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Market diffusion of residential PV + battery systems driven by self-consumption: a comparison of Sweden and Germany

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Abstract

With increasing number of installations of photovoltaic (PV) systems and lower equipment costs, the subsidies dedicated to residential PV systems are reduced in many countries. Instead of the subsidies for selling PV electricity, prospectively self-consumption is the key parameter for the profitability of PV systems. In this paper, we study the market diffusion of residential PV systems for detached houses in Germany and Sweden. For this, we develop a hybrid model of the adoption of PV installations driven by self-consumption. We model the profitability and 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. We also study 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 a large difference in the market share of PV systems in Germany and Sweden in 2040. A base case scenario results in a market share for PV systems of 65% of the German detached houses in 2040, compared to 12% in Sweden. The 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 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 less than half of the German price, the profitability is the main limiting factor. This is reflected in the hybrid adoption model, where the market diffusion is dependent on both the profitability and the adoption rate. The market share for battery systems is 5% in Germany and 0% in Sweden in 2040 in the base case scenario. 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.

Key words: Market diffusion; self-consumption; PV; battery; technology adoption

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1 Introduction

Solar photovoltaics (PV) is a renewable energy technology that is highly suitable for micro-scale electricity production, for example for residential applications. The adoption of PV technology has been large, even in countries with moderate solar irradiance. However, since PV electricity production was previously associated with high cost, national subsidy schemes were needed to make PV competitive on the electricity market. With reduced costs and higher market shares of PV systems, the subsidy schemes are reduced on many markets. It is therefore important to study the future adoption of PV technology, also known as market diffusion, on a competitive electricity market without dedicated subsidy schemes.

The market diffusion of innovative technologies, occurs via accumulative adoption by the customers (Stoneman, 1995). The development of diffusion typically starts with low adoption rates, increases continuously until the point of infliction and then decreases in dynamics until the saturation level is reached (Karshenas and Stoneman, 1995), (Rogers, 1962). 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), (Modis and Debecker 1988).

For the vast majority of households, decisions to invest in PV systems are primarily driven by the expected economic performance of the PV system (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, insolation, and the ratio of self-consumption (Couture et al. 2014). From those factors, it is found that particularly the electricity prices have a significant effect on adoption likelihood of energy related investments and energy saving behaviours (Long 1993), (Walsh 1989), (Pitts and Wittenbach 1981), (Dillman et al. 1983). Analyses based on US households for example show that with a 1% rise in the energy prices, there is a 0.21% rise in conservation items (Long 1993). It can thus be assumed that electricity prices have an equally high impact on the investment in PV self-consumption systems.

There exist various support schemes for the promotion of PV systems. The majority of the support schemes reduce the added value of self-consumption, since only the feed-in and not the self-consumed electricity are subsidized. However, the overall profitability of the PV system is increased and self-consumption is thus indirectly supported. . Especially feed-in laws have proven to be effective

(Muñoz et al. 2007), a tool that is widely used as a promotional tool in Austria, France, Germany, Greece, Luxemburg, Portugal, and Spain as well as other countries worldwide (Islam 2014). Other countries such as Norway, Sweden and Switzerland use payment bonus or tax credit programs for residential PV installations (IEA PVPS 2017). When the feed-in subsidies are phased out or decreased, self-consumption is likely to be the most important market driver for the expansion of PV systems in a post-subsidy era (Lang et al. 2016).

The adoption of flexible technologies such as stationary batteries is currently encouraged in Germany and Sweden by the implementation of a payment bonus (KfW 2016, Regulation 2016:899 § 5). Guidolin and Mortarino (2010) analysed diffusion of the PV systems of 11 countries using the Bass model and showed that government policy incentives have promoted the market diffusion of PV systems. Similar findings for Japan are reported by Zhang et al (2011).

In this paper, we calculate and compare the market diffusion of residential PV systems until 2040 in Germany and Sweden. Both countries have similar solar irradiation, but large differences in other influencing parameters: On the one hand, the end consumer price of electricity for private customers is more than twice as high in Germany than in Sweden, but the underlying wholesale prices of electricity are similar. The self-consumption of PV electricity will thus make a larger impact on the profitability in Germany than in Sweden. On the other hand, the electricity demand for an average single-family house is higher in Sweden than in Germany, which leads to generally higher self-consumption rates in Sweden than in Germany for similar PV systems. Thus, the aim of the study is to analyse the differing conditions in Sweden and Germany and assess the market diffusion of residential PV systems in the two countries. By taking the differences in economic and physical conditions into account, the market diffusion can be simulated by using a model for the adoption of residential PV systems. Furthermore, a sensitivity analysis is conducted to examine how different parameters affect the market diffusion.

2 Support of self-consumption

This section gives an introduction of the support schemes for PV electricity, energy storage and direct and indirect support for self-consumption of residential PV.

2.1 Germany

Direct support of self-consumption

The German Renewable Energies Act (EEG) 2009 introduced a premium dedicated for self-consumed electricity. The premium was added to the saved electricity expenses, it made the value of self-consumed electricity higher than the value of sold electricity.. The premium initially amounted to 25 EUR-ct/kWh in 2009 and decreased in subsequent years. By 2012 it was abolished, due to increasing electricity prices and decreasing levelized costs of electricity (LCOE) of PV systems (Schill et al., 2017). Other support measures for renewable self-consumption still exist. The most important ones are presented in the following: Residential renewable energy systems get guaranteed and priority interconnection with the public grid and priority feed-in of produced electricity. The grid connection is paid for by the system owner, but possible extra grid related costs (grid reinforcement, grid extension) are covered by the grid operator and therefore by the general public (Friedrichsen et al., 2016).

Feed-in of excess generation: Excess PV generation can be sold under a FiT (feed-in tariffs) 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 2012, the feed-in is limited to a maximum of 70% of the installed power (BDEW, 2013).

Subsidization of battery storage: In 2013, the "KfW program 275" was introduced, which is a program that subsidizes the installation of battery storage 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 is since then gradually decreasing to 10% at the end of the program in 2018.The KfW program intends to incentivize the development of a system friendly operation of battery storage systems and therefore includes requirements for the eligibility of the systems: Most important, the maximum grid feed-in of the PV system is limited to 50% of the systems installed power (KfW Bankengruppe, 2016).

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 (European 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 levelized costs of electricity (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 retail price (right part of Figure 1), 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. 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 Deuschland e.V., 2017). In 2009 the achievable revenue was about 10 EUR-ct /kWh (left part of Figure 1). Accordingly, there is now room for self-consuming households to increase self-consumption, even if it involves additional costs for technologies such as batteries (Schill et al., 2017).

