What drives the profitability of household PV investments, self-consumption and self-sufficiency?

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Abstract

Many countries introduced subsidy schemes that were successful in incentivising investments into residential solar PV. The resulting growth of the global PV market was accompanied by cost reductions for PV systems, reductions of PV subsidies and, often, increasing electricity retail prices. Along with decreasing costs for battery storages, these developments made self-consumption and self-sufficiency continuously more attractive. However, the profitability of PV-storage systems depends on many factors, including technological, political and geographical aspects. We present a simulation model to identify the most profitable sizes of PV and storage systems from a household perspective and explore what drives the profitability of self-consumption and self-sufficiency. We compare and contrast Germany and Ireland to account for regulatory and geographical differences. Our results show that PV-storage systems are generally profitable in Germany and that, after minor technology cost reductions, this result holds even in the absence of subsidies. In Ireland, such systems are not yet profitable but this may change soon with expected technology costs reductions. The share of electricity demand that will be required from the grid may be reduced to 25-35%. Implications for the electricity retail business and policy makers are discussed including distributional concerns and system efficiency considerations.

1 Introduction

Many countries worldwide have adopted policies to support the expansion of renewable energy sources (RES) aimed at reducing greenhouse gas emissions and combating climate change. The European Union (EU), for instance, aims for a 27% share of RES in final energy consumption by 2030 whereas more than two thirds of gross final European energy consumption shall be provided through RES by 2050, with a yet higher share for electricity (COM 2011).

While the support schemes adopted in different countries differ in nature (see Solangi et al. (2011) or Steinhilber et al. (2016) for overviews), they were very effective in incentivising investments into RES. As a result, the installed RES capacities have increased rapidly. The installed solar photovoltaic (PV) capacity, for instance, has reached more than 300 GW globally at the beginning of 2017 with around 70 GW having been installed in 2016 alone.[1] This strong growth of the PV market has led to strong cost reductions for new PV systems (Feldman et al. 2015; Candelise et al. 2013) and the cost reductions came along with reductions of the PV subsidies. At the same time, depending on how the different governments decided to levy the RES subsidies, electricity retail prices increased. As a result, solar PV has reached 'grid parity' in many countries in recent years (Khalilpour & Vassallo 2015; Hagerman et al. 2016; Karakaya et al. 2015; La Munoz et al. 2014; Bardt et al. 2014). This means that in these countries self-consumption of the electricity generated from PV became more attractive than feeding the electricity into the grid and getting paid the subsidy. Self-consumption, self-sufficiency and grid parity have sparked an increasing interest by researchers and consumers recently (Ellsworth-Krebs & Reid 2016; Luthander et al. 2015). We use the terms self-consumption and self-sufficiency as described by Luthander et al. (2015), who define $self-consumption = \frac{self-consumed\ PV\ electricity}{total\ electricity\ generation\ from\ PV}$ and $self-sufficiency = \frac{self-consumed\ PV\ electricity}{total\ electricity\ demand}$. Since battery storage costs also decreased strongly over recent years and storages can help to increase self-consumption and self-sufficiency, a growing share of the literature on self-consumption and self-sufficiency includes PV storage systems (Chatzivasileiadi et al. 2013; Vieira et al. 2017). In this context, Graebig et al. (2014) found that self-sufficiency as a goal in its own right is similarly important for consumers as economic considerations in determining their interest in PV storage systems. However, since their willingness to pay for self-sufficiency is certainly not unlimited, the quantification of the costs associated with different levels of self-sufficiency gains importance.

The statements by the EU (COM 2016) that consumers should be put at the heart of energy markets and that they should be empowered and become more active market participants (e.g., through distributed generation, demand response and self-consumption) can be interpreted as a clear support of so-called prosumers (i.e. consumers that are also producers). Prosumers are undoubtedly more active than traditional consumers and they have a natural interest in self-consumption. However, there are also critical views on self-consumption (Simshauser 2016; Khalilpour & Vassallo 2015). This criticism is not directed at the PV expansion and self-consumption as such but mainly raises distributional concerns under current regulation.

