remuneration for the feed-in of renewable electricity into the public grid. SolarPower Europe (2017) provides a comprehensive overview of current support schemes. Feed-in remuneration for small-scale systems can take the form of feed-in tariffs (FiT) or feed-in premiums (FiP). Another, more indirect form of feed-in remuneration, is net metering or net billing (Held et al. 2014). Feed-in remuneration typically supports self-consumption, since they value excess produced electricity and therefore improve the return on investment. Of course, this is only true up to a certain level of remuneration: If feed-in remuneration exceeds the electricity end-consumer price, self-consumption is inhibited; it is then more economical to feed-in the entire PV produced power.<sup>6</sup>

### **Self-consumption rate**

The self-consumption rate<sup>7</sup> is an indicator of the match between the PV production and onsite consumption. A high self-consumption rate generally increases the economics for PV self-consumption and is therefore a critical driver for its profitability. How much electricity a household consumes at any given time is to a significant extent determined by whether (and how many) household members are at home at that point in time. Therefore, if household members are at home during the day, when the PV electricity is produced, then the amount of direct self-consumption will likely be higher than in the case of absent household members (Klingler et al. 2016). Moreover, technological solutions can help improve the self-consumption ratio by means of increase or dispatch of onsite electricity consumption (see Section 2.1.1.3).

#### **2.1.1.2 Behavioural drivers**

Behavioural drivers refer to a range of (primarily) non-financial motivations and barriers associated with the adoption of a technology. A compelling economic case is not necessarily enough motivation for a household to adopt PV self-consumption, and vice versa. In the past, some consumers have invested in PV systems when it was not financially advantageous to do so (Tatum 1992). Other consumers may not adopt PV self-consumption systems even when it would be profitable.

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<sup>6</sup> This was the case in Germany: up until the year 2012 the FiT exceeded the residential end-consumer electricity price (Quaschnig 2012); see also Section 2.1.2

<sup>7</sup> Self-consumption rate is defined as the self-produced electricity that can be consumed onsite divided by the total electricity production

Some of the factors that motivate or hinder residential consumers to become PV self-consumers are discussed below, starting with the motivations. The importance of the factors varies between individual households. There is little agreement across the literature on the ranking of factors regarding their importance. The exceptions are finance and environment, which are generally considered as the most important motivations or barriers (Balcombe et al. 2013). Related collections of motivating and hindering factors can be found in (Balcombe et al. 2013), (Bergman et al. 2009), (Oberst and Madlener 2014).

- *Perception of economic benefits*: As stated before, the expectation of gaining economic benefits is the most important consideration in the investment decision for a self-consumption system. It is worth noting that the perception of costs and benefits is sometimes inaccurate and differs significantly between individual households (Grösche and Vance 2008). For example, in a survey on microgeneration in London, Ellison (2004) finds that most of the respondents assumed the costs of a PV system to be considerably lower than they actually were. Sauter and Watson (2007) state that "this lack in information applies also to the expected generation of electricity" from this technology.
- *Perception of environmental values*: Environmental attitudes and beliefs are an equally relevant factor for consumers' investment decisions: Achtnicht (2011) and Claudy et al. (2011) find that environmental concerns affect householders' choices for heating systems. In similar studies on microgeneration and self-consumption, Claudy et al. (2010) and Leenheer et al. (2011) find a positive effect of the perceived possibility to help improve the environment on the intention to produce one's own electricity.
- *Self-sufficiency*: Self-sufficiency motivates consumers that value the ability to (partly) sustain themselves and gain independence from third parties. The importance of self-sufficiency in the decision process for self-consumption is supported by the findings in (Gähns et al. 2015), (Oberst and Madlener 2014). According to Palm and Tengvard (2011) the adoption of small-scale self-consumption systems is a way to "protest against 'the system', with its large dominant actors, or a way to become self-sufficient". Additionally, increases in end-consumer electricity prices also contribute to a desire to protect against future price rises by means of some degree of self-sufficiency (Praetorius et al. 2010).
- *Interest in innovative technologies*: Particularly the early adopters of self-consumption technologies include many technology enthusiasts, who are motivated by an interest in the technologies themselves (Caird and Roy 2010).
- *Status and prestige*: Many studies demonstrate that people want to show their environmental commitment to others (Pedersen 2000), (Rohracher 2003), (Skill 2008) or their ability to handle complex technologies (Palm and Tengvard 2011). Self-production technologies such as PV systems, which are

visible to others, offer the opportunity for householders to make a statement about their environmental beliefs and technological abilities (Palm and Tengvard 2011).

Barriers associated with adopting self-consumption technologies are mostly based on financial considerations or simply the uncertainty about the validity of the above described motivating factors.

- *High investment*: Apart from the possibility of losing money with the installation of a self-consumption system, residential consumers are deterred from the purchase of such a system by high upfront investments. An additional barrier is the long or uncertain payback time (Balcombe et al. 2013), (Caird and Roy 2010).
- *Uncertainty*: Uncertainty includes a range of hindering factors, from an uncertainty about the economic case to a lack of confidence in the actual environmental benefits. A lack of trust in the performance and reliability of new and unfamiliar technologies is also a major barrier for the adoption of self-consumption. A reason for high levels of uncertainty is that households find it difficult to obtain reliable information due to complicated legislation or the relative novelty of the technology (Balcombe et al. 2013), (Caird and Roy 2010).

In general, non-financial values encourage the adoption of PV systems rather than hinder it. Although these values are not considered sufficiently strong to drive the scale-up of residential self-consumption on its own (Scarpa and Willis 2010), a positive view of self-consumption and its social acceptance is a key driver of market formation (Praetorius et al. 2010).

### **2.1.1.3 Technology drivers**

In addition to economic and behavioural drivers, technological developments can also influence the scale-up of PV self-consumption. In this section, the focus is on currently discussed technologies that are likely to affect residential self-consumption in the short- to medium-term. Self-consumption enhancing technologies can be categorized into technologies that enhance self-consumption ratios by means of increasing a household's total electricity consumption, and technologies that enable a dispatch of electricity consumption to improve the match between onsite production and consumption.

#### **Technologies increasing consumption**

One solution to increase self-consumption ratios is to increase the household's electricity consumption by substituting other forms of energy consumption with electricity. The most discussed options in the household sector are electric heat and electric mobility.

- *Electric heat*: Heat can be provided in the form of direct electric heating or in combination with a thermal storage unit. In the first case only the building substance works as heat storage, in the latter case the most common thermal

storage is a water tank. In scenarios that project the electrification of residential heat, heat pumps have become the dominant technology (Fawcett 2011), (Fawcett et al. 2015), since their installation is part of the renewable energy target in the EU<sup>8</sup>. Therefore, ownership rates of heat pumps are generally increasing, although they vary between the EU countries (Heiskanen and Matschoss 2016). Many studies analysing the effect of electric heat on self-consumption ratios thus focus on heat pumps, for example (Thygesen and Karlsson 2014), (Vrettos et al. 2013), (Williams et al. 2012). The expected potentials are promising: With the installation of a heat pump in combination with a 500 l hot water storage, Vrettos et al. (2013) for example find an increase of the self-consumption ratio by 15% for a single family home and a 10.8 kW PV system. It has to be considered though that most heat is consumed during the cold season, when less PV electricity is produced.

- *Electric mobility*: In the discussion of electric mobility in the household sector, the focus is almost exclusively on electric cars. However, electric vehicles are believed to only make a limited contribution to increasing the self-consumption rate. This is because of the mismatch between the timing of PV production and the charging patterns of electric vehicles. The car's battery is usually recharged in the late afternoon after returning home (Munkhammar et al. 2013). The development of the electric vehicle market is nevertheless noteworthy as it can potentially improve the economic case for a stationary battery: PV power could be stored temporarily for the later charging of the electric car.

### **Technologies enabling dispatch of consumption**

Dispatchable consumption refers in this context to the shift of electricity consumption to hours with onsite production in order to improve the self-consumption ratio. Consumption or load shifting generally requires an energy management or home automation system and is only a feasible option for appliances with (physical) storage, such as the above described heat pumps. The consumption of other residential appliances, like lighting, cannot be scheduled (Masa-Bote et al. 2014). An option to further improve self-consumption ratios and to increase convenience, additional electricity storage systems can be installed to separate the availability of electricity from the time of its production.

- *Energy management systems*: The simplest form of appliances scheduling is to turn the appliances on at times when PV electricity is produced. Households can do it manually or with a timer. And indeed, this form of appliance scheduling is found in real life: Changes in consumption behaviour can be observed, after the

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<sup>8</sup> Within the EU, ambient heat that is captured by heat pumps is classified as renewable, "provided that the final energy output significantly exceeds the primary energy input required to drive the heat pumps" (EU 2009, 2016).

installation of a self-consumption system, in particular among early adopters with a strong interest in technology. Dobbyn and Thomas (2005) report that households in this group try to use "washing machines and the like on peak generating times". However, the effect is only found in few households and is likely to diminish further over time (Bergman 2009), (Dobbyn and Thomas 2005). In the future, energy management systems are expected to become more popular. Products optimizing self-consumption are already becoming more diverse and sophisticated (Röpke 2012). They range from simple relay-based solutions that activate electric appliances when a certain threshold of electricity production is surpassed, to complex control algorithms that incorporate weather and load forecasts and provide extensive monitoring options of electricity production and consumption<sup>9</sup>.

- *Batteries*: Self-consumption rates can be further improved with the installation of onsite electricity storage technologies. Lithium-ion batteries are currently the dominant technology (Kairies et al. 2015). Due to increasing production capacities, which are mainly driven by the anticipated market uptake of electric vehicles, prices for lithium-ion battery packs are projected to fall from 300 EUR/kWh to 100 EUR/kWh in 2020 (Reid and Julve 2016). Second-life batteries from electric vehicles could even sell for less: Fischhaber et al. (2016) expect 50 EUR/kWh in 2020. Batteries for the enhancement of self-consumption are therefore widely discussed, since they also promise larger potentials than appliance scheduling.

Despite technological improvements, scheduling of household appliances has a relatively small potential and can increase the self-consumption rate only by a few percent (Widén and Munkhammar 2013). Widén (2014) for example evaluates 200 Swedish households with installed PV power of 3 to 9 kW and finds that load shifting of washing machines, dryers and dishwashers can increase PV self-consumption by around 200 kWh/yr on average. That is less than 4% of the average household consumption in Sweden (Statens Energimyndighet 2015). The load shifting potentials for electric vehicles are limited due to a poor availability at home during the day (Lampropoulos et al. 2010). Heat pumps and stationary batteries therefore provide the most promising dispatchable loads.

Besides improving individual self-consumption rates, the described solutions for dispatching residential load enable consumers to participate in the balancing power market. This could potentially increase economic benefits for the consumers (Sterner et al. 2015). Due to complicated legislation, this is currently not possible in practice, however, it is seen as a theoretically viable option for dispatchable residential loads (Gottwalt et al. 2011), (Strbac 2008).

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<sup>9</sup> For example the Sunny Home Manager by SMA Solar Technology (2017).

### 2.1.1.4 Summary

Table 1 provides a summary of the most important drivers for self-consumption discussed in the previous section. It attempts to illustrate the complexity of the subject, by showing that all drivers can both motivate or hinder PV self-consumption.

Currently, a positive attitude towards solar electricity technologies and the idea of self-sufficiency encourage the adoption of PV self-consumption, while the high costs of technology still prevent adoption for the majority of households. New technologies and lower prices could improve the economic benefit offered by self-consumption technologies in the future. However, if and when this will be the case, remains debated.

Table 1: Main drivers that motivate or hinder residential PV self-consumption.

<b>PV self-consumption</b>		
	<b>hindering factors</b>	<b>motivating factors</b>
<b>Economics</b>	high PV system costs low electricity prices, fixed charges  low self-consumption rate low insolation	low PV system costs high electricity prices, volumetric charges feed-in remuneration high self-consumption rate high insolation
<b>Be- haviour</b>	uncertainty, lack of trust	environmental awareness, self-sufficiency, prestige
<b>Tech- nology</b>	additional technology costs	improved self-consumption, additional business opportunities

### 2.1.2 Solar self-consumption in Germany

For the discussion of self-consumption of solar electricity, Germany provides an interesting case: PV self-consumption in Germany is driven by direct and indirect support measures and incentives, and is therefore considered to be higher than in most other countries (Schill et al. 2017). A comparison of the support schemes in Germany and Sweden can be found in Publication V, on which the following subsection is based.

#### 2.1.2.1 Direct support of self-consumption

The German Renewable Energies Act (Erneuerbare Energien Gesetz, EEG) 2009 introduced a tariff dedicated for self-consumed electricity. Compared to the feed-in remuneration, the self-consumption tariff was lower. However, it was added on to the

saved household electricity prices and therefore in total the more economic option for the households. The premium initially amounted to 25 ct/kWh in 2009 and decreased in subsequent years. By 2012 it was abolished, due to increasing electricity prices and strongly decreasing LCOE of PV systems (Schill et al. 2017). Other support measures for renewable self-consumptions still exist. The most important ones are presented in the following:

### **Feed-in of excess production**

Excess PV electricity production can be sold under a FiT or a FiP regime or directly into the wholesale market, or to aggregators or others (Couture et al. 2014). Currently the best option is the feed-in tariff. Since the EEG amendment of 2012, the feed-in is limited to a maximum of 70% of the system's installed power (BDEW 2013).