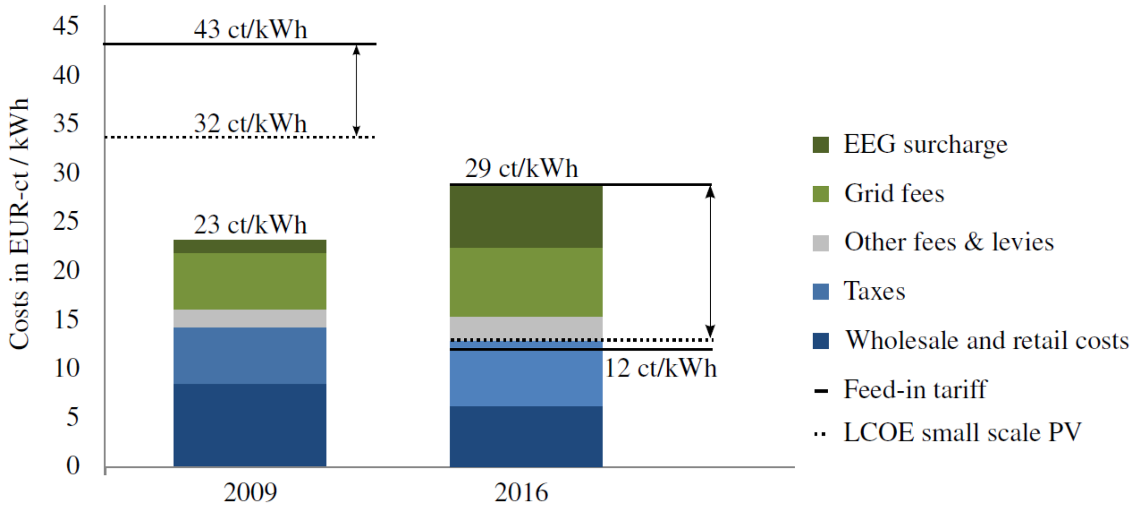

Figure 1: Electricity prices for residential consumers, feed-in tariffs and levelized costs of electricity (LCOE) for small scale PV in Germany in 2009 and 2016 (BDEW, 2017), (Breyer et al., 2015), (Kost and Schlegel, 2010), (Solarenergie Förderverein Deuschland e.V., 2017).

2.2 Sweden

Direct support of self-consumption

There is no dedicated support measure for self-consumption of renewable electricity production in Sweden. However, there are other subsidies for renewable electricity production affecting the value of self-consumed PV electricity, presented below.

Feed-in of excess production: Excess PV production can be sold to an electricity retailer, which can be the same or another company than the distribution system operator (DSO). There are approximately 120 electricity retailers and 160 DSOs in Sweden and every household is free to choose electricity retailer for buying and selling electricity. Fees and compensations are different for each electricity retailer and DSO. Residential renewable energy systems get guaranteed and priority interconnection with the public grid and priority feed-in of produced electricity.

Since 2015, micro-producers of renewable electricity are eligible for a tax deduction for the feed-in electricity (Palm, 2018). The tax deduction amounts to 0.60 SEK (EUR-ct. 6.1) per kWh of renewable electricity fed into the grid at the access point during the calendar year (Regulation No. 2014:1468). The tax deduction covers up to 30,000 kWh or the amount of electricity withdrawn from the electricity grid within one year (Act No. 1999:1229, Chapter 67 § 30-31). There is currently no end date for the tax deduction and the amount might be changed in the future.

The tax deduction leads to a value of feed-in electricity almost the same as the value of self-consumed electricity in 2016, see Figure 1. An extra surcharge from the electricity retailer on the bought electricity might however slightly increase the revenue of the self-consumption.

Subsidization of PV system and battery storage: Since the 1st of July 2009 there is an investment subsidy for PV systems (Regulation No. 2009:689). When it was introduced, the subsidy covered 60% of the total costs of the PV system, including the installation costs (Palm 2018). The investment subsidy has been has gradually been reduced due to the declining PV system costs. The waiting list was sometimes long due to lack of funding, which reduced the number of installations even if it was profitable for households to install PV systems (Palm 2018). As of 2016, private persons can apply for 20% of the total investment, and the PV systems must be installed before the end of 2019 (Regulation No.

2009:689 § 5). Between 1st of January 2016 and 31st of December 2019 there is a dedicated subsidy of 60% of the investment cost for stationary energy storages aiming to increase the self-consumption of renewable electricity generation (Regulation No. 2016:899 § 5). The grant is limited to maximum 30,000 SEK (EUR 3,070). There is currently no decision of investment subsidies for installations of PV systems and energy storage after 2019.

In order to increase the renewable electricity production, a market-based electricity certificate system for producers of renewable electricity was introduced in 2003 (Linderoth and Yde Aksenes 2017). The cost of the certificate system is added to the end customer electricity price. For small-scale PV power it is possible to get electricity certificates for the whole electricity production. That would however require an extra electricity meter placed directly in connection to the PV inverter. The extra cost associated with the meter means that small-scale producers often only apply for electricity certificates for the excess electricity reported to the electricity retailer (Lindahl 2017).

Indirect support of self-consumption

Similar to Germany, Sweden has a volumetric tariff for residential electricity, except for a fixed subscription cost (Lindahl, 2017), (Stridh et al., 2014). The added value of the self-consumed electricity is the taxes and fees added to the buying price of electricity, see Figure 2. In the figure and for the initial assumptions in the market diffusion model, we use the electricity price on the Nord Pool spot market and electricity certificates for the revenue of selling electricity. The spot market prices are means for March to October 2009 and 2016, since the PV production in the between November and February is generally very low.

The low end consumer electricity price in Sweden leads to a lower value of the self-consumed electricity of the PV electricity than in Germany. Assuming an LCOE of 13 EUR-ct/kWh in Sweden in 2015, the revenue is negative independent on the level of self-consumption (Breyer et al., 2015). Another study from 2014 calculated the LCOE for a typical residential PV system to 1.04 – 1.44 SEK (EUR-ct 10.5-14.7) per kWh (Stridh et al., 2014), indicating that the profitability of a PV system is highly dependent on the assumptions of life expectancy of the PV system, discount rate, investment cost and electricity production yield per installed kW.

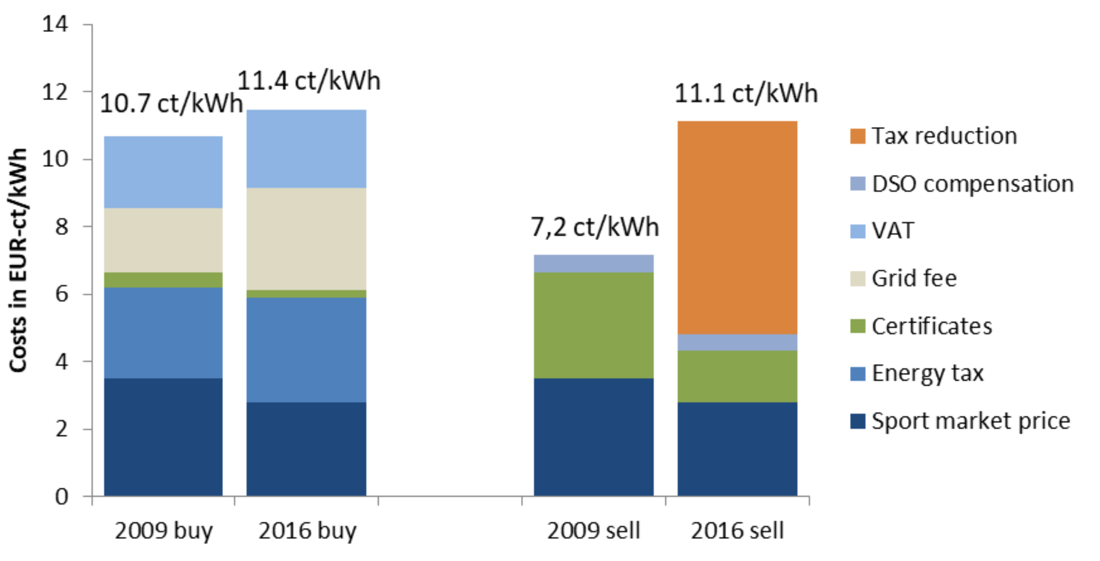

Figure 2: Mean electricity prices for residential consumers for small scale PV in Sweden in 2009 and 2016 during March to October (Nord Pool Spot, 2017), (Regulations No. 2008:853, 2015:595 and 2014:1468), (Swedish Tax Agency, 2017), (Swedish Energy Agency, 2016 and 2017), (Stridh et al., 2014). Fixed costs are excluded.