In order to explore how imminent the issues of self-consumption and self-sufficiency are in different countries, what levels of self-consumption and self-sufficiency can be expected, at what costs, and what the main drivers are, we compare and contrast two EU countries which differ strongly in terms of their solar energy policy as well as their geographical and meteorological conditions and solar PV potential. These are Germany and Ireland. This comparison makes an interesting case study as their overall targets for electricity generation from RES are similarly ambitious (Ireland pursues a 40% target for electricity from RES by 2020, Germany a 40-45% target by 2025), while the legislation around RES expansion, particularly in terms of support for solar PV differs substantially (see section 2). In each country, we consider two household sizes and 100 individual load profiles within each household size. Using these load profiles, the techno-economic assessment is carried out with a simulation model implemented in MATLAB. We also use our model to quantify the

[1] See e.g.: http://www.climateactionprogramme.org; http://www.solarserver.com/

costs associated with different levels of self-sufficiency. In an Irish context, research on residential PV is scant. While La Monaca & Ryan (2016) analyse the impact of different support schemes for residential PV in Ireland, they do not include storage or a detailed driver analysis into their work. To our knowledge, our paper is the first to analyse drivers and costs of PV-based self-sufficiency in Ireland.

The remainder of this paper proceeds as follows. In section 2, we summarise the regulatory framework conditions in relation to solar PV support in Germany and Ireland and describe a selection of related work. In section 3, we provide an overview of the input data for our analyses. In section 4, we describe the simulation model used in this paper. We present the results in section 5 before we discuss their implications and limitations in section 6 before section 7 concludes.

2 Renewable policy background and related work

With the introduction of the Renewable Energy Act (“EEG”) in 2000, Germany provided attractive investment conditions for PV based on a feed-in tariff (FIT) scheme. As a result, the installed peak capacity of photovoltaic (PV) plants has significantly increased from 1 GW_p in 2004 to over 40 GW_p in 2016 (BMWi 2016). Since 2009, the FIT for small PV plants (< 10 kW_p) was reduced from 43 cent/kWh to 12.3 cent/kWh in 2016 (BNetzA 2016) while the average price of turnkey PV systems (< 100 kW_p) decreased from 4,100 €/kW_p to 1,130 €/kW_p over the same period of time (Photovoltaics Centre 2016). RES support payments are levied on a per unit (kWh) basis in Germany. The per unit contribution to RES expansion increased from 1.33 cent/kWh in 2009 to 6.35 cent/kWh in 2016 leading, among other effects, to a residential electricity retail price increase from 21.4 cent/kWh to 27.7 cent/kWh which made self-consumption continuously more attractive altogether (Johann & Madlener 2014). Since battery storages can help to increase PV self-consumption and, hence, profitability, up to 60% of the new installed PV systems in Germany are equipped with a battery storage system (ISEA 2016).

In Ireland, the support of RES was also based on a FIT scheme. The first Irish Renewable Energy Feed-in Tariff scheme (REFIT 1) was introduced in 2006. Unlike in Germany and many other countries, however, the Irish REFIT does not provide support for solar energy so far. Moreover, REFIT is levied by the Public Service Obligation (PSO), i.e. it is paid for on a per household rather than on a per unit basis. As a result, residential electricity retail prices (per kWh) have not increased to a similar extent. They amount to approximately 18 cent/kWh[2] which is much lower than in Germany. In addition, compared to Germany, the meteorological conditions are less favourable for PV. Altogether, it is therefore obvious that the investment conditions for PV in Ireland have not been favourable. Consequently, the installed peak capacity in the Republic of Ireland only totals around 2MW_p by the end of 2016. However, the Irish government in their energy white paper released in December 2015 state that they envisage a diversification of renewable energy sources (DCENR 2015). While onshore wind is planned to continue to make a significant contribution, it is debated whether the new scheme should also support solar PV.

[2] See: www.bonkers.ie

Beyond these regulatory differences, however, there are many other parameters that drive the profitability of self-consumption. Assessing their impact is important to understand how imminent the issue is and what levels of self-consumption can be expected. The literature on grid parity, self-consumption and PV battery storage systems has grown rapidly in the recent past and many drivers have been analysed. Huijben & Verbong (2013), Spertino et al. (2014), Karakaya et al. (2015) and Hagerman et al. (2016), for instance, analyse different drivers of PV grid parity, including PV installation costs, electricity prices, meteorological conditions of different locations and their impact on solar power availability and the policy framework (e.g. the availability of a FIT or other relevant regulations). However, their research does not explicitly include storage systems. Hoppmann et al. (2014) and Vieira et al. (2017) include storages and explore the impact of storage cost as well electricity price variations. However, they do not explicitly account for geographical characteristics and their impact or the impact of varying electricity consumption levels and profiles. Nyholm et al. (2016) use load data from around 2,000 households taking into account geographical and demographic characteristics and their impact on the demand side of households to analyse to which extent batteries can increase self-consumption levels. However, they focus on the technical side of self-consumption without conducting a detailed analysis of economic drivers. Finally, Khalilpour & Vassallo (2015) and Khalilpour & Vassallo (2016) carry out detailed analyses of drivers of self-consumption and PV storage systems in Australia. Their driver analyses include sizes of PV and storage, the availability of a FIT, the impact of PV and battery technology costs and the geographical/meteorological impact on the supply side (PV generation). They also consider houses with different amounts of electricity consumption but this analysis is limited to few houses and does not consider the impact of different load profiles in detail. We group the different drivers that were identified in the literature into finance-related and quantity-related drivers (see Figure 1).