### **Subsidization of stationary batteries**

In 2013, a new program financed by the German state development bank *KfW Bankengruppe* was introduced. This so-called "KfW program 275" subsidizes the installation of a battery connected to small-scale PV systems. The KfW program supports stationary batteries for self-consumption purposes with low-interest loans and payment bonuses. In the first phase, payment bonuses could be up to 30% of the investment for the battery system. In the second phase, the bonus started with 25% and has since been gradually decreased to 10% at the end of the program in 2018. The KfW program is intended to incentivize the development of a system-friendly operation of battery systems. Eligibility requirements are structured accordingly. Most importantly, the maximum grid feed-in of the PV system is limited to 50% of the system's installed power (KfW Bankengruppe 2016).

#### **2.1.2.2 Indirect support of self-consumption**

Except for fixed subscription cost, Germany applies a volumetric tariff for residential electricity, i.e. grid fees and other parts of the electricity price are charged for each kWh of electricity consumed from the public grid (EU Commission 2015). Such volumetric pricing generally tends to incentivize self-consumption. This is especially true in the case of Germany, where the volumetric charging includes the EEG surcharge, grid fees and taxes and therefore contributes considerably to this situation, in which the LCOE from PV are cheaper than electricity end-consumer prices. Additionally, the feed-in tariff for small-scale PV systems has been decreasing strongly. By 2016 the FiT was much lower than the end-consumer price (right part of Figure 2), making it more profitable to substitute grid consumption with self-produced electricity and only benefit from the feed-in remuneration when excess electricity is produced. Assuming a LCOE of 13 EUR-ct/kWh (Breyer et al. 2015), the achievable revenue is about 16 EUR-ct/kWh for each self-consumed kWh of electricity (see Figure 2). It is therefore higher than back in 2009, when electricity prices were lower and feed-in tariffs and levelized costs were much

higher (Kost and Schlegel 2010), (Solarenergie Förderverein Deutschland e.V. 2017). In 2009 the achievable revenue was about 10 EUR-ct/kWh (left part of Figure 2). Accordingly, there is now an economic incentive for households to increase self-consumption, even if this involves additional investment for technologies such as batteries (Schill et al. 2017).

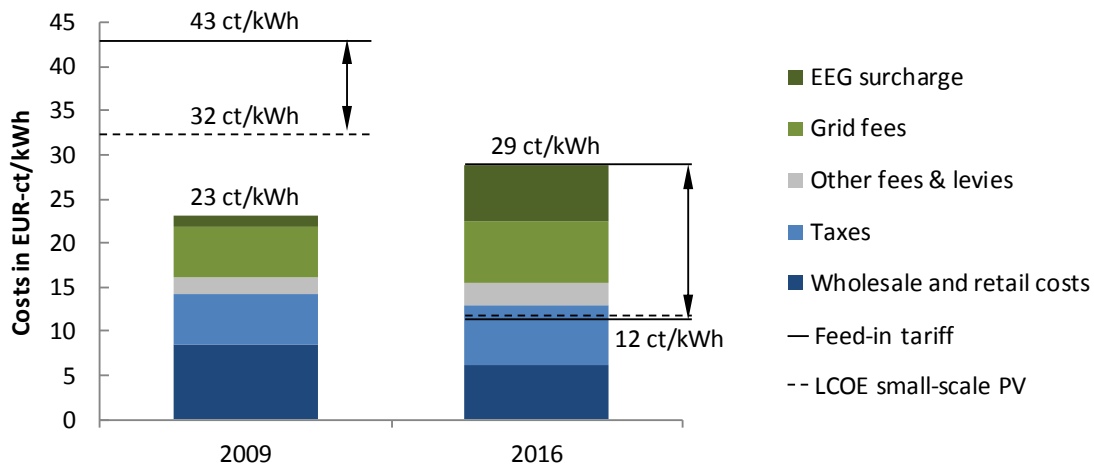


Figure 2: Electricity prices for residential consumers, feed-in tariffs and levelized costs of electricity (LCOE) for small-scale PV in Germany in 2009 and 2016 (BDEW 2017), (Breyer et al. 2015), (Kost and Schlegel 2010), (Solarenergie Förderverein Deutschland e.V. 2017).

PV self-consumption in private households became only relevant in 2009, with its explicit support through the EEG amendment. The remunerated self-consumption was rising continuously between 2009 and 2012 and reached 0.73 TWh in 2012, before the self-consumption bonus was abolished (Bardt et al. 2014), (BNetzA 2009–2011). Although this amount cannot be unambiguously assigned to private households, it can be assumed that the major proportion is due to the residential sector, since only small-scale systems were supported.

Since the financial support for PV self-consumption was abolished, the market development is no longer recorded and it is therefore merely estimated by means of the recordings of installed PV systems. It is assumed that most newly installed systems aim for some degree of self-consumption, since it is the most economic option under the current conditions. Elstrand et al. (2015) assume residential PV self-consumption of 1.3 TWh in 2014 and Prognos (2016b) expect PV self-consumption in 2016 to amount to 1.9 TWh. The development of PV self-consumption in the household (HH) sector is listed in Table 2.

Table 2: Development of residential self-consumption in Germany 2009–2016 (Bardt et al. 2014), (BDEW 2015a), (BNetzA 2009–2011), (Elsland et al. 2015), (Prognos 2016b).

	<i>Unit</i>	<b>2009</b>	<b>2012</b>	<b>2016</b>
<b>HH consumption</b>	<i>TWh</i>	142	138	129
<b>HH self-consumption</b>	<i>TWh</i>	0.005	0.73	1.9

In 2016, residential PV self-consumption amounted to 1.5% of the sector's, and less than 0.4% of Germany's electricity consumption of 527 TWh. Nevertheless, the dynamic development of PV self-consumption in the past years led to a controversial debate about potential advantages and drawbacks in case of a high share of self-consumers. The discussion resulted in the amendment of the EEG in 2014. It introduced several changes that counteract some forms of self-consumption. Among others, it was determined that individual self-consumers with projects larger than 10 kW are required to pay 40% of the EEG surcharge for the self-consumed electricity. Additionally, 100% of the EEG surcharge is to be paid, if the owner of the PV system and the electricity consumer are not identical persons (BDEW 2015b). These changes do not affect smaller self-consumers in self-owned houses, like most single-family households. The economic benefit of self-consumption in larger multi-family buildings diminishes though. In multi-family homes, the identity of owner and consumer of the PV electricity would be different and therefore the EEG surcharge has to be paid. The EEG surcharge amounts for 2017 to 6.88 ct/kWh<sup>10</sup>. The effects of the EEG amendment are yet to be evaluated. Nevertheless, PV self-consumption is still expected to increase, due to falling technology costs (Mayer et al. 2015), (Spertino et al. 2013) and the possibility to further increase self-consumption, e.g. with the connection of a battery (Hoppmann et al. 2014).

## 2.2 Literature review of previous modelling approaches

Modelling the market diffusion of innovative technologies, such as self-consumption systems, has been a field of research for some decades, yet the market diffusion of self-consumption systems itself has not received much attention up to now. Therefore, this literature review aims at identifying important aspects and insights regarding the diffusion of innovative technologies (Section 2.2.1). Models that address market potentials and diffusion of self-consumption systems itself are presented in Section 2.2.2. Their ability to answer the research questions of this thesis is discussed at the end of the section.

<sup>10</sup> <https://www.netztransparenz.de/EEG/EEG-Umlage>

### 2.2.1 Stylized aspects on the market diffusion of solar self-consumption

In order to answer the research questions, it is not only necessary to be able to estimate the realizable potentials of residential self-consumption. The diffusion, i.e. the temporal development of the exploitation of potentials, is equally important. Current concepts of the modelling of the diffusion of innovative technologies are outlined in this section.

#### **Technology adoption: Decision-based or epidemic?**

Today's theory of the market diffusion of innovative technologies is based on early works such as (Rogers 2003) and (Bass 1969). The market diffusion, also known as technological diffusion, occurs via accumulative adoption by decision makers (Stoneman 1995). Nearly all existing studies assume that diffusion typically starts with low adoption rates, increases continuously until the point of inflection and then decreases in dynamics until the saturation level is reached (Karshenas and Stoneman 1995), (Rogers 2003). The resulting time path of diffusion often follows a sigmoid trajectory or so-called S-curve, a characteristic shape that is supported by empirical evidence (Griliches 1957), (Lilien et al. 2000), (Mansfield 1986), (Meade and Islam 2006), (Mellit and Pavan 1988).

The diffusion of innovative technologies can be modelled as an epidemic process. This approach has initially been developed to analyse the spread of infectious diseases through the population. Since then it has been further developed and is being applied to technology diffusion modelling. In epidemic modelling, the diffusion curve is explained by the contact between users and non-users of a technology, which leads to an increasing number of adopters over time (Elsland (2015)). The approach is also applied in the context of solar electricity production, e.g. Islam (2014) applies a model based on Bass (1969) and Rogers (2003) to analyse the diffusion of PV solar cells. Epidemic models are also used by Lund (2006) and Guidolin and Mortarino (2010) to analyse the diffusion of renewable energy technologies.

However, there are limitations to epidemic growth modelling, which are manifested essentially in their characteristic shape and the restricted consideration of heterogeneity. According to Elsland (2015) a crucial limitation is the continuously increasing diffusion level, which is not always the case in reality. In terms of heterogeneity, epidemic models analyse adoption on an aggregated level by neglecting specific decision criteria among potential adopters. Due to this fact, Fleiter and Plötz (2013) and Geroski (2000) point to the restricted possibility to draw policy conclusions from epidemic models, since they do not provide a theoretical framework to explain the decision to adopt a technology.

An alternative approach to model the diffusion of technologies is based on decision making with the underlying assumption that users make rational choices aiming to maximize their utility (Marschak 1960), (Thurstone 1927). This decision-based approach reflects the heterogeneity of potential adopters: Adopters differ in their characteristics, which results in different utilities from the adoption of a new technology. For instance, potential adopters may consume more or less electricity, which results in a varying profitability of a PV self-consumption system. Under the assumption that profitable

technologies are adopted, they penetrate the market according to changes in the cost and cost related factors of the technology over time (Fleiter and Plötz 2013), (Geroski 2000). For this thesis, a hybrid model was developed that combines the advantages from both the decision-based and the epidemic modelling approaches.

### **Representation of cost and price development in decision-based models**

An informed understanding of the future costs of self-consumption technologies is essential to model the decision for the adoption of a technology and thus to quantify its market uptake. A common approach in energy modelling is the application of learning curves or experience curves (Elsland 2015). Learning curves depict the development of production cost as a function of increased cumulative production and have been described as the most objective method to project future costs of technologies. Instead of mere production cost, experience curves depict technology price development by accounting for all cost factors (technological process, sales, depreciation, etc.) and, while more uncertain than learning curves, are also suitable to estimate future costs (Schmidt et al. 2017).

Besides the technology costs, the economic case and thus the decision-making for the adoption of a self-consumption technology is dependent of the current and future electricity costs. However, in real life, the consumers' expectation of electricity prices is based on empirically witnessed price development. The actual electricity prices, that will occur in the future, are not known (Elsland 2015). There is empirical evidence that residential consumers tend to combine the witnessed trend of a past reference period and the total price level in the decision year to calculate an assumed price development for the investment cycle (Bauermann et al. 2014), (Henkel 2011). Kranzl et al. (2013) suggest to use a reference period of three years as a basis for price expectations. In this thesis, exogenous technology cost and electricity price development curves are applied within the decision-based part of the model.

### **Behavioural drivers and market diffusion**

Behavioural drivers, i.e. the perception of the earlier described motivating and hindering factors is often translated in a consumer's absolute high or low willingness to pay (WTP) or relative willingness to pay more (WTPM) for a new product, or sometimes into an implicit discount rate as in (Schleich et al. 2016). This is usually done by means of a household survey. Amador et al. (2013) and Peters and Dütschke (2014) for example show that householders display a higher WTP for non-financial values such as innovativeness and environmental benefits. And Borchers et al. (2007) find that consumers value solar electricity higher than electricity from other sources. Regarding self-consumption technologies, the idea of self-sufficiency and the possibility to make a positive contribution to the transition towards a more sustainable energy system trigger a

high willingness to pay in private householders (Graebig et al. 2014), (Longo et al. 2008), (Oberst and Madlener 2014).