2.3 Summary of support schemes

A summary of the support schemes for residential PV systems is presented in Table 1. Direct and indirect support for PV self-consumption is higher in Germany compared with the support in Sweden. This is reflected in an estimated 240,000 installed PV systems for self-consumption in Germany in 2015 (installations from 2009 on: ÜNB 2017) compared to less than 10,000 in Sweden (SCB 2017).

Table 1: Overview of financial conditions for small-scale PV in Germany and Sweden in 2016.

	Germany	Sweden
Electricity prices	high prices (223% of LCOE[1]) volumetric charges	low prices (85% of LCOE[1]) volumetric charges
PV system	Feed-in tariff	Tax deduction + electricity certificates + spot market price
	Low interest loans Grid connection	Payment bonus (20%) Grid connection
Battery	Payment bonus (2017: 13%) Low interest loans	Payment bonus (60%)

[1]with an LCOE of 13 EUR-ct/kWh

3 Residential Consumers in sweden and Germany

This section describes the residential electricity consumption profiles, PV production and the matching between production and consumption.

3.1 Residential electricity consumption

The calculations on self-consumption conducted in this study are based on electricity consumption profiles of single-family households. In this paper, hourly electricity consumption time series for each household over one year is used. The time series provide information not only about the consumed amount of electricity, but also about the consumption behaviour.

To account for seasonal fluctuations in both solar electricity production and residential consumption, the profiles are required to be recorded for an entire year, i.e. 8760 hours. Due to significant differences between individual households, it is equally necessary to use individual load profiles instead of aggregated data (Luthander et al. 2015).

Data and data preparation

The applied data for Germany originates from a smart-meter field study that was conducted in 2009 and 2010 in Germany and Austria (for details see (Schleich et al. 2013)). The participation in the survey was voluntary and besides hourly recorded consumption data, the data set comprises additional information on the individual households. The homeowners of the German field study comprise larger households with higher electricity consumption compared to the average German population, which is currently 3483 kWh/year (BDEW 2016). For the subsequent evaluation, the household size therefore is used to quote the data set in order to get a better representation of German households in general.

The Swedish household profiles originate from one municipality-owned energy utility in south-west Sweden (Luthander et al. 2017). The houses are categorized as electric heated or non-electric heated by the utility. The smart meter load data was recorded in 2014 by the local energy utility. The hourly load data is measured for 5174 customers, of which 2431 customers are categorized by the energy utility as single-family households. The households are distributed over two small cities and a rural area, and it is thus considered that the data is representative for single-family houses in the southern part of Sweden.

The recorded hourly consumption was restricted to “reasonable” levels to allow for a robust analysis. Hourly electricity consumption records below 20 Wh were considered as unreasonable, given the fact that already a small refrigerator consumes more, and all participants in the German smart-meter study stated to own at least one. In these cases, a malfunction of the smart meter can be assumed. Erroneous values are excluded from further processing and data sets with more than 20% unjustifiable values are excluded entirely from the analysis. All in all, hourly data from 415 German households and 393 Swedish households was selected to be used within this study.

Consumption behaviour in Sweden and Germany

Several measures can be used to evaluate and characterize residential load curves (the characteristics applied here are taken from (Bossmann and Staffell 2015)). Table 2 contains an assessment of the average German (DE) and Swedish (SE) household load curves as derived from the available smart meter data. In Table 2

- L is the hourly mean load (measured in W) in hour t
- ΔL is the unbroken series of load changes in a single direction (i.e. the extend from a local minimum to maximum)
- T is temperature (measured in °C)
- t_{peak} is a definition of which time contains the peak load

Temperature sensitivity is represented by the negative differential of load with respect to temperature, since demand is expected to rise as more heating is required, which is as T falls. This can be thought of as the average slope of the data on the left side of Figure 3, for temperatures below 15°C.

Table 2: Evaluation characteristics for single-family houses (SFH) and two-family houses (2FH) household load curve in Sweden (2014) and Germany (2010), calculated as the average over the individual households.

		Unit	Notation	DE	SE
Load duration curve	Total demand	*kWh*	D	3,618	10,909
	Minimum load	*W*	min(L)	65	142
	Mean load	*W*	mean(L)	393	1,245
	Maximum load	*W*	max(L)	3,800	6,581
	Min/Max load ratio		min(L)/max(L)	1.7%	2.2%
	Capacity factor		mean(L)/max(L)	10%	19%
Load change	Maximum load change	*W*	ΔL_{pos}	626	921
		W	ΔL_{neg}	-648	-995
	Diurnal capacity factor		$mean(L)\|_{day}/max(L)\|_{day}$	36%	49%
Peak time	Hour of max load		$median(t(max(L)\|_{day}))$	15	15
	Load share at daytime		$mean(L)\|_{8-20h}/mean(L)\|_{day}$	64%	57%
Temperature sensitivity	Mean temperature sensitivity	*W/°C*	$-mean(dL/dT\|_{T<15°C})$	6.4	82.4
	Peak temperature sensitivity	*W/°C*	$-mean(dL/dT\|_{T<15°C,tpeak})$	11.4	89.0
PV production	Mean PV output	*kWh/kW*	P_{PV}	971	908[1]

The Swedish household in this study consume in average 10,909 kWh, with the hourly load ranging on average between 142 W and 6.6 kW, compared with 3,618 kWh for the average German household. While Sweden's household demand is 3 times that of Germany's, the maximum load is only 173% that of the German household's average. Further, the Swedish households show a lower load fluctuation than the German ones. The capacity factor over one year is 9% lower and the diurnal capacity factor is even 13% lower than in Germany.

Swedish residential demand is 12 times more sensitive to temperature than German, with peak load rising by over 89 Wh/h on average for every degree

1 PV production data available from: http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php#

that the temperature falls. This mirrors the share of electric heating in both countries: In Sweden over 30% of single-family households heat mainly and over 50% partly with electric heating systems in the end of 2014 (Swedish Energy Agency 2007-2016). In contrast, only 4% of German households heat electric (BDEW 2016, 2015). The temperature sensitivity of peak loads in Swedish and German households is depicted in Figure 3.

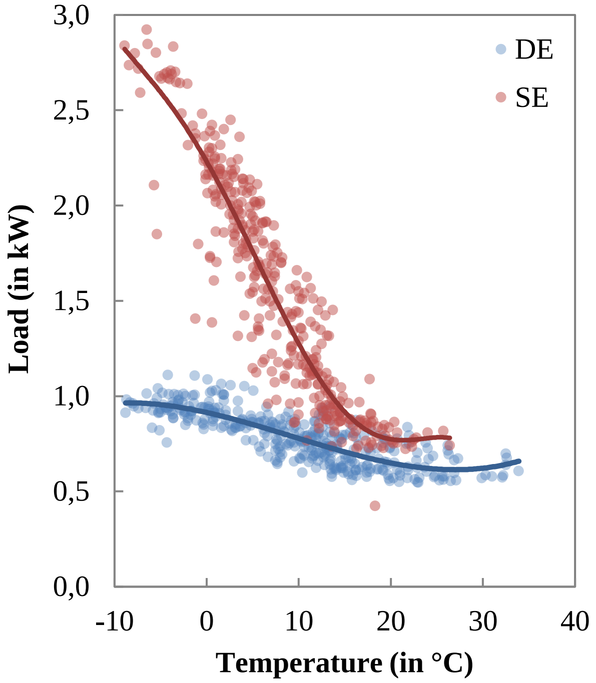

Figure 3: The temperature sensitivity of peak load in German and Swedish SFH and 2FH households; data from 2010 (Germany) and 2014 (Sweden).