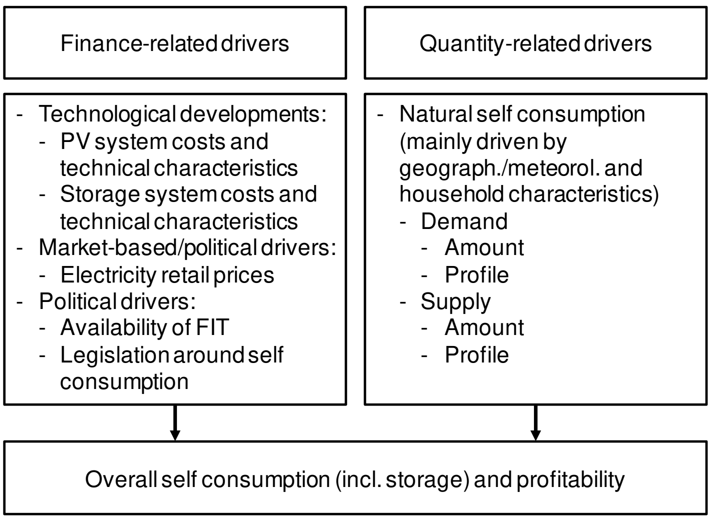

Figure 1: Framework of drivers of self-consumption and its profitability

From the above descriptions, it becomes obvious that many drivers were analysed in the past but that comprehensive analyses are rare. The most comprehensive research is that by Khalilpour & Vassallo (2015) and Khalilpour & Vassallo (2016). However, while they do consider the impact of different geographical locations, this analysis is mainly limited to the supply side, i.e. they do not consider different load profiles in detail that depend on geographical or demographic characteristics. Moreover, they do not quantify the costs of different levels of self-sufficiency. As mentioned above, we therefore analyse the profitability of PV investments and self-consumption from the perspective of a household by comparing and contrasting Germany and Ireland and considering the framework of drivers illustrated in Figure 1 in a comprehensive way.

3 Data

In this section, we describe the input data to our analyses and their sources. While section 3.1 focusses on the demand side, we describe the supply side data in section 3.2. Further general input assumptions are presented in section 3.3.

3.1 Demand side data

This work focuses on the comparison of PV stand-alone systems and PV storage systems in German and Irish 3 person and 5 person households respectively.

For Germany, we used synthetic load profiles generated by a simulation tool of the Technical University Chemnitz (Pflugradt 2016). This simulation tool has been applied in several publications to generate load profiles for German households, e.g. (Stenzel et al. 2015; Linssen et al. 2015; Vrettos et al. 2013). The profile generator simulates the behaviour of the residents based on a demand model, and includes typical operation patterns for residential electrical devices. The load profile is calculated by adding up the energy use of each device.