As stated, the magnitude of the WTP depends on the household's favourable or unfavourable attitude towards the new product. This is also in accordance with Rogers' (2003) theory "Diffusion of Innovations": In relation to the attitude towards a product, Rogers defines five adopter categories: (1) *Innovators*, (2) *Early Adopters*, (3) *Early Majority*, (4) *Late Majority*, and (5) *Laggards*. From these groups, the innovators look most favourable upon a product, show the highest WTP, and therefore are the first to adopt it. In his theory, Rogers additionally identifies socio-economic characteristics and personality variables that describe the consumer's position in the adoption process. The ideal type of an innovator is described as a person better educated and younger than the average population with a higher income and social status, and more prepared to take risks.

Rogers' theory is applied to describe the adoption process of solar generation and self-consumption technologies for example by Bergman, Hawkes, et al. (2009), Claudy et al. (2011), Couture et al. (2014), Faiers and Neame (2006), Jager (2006), Karakaya et al. (2015), Leenheer et al. (2011), and Peter et al. (2002). In their studies, the adoption process of self-consumption technologies is described as in its early stage and current users therefore identify as innovators or early adopters.

Further, Bergman, Hawkes, et al. (2009) find that consumers "installing microgeneration in the UK match Rogers' description of innovators and early adopters and their socio-economic profile is different from that of the general population". A study in Germany finds that early adopters usually have higher than average environmental problem awareness, and they are more aware of the relative advantages of PV systems. Studies of PV adopters in the UK (Keirstead 2007) and the Netherlands (Jager 2006) find they were older than the average population, better educated, had a higher environmental awareness, were wealthier and more likely to own their own home. Although Rogers describes early adopters as younger, in this case that is not necessarily a contradiction: the adoption of PV systems is mostly restricted to homeowners and higher age groups are overrepresented in this group. Regarding the age, the group of homeowners can therefore not be compared with the entire population. Accordingly, Devine-Write (2007) finds that older people are more aware of PV technologies, but less likely to install them.

Figure 3 depicts the adoption process as described by Rogers (2003). The lines at the bottom and top of the figure align personality characteristics and perceived product value and WTP with adopter groups. Note that the density curve and the S-shaped cumulative curve represent the same data, but the density curve shows the adoptions in each year, while the S-shaped curve shows the cumulative adoptions over time.

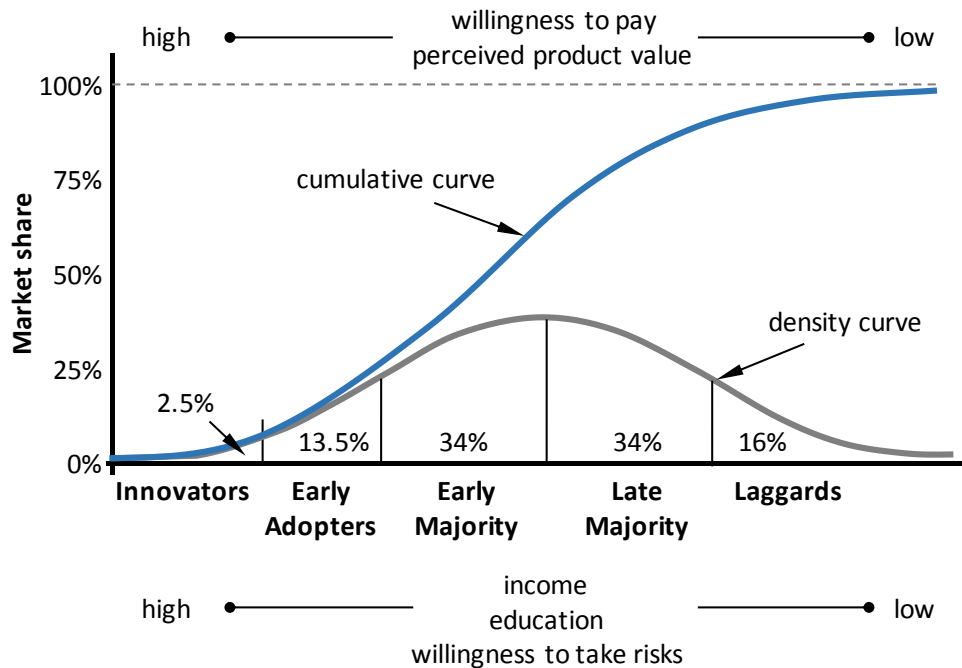


Figure 3: Schematic representation of technology adoption curves and adopter groups with defining characteristics.

### Peculiarity of self-consumption technologies

In this subsection, a number of stylized aspects from studies on technology diffusion and user acceptance are identified that should be considered in the development of a model for the market diffusion of self-consumption technologies.

Some characteristic features of the self-consumption technologies are to be emphasised in order to illustrate why the modelling of its market requires a new methodological approach:

- Self-consumption is a relatively new concept and with the adoption of a self-consumption technology, residential consumers generally add an appliance to their household instead of replacing an old one (as they would do with the adoption of a new heating technology). Therefore, the adoption process cannot be represented with a stock-model approach.
- Unlike other residential appliances, self-consumption technologies offer the possibility to not only save money but to gain financial revenues.
- The green image is perceived to be particularly strong for solar self-consumption by some adopter groups, which triggers high willingness to invest at early market stages.

Due to these features, the market diffusion of self-consumption is a special case. In the following section, existing models used to investigate the market potential and diffusion of solar self-consumption technologies are presented. In addition, the suitability of these

models to answer this thesis' research questions is discussed and research gaps are identified.

### **2.2.2 Review of existing self-consumption models**

Few studies on PV self-consumption potentials and fewer on its market diffusion exist. Market potentials are addressed by Prognos (2016a), Huber et al. (2013) and Kaschub (2017). Further implications for the market diffusion are given by Bardt et al. (2014), Jägemann et al. (2013) and Winkler et al. (2016). The most relevant studies for this work are the ones by Jägemann et al. (2013) and Kaschub (2017), since they focus on the household sector and the self-consumption with PV systems and batteries.

In all of the studies, economic considerations are seen as the main driver for the adoption of a self-consumption system. Economic drivers such as cost development and feed-in remuneration are therefore implemented in all of the models applied in the studies. In addition, all studies consider consumption behaviour to some extent. However, only two of the studies account for the differences of consumption behaviour between individual households: Jägemann et al. (2013) use 250 synthetic load profiles to represent the electricity consumption behaviour of households with 1 to 5 residents and Kaschub (2017) applies 88 empirical load profiles. However, no meta-data was recorded with the empirical profiles and therefore no connection between the households and their consumption behaviour can be made. The individual consumer's preferences are neglected by all of the here discussed studies.

Regarding technology drivers, Kaschub (2017) focusses on the effect of electric vehicles on the profitability of self-consumption. The electric vehicles are represented by individual charging profiles and different charging options are considered. Winkler et al. (2016) include heat pumps in the consumers' investment decision for a self-consumption system and thus model the interdependencies between the two technologies. Electric heat is also addressed by Huber et al. (2013): Their study focussed on the application of direct electric heat to increase self-consumption rates.

The market diffusion of self-consumption technologies that results from different market drivers is modelled for example by Winkler et al. (2016). They apply a hybrid approach that combines the market potentials that result from the consumers' investment decision and a technology adoption rate to model the time course of the technology diffusion. Bardt et al. (2014) and Jägemann et al. (2013) use simpler approaches for the assessment of market dynamics.

Table 3 summarizes the drivers that are covered by the six models from literature. The symbol '✓' indicates if a specific driver is integrated and '-' if it is not. '(✓)' is used if a driver is only integrated in a limited way.

Table 3: Analysis of different studies on market potentials and market diffusion of self-consumption technologies

	Bardt et al. (2014)	Jägemann et al. (2013)	Huber et al. (2017)	Kaschub (2017)	Prognos (2016a)	Winkler et al. (2016)
Economic drivers	✓	✓	✓	✓	✓	✓
Consumption behaviour	(✓)	✓	(✓)	✓	(✓)	(✓)
Consumer preferences	-	-	-	-	-	-
Technology drivers	-	-	✓	✓	-	✓
Market diffusion	✓	✓	-	-	-	✓

While all market drivers are considered in existing research, none of the studies captures all of the relevant drivers. Particularly the representation of consumers' preferences is neglected. Therefore, a new modelling approach is developed that is described in the following section.



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### 3 MATERIAL AND METHODS

Based on the research questions raised and the specific aspects of self-consumption, the scope of the applied methodology can be established.

In general, the developed methodology has to be capable of providing an adequate representation of consumer-specific behaviour and related investment decisions. Moreover, various market drivers need to be captured and the resulting findings translated into market potentials and the actual market diffusion.

More precisely, in order to attain an adequate assessment of PV self-consumption in the residential sector, the methodology must consider the following features:

- consideration of behavioural drivers, like consumption behaviour and preferences
- consideration of technology drivers, i.e. new equipment such as electric vehicles, heat pumps or control systems for different storage operation
- consideration of economic drivers, such as cost development
- realistic simulation of market potentials and market diffusion

Figure 4 provides an overview of the requirements and the chosen methodological approaches.

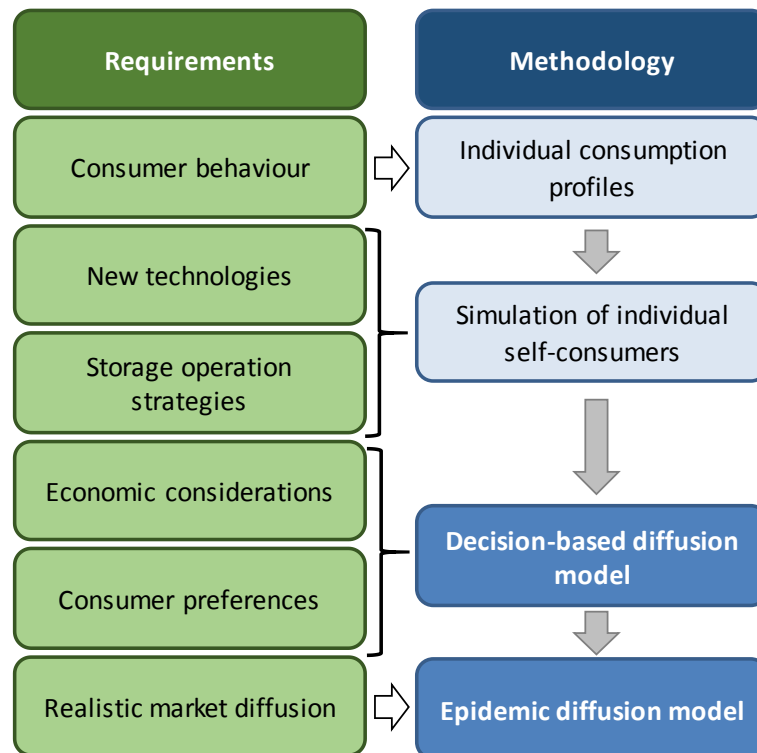


Figure 4: Overview of the requirements of the research questions and the chosen methodology.

The electricity consumption behaviour can be reflected in the developed methodology using individual consumption profiles that are statistically evaluated in this thesis. The match between PV electricity production and residential consumption is simulated for each consumer individually, considering electric vehicles, heat pumps and battery units. The consumer's investment decision in a self-consumption system is modelled under consideration of the system's economics and the consumer's non-financial preferences. The individual investment decisions are subsequently translated into a realistic trajectory of market diffusion.

The combination of using individual consumption profiles for the simulation of self-consumers with a downstream hybrid diffusion model is suitable for answering the research questions of this work.

A number of aspects are explicitly excluded from the scope of the analysis to reduce modelling complexity and to focus on the most relevant aspects. These include the analysis of potentially changing electricity consumption, changing consumption behaviour and changing heat demand in future households. Potential technological improvements in both PV systems and household appliances are also excluded. Further, questions related to possible effects of residential self-consumption on the electricity price are not considered.

In the following sections, the applied data, the reasons for its selection, and the developed methodology are described in more detail. The formal descriptions of the developed model in particular have already been used in the publications that make up this cumulative dissertation. The respective publications are referred to in the footnotes.

#### **3.1 Individual consumption profiles**

As pointed out earlier, individual electricity consumption profiles are the main input data for the simulation of self-consumption. The term consumption or load profile is defined as the 8760h time-series of electricity consumption of an individual household, which is recorded in a high time resolution and therefore provides information not only about the consumed amount of electricity, but also about the consumption behaviour.

In the following section, the requirements for the profiles are discussed and the consumption profiles that are applied in this work are presented.

### 3.1.1 Important factors affecting PV self-consumption

#### Seasonality

The consumption profiles used for the simulation of self-consumption of PV electricity are required to be recorded for at least 12 month. This necessity arises due to the seasonally fluctuating nature of PV production and the equally time dependent household consumption, which requires analysing the entire course of a year in order to address self-consumption aspects. As an example, Figure 5 depicts the daily average PV electricity production from a 3 kW system and household electricity consumption for each month of the year 2014.