However, the high share of electric heating cannot be the only explanation for the relatively high electricity consumption of Swedish households: Even on a summer day, the average electricity demand on a summer day is 646 Wh for Swedish households without an electric heating system, and 1,417 Wh for households with electric heating. That is considerably more than the average German household that consumes 440 Wh in summer and merely 576 Wh on a winter day.

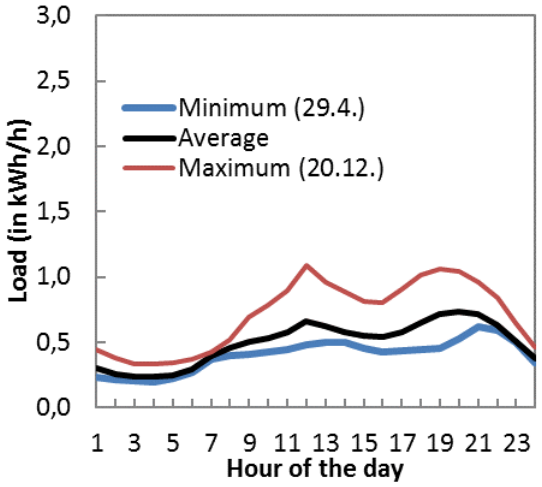

Figure 4: Average SFH household consumption and average consumption on the day with the lowest and highest consumption for Germany (left) and Sweden (right).

3.2 PV power production

The PV production profiles are simulated based on global irradiance data for the same year as the recorded household demand data to ensure consistency. The methodology for the simulation was taken from Schubert (2012) and adapted to fit this study's purpose. Since the orientations of the individual households are not known, the PV production is calculated for a non-shadowed 35° southwest-oriented gabled roof with a tilt of 30°. For the Swedish households, hourly PV production data from the municipality where the houses are located is calculated using global irradiance data for 2014 from the STRÅNG model (SMHI, 2017). The irradiance data for Germany in 2010 was taken from a weather station in Würzburg a city located in the middle of the country that represents the national average (DWD 2016).

In contrast to the residential consumption, the PV output in Germany and the considered (southern) part of Sweden is rather similar (cf. Table 2)

3.3 Self-consumption and self-sufficiency

The two measures self-consumption and self-sufficiency are often used to evaluate and assess PV systems integrated into buildings (Luthander et al., 2015). The self-consumption can be calculated as $\varphi_{SS} = M/P_{PV}$ and the self-sufficiency as $\varphi_{SS} = M/P_{HH}$ with the PV production as $P_{PV} = \sum_{t=t_1}^{t_2} P_{PV}(t)$, the household electricity demand as $P_{HH} = \sum_{t=t_1}^{t_2} P_{HH}(t)$ and the self-consumed on-site electricity production as $M = \sum_{t=t_1}^{t_2} M(t)$. Without a battery storage, the self-consumed electricity production is defined as $M(t) = \min(P_{HH}(t), P_{PV}(t))$. If a battery storage is added, self-consumed electricity production is defined as $M = \min(L + P_{Batt}, P)$ where $P_{Batt}$is the power to and from the battery unit. Charging is defined as $P_{Batt} > 0$ and discharging as $P_{Batt} < 0$.

The self-consumption and self-sufficiency for the German and Swedish households are shown in Figure 5 as a function of PV system size. The variations in self-consumption and self-sufficiency between the households are lower (higher R^2) in Germany than in Sweden. The average self-consumption decreases faster in Germany than in Sweden with increasing PV system size due to the lower average electricity consumption in Germany than in Sweden, see Figure 4. The self-sufficiency is generally higher in Germany than in Sweden mainly due to a lower mismatch between PV electricity production and household load on a seasonal basis.

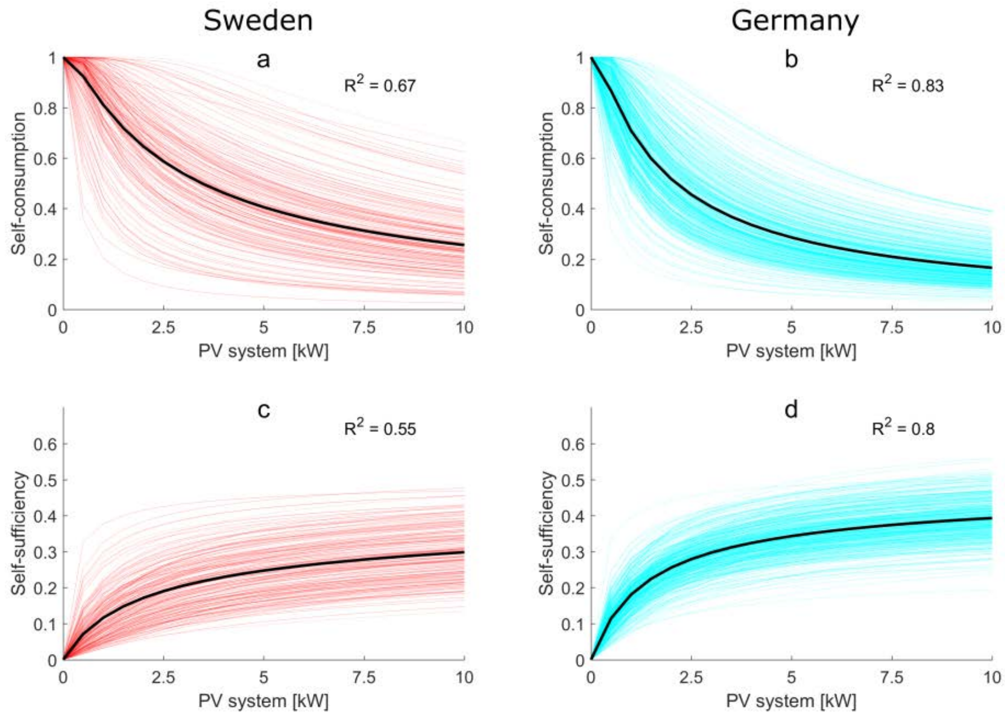

Figure 5: Self-consumption (a and b) and self-sufficiency (c and d) for different yearly PV electricity production normalized to household electricity demand in each building. Results for Sweden in red (a and c) and for Germany in cyan (b and d). Each building is shown as a red or cyan line and the mean values as black lines.

If batteries are added to the houses, the average self-consumption and self-sufficiency are affected as in Figure 6. The self-consumption (Figure 6a and b) increases until the battery size reaches approximately 5 kWh. A larger battery capacity does not increase the self-consumption significantly. This indicates that a larger battery will store more electricity than is mostly used during the evening, night and morning. The full capacity of the battery is therefore not used during these days. The self-sufficiency shows a similar pattern. Especially for PV systems up to approximately 5 kW, a battery of more than 1 kWh per kW PV system does not increase the self-sufficiency significantly (Figure 6c and d).