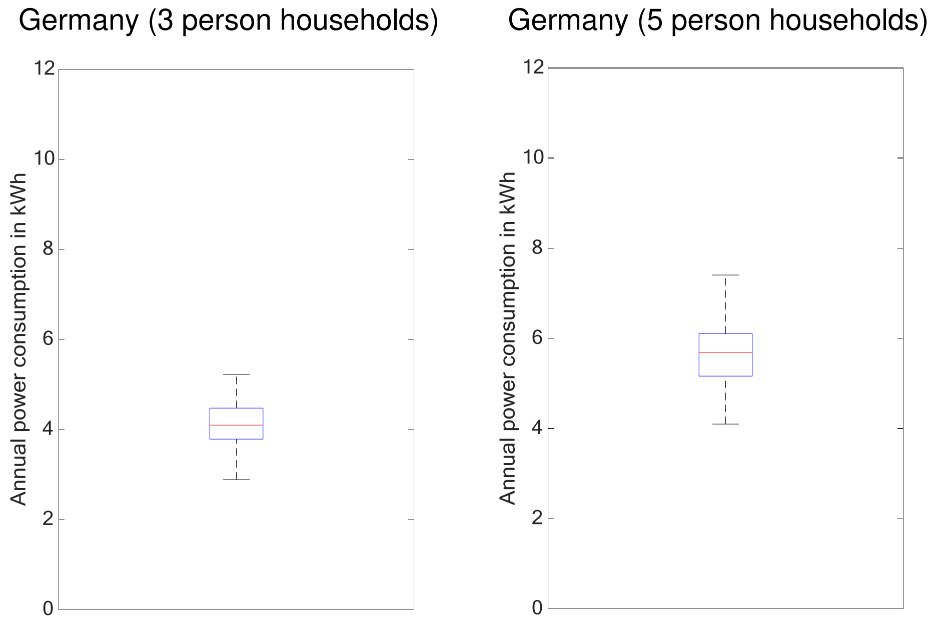

Figure 2: Box plot of the annual power consumption of the 100 load profiles of German 3 person (left) and 5 person (right) households

The profile generator provides load profiles of predefined households. To model a German 3 person household, we chose the predefined household *CHR03 Family, 1 child, both at work*. To model a German 5 person household, we chose the predefined household *CHR05 Family, 3 children, both with work*. We generated 100 profiles for 3 person and 5 person households each for the year 2014 in a 30-min resolution. In the case of 3 person households, the annual power consumption varies between 2,888 kWh and 5,217 kWh, while the median is 4,104 kWh (cf. Figure 2). For 5 person households, the annual power consumption varies between 4,099 kWh and 7,407 kWh, while the median is 5,664 kWh.

For Ireland, household electrical load measurement data was available from the time of use (TOU) consumer field trial conducted in 2009-2010 (Commission for Energy Regulation 2011; Irish Social Science Data Archive 2012; Di Cosmo et al. 2014; McLoughlin et al. 2015). The Irish Commission for Energy Regulation (CER) co-ordinated a randomised controlled trial in Ireland introducing electricity smart meters in approximately 5,000 households. These were generally divided into control and treatment groups, where the treatment groups were exposed to a number of different TOU tariffs and stimuli (Di Cosmo et al. 2014), while the control group did not receive any stimuli. In order to avoid distortion effects from any stimuli, we only used measurement data from 3 person and 5 person households in the control group in this paper. Electrical load was measured in a half-hourly resolution and we used data from the entire year 2010. As for Germany, 100 load profiles were used for each considered household size. In the case of 3 person households, the annual power consumption in Ireland varies between 906 kWh and 8,033 kWh, while the median is 4,460 kWh (cf. Figure 3). In the case of 5 person households, the annual power consumption varies between 2,510 kWh and 10,485 kWh, while the median is 6,250 kWh.