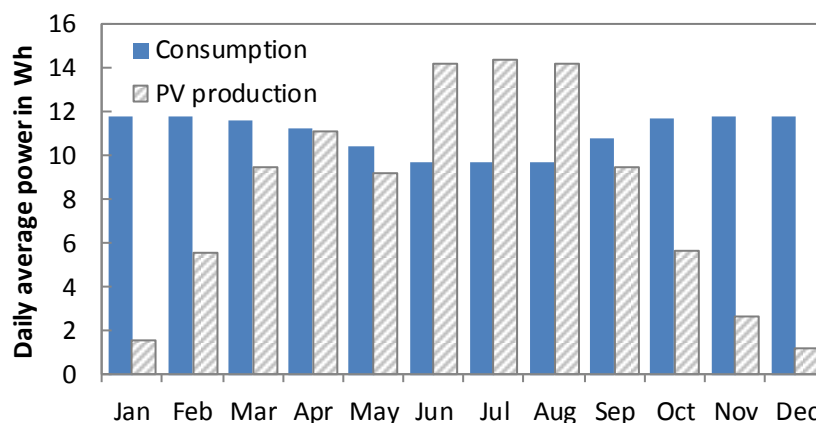


Figure 5: Example of daily average PV electricity production and consumption in each month. PV electricity production from (Einleuchtend e.V. 2016) and consumption from (VDI 2008) both for the year 2014.

#### Time resolution

To address the match between electricity production and consumption, the profiles are also required to be recorded in a high time-resolution. Fluctuations in electricity production and consumption generally cause mismatches between the two. As these mismatches are evened out by aggregating over time, a lower time resolution than hourly data will always lead to an overestimation of self-consumption (Luthander et al. 2015). Even with the application of hourly data compared to 1-min resolution, sharp load peaks are underestimated. Such load peaks result for example from devices such as cycled refrigerators and freezers or, on the production side, under scattered cloud conditions (Cao and Sirén 2014). In Figure 6 PV production and residential consumption are depicted for an exemplary day in 1-min, 15-min and hourly resolution.

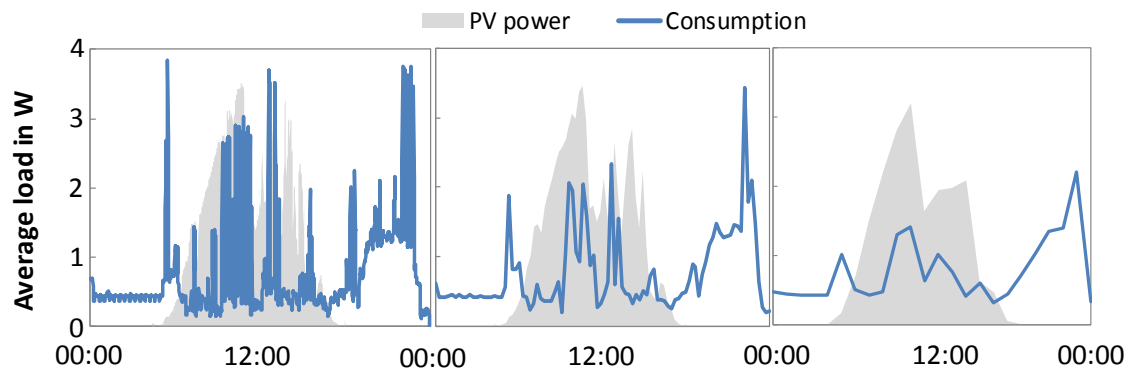


Figure 6: Example of the difference in PV self-consumption when using 1-min (left), 15-min (middle) and hourly (right) data. PV electricity production from (Einleuchtend e.V. 2016) and consumption from (VDI 2008) both for 2014.

### Individual households

The aggregation of consumption profiles that are applied in so-called standard load profiles, equally even out stochastic fluctuations (see Figure 7).

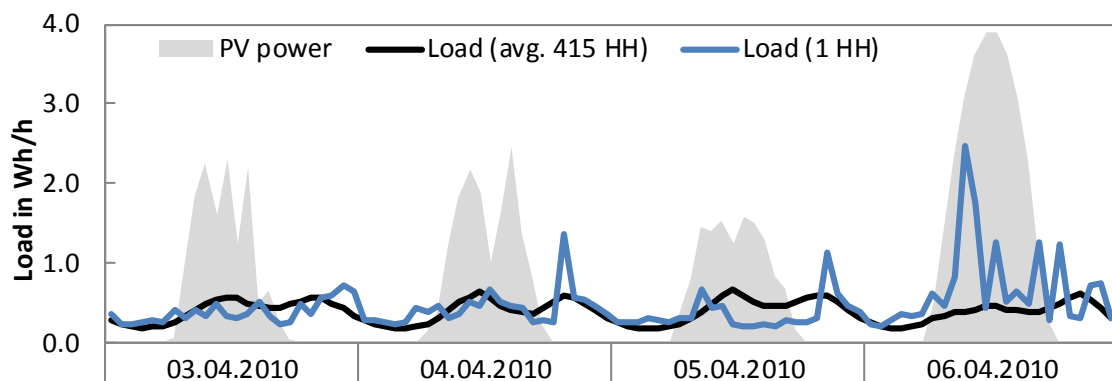


Figure 7: Smoothing effect of aggregating household consumption profiles with electricity production from a 5 kW PV panel as a reference.

It can therefore be concluded that for the analysis of solar self-consumption, it is required to use *individual consumption load profiles* that are recorded for at least *12 month* with an *hourly* or higher *time-resolution*. Due to complexity and computing time, hourly data was used in this work

### 3.1.2 Overview of the applied profiles

Within this work, electricity consumption profiles were used to reflect the individual household's consumption behaviour, and further the charging behaviour of electric vehicles and the heat pump operation. The applied profiles are presented in the following.

### 3.1.2.1 Household consumption profiles

The applied household data originates from a smart-meter field study that was conducted in 2009 and 2010 in Germany and Austria. Besides hourly-recorded consumption data, the data set comprises additional information on the individual households (such as household size, income, presence of different appliances, number of children and age). Such information is used to assign charging profiles of electric vehicles and heat pump profiles to the individual households. The average load in summer and winter of the applied individual household profiles is depicted in Figure 8.

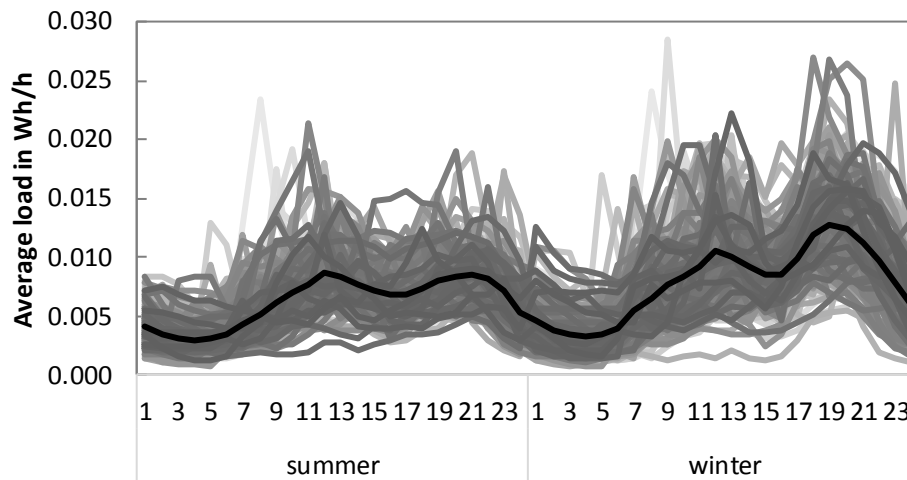


Figure 8: Average load of the applied load profiles for household consumption in summer (left) and winter (right). Black line: Average of all profiles.

### 3.1.2.2 Charging profiles of electric vehicles

The electric vehicle charging profiles are simulated based on vehicle usage data. The vehicle usage data originates from the German Mobility Panel (MOP, (MOP 2010)). MOP is a household travel survey that has been performed since 1994 with 1,000 participants every year. The participants report their trips during one week and additionally give information about their socio-demographics in a questionnaire. The vehicle usage data is translated into charging and discharging profiles, considering battery size, charging power and the availability at a charging point (for details see (Gnann 2015)). Since the vehicle usage data is only available for one week, also the charging profiles are only simulated for one week. To obtain the charging behaviour for the entire year, the charging profiles for Monday through Sunday are assembled into a yearlong profile, considering the day structure of the year as well as national holidays.

To assign a charging profile to each individual household, the similarity in socio-demographic characteristics between each household and each charging profile was calculated. Matching variables are: *age*, *sex*, *education* and *employment* of the respondent as well as *household size*, *income* and *type of household*.

### 3.1.2.3 Load profiles of heat pumps

The load profiles representing the operation of a heat pump in the individual households originate from an average load profile (e.g. available from (SWM 2017)). In this thesis, it is assumed that the load of the heat pump can be shifted to maximize the self-consumption in the household, thus the structure of the initial load is less important than in the case of electric vehicles. The load profile is therefore the same for every household, but it is scaled according to the individual heating demand (see Publication II).

The individual electric vehicle charging and heat pump profiles resulting from the above-described assumptions, are depicted in Figure 9.

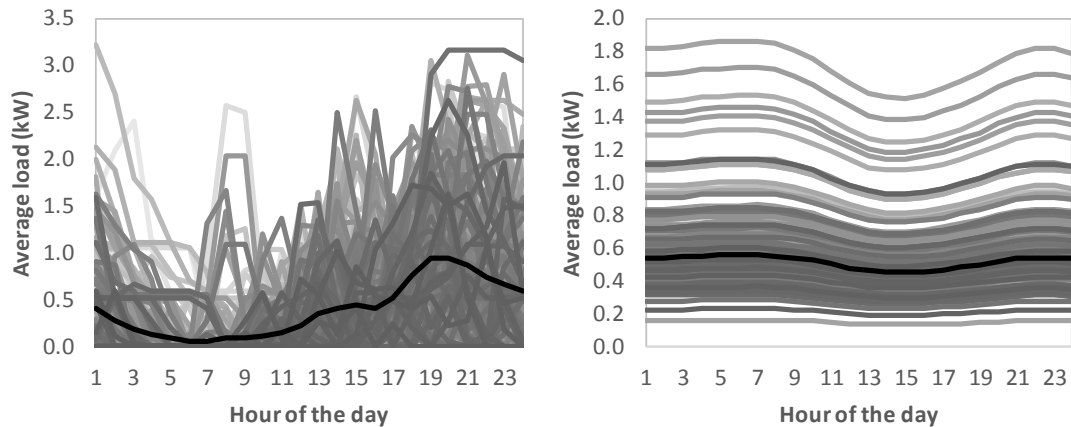


Figure 9: Applied load profiles for electric vehicles (left) and heat pumps (right). Black line: Average profile.

## 3.2 Model simulations

The first step of the developed model is to determine the optimal heat pump and battery operation for each household with its individual electricity consumption profile using different sizes for PV system and battery. The objective is to minimize the electricity purchase from the public grid and maximize self-consumption rates. Based on the electricity supply simulations, the utility for each household with different system configurations is calculated individually. Finally, the individual utility-maximizing decisions are aggregated to market shares of PV + battery systems. The model is structured as in Figure 10: Based on individual consumption data and user preferences (upper part of the figure) and using techno-economic parameters (lower part), the market shares of PV + battery systems are determined in three steps (central part): self-consumption is simulated for individual households (Section 3.2.1); the utility maximising system configuration is chosen, and the technology choices are transformed into market shares (Section 3.2.2).

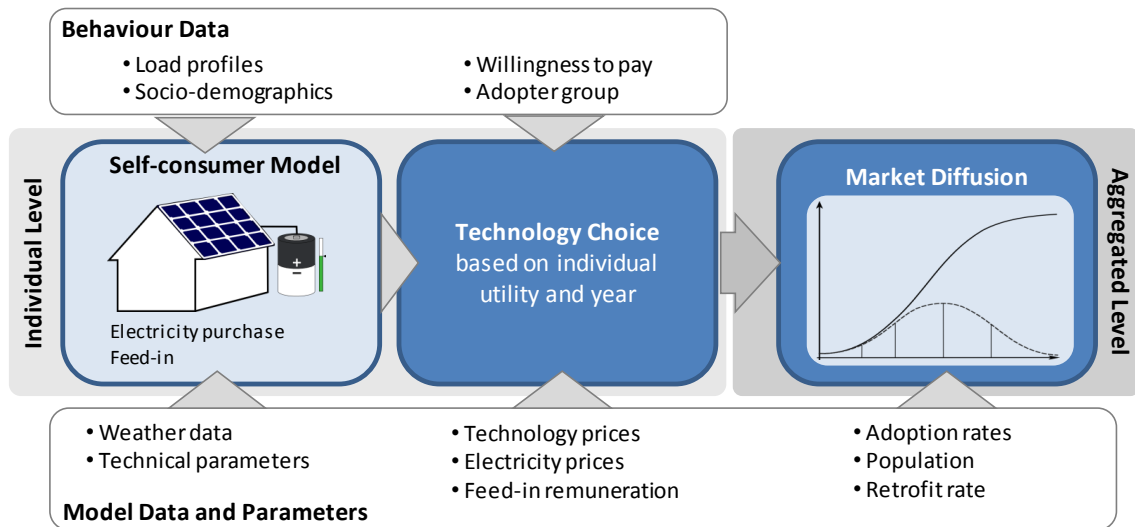


Figure 10: Overview of the developed model for the market diffusion of PV + battery systems (Publication II, IV, V).