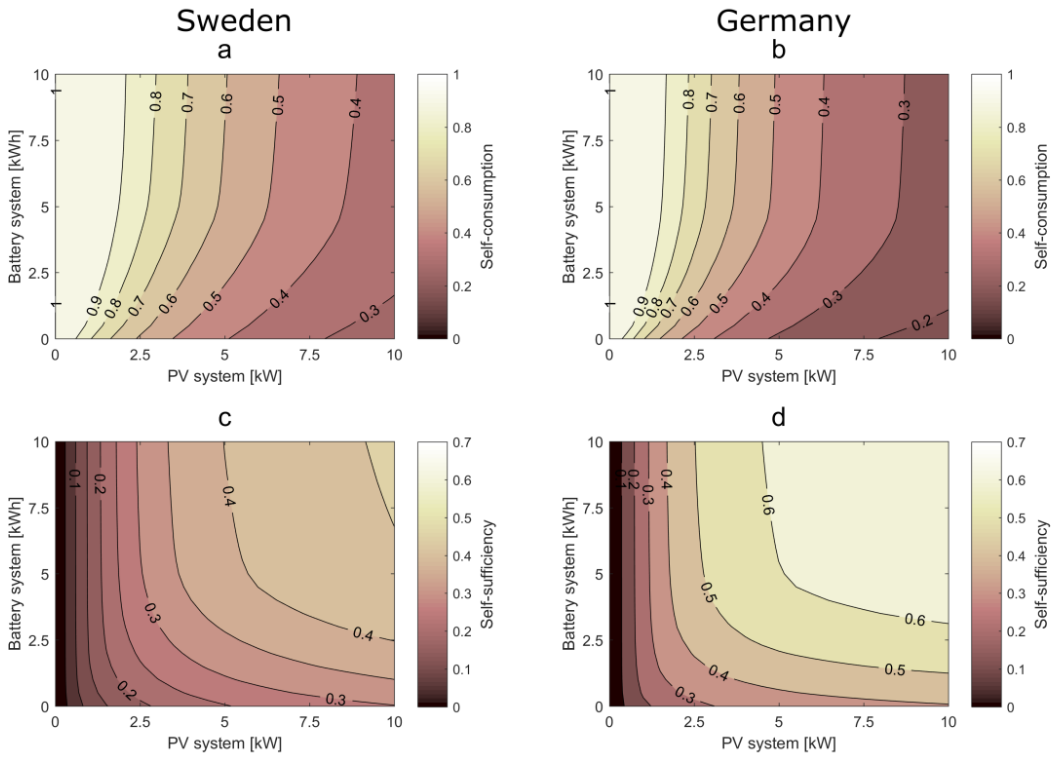

Figure 6: Self-consumption (a and b) and self-sufficiency (c and d) for different PV capacities (x-axes) and battery capacities (y-axes). Results for Sweden (a and c) and Germany (b and d).

4 Modelling self-consumption and market diffusion

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 (1962) 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 modelling analyses adoption in general 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 don't 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). In this study, we develop and apply a hybrid model, combining the advantages from both the epidemic and the decision-based modelling approaches.

4.1 Market diffusion model

In the developed market diffusion model (see Figure 7), the market shares of PV + battery systems are based on individual consumption data and using techno-economic parameters and are determined in three steps: self-consumption is simulated for each consumption profile and various system configurations (section 4.2); based on the total cost of ownership, feed-in tariffs and the cost for electricity purchase, the utility maximising system configuration is chosen for each consumption profile (section 4.3); the technology choices are transformed into market shares (section 4.4). Parameters with asterisk are applied in a sensitivity analysis.

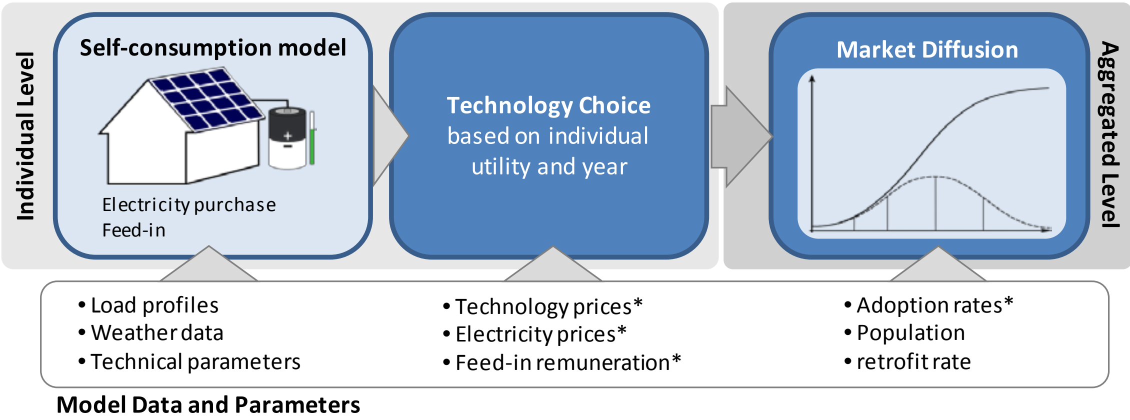

Figure 7: Overview of the proposed model for the market diffusion of PV + battery systems.

4.2 Simulation of individual self-consumers

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

$$\text{Min} \sum_{\text{h}=\text{h}_{\text{min}}}^{\text{h}_{\text{max}}} C_h \left((1 + (1-\eta))\, P_{Batt,pos,h} + \eta\, P_{Batt,neg,h}\right) \quad (2)$$

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 $\eta = \eta_{Batt} \times \eta_{AC-DC}$ = 89%. The objective function is subject to technical restrictions, such as capacity limits. The consumption of self-generated electricity is favoured with the implementation of the following cost function ($A(t) < B(t)$):

$$C_h := \begin{cases} A(t), & P_{HH,h} + P_{Batt,h} \leq P_{PV,h} \\ B(t), & \text{else} \end{cases} \quad (3)$$

with the household's electricity demand P_{HH}, battery load $P_{Batt} = P_{Batt,pos} + P_{Batt,neg}$ and the PV production P_{PV}. Note that the amount of $A(t)$ and $B(t)$ is in this case not important, as long as $A(t) < B(t)$ the battery operation is optimized to maximize self-consumption. In the cases of Sweden and Germany, $A(t)$ represents the feed-in remuneration and $B(t)$ the electricity purchase price. In Germany, both feed-in remuneration and electricity price are generally fixed, thus $A(t) = A$ and $B(t) = B$, whereas in Sweden both can be time-variable, if the option of a real-time pricing (RTP) electricity tariff is chosen.

Note that different battery capacities and PV panel sizes are applied and the battery operation 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 self-consumption model described above. 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 subsequent utility calculation.

4.3 Total cost of ownership and utility calculation

In a second step the economic potential is 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_a) consists of the investment annuity (i.e. capital expenditure) a^{capex} and the yearly operating expenditure a^{opex}

$$TCO_a = a^{capex} + a^{opex} \quad (4)$$

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

$$a^{capex} = \frac{(1+i)^n \cdot i}{(1+i)^n - 1} I_0 \quad (5)$$

with the discount rate *i* and the investment for the PV + battery system I_0.

Additionally, the annual cost of electricity purchase (CEP_a) is considered, which is calculated as the sum of electricity supplied from the grid p_e in kWh times the cost for electricity *E* in EUR/kWh over the course of one year. The cost of electricity purchase is reduced by the amount of excess electricity feed-in e_e in kWh/year times the remuneration *F* in EUR/kWh:

$$CEP_a = \sum_{t=1}^{8760} (E(t)p_e - F(t)e_e) \quad (6)$$

In case of high feed-in tariffs or large PV systems, the CEP_a can also become negative. Finally, the factors TCO_a and electricity purchase 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 τ and it is assumed that each household buys the option that maximizes its individual utility, i.e.

$$\max_{\tau}(-TCO_{\tau\, a} - \; CEP_{\tau\, a}) \tag{7}$$

Calculating the electricity supply option for each user and year that maximizes utility and summing up all households for which this would include a PV or PV + battery system, we obtain the shares of potential self-consumers in the sample and the average installed PV panel size and battery capacity for each year. This part of the model has been published before with similar configurations in (Klingler 2017).