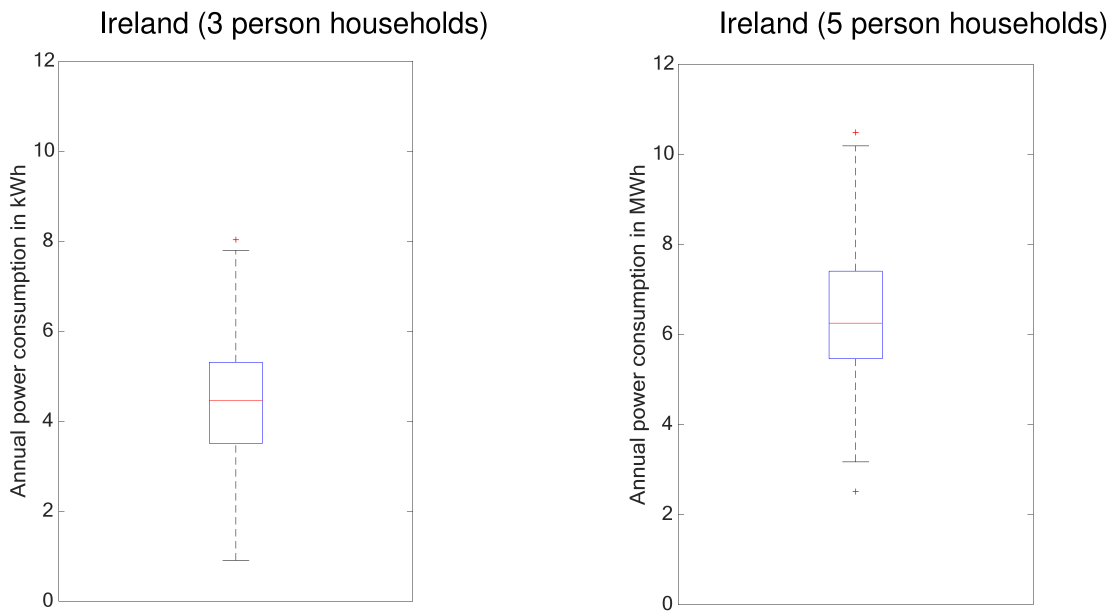

Figure 3: Box plot of the annual power consumption of the 100 load profiles of Irish 3 person (left) and 5 person (right) households

3.2 Supply side data

We generate solar PV power generation profiles on the basis of site-specific solar radiation profiles. For our study, we use solar radiation profiles from near Dublin in Ireland and Karlsruhe in Germany. The profiles are converted into power generation profiles using a physical PV model (Ritzenhoff 1992; Bertsch et al. 2014; Ruppert et al. 2016). This model calculates the PV modules' electrical yield based on incident light, module efficiency and its orientation described by longitude, latitude, tilt and azimuth of the modules. The calculation splits solar radiation into direct and diffuse solar radiation and considers the ambient temperature to determine accurate module efficiencies. Furthermore, the albedo effect, average losses from shadowing, module mismatching or cable and inverter losses are taken into account. For reasons of simplicity, we assume a south orientation of the modules in both countries. The inclination angle is set to 34° in Germany which represents the mean of

German residential PV systems (Mainzer et al. 2014). For Ireland, this angle is set to 39°, which reflects the more northern location and turns out as preferable inclination from the physical PV model. The results of this model are PV generation profiles in half-hourly resolution. As mentioned above, the German analyses are consistently based on conditions of the year 2014, while the Irish analyses are based on 2010. According to our PV model, the total annual PV power output amounts to approx. 1,200 kWh/kW$_p$ in Germany (Karlsruhe, 2014) and approx. 900 kWh/kW$_p$ in Ireland (Dublin, 2010). For the interpretation of the results, it is important to bear in mind that the solar radiation in 2014 in Karlsruhe deviates from the long-term average by approx. +5% (DWD 2017), while the radiation in 2010 in Dublin is approx. 7% higher than the long-term average according to MERRA data.

3.3 General assumptions for our analyses

Table 1 provides an overview of further basic assumptions for the analyses, the results of which are presented in section 5 including their corresponding sources. In several of the analyses carried out, these assumptions are varied to explore how they drive the profitability of PV investments and self-consumption. However, if not stated explicitly that they are varied, these are the input assumptions for the simulation model.

Table 1: Parameters with values used for the IRR calculations

Name	Germany	Ireland	Comment
PV system price	$p_{PV} = 1{,}130$ €/kW$_p$		Average purchase price for a turnkey PV system based on (Photovoltaics Centre 2016)
Battery system price	$p_{Batt} = 500$ €/kWh		Based on (Kaschub et al. 2016)
Installation costs	$P_{Inst} = 1{,}330$ €		The average installation costs of a PV storage system based on (ISEA 2016)
Annual PV insurance premium	$A_{PV,ins} = 70$ €/a		Based on (Photovoltaikversicherung 24 2016)
Annual hire of meters	$A_{meter} = 40$ €/a		Based on (Avacon AG 2016)
Annual maintenance costs	$a_{PV,main} = 10$ €/(kW$_p \cdot$ a)		Based on (SolaranlagenPortal 2016)
Electricity price	$p_{elect} = 27.8$ cent/kWh	$p_{elect} = 18.0$ cent/kWh	Average retail electricity price for private households including value added tax (VAT) based on (Verivox GmbH 2016) & www.bonkers.ie
Increase of electricity prices	$\frac{\Delta p_t}{p_0} = 2\%$		
Inflation rate	$i_{Inf} = 2\%$		
PV feed-in tariff	$e_{PV} = 12.3$ cent/kWh	$e_{PV} = 0$ cent/kWh	PV feed-in tariff for small PV plants (< 10 kW$_p$) (BNetzA 2016)
Cycle stability	$Z_{max} = 5{,}000$		Based on (VDE 2015)

4 Simulation model

The simulation model for the techno-economic assessment of a PV-storage system is implemented in MATLAB.[3] It calculates all energy flows between the system components, e.g. consumer, PV system, electricity grid and battery storage system. The model is typically applied in the residential sector with small roof-mounted PV installations (≤ 20 kW_p) and battery storage systems (≤ 100 kWh) (Lühn & Geldermann 2017).