### 3.2.1 Simulation of individual self-consumers

In this section, the steps to model individual self-consumers are described. The first step of the model is to simulate PV electricity production (Section 3.2.1.1). In a second step, the optimal operation of the heat pump is determined (Section 3.2.1.2). Since heat pumps are considered to be installed in combination with a thermal storage, i.e. a hot water tank or the thermal mass of the building, its optimal operation is the most economical solution to raise the household's self-consumption. In this thesis, the charging of electric vehicles is not optimized, but all vehicles are charged after the last trip. Most of the vehicles are not at home during the day, so the possibility to shift charging loads to midday hours to increase direct self-consumption is limited.

In a third step, the battery operation for each household with its individual electricity consumption profile is determined, using different sizes for PV panel and battery (Section 3.2.1.3). The objective is to minimize the electricity purchase from the public grid and maximize the self-consumption rate.

#### 3.2.1.1 PV electricity production

The PV electricity production profiles in this thesis are simulated based on hourly radiation and temperature data provided by the German Meteorological Service from a weather station near the city of Würzburg (DWD 2016). In order to maintain consistency, the weather data was taken for the same period as the electricity consumption recordings, i.e. from November 2009 until November 2010. The PV production model is based on a study of Schubert (2012).

### 3.2.1.2 Heat pump operation<sup>11</sup>

The objective function of the linear optimization problem minimizes the costs of the load shifting activity:

$$\text{Min } \sum_{i=h_{min}}^{h_{max}} \sum_{j=h_{min}}^i P_{ts,ij} \cdot (C_j \cdot (1 + |j - i| \cdot cif_{ts}) - C_i) \quad (1)$$

with the shifted load from hour  $i$  to hour  $j$   $P_{ts,ij}$ , the hourly electricity price  $C$  and the consumption increase factor  $cif_{ts}$ , where  $i \neq j$  and  $i, j \in [h_{min}; h_{max}]$ . Technologies that include a thermal storage, such as heat pumps, show an increase in consumption if the time of heat production and demand is displaced (Boßmann 2015).

The ability of a process to adjust its load is primarily restricted by the load bounds, i.e. the minimal and maximal load  $P_{min}$  and  $P_{max}$ , respectively:

$$P_{min} \leq P + P_{ts} \leq P_{max} \quad (2)$$

with the original charging load in each hour  $P$ , the shifted load to and from each hour  $P_{ts}$ , and the discharge of the storage  $P_{dis}$ .

Additionally, the load shifting ability is restricted by the storage capacity:

$$\begin{aligned} SFL_{min} \leq & \sum_{h=h_{min}}^i P_h - \sum_{h=h_{min}}^i \sum_{j=h_{min}}^i P_{ts,hj} + \\ & \sum_{h=h_{min}}^i \sum_{j=h_{min}}^i P_{ts,jh} \cdot (1 + |j - h| \cdot cif_{ts}) - \sum_{h=h_{min}}^i P_{dis,h} \leq SFL_{max} \end{aligned} \quad (3)$$

with the minimal and maximal storage fill levels  $SFL_{min}$  and  $SFL_{max}$ , respectively. Instead of calculating the thermal storage size in absolute terms, the hourly deviation of the storage level is determined relative to the initial storage level under the non-optimized process load  $P$ . The maximum deviation is assumed to represent the storage size. The formal description of the determination of the storage bounds is published in (Boßmann 2015).

### 3.2.1.3 Battery operation<sup>12</sup>

Subject to the technical restrictions of the installed battery as well as the household's electricity consumption and PV production profile, the optimal battery operation (charging and discharging) is determined for each hour of the optimization interval  $h$  for each user by minimizing the objective function

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<sup>11</sup> This part of the model was applied in Publication II.

<sup>12</sup> This part of the model was developed in (Klingler and Marwitz 2016), and applied in Publication I, II, III, IV and V.

$$\text{Min } \sum_{h=h_{\min}}^{h_{\max}} C_h (\eta^{-1} P_{Batt,pos,h} + \eta P_{Batt,neg,h}) \quad (4)$$

with the control variables  $P_{Batt,pos}$  (charging) and  $P_{Batt,neg}$  (discharging). Efficiency losses due to energy conversion in the battery and the AC-DC inverter are considered via the efficiency factor  $\eta = \eta_{Batt} \cdot \eta_{AC-DC} := 88\%$ .

The objective function is constrained by the battery's power limits  $P_{Batt,min}$  and  $P_{Batt,max}$ :

$$P_{Batt,min} \leq P_{Batt,i} \leq P_{Batt,max}, \quad \forall i \in [i_{min}; i_{max}] \quad (5)$$

and are also subject to the limits of the storage capacity  $SFL_{Batt,min}$  and  $SFL_{Batt,max}$ :

$$SFL_{Batt,min} \leq \sum_{h=h_{min}}^i [(1-d)^i SFL_0 + (1-d)^{i-h} P_{Batt,h}] \leq SFL_{Batt,max} \quad (6)$$

The storage fill level  $SFL_{Batt}$  is a function of the battery load  $P_{Batt} = P_{Batt,pos} + P_{Batt,neg}$  and considers self-discharge with the discharge rate  $d$  and an initial storage fill level  $SFL_{Batt,0} = SFL_{Batt}(t_0)$  at the beginning of the optimization interval.

The implemented cost function  $C$  generally favours the consumption of self-produced electricity (see Section 3.2.1.4).

#### 3.2.1.4 Load control strategies<sup>13</sup>

Available storages (battery, thermal, etc.) in households with PV systems for the purpose of self-consumption, can be operated with different objectives. In the self-consumption model developed in this work, these different control strategies are triggered through a cost function that serve as control signals  $C(t)$  in the objective function of the load optimization. Figure 11 provides a schematic representation of different possible cost functions. For an easier understanding, the household's electricity consumption and the storage discharging are not included in the figure.

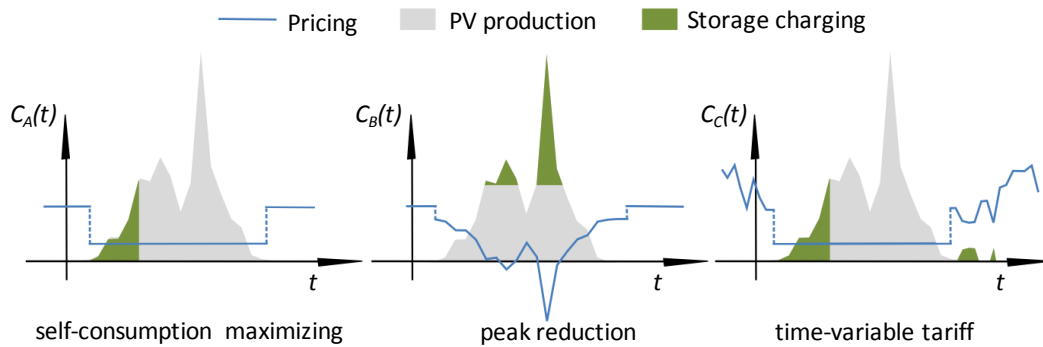


Figure 11: Schematic representation of different pricing signals for load control in self-consumption households, and corresponding storage charging.

<sup>13</sup> This part of the model was developed and applied in Publication III.

Storage systems in self-consuming households are predominantly applied to increase the amount of self-consumed electricity (left part of Figure 11). To that end, the storage is charged as soon as the PV electricity production exceeds the household's consumption, and discharged as soon as the PV production falls below the consumption. Since this is a rather simple strategy, it is already applied in real-life battery systems, and is often used as a baseline to benchmark more complex strategies (for example in (Weniger, Bergner, Tjaden, et al. 2015)). This operation strategy can be achieved with a simple relay; there is no need for an optimization. But in the optimization model presented here, the self-consumption maximizing strategy can be simulated with the cost function  $C_A(t)$ .

The more complex functions  $C_B(t)$  and  $C_C(t)$  induce a more system-friendly storage operation: with the function  $C_B(t)$  (middle part of Figure 11) the high feed-in loads of the PV system are reduced by charging the storage in the hours with the highest PV production, thus reducing the strain on the public grid. Function  $C_C(t)$  (right part of Figure 11) considers a time-variable electricity tariff that reflects the cost of electricity production. The storages are charged at hours with low prices when no self-produced electricity is available. In real-life, the cost functions  $C_B(t)$  and  $C_C(t)$  require forecasted data, such as predictions for the household consumption or PV production. To facilitate the optimization, most models assume perfect foresight for these parameters. However, to gain a more realistic representation of self-consumption, and realistically assess the effect of a system-friendly battery operation, the possibility to calculate the optimal storage operation with forecast-based data is implemented. In this thesis, artificial neural networks (ANN) are used to obtain these forecasts.

For solar electricity production, ANN have been studied extensively and show high forecasting skills (Widén et al. 2015). Martín et al. (2010) compare the forecasting results of persistence, autoregressive, fuzzy-logical and neural networks when predicting local half-daily solar irradiance with a maximum horizon of three days. They conclude that the most accurate results are obtained with ANN. This result is confirmed by Pedro and Coimbra (2012), who compare forecasting results for a local PV power plant with a time horizon of one and two hours. Further, Fernandez-Jimenez et al. (2012) and Paoli et al. (2010) have implemented and evaluated different types of neural networks to locally predict the electricity production of PV systems. Their results show that ANN are able to serve the purposes of irradiation and PV production prediction with the lowest forecast deviations compared to other methods. Based on these findings in the literature, ANN were developed to forecast PV production and household load.

### **3.2.2 Market potentials and market diffusion**

The described heat pump and battery operation is applied for different PV system sizes and battery capacities and the operation of the equipment is simulated for each PV + battery combination to meet the needs of the individual households. The electricity supply is simulated for each consumption profile with the earlier described self-consumption

model. For all but Publication III, the self-consumption maximizing storage operation strategy is used.

The results are aggregated into two indicators for each individual household and PV + battery system configuration: the household's *electricity purchase* from the public grid and its (remunerated) *PV feed-in*. Both indicators are applied within the utility calculation described in the following.

### 3.2.2.1 Total cost of ownership and utility calculation<sup>14</sup>

To model the market diffusion of self-consumption technologies, in the first step the economic potential and utility are determined for each consumption profile. Each user's total cost of ownership (TCO) is calculated for different PV + battery systems. The annual total cost of ownership (TCO<sub>a</sub>) consists of the investment annuity (i.e. capital expenditure)  $a^{capex}$  and the yearly operating expenditure  $a^{opex}$

$$TCO_a = a^{capex} + a^{opex} \quad (7)$$

The operating expenditures consist solely of operation and maintenance costs. The equivalent annual cost method is used to calculate the investment annuity

$$a^{capex} = \frac{(1+i)^n \cdot i}{(1+i)^n - 1} \cdot I_0 \quad (8)$$

with the interest rate  $i$  and the investment for the PV + battery system  $I_0$ .

Additionally, the annual cost of electricity purchase (CEP<sub>a</sub>) is considered, which is calculated as the amount of electricity supplied from the grid  $p_e$  in kWh/yr times the cost for electricity  $k_e$  in €/kWh.

The cost of electricity purchase is reduced by the amount of excess electricity feed-in  $e_e$  in kWh/yr times the remuneration  $r_e$  in €/kWh:

$$CEP_a = k_e \cdot p_e - r_e \cdot e_e \quad (9)$$

For the electricity price, the average over three years can be taken to reflect some foresight of the ongoing price development, as suggested by Kranzl et al. (2013).

Finally, the factors TCO<sub>a</sub>, electricity purchase and the willingness to pay more (WTPM) of the households are combined to the utility of the different PV + battery options. In each year  $a$ , the utility is calculated for each household and each PV + battery system configuration  $\tau$  and it is assumed that each household buys the option that maximizes its individual utility, i.e.

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<sup>14</sup> This part of the model was developed in Publication IV, and applied in Publication II, IV and V.

$$\max_{\tau} (-TCO_{\tau a} * (1 - WTPM) - CEP_{\tau a}) \quad (10)$$

Calculating the electricity supply option for each user and year that maximizes the utility and summing up all households for which this would include a battery, the shares of potential self-consumers in the sample and the average installed PV panel size and battery capacity for each year is obtained.

### 3.2.2.2 Aggregation and market diffusion<sup>15</sup>

Due to a number of reasons, such as lack of information, financing options or uncertainty, the actual purchase of a self-consumption system is inhibited or deferred in real life (Steinbach 2015). These numerous influences cannot be modelled individually; however, the effects are represented in the model with the introduction of an adoption rate. The adoption rate for this work is required to be dynamic. To quantify it, it can be referred to empirical adoption processes of other household appliances, such as heat pumps.