4.4 Aggregation and market diffusion

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 study is required to be dynamic and is assumed to be a function of the market share of the technology. In order to quantify the adoption rate of PV in the residential sector, we refer to the diffusion of residential heat pumps on the Swedish market. The reason for this comparison is the that investments in heat pumps are in general made based on long-term economic savings of the electricity bill, which is likely to be the case for residential PV systems on a well-established market. Based on statistics of type of heating systems in the whole sector since 1982 the adoption rate for heat pumps was calculated (SCB, 2000-2006; Swedish Energy Agency 2007-2014). Since heat pumps are available in many sizes suitable for both waterborne and direct electric heating systems, they were considered to be a profitable long-term investment for all households. The only exception was houses with district heating as the only heating source. This made it possible to calculate the yearly adoption rate of heat pumps as a function of the market share. The same adoption rate as for heat pumps is used for the PV + battery systems which are identified as profitable during their life time. The following (normal) distribution function is fitted to the empirical heat pump data set:

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

with the market share x and the minimum adoption rate φ_{min} . The parameter values can be found in Table 3, and the fit functions are depicted in Figure 8. Since differences in attitude towards PV + battery systems are not considered in this study, and due to cultural similarities between Germany and Sweden, the adoption rate defined in Table 3 is applied for both countries.

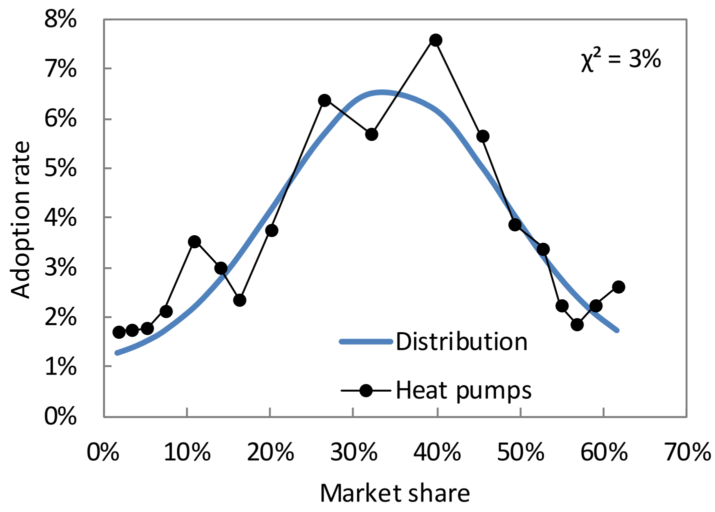

Figure 8: Empirical data and corresponding distribution function for adoption rates of heat pumps in Swedish households.

Table 3: Parameters for the dynamic adoption rates for PV + battery systems.

Parameter	Value
σ	13.5%
μ	34.5%
A	1.89%
φ_{min}	1.00%

4.5 Modelling parameters

The model parameters we use for this study are presented in Table 4. For the model parameters concerning technology and electricity prices in Germany, we refer to an existing study on behalf of the German Ministry for Economic Affairs and Energy (Winkler et al. 2016). Unlike the mentioned studies, we assume a constant electricity purchase price for both Germany and Sweden. The technology prices are given with taxes and the price development is assumed to be similar in both countries. In our scenario, we assume that the feed-in tariff in Germany is abolished in 2020, when more than 52 GW of PV power are installed. In Sweden, the current capital investment subsidy ends in 2019, since a prolongation of the subsidy is not yet reported. The tax deduction of approximately 6.1 EUR-ct for excess electricity that is fed into the grid has currently no end-date. Since the market diffusion model in this paper is aimed to model a market without subsidies, the tax deduction is assumed to end in 2019.

Table 4: Model parameters for the economic evaluation of self-consumption for Germany and Sweden.

		Germany		Sweden	
	unit	2015	2040	2015	2040
Electricity price	*EUR/MWh*	28.8	28.8	11.4	11.4
Feed-in[1]	*EUR/MWh*	12.8	4.5	10.5	4.5
PV system price	*EUR/kW*	1848	1092	1848	1092
PV O&M costs	*EUR*	93	55	93	55
Battery price	*EUR/kWh*	907	470	907	470
Payment bonus PV[2]		--	--	20%	--
Payment bonus battery		25%	--	60%	--
Life length PV/battery	*Years*	20/20	20/20	20/20	20/20
Discount rate	*%*	5	5	5	5

[1]The FiT in Germany is granted for 20 years. PV systems installed after 2020 get the average revenue from direct marketing on the spot market. The tax deduction for feed in electricity in Sweden is assumed to end in 2019, whereas the electricity certificates remain.

[2] Until the end of 2019, Swedish owners of PV systems can apply for capital subsidy of 20% and for storage system 60%.

5 Results

The results of the market diffusion modelling are presented in this section. Sensitivity analyses are used to assess the uncertainties in the model results.

5.1 Evaluation of individual households

In this section we analyse the influence of individual consumption behaviour on PV self-consumption. We thus simulate self-consumption with PV + battery systems of various system configurations for all household profiles. For an easier understanding, the dimensions of the analyses have to be reduced and thus we limit the evaluation in this section to one PV + battery system configuration. A 5 kW PV system is assumed, which is the maximum size to fit on the west-facing side of an average saddle roof and the average installed system on German households (calculated from ÜNB (2017)). This system is combined with a 7.5 kWh battery, which is the average installed capacity in Germany (Figgener 2017).

In Germany as well as in Sweden, the feed-in remuneration for electricity from a PV system is considerably lower than the electricity purchase price, which can be saved when the PV electricity is consumed onsite in the producing household. The key factors for the economics of PV self-consumption and its enhancement through a battery are thus the amount of direct consumption of the self-produced electricity and the amount of electricity stored in the battery and supplied to the household at a later point in time, respectively. Even more so, since in our scenario we consider an abolishment of the PV promotion in the near future. The distribution of self-consumption rates over individual households in Sweden and Germany for PV and PV + battery systems is depicted in Figure 9.

Generally, in Sweden the self-consumption rates for households with a 5 kW PV system are higher than in Germany. That holds for the average over all households with or without battery enhancement. A Swedish household can directly self-consume 2,272 kWh/year on average, while a German household on average only uses 1,427 kWh/year directly. With a 7.5 kWh battery in combination with the PV system, the average self-consumption rises to 3,028 kWh/year in Sweden and 2,449 kWh/year in Germany. The higher amount of self-consumption in Sweden is due to the larger electricity demand in general. Although 5 kW is the average size of installed PV systems on German rooftops, the system is clearly oversized for the average German household. Between the households, the spread in self-consumption rates is quite significant, however the variance is smaller than the variation in yearly consumption (Sweden: $v_{\text{yearly demand}}$ = 52%, Germany: $v_{\text{yearly demand}}$ = 46%).