The input parameters for the model calculations include data of the consumer, PV system, electricity grid and battery storage system (cf. Figure 4). The model is based on an energy balance between the supply and the demand side. We performed our simulations with a time resolution of 30 min in line with the aforementioned availability of load and PV data.

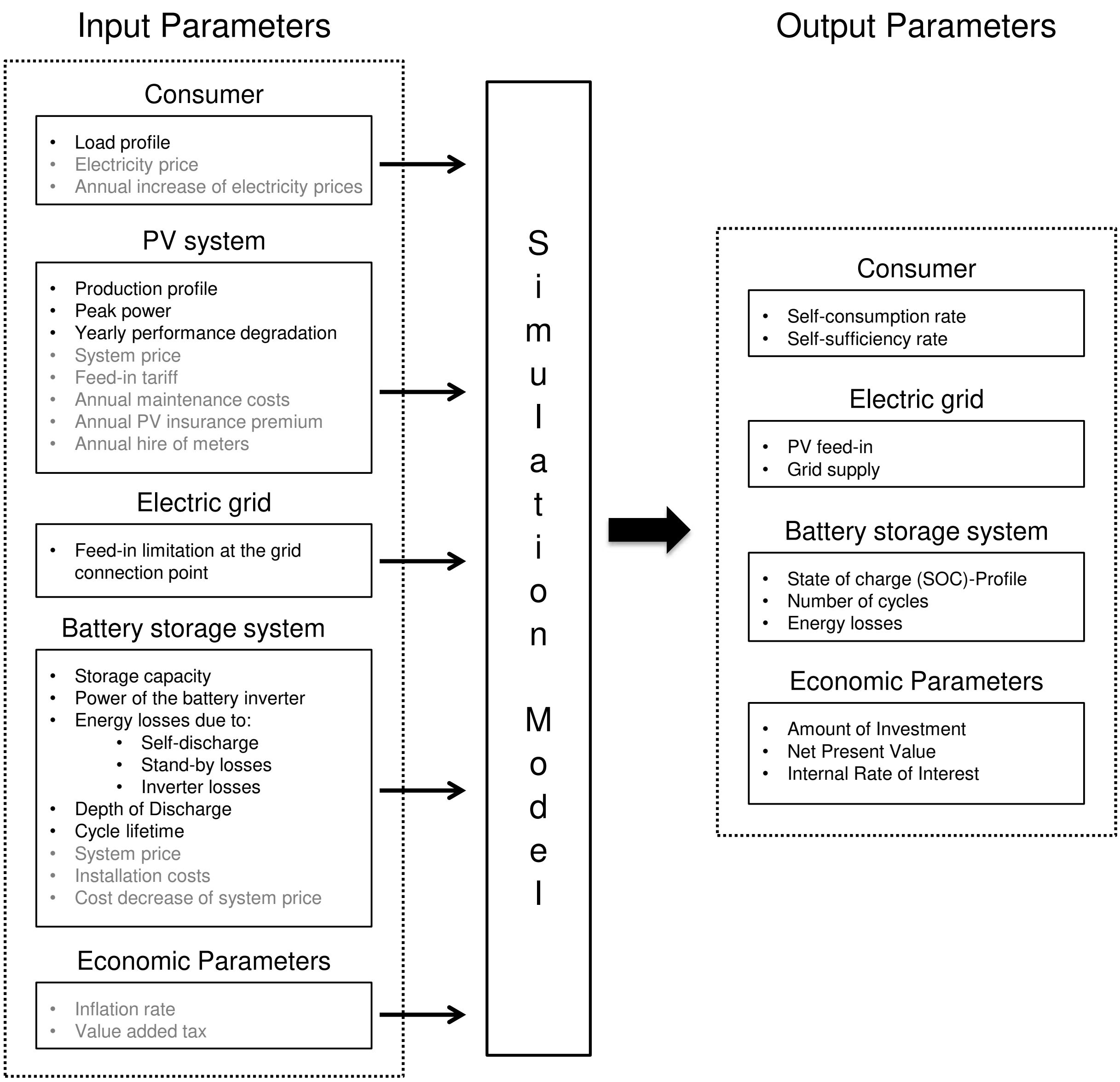

Figure 4: Structure of the simulation model (grey: economic parameters; black: technical parameters)

[3] The simulation model was developed within the e-home energy project 2020 (project duration: 2011-2016). In this project, one of the largest German DSOs investigated, in close cooperation with six research institutes from Lower Saxony (Germany), the evolving requirements of the German electricity supply networks, which arise from projected developments in power generation and consumption (Ahmels et al. 2016).