For example the following (normal) distribution function based on empirical data of the diffusion of heat pumps is applied in Publication V:

$$\varphi(x) = A \cdot \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] + \varphi_{min} \quad (11)$$

with the market share  $x$  and the minimum adoption rate  $\varphi_{min}$ . The parameter values can be found in Table 4, and the fit function is depicted in Figure 12.

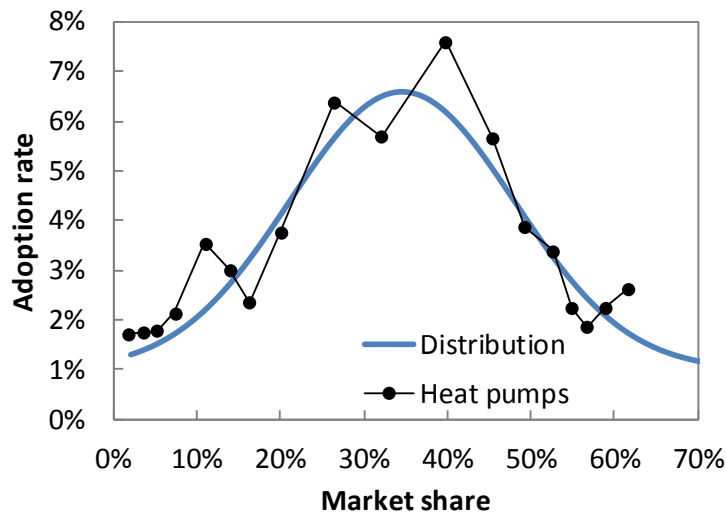


Figure 12: Empirical data and corresponding distribution function for adoption rates of heat pumps in Swedish households (Publication V).

<sup>15</sup> This part of the model was developed in Publication IV, and applied in Publication IV and V.

Table 4: Parameters for the dynamic adoption rates for PV + battery systems  
(Publication V)

Parameter	Value
$\sigma$	13.5%
$\mu$	34.5%
A	1.89%
$\varphi_{min}$	1.00%



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## 4 RESULTS

The results presented in the following section are calculated with the methodology described in Section 3. However, between the different publications changes were made in input data and model configurations. Therefore, only comparable figures are given in this section and all other results are described qualitatively.

### 4.1 Consumer behaviour and preferences

#### Consumer behaviour

As discussed in Section 3.1.1, the household sector is very heterogeneous and it is thus not sufficient to use a single electricity consumption profile for its representation.

In Publication I, a cluster analysis was conducted and four homogeneous groups identified that collectively provide a better representation of the heterogeneous household sector than a single electricity profile would. The four groups are characterised through their distinctive electricity consumption pattern that is in turn explained by the households' behaviour. Further, it was found that the socio-demographic parameters *employment* and the *presence of children* are distinguishing factors for different types of self-consumers; unemployment and the absence of children generally lead to higher self-sufficiency rates.

The average load profiles for the four cluster groups are depicted for summer and winter in Figure 13. Cluster 1 and Cluster 2 consist mostly of households with employed members and children. Cluster 3 comprises mostly unemployed households without children. Cluster 4 consists mostly of employed households without children.

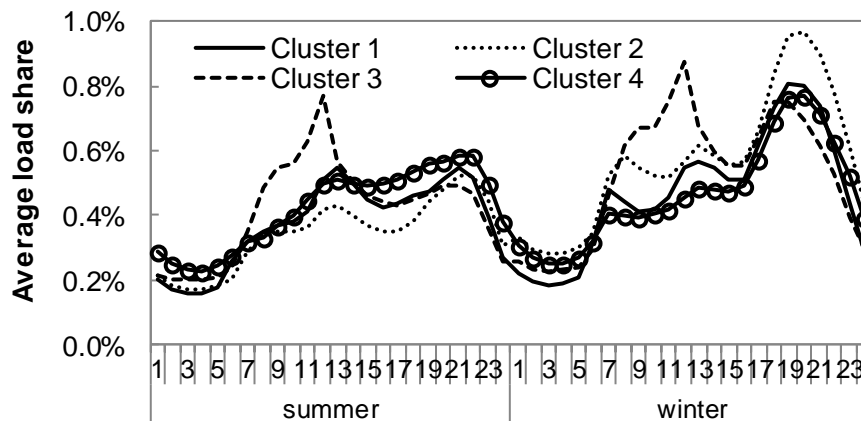


Figure 13: Yearly average load share over for summer (left) and winter (right) for the four cluster groups.

The key factors affecting the economics of PV self-consumption and its enhancement through a battery are how much of the self-produced electricity is consumed directly, and how much is stored in the battery and supplied to the household at a later point in time. From the viewpoint of profitability, it was thus found that households with high yearly

electricity consumption generally benefit more from a PV self-consumption system. Households with large differences in electricity consumption between summer and winter benefit less from combining a PV system with a battery than others. In these households, the battery is rarely used in the winter period due to higher electricity consumption and considerably lower PV production.

Under the current legislation in Germany and the current electricity prices, however, the difference in revenues is on average small between the cluster groups (see Table 5) (Publication I).

Table 5: Average total electricity consumption, electricity supply from a 5 kW PV system and from a 7.5 kWh battery (in combination with the 5 kW PV system), self-sufficiency rates  $r_{SF}^{16}$  with the PV and PV + battery system for the cluster groups and the entire household sample.

	unit	Cluster 1	Cluster 2	Cluster 3	Cluster 4	entire sample
Total	<i>kWh/yr</i>	3,827	4,634	3,601	4,891	4,344
PV	<i>kWh/yr</i>	1,360	1,382	1,424	1,604	1,427
Battery	<i>kWh/yr</i>	1,078	1,198	1,000	1,291	1,021
$r_{SF PV}$		36%	30%	40%	33%	34%
$r_{SF PV+Batt}$		64%	56%	67%	59%	61%

Even though four distinct consumption groups could be identified within the household sector, the individual consumption profiles still differ within one group. For the subsequent analysis, a large number of individual consumption profiles was therefore used to represent the residential sector. This will produce the most precise results.

### Consumer preferences

Besides the financial differences in the benefit of a battery for self-consumption enhancement, also preferences expressed in a non-financial appreciation is different between individual households. This leads to a different WTP.

To address the consumers' preferences in this work, it was referred to a market research survey that was conducted in 2015. In this survey, 1101 households participated, including 436 homeowners. All homeowners were considered as potential adopters of PV + battery systems (Publication IV).

Participants were asked about installed self-consumption technologies, such as PV systems and complementary batteries. In the case that such technologies were not already present in the household, participants were asked about their interest in these options. Householders were further asked to give price estimations for different battery systems and whether or not they were interested in the product. For at least those households, that

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<sup>16</sup> Self-sufficiency rate is defined as the electricity consumption supplied with self-produced electricity divided by the total electricity consumption

did already own a battery system or planned to purchase one within the next 12 months, it can be supposed that they were sufficiently informed about the technology and possible benefits. Therefore, if households of this group stated an interest in the product, their price estimation is assumed to be equal to their willingness to pay (WTP) (Publication IV). This group's median price estimations for different battery sizes are listed in Table 6. According to Rogers' (2003) adopters of innovative technologies, this group was classified as Innovators.

Table 6: Price estimations for different battery systems of households owning a battery system or planning the purchase within the next 12 months (Publication IV)

	Battery capacity [kWh]	Price estimation Innovators (Median) [EUR]
Battery 1	8.7	9,750
Battery 2	7	8,000
Battery 3	2.2	4,750

Using the developed self-consumer model, the actually achievable revenue of the installation of a battery system is calculated (supposing a PV system is already installed). With a 7 kWh battery, varying PV size, and depending on their consumption profile, innovators can save between 697 and 4,356 EUR during the battery's operating life of 10 years. The savings are calculated only from the self-consumption enhancement through the battery and are therefore additional to the savings through direct self-consumption. Based on this economic assessment, the willingness to pay more of the innovator group results, on average, in about 60% of the actual battery system costs (Publication IV).

## 4.2 New technologies: electric vehicles and heat pumps

As discussed in Section 2.1.1.3, new technologies such as electric vehicles and heat pumps can affect self-consumption rates and thus the economics of a self-consumption system. Figure 14 shows the yearly amount of direct consumption of the PV produced electricity as a function of the household's total yearly electricity consumption. As described in Section 3.1.2, an individual heat pump profile and a charging profile for an electric vehicle were added to each household to simulate the self-consumption for households that own an electric vehicle (blue x symbols), a heat pump (red cross symbols) or both, an electric vehicle and a heat pump (purple asterisk symbol). As can be seen in the figure, the amount of direct consumption varies strongly among different households. Generally, the higher the household's yearly electricity consumption, the higher the amount that can be consumed directly from the PV system. The electrification of the supply of the household's heating and mobility demand with heat pumps and electric vehicles alters the consumption behaviour on the one hand in terms of the yearly consumed amount, and on the other hand in terms of the consumption structure and thus

affects the ability of the households to self-supply their electricity demand. In general, the increased electricity consumption enables a higher direct use of PV production: with an electric vehicle a household's direct self-consumption increases on average by 333 kWh/yr. With a heat pump, direct self-consumption increases by 1032 kWh/yr and with both technologies by 1407 kWh/yr (the figures are calculated for a 5 kW PV system). The heat pumps that are able to shift their load towards hours with high PV production contribute more to increased direct consumption than the electric vehicles that charge mostly in the evenings.

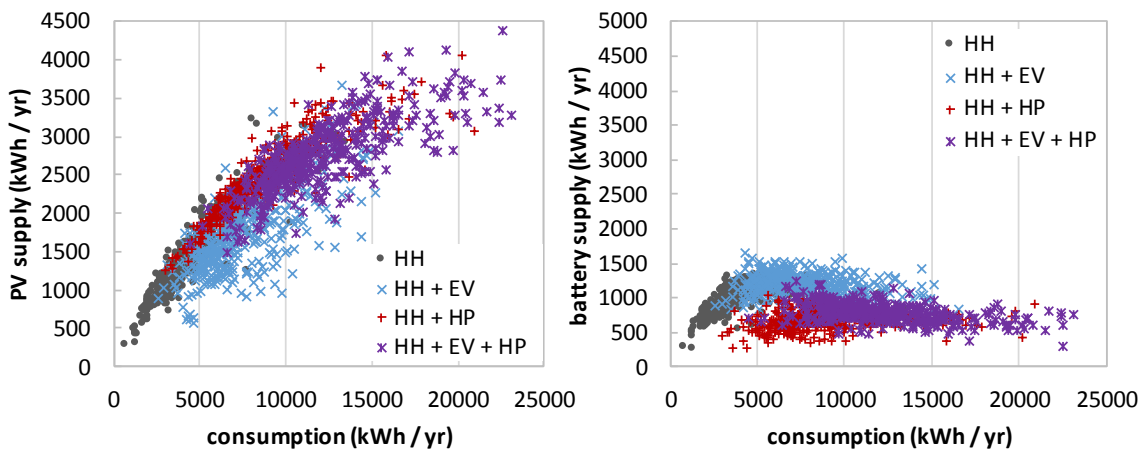


Figure 14: Simulated electricity supply from a 5 kW PV system with a 7.5 kWh battery as a function of yearly electricity consumption. The direct supply from the PV system (left) and from the battery (right). Depicted are individual households (HH) ( $N = 415$ ) with or without an electric vehicle (EV), a heat pump (HP) or both (Publication II).

Corresponding to the higher share of direct consumption, the equipment with a heat pump reduces the electricity supply from the battery by 358 kWh/yr on average (for a 5 kW PV system with a 7.5 kWh battery). Since the load of the heat pump can be shifted, less excess electricity is produced that can be stored in the battery. In contrast, households with an electric vehicle increase the usage of a battery by 98 kWh/yr on average when the charging load in the evenings is supplied with stored electricity.

Table 7: Average total electricity consumption, electricity supply from a 5 kW PV system and from a 7.5 kWh battery, and self-sufficiency rates  $r_{SF}$  with the PV and PV + battery system for the household sample equipped with an electric vehicle (EV), a heat pump (HP) or both (Publication II).

	unit	HH	HH + EV	HH + HP	HH + EV + HP
Total	<i>kWh/yr</i>	4,344	7,623	8,754	12,061
PV	<i>kWh/yr</i>	1,427	1,760	2,452	2,733
Battery	<i>kWh/yr</i>	1,021	1,191	663	777
$r_{SF}   PV$		34%	24%	29%	24%
$r_{SF}   PV+Batt$		61%	41%	37%	31%

Although households with heat pumps and electric vehicles profit most from the installation of PV systems and PV + battery systems, respectively, the population of these households is currently very small. To calculate the potential adopters of PV + battery systems, both the profitability of the system within each group as well as the share of each group in the entire population of households has to be taken into account. Figure 15 compares the share of potential adopters within each group (left part) with the share of the group in the population (right part).