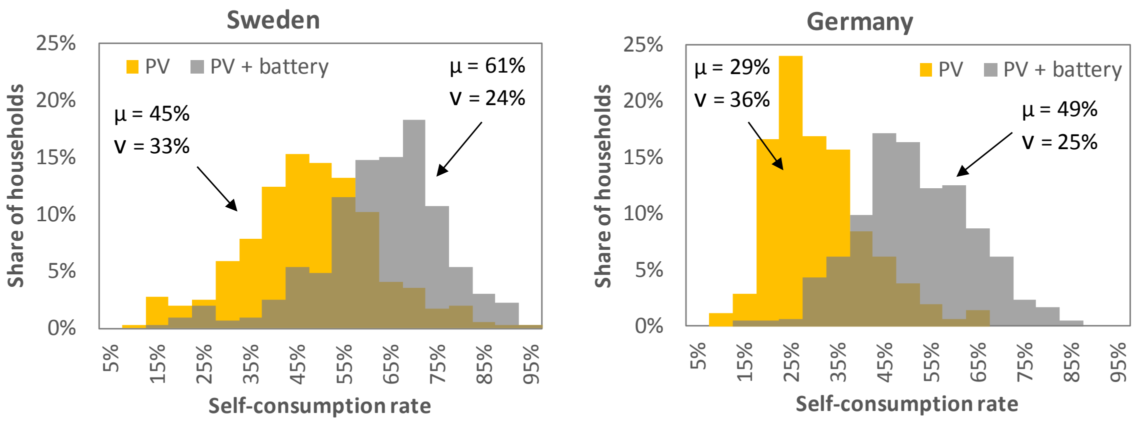

Figure 9: Distribution of self-consumption rates for individual households with a 5 kW PV system and a 5 kW PV + 7.5 kWh battery system in Sweden (left) and Germany (right) with mean values (μ) and variance (v).

Since the diffusion of electric heating in Sweden increases the electricity consumption even on summer days (see Section 3.1), the high share of electric heating and the corresponding high temperature dependency of the Swedish consumption profile affect the self-consumption rates in a positive way, even though most of the electricity is consumed in the winter month with a relatively low PV production. With a 5 kW PV system, the self-consumption rate is 48% on average, while households without electric heating reach a self-consumption rate of 38% on average. Both households, with and without electric heating benefit equally from the 7.5 kWh battery, and are able to increase their self-consumption rates by 15% on average.

Although the self-consumption rates are generally more than 10% higher in Sweden than in Germany, the economic benefit is significantly higher in Germany. Figure 10 depicts the amount of self-consumed electricity for Sweden in Germany with a 5 kW PV system and a 5 kW PV + 7.5 kWh battery system in comparison with the revenue that could be achieved with these self-consumption systems. Revenues can be generated through savings in electricity purchase and PV electricity feed-in. The economic revenue is calculated with the feed-in remunerations and the electricity prices as of 2015.

The electricity purchase prices are with around 28 EUR-ct/kWh more than twice as high as the prices in Sweden with 11 EUR/MWh. The difference in feed-in remuneration is relatively small with 12 EUR-ct/kWh in Germany and 10 EUR-ct/kWh in Sweden. The small difference between feed-in remuneration and electricity price in Sweden explains the very small variation in the economic benefit between the individual households: It is currently almost irrelevant whether the electricity is fed into the grid or consumed onsite. Since this deduction of approximately 6 EUR-ct/kWh makes up a large part of the selling price, the profitability of self-consumption will drastically increase when it is abolished. It is also not likely that is remains unchanged throughout the whole lifetime of a PV system.

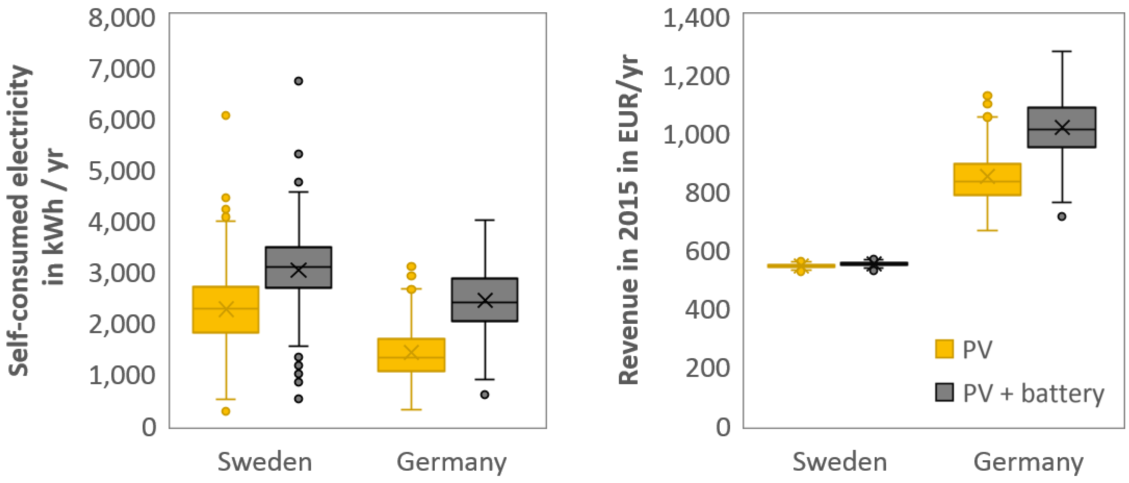

Figure 10: Self-consumed amount of electricity with a 5 kW PV and 5 kW PV + 7.5 kWh battery system (left) and financial benefit of self-consumption (right) for Sweden and Germany.

In 2015 PV self-consumption with a 5 kW system was therefore economically unfeasible for all households in Sweden, with or without a battery system. In Germany, it was economical for around 30% of the households, but a 7.5 kWh battery was unfeasible for all German households.

5.2 Market diffusion of self-consumption in Sweden and Germany

In the assessment of the market diffusion of PV + battery systems, all sizes of PV systems and batteries are considered. The differences between the individual households and the different economic parameters in each year lead to the distribution of potential adopters depicted in Figure 11.

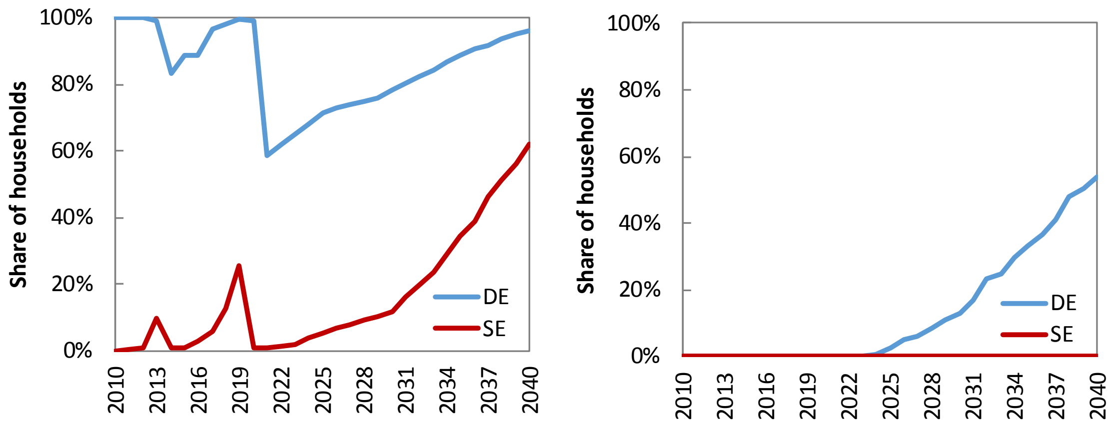

Figure 11: Potential adopters in Sweden and Germany: the share of households for which a PV system (left) or a PV + battery system (right) is profitable.