The battery storage system is operated in a way which maximises the household self-consumption and thus reduces the amount of electricity that must be purchased. We choose this simple operating strategy because it is used in most PV storage systems available on the market in 2017. This operating strategy stores the PV power surplus during the daytime and uses it to supply loads in the evening and at night. Electricity produced from the PV system is used preferably to supply the household electricity demand. When the PV electricity generation exceeds the electricity demand of the household, the simple operating strategy immediately starts charging the battery (cf. eq. (1)). On days with high insolation, the battery is fully charged before noon and the PV power surplus must be fed into the grid (cf. eq. (2)). When the PV electricity generation is insufficient to satisfy the electricity demand, the battery starts to discharge (cf. eq. (3)). When the battery is fully discharged, the electricity demand is covered by electricity purchased from the grid $P_{grid} < 0$ (cf. eq. (4)). Thus, the simple operating strategy maximises PV self-consumption by using each kilowatt-hour produced by the PV system to cover the electricity demand of the household. Power exchange between the battery storage system and the grid is not possible in our analysis.

Some major manufacturers, such as SMA Solar Technology, sell storage systems with enhanced operating strategies. For example, grid-optimised operating strategies can be used to reduce curtailment losses when the PV storage system needs to comply with a feed-in limitation (Lühn & Geldermann 2017). For reasons of comparability, however, the simulations for the two countries in this paper are carried out without any feed-in limitation.[4] In this case, the simple operating strategy generates higher cash-flows than the grid-optimised alternatives and thus we perform our simulations with this operating strategy.

Table 2: Simple operating strategy

Conditions				Consequence			
$P_{PV} > P_{load}$	and	$SoC < 1$	than	$P_{batt} = P_{PV} - P_{load}$	and	$P_{grid} = 0$	(1)
		$SoC = 1$		$P_{batt} = 0$		$P_{grid} = P_{PV} - P_{load}$	(2)
$P_{PV} \leq P_{load}$		$SoC > 0$		$P_{batt} = P_{PV} - P_{load}$		$P_{grid} = 0$	(3)
		$SoC = 0$		$P_{batt} = 0$		$P_{grid} = P_{PV} - P_{load}$	(4)

For the economic assessment, we compare the cash-flows of a PV storage system with the cash-flows of a household without such a system. As in Braun et al. (2009), Colmenar-Santos et al. (2012) and Mulder et al. (2013), we perform Internal Rate of Return (IRR) calculations for a range of PV and battery sizes. The IRR is the interest rate that leads to a Net Present Value (NPV) of 0 €. The nomenclature is given in Table 3.

The NPV consists of the additional revenues R and the additional costs C of a PV storage system:

$$NPV = R - C = R_{feed-in} + R_{purchase} - C_{inv} - C_{operation} + R_{liquid} \quad (5)$$

[4] According to current legislation in Germany (Renewable Energy Sources Act), the feed-in limit at the grid connection point is 0.7 kW/kW$_p$.

The financial revenues $R_{feed-in}$ [€] from the grid feed-in are based on the energy feed-in E_{feed_in} [kWh/a], the feed-in tariff e_{PV_tariff} [€/kWh] and a yearly performance degradation of 1% for PV system b:

$$R_{feed-in} = \sum_{t=1}^{T_{Inv}} E_{feed\_in} \cdot e_{PV\_tariff} \cdot (1-b)^t \cdot (1+IRR)^{-t} \quad (6)$$

Without a PV storage system, the household must purchase all of its electricity from the grid. With a PV storage system, the household can use self-generated electricity to reduce its purchase costs. The amount saved, $R_{purchase}$ [€], is calculated as follows:

$$\mathrm{R_{purchase}} = \sum_{t=1}^{T_{Inv}} \mathrm{E_{EV}} \cdot \mathrm{p_{elect}} \cdot \left(1 + \frac{\Delta \mathrm{p_t}}{\mathrm{p_0}}\right)^{t} \cdot (1-\mathrm{b})^{t} \cdot (1+\mathrm{IRR})^{-t} \quad (7)$$