While a battery is economically feasible for households with an electric vehicle as early as 2014, the share of this group within the entire population of households is lower than 1% in 2014; in 2040 it reaches 31% (Publication II).

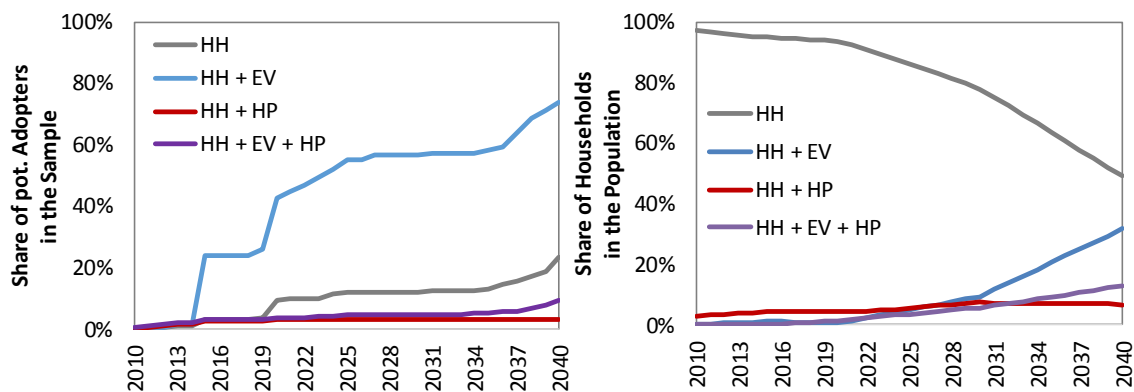


Figure 15: Share of potential adopters of PV + battery systems in the sample of considered households (left) and share of the considered households in the population (right).

### 4.3 System-friendly storage operation

Most system-friendly battery operation strategies require PV production and load forecasts to ensure that electricity is provided to the energy system at times of high electricity prices that correspond with the underlying costs of its production. Further, the

forecast-based operation reduces the feed-in peaks from the PV system that could otherwise be challenging to the distribution grid.

Figure 16 illustrates the forecasted data, in this work calculated by ANN, in comparison with recorded data for one sunny week in August 2014. The quality of the forecasts is high in comparison with simpler persistence forecasts, particularly the pattern of electricity production is adequately captured. The household's load pattern is however more volatile and harder for the ANN to predict. Despite the high forecast quality, PV production and household consumption peaks are systematically underestimated. These forecasting errors lead to an increased feed-in from the battery to the grid and thus to a reduced supply of the household's electricity consumption (Publication III).

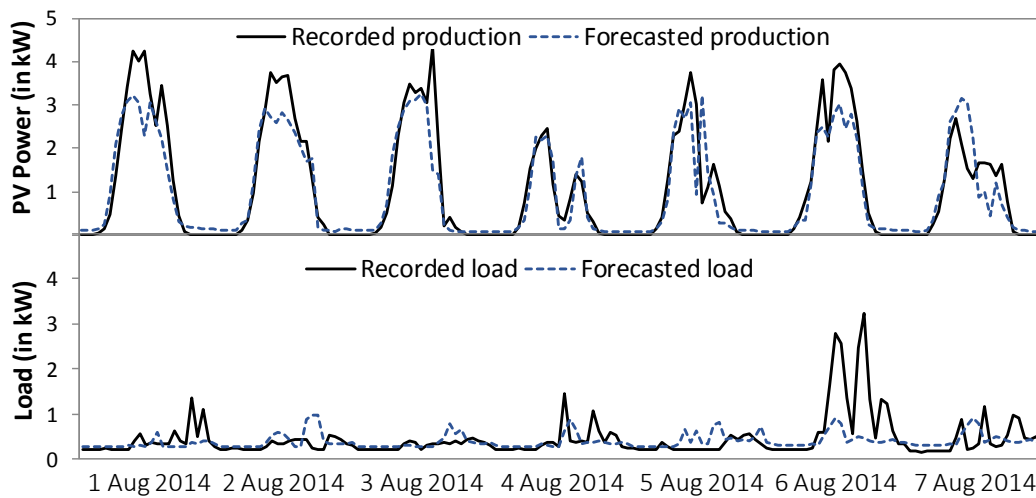


Figure 16: Forecasted vs recorded PV electricity production (upper panel) and forecasted vs recorded load (lower panel) for the week 1 to 7 August 2014 (Publication III).

For this work a case study was calculated, using an example household with an annual consumption of 3,300 kWh/yr equipped with a 5 kW PV system in combination with a 5 kWh battery. As a result, the annual grid feed-in was 5% higher (3,377 kWh/yr vs. 3,210 kWh/yr) with the forecast-based strategy than with a simple relay-based strategy and the household supply from the battery was 16% lower (793 kWh/yr vs. 939 kWh/yr). Due to the resulting undersupply of the household's consumption, the self-sufficiency rate is only 65%, while a self-sufficiency rate of 70% is achieved with the simple strategy (Publication III).

Since the most profitable use of self-produced electricity in Germany is currently its onsite self-consumption, the economic evaluation of these forecasting errors shows that the additional gains from the higher feed-in do not make up for the losses in savings due to reduced self-consumption. Correspondingly, it is found that even small forecasting errors render a system-friendly battery operation financially disadvantageous in comparison to simpler relay-based approaches. In the future, if policy makers want to

promote the application of system-friendly strategies, it is advisable that private households are provided with more accurate forecast data or other incentives are introduced. With the current legislation however, a system-friendly battery operation reduces the profitability of a PV + battery system (Publication III).

#### 4.4 Market potential and diffusion of PV + battery systems

To draw conclusions about the market potential of PV + battery systems and possible market diffusion trajectories, assumptions concerning cost developments for technologies and electricity have to be made. The necessary input data for the model in Publications IV and V, from which derive the here discussed quantitative findings, is drawn from an existing study on behalf of the German Ministry for Economic Affairs and Energy (Winkler et al. 2017), see Table 8.

Table 8: Model parameters for the economic evaluation of self-consumption

	unit	2015	2020	2030	2040
Electricity price	€/MWh	28.8	28.6	27.8	26.6
FIT	€/MWh	12.8	11.3	0	0
PV price	€/kWp	1,553	1,226	1,077	926
Battery price	€/kWh	907	655	548	441
Discount rate	%	2	2	2	2

To assess the market potential and the diffusion of PV + battery systems, self-consumption was simulated with all available 415 household profiles and different sizes of PV panels and batteries.

##### Market potential

The above listed assumptions and thus the market potential in every year are subject to many uncertainties. To address these uncertainties, a sensitivity calculation was executed. The effect of the individual parameters on potential adopters is shown in Figure 17 for the year 2030. Starting from the year 2017 (the first year without empirical data): the input parameters were increased and decreased by 25% and 50% relatively to the base-case parameters.

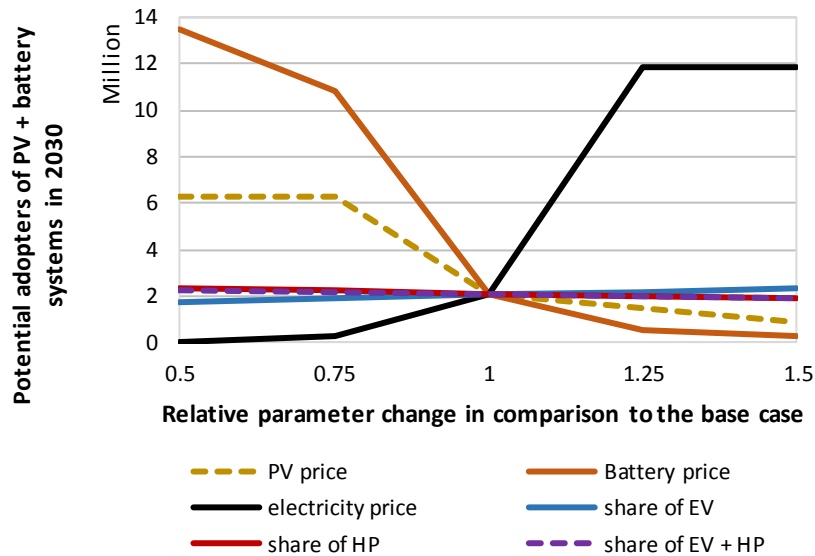


Figure 17: Results of sensitivity calculations: Potential adopters of PV + battery systems as a function of the relative parameter change (Publication II).

Concerning the market potential, the market conditions, particularly electricity prices, are the main driver for the market uptake of PV + battery systems for self-consumption (Publications II, IV, V). Higher electricity prices also lead to the diffusion of larger systems. However, even with constant electricity prices and an abolition of government subsidies, PV self-consumption is likely to gain significant market shares due to decreasing technology costs. Only for a small number of households, even a drop in the battery price of 50% does not make the installation of this technology profitable. Compared to the effect of electricity and equipment prices, the shares of households with heat pumps and electric vehicles have a relatively small effect on the market potential. However, with a higher diffusion of electric vehicles and a lower diffusion of heat pumps, the market potential increases. Further, fast decreasing battery prices are likely to occur in the case of second-life usage of batteries from electric vehicles and are thus potentially connected with a higher share of electric vehicles (Publication II).

In summary: If favourable conditions occur, the installation of a PV + battery system is economically feasible for all households in detached and semi-detached houses in Germany, i.e. an estimated 13.9 million households. However, under unfavourable conditions, there is no economic case for batteries for the enhancement of PV self-consumption.

However, PV self-consumption systems without a battery unit are likely to further increase their market potential even with constant electricity prices and an abolition of feed-in tariffs, due to ever decreasing equipment prices.

### Market formation and diffusion

The differences in economic benefit to the individual households and the differences in the WTPM lead to a yearly distribution of potential adopters, which is depicted in

Figure 18, distinguished by adopter groups. In this graph the householders are identified as potential adopters, when the self-consumption system with the maximum utility includes a battery of any capacity size.

The spread between the individual households within an adopter group, which results from the differences in the consumption behaviour, is quite significant. For some householders of the early majority group for example, the self-consumption technology that maximizes the consumer's profitability already includes a battery in the year 2016, for others a battery is not profitable even after 2050 (Publication IV).

Further, as the diffusion theory suggests, the influence of consumer preferences that are expressed in a higher willingness to pay is decisive, particularly in the early stages of the technology's market uptake, when primarily innovative households constitute the adoption process (Publication IV).

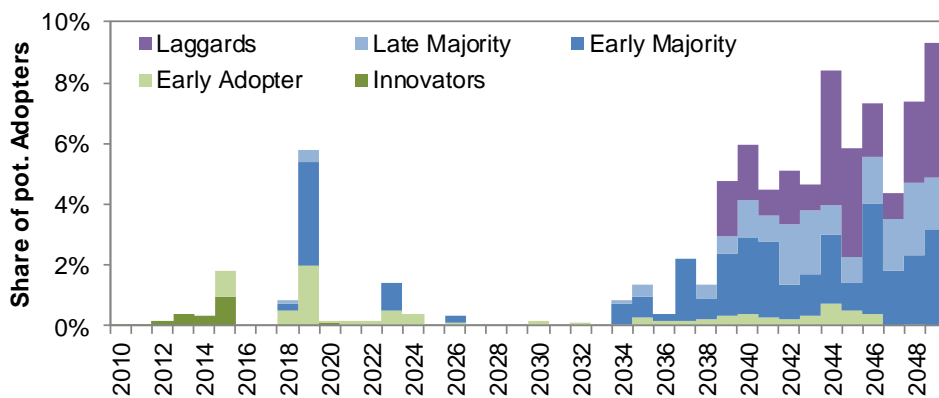


Figure 18: Share of potential adopters for PV + battery systems in each year from 2010 until 2050 distinguished by adopter group (Publication IV).

After the early stages of the market formation, in the medium-term, until 2030, the electricity prices are the main driver for the installation of battery enhanced self-consumption systems. The sensitivity of investment decisions towards electricity prices can even be enhanced by the consumers' anticipation of rising electricity prices. Particularly in Germany, household end-consumer electricity prices are not only determined by electricity production costs but also heavily influenced by levies and taxes. Therefore, political decisions regarding changes in levies on the electricity price will have a decisive impact on the market diffusion of self-consumption systems (Publication IV). Another major driver for the market diffusion of PV + battery systems in the medium to long term are decreasing battery prices. Thus, if battery system costs decrease less than expected, it is likely that only the technology enthusiasts of the innovator and early adopter groups will purchase such a self-consumption system and no broad-based market uptake occurs. The sensitivity towards battery prices also means that expected developments in the battery market, such as the use of second-life storages from electric vehicles or the discovery of new and cheaper battery materials can have a strong impact on the market penetration of PV + battery systems (Publication II, IV).