In Germany, up until 2012 self-consumption was incentivised directly and thus profitable for every household. With relatively high electricity prices and FiT, PV self-consumption is still profitable for most households until 2020, when in our scenario the FiT is abolished. In Sweden, due to relatively low electricity prices PV self-consumption is only profitable with use of the payment bonus that is abolished in 2019. After the abolishment of government subsidies, sinking equipment costs drive the profitability in both countries. Batteries are only profitable with the high electricity prices in Germany and only when the battery price has decreased by 30% in 2023.

When additionally to economic considerations, the adoption rate is considered, the distribution of potential adopters results in the market diffusion of PV + battery systems that is depicted in Figure 12. The figure shows the development of market shares of self-consumption systems in each year and the resulting range from the sensitivity analysis.

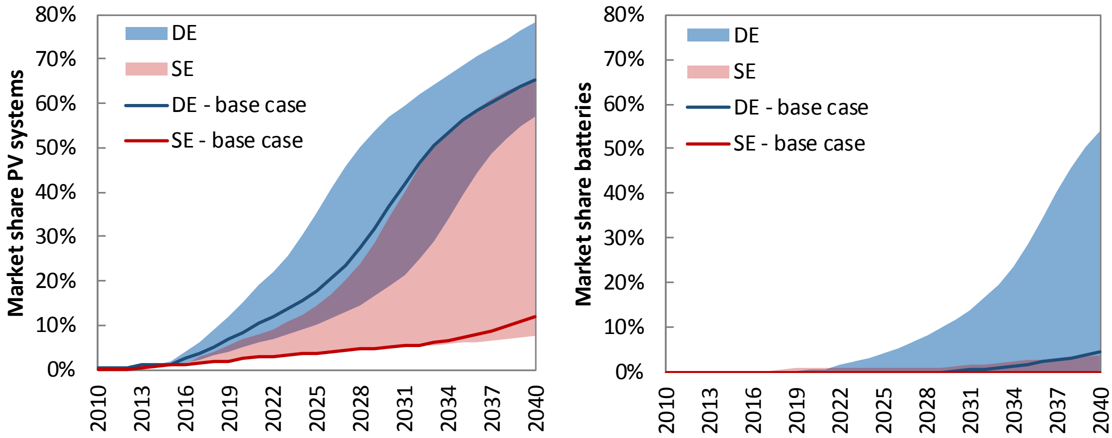

Figure 12: PV systems (left) and battery (right) market shares for Sweden and Germany. Shown are the values for the base case (solid line) together with the ranges from the sensitivity calculations.

In our base case, in 2040 65% of all German households own a PV system and 5% combine it with a battery. That corresponds to around 9.7 million PV systems with an average size of 2.6 kW and 0.7 million stationary batteries with an average size of 2.5 kWh. In Sweden, 12% of all households own a PV system, which corresponds to 0.24 million systems with an average size of 2.9 kW. The installed system sizes in both countries are relatively small in comparison with the currently installed system sizes of 5 kW (calculated from ÜNB 2017). Since electricity purchase prices in 2040 are significantly higher than selling prices, the profitability increases with higher self-consumption rates and therefore with smaller systems, even when considering the relatively higher investment per kW.

To address the influence of the main parameters on the modelling results, we conduct a sensitivity analysis. The detailed results of the sensitivity calculations are listed in Table 5.

Table 5: Resulting market shares for PV and PV + battery systems in the year 2040 for different sensitivity calculations; in bold: minimum and maximum values.

Market share in 2040	**PV systems**		**Batteries**	
	SE	DE	SE	DE
base case	12%	65%	**0%**	5%
electricity price +2%	**64%**	70%	**4%**	**54%**
electricity price -1%	**7%**	60%	**0%**	**0%**
lifetime 25 years	43%	69%	1%	13%
2% discount rate	63%	70%	**4%**	40%
10% higher CAPEX	8%	65%	**0%**	3%
10% lower CAPEX	33%	68%	1%	11%
1% higher adoption rate	17%	**78%**	**0%**	8%
0.5% lower adoption rate	10%	**57%**	**0%**	2%

The uncertainties in the market diffusion of PV systems in Germany is mainly driven by the unknown adoption rate, with initially high electricity prices and decreasing equipment costs, self-consumption is profitable for most households in all parameter variations. This is different for batteries: here the market uptake is only enhanced when the electricity price is rising or the household expect less revenue (represented by a lower discount rate). If the electricity price is decreasing in the future, batteries are no longer a profitable option in Germany.

This behaviour is confirmed when looking at the Swedish market that is inhibited by relatively low electricity prices. When electricity prices were to increase in the future, the market share of PV self-consumption systems could be more than 5 times higher and even batteries would be a profitable option for some households.

6 Discussion

In our study, we found that the generally higher electricity consumption of Swedish households positively affects the rates of direct self-consumption. The high consumption is partly due to the well-advanced diffusion of heat pumps for space heating and domestic hot water provision. We can therefore conclude that the installation of a heat pump benefits the profitability of PV self-consumption, even though the heat pump's electricity demand mainly occurs in the cold period when PV production is low. Even better would be if the heat pumps could be controlled to produce domestic hot water during periods with excess electricity. Correspondingly, the benefit of a battery in combination with the PV self-consumption system is decreased with higher household electricity consumption, since less excess PV electricity is produced. Further research could address how other new technologies, such as electric vehicles or home-automation affect the profitability of self-consumption systems.

Concerning the possible market diffusion, the market conditions, particularly electricity prices, are the main driver for the market uptake of PV + battery systems for self-consumption. Higher electricity prices also lead to the diffusion of larger systems. However, even with constant electricity prices and an abolishment of government incentives, PV self-consumption is likely to gain significant market shares in both countries due to decreasing equipment prices. With these findings in mind, future research could address the electricity price development in Sweden in particular, since two out of eight nuclear reactors currently in operation will be phased out by 2020. Further, the price spreads in RTP electricity tariffs are probable to be higher 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.

Regarding the validation of our results, we were able to reproduce the estimated past PV installations in Germany. In our model, the installation of batteries was not profitable for any of the considered households until the year 2023. This finding differs from the reality of an estimated 60,000 installed batteries in Germany in 2017 (Figgener et al. 2017). However, from a previous study, we know that this effect can be explained by the households' attitude towards self-consumption, which can lead to a willingness to pay that exceeds the potential profit from a PV + battery system (Klingler 2017). Further, the recommendation of the installers has a significant impact in the early market formation. Both aspects are particularly relevant in the early stage of the market uptake and are therefore out of scope of this study that focusses on the medium-term without government subsidy schemes.

The sensitivity analysis shows that the adoption rate has the largest impact on the market diffusion of PV systems in Germany, while the electricity price is the most influential factor in Sweden. This is partly due to that PV systems are profitable for almost every household in Germany already at an early stage, which means that the adoption rate plays a central role. For Sweden, with low electricity prices, the most important parameter in order to increase the market diffusion is to increase the profitability of a PV system. Other factors have less impact in both countries. These findings can be applied to other countries, which have either low or high electricity prices, as a first assessment of the importance of different parameters on the local market diffusion.

7 Conclusions

The results of this paper show a large difference in the market diffusion of residential PV systems among the German and the Swedish households until 2040. The market diffusion in Sweden is also much more sensitive to changes in parameters such as discount rate and development of electricity price than in Germany. From the study it can also be concluded that the market share of battery storage systems reaches 5% in Germany and is non-existent in Sweden in 2040. In the studied scenario and sensitivities, profitability is the market driver. Thus, with favourable condition such as high electricity price increments and low discount rate, the market share for battery storage systems can exceed 50% in Germany. Even in the most profitable case, the market diffusion of battery systems in the Swedish households will be merely 5% in 2040.

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