To assess the range of the market shares of PV systems and PV + battery systems that are to be expected, another sensitivity analysis was conducted. The resulting ranges are depicted in Figure 19. The sensitivity analysis shows that the adoption rate has the largest impact on the market diffusion of PV systems in Germany. In other, less advanced self-consumption markets, such as Sweden, the electricity price is the most influential factor. This is partly due to the fact that PV systems are profitable for almost every household in Germany already at an early stage, which means that the adoption rate naturally plays a central role.

The market share of the considerably less profitable option, the additional installation of a stationary battery, is most sensitive towards changes in the electricity price. The sensitive behaviour points to the fact that the diffusion of this technology mainly depends on the development of its economic case (Publication V).

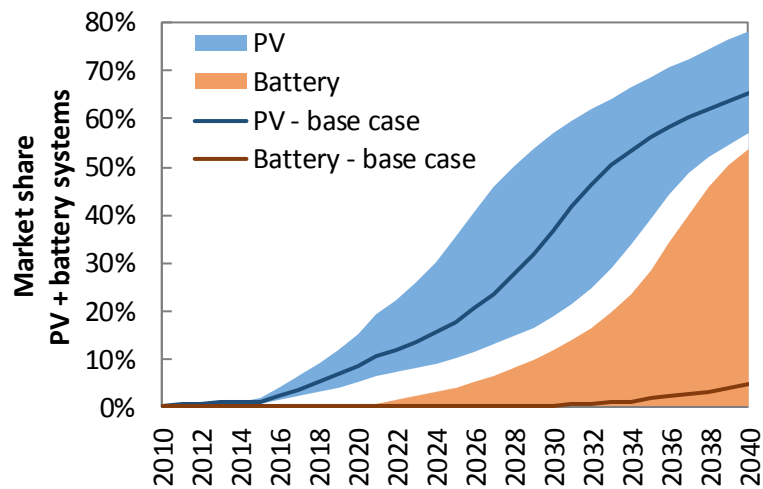


Figure 19: PV systems (blue) and battery (orange) market shares until 2040. Shown are the values for the base case (solid line) together with the ranges from the sensitivity calculations (shaded area).

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## 5 DISCUSSION, CONCLUSIONS AND OUTLOOK

### 5.1 Summary of achievements

The objective of this thesis was to systematically investigate the current and future market potential for residential self-consumption with PV and PV + battery systems in Germany. The drivers that influence the market diffusion at an early and medium-term stage were to be identified. In the following, the main findings are summarized based on the research questions raised:

i. **How do consumer behaviour and preferences influence the profitability of residential PV + battery systems?**

The electricity consumption behaviour has a significant impact on PV self-consumption and battery enhanced PV self-consumption, and consequently on the profitability of such systems. Households with high yearly electricity consumption benefit more from a PV self-consumption system and households with high consumption in the evening hours benefit from a battery to match the PV electricity production with the consumption. Even though a number of distinct consumption patterns could be identified within the household sector, in order to attain more precise results, it was suggested to use a large number of individual consumption profiles to adequately represent the residential sector in the analysis of self-consumption.

Besides the financial differences in the profitability of a battery for self-consumption enhancement, also preferences expressed in a non-financial appreciation are different between individual households. For households that are keen to adopt the new technology, the willingness to pay more (WTPM) calculates, on average, to about 60% of the actual battery system costs.

ii. **How do electric vehicles and heat pumps influence profitability of PV + battery systems?**

Both, electric vehicles and heat pumps, increase the household's electricity consumption and consequently the amount of self-consumed electricity. This in turn increases the consumer's profitability of a PV system for self-consumption. Further, the diffusion of electric vehicles can potentially increase the market for stationary batteries for the enhancement of self-consumption. They do so by enabling to charge the electric vehicles, after their arrival at home in the evening hours, with self-produced PV electricity. In contrast, the installation of heat pumps or other forms of electric heating systems increases the direct consumption of PV electricity and thus reduces the profitability of a stationary battery. This is particularly the case, if the heat can be stored and thus the heating loads can be scheduled for hours with PV production. However, although the diffusion of electric vehicles and heat pumps affects the market for PV + battery system, their

share among the entire population of households is currently small and will only have a significant effect on the market potential in the medium-term.

iii. **How does a system-friendly battery operation influence the consumer's profitability of PV + battery systems?**

In order to operate the stationary battery of a PV + battery self-consumption system in a system-friendly way, forecasted values for PV electricity production and household load are required. Artificial neural networks were successfully used in this thesis for the forecasting of electricity production and consumption, and showed relatively small forecasting errors. However, even small forecasting errors result in a higher level of remunerated electricity feed-in and a reduced amount of self-consumption. Since the most profitable use of self-produced electricity in Germany is currently its onsite self-consumption, the forecasting errors, and hence the system-friendly battery operation, therefore lead to a reduced profitability. This finding refers to a system-friendly self-consumption and does not consider the future possibility of applying the battery to trade its flexibility potential in the future.

iv. **What is the market potential of PV + battery systems in Germany? What are the main drivers for market formation and diffusion of PV + battery systems in the short- to medium-term?**

In this work, it was found that under favourable conditions, such as increasing electricity prices or decreasing battery prices, the installation of a PV + battery system will be feasible for all households in single- and two-family houses in Germany, i.e. an estimated 13.9 million households. Unenhanced PV self-consumption is likely to further increase its market potential even with constant electricity prices and an abolition of feed-in tariffs, due to ever decreasing equipment prices. The market potential of batteries for the enhancement of PV self-consumption is, however, negligible under unfavourable conditions.

In the early stages of the market diffusion of PV+ battery systems, the WTPM of the innovative households is decisive for the early stages of market formation. In the medium- to long-term, the electricity and battery prices as well as the adoption rates are the main driver for the installation of battery enhanced self-consumption systems.

This thesis addresses fundamental questions towards a comprehensive understanding of residential PV self-consumption and its market diffusion in Germany. Therefore, a model was developed that represents all relevant economic, behavioural and technological market drivers in great detail. This was achieved by the new combination of different methodological approaches and new methodological developments.

The methodological achievements of this thesis include the detailed representation of electricity consumption behaviour, which is reflected in the developed methodology by using *415 individual consumption profiles*. The consumption behaviour was statistically

evaluated by means of *cluster and regression analysis*. The match between PV electricity production and residential consumption was *simulated* considering *electric vehicles, heat pumps* and *battery* units. In this simulation, the operation of battery and heat pump was based on a *linear optimization* approach that maximizes self-consumption. In the case of a time-variable tariff, *artificial neural networks* were applied to provide the required load forecasts. The market diffusion of self-consumption systems was modelled with a newly developed *hybrid approach* that models the consumer's investment decision considering the system's economics and the consumer's non-financial preferences. The individual investment decisions are subsequently translated into a realistic trajectory of market diffusion.

## **5.2 Critical discussion and directions for further research**

From the tasks addressed in this work and the outcomes of the different publications, a number of aspects can be identified that require further discussion and thus outline the directions for further research.

### **5.2.1 Simulation of individual self-consumers**

In this thesis, it was found that self-consumption rates for PV and PV + battery systems differ between individual households and therefore also the economic benefit varies. This conclusion was reached from simulations based on individual electricity consumption profiles. As the smart-meter field study, which provided the consumption profiles for this analysis, was conducted in 2009 and 2010, technologies have changed since then, for example the use of LEDs as a replacement for incandescent light bulbs was less common in German households then than it is now. It is likely that the diffusion of highly efficient lighting has reduced the evening peaks in electricity consumption in some households (Publication I). On the other hand, new technologies like electric vehicles or the electrification of residential heating systems, which are addressed in this work, are likely to effect the residential electricity demand in a more substantial way.

For the calculations of self-consumption in households with an electric vehicle, each individual household electricity consumption profile was combined with an individual charging profile. In the conducted simulations, each household therefore is considered to be equipped with only one electric car. A second electric vehicle could further increase the benefit of a battery, but was not part of the analysis. Further, charging at home was assumed for all electric vehicles, since the objective was to increase the self-consumed amount of PV electricity. In the future, it is possible that charging at work is incentivised or otherwise encouraged, since additional charging options are supposed to increase the flexibility in the energy system. This option could reduce the effect of the vehicle charging on PV self-consumption (Publication II).

Concerning the effect of heat pumps, it was found that, particularly with the option of load scheduling, the direct self-consumption is increased with a heat pump and correspondingly the benefit of a battery system is reduced. To allow for an easier analysis, the decreasing heat demand with the ever better insulation of buildings was not considered in the calculations. In the considered time horizon, the effect could however be relevant (Publication II).

Additional to the improvement of individual self-consumption rates, the above described solution to dispatch residential loads and the operation of a battery system theoretically enable the option to participate in the balancing power market. This option could further increase economic benefits in the future (Sterner et al. 2015). Another business concept for the marketing of self-consumption systems is the offer of an electricity flat rate<sup>17</sup> for households equipped with a PV + battery system. Both marketing concepts could further increase the individual utility, but were not within the scope of this thesis.

### **5.2.2 Modelling market potentials and diffusion**

The presented results provide insight into the market potentials and diffusion of PV + battery systems for self-consumption purposes. The overall number of installations in the short- to medium-term is found to be relatively small. Further, decreasing sizes of PV + battery systems can be expected. The developed model has been validated to empirical market data and shows very good results: for the year 2015, the statistics estimate around 240,000 PV systems for the purpose of self-consumption (installations from 2009 on: ÜNB 2017) and roughly 34,000 decentralised battery systems (Kairies et al. 2015). This estimation from the statistics is in the same magnitude as the findings of this work with 169,100 PV systems and 48,466 battery units (Publication V), (Publication IV).

For future years, the number of self-consumption systems to be expected is partly limited by the number of single- and two-family homes, and additionally by the adoption rates. However, particularly the assumptions about the adoption rates applied within this work are subject to uncertainties. In future research, these parameters that characterise the gap between a profitable business case and the actual adoption could be modelled in more detail. For example, the spreading of knowledge from one potential technology adopter to the next, or the perception of financial risks could be investigated further (Publication V).

Additionally, new business models could be developed to include multifamily homes and apartments into the group of self-consumers. This would increase the total population of potential PV + battery adopters and therefore the number of installations (Publication IV).

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<sup>17</sup> Currently offered by beegy ([www.beegy.com](http://www.beegy.com)) and sonnen GmbH ([www.sonnenbatterie.de](http://www.sonnenbatterie.de))

Concerning consumer preferences, the presented study is able to provide an approach to integrate the willingness to pay more, and thus non-financial reasons for a purchase, into a market diffusion model. The market survey, which was analysed for this work, provided useful information regarding valued attributes of battery systems and could provide the willingness to pay for the innovator group. The WTP for the other adopter groups has been estimated taking into account their respective preferences. Furthermore, the survey did not provide consumer preferences regarding the PV system. Herein lies an interesting research question, as the preference regarding the size of the PV + battery system and the corresponding self-sufficiency rates could possibly affect the results on the configuration of the average installed system (Publication IV).

In the conducted sensitivity analysis, it was found that the developed market diffusion model is highly sensitive to electricity and technology costs (Publication II, IV, V). Future research could therefore focus on the cost development. Regarding the development of electricity prices, the price spreads in RTP electricity tariffs are particularly likely to increase in the future due to higher shares of intermittent power production and diffusion of new technologies such as electric vehicles. This can have an impact on the profitability of self-consumption in the medium-term, if such an electricity tariff will be available for households (Publication V). On the technology side, the diffusion of electric vehicles is likely to increase the availability of second-life batteries from the electric cars and therefore possibly reduces the cost of stationary battery systems (Publication II).

### **5.3 Concluding remarks**

For a holistic understanding of the market diffusion of self-consumption technologies, a market diffusion model is required that, based on individual electricity consumption profiles, considers economic, behavioural and technological market drivers. The interdisciplinary combination of technical modelling of PV electricity production and its onsite consumption as well as sociological data on consumer behaviour and preferences brings forward its realization. With the developed methodology and with the strong improvement of the database within the work of this thesis, individual households are analysed in detail. By aggregating the resulting findings onto the level of the entire residential sector, a profound knowledge on the preconditions of the market formation, uptake and potential in the case of PV self-consumption is attained. This knowledge contributes to a better understanding of market dynamics in the context of electricity self-consumption in the residential sector.



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The transformation of the energy system includes increasingly active market participation by formerly passive consumers via the installation of photovoltaic (PV) systems for decentralized production and on-site consumption of electricity, so-called self-consumption. A holistic understanding of the market diffusion of PV + battery systems for self-consumption requires a technology diffusion model that considers economic, behavioural and technological market drivers. A model is developed that considers technical restrictions of PV production and flexible electricity consumption as well as sociological data on consumer behaviour and preferences. An individual analysis of 415 real-world household electricity consumption profiles, as well as electric vehicle charging and heat pump operation profiles allows to determine the system configuration that will optimize individual profitability. The profitability of each system is calculated based on its total cost of ownership and the consumers' preferences expressed in a willingness to pay more. The developed method closes an important research gap and allows to attain a profound knowledge on the preconditions for market formation and development, and to assess the potential of PV self-consumption.