The investment C_{inv} [€] includes acquiring and installing the PV and battery storage systems. The investment for the PV system is calculated from the specific PV investment costs $p_{PV,t=0}$ [€/kW_p] and the peak power of the PV system $P_{PV,max}$ [kW_p]. The investment for the lithium-based battery storage system is calculated from the specific battery investment costs $p_{Batt,t=0}$ [€/kWh] and the storage capacity W_{Batt} [kWh]. We also considered the installation costs for the PV storage system P_{Inst} [€]. Thus, the initial investment is calculated as follows:

$$C_{inv} = -\left(P_{PV,max} \cdot p_{PV,t=0} + W_{Batt} \cdot p_{Batt,t=0} + P_{Inst}\right) \cdot (1+VAT) \quad (8)$$

Along with his initial investment, the operator of the PV storage system must also pay the annual maintenance costs $a_{PV,main}$ [€/(a·kW)], the annual hire of meters A_{meter} [€/a] and the annual PV insurance premium $A_{PV,ins}$ [€/a]. Thus, the yearly operating costs are:

$$C_{operation} = -\sum_{t=1}^{T_{Inv}} \left(P_{PV} \cdot a_{PV,main} + A_{meter} + A_{PV,ins}\right) \cdot \left(1+i_{Inf}\right)^{t} \cdot (1+IRR)^{-t} \quad (9)$$

The useful life of the PV system is assumed to be 20 years, a conservative estimate (German Solar Energy Society 2012). In our case, the planning horizon is also 20 years, so that no replacement of the PV system is required. The useful life of a battery is restricted by either its cycle or its calendar lifetime. The cycle lifetime of the lithium-ion-based battery system is set at $Z_{max} = 5000$ cycles, and the calendar lifetime at 20 years (Weniger et al. 2014). Thus, the useful life of the battery is only restricted by the cycle lifetime within the planning horizon of 20 years. If the battery must be replaced within 20 years, the replacement investment for the battery storage system C_{rep} [€] needs to be considered (cf. eq. (13)).

$$C_{rep} = -\sum_{t=1}^{T_{Inv}} W_{Batt} \cdot p_{Batt,t} \cdot f_t \cdot (1+USt) \cdot (1+IRR)^{-t} \quad (10)$$

Batteries replaced within the planning horizon have a significant liquidation value, R_{liquid} [€]. This is calculated as follows:

$$R_{liquid} = + W_{Batt} \cdot p_{Batt,T} \cdot \frac{\sum_{t=1}^{T_{Inv}} Z_t}{Z_{max}} \cdot (1 + IRR)^{-T_{Inv}} \quad (11)$$

We perform our economic assessment of PV storage systems in Germany and Ireland for a 2016 installation date.

Table 3: Nomenclature

Parameter	Meaning	Parameter	Meaning
t	Time index	q	Interest rate
T_{Inv}	Planning horizon	E_{feed_in}	Annual PV power feed-in
$P_{PV,max}$	Peak power of PV system	e_{PV_tariff}	PV feed-in tariff excluding VAT
$p_{PV,t}$	PV system price without VAT in t	f_t	Binary variable (Replacement of battery system is required: yes/no)
W_{Batt}	Usable storage capacity	$A_{PV,ins}$	Annual PV insurance premium including VAT in t=0
$p_{Batt,t}$	Battery system price excluding VAT in t	A_{meter}	Annual hire of meters including VAT in t=0
P_{Inst}	Nonrecurring installation prices for the PV storage system excluding VAT	$a_{PV,main}$	Annual maintenance costs for the PV storage system including VAT in t=0
E_{EV}	Self-consumption	i_{Inf}	Inflation rate
p_{elect}	Electricity price including VAT in t=0	Z_t	Annual number of cycles in t
$\frac{\Delta p_t}{p_0}$	Annual increase of electricity prices	Z_{max}	Cycle stability
b	Degradation factor of the PV system	VAT	Value added tax

5 Results

Turning to the results of our analysis, we first look at the profitability of PV stand-alone systems (section 5.1), before we investigate what drives the profitability of PV-storage systems (section 5.2). Finally, we conduct a sensitivity analysis to explore the impact of varying annual power consumption and varying load profiles (section 5.3). If not stated differently, we assume PV system costs of 1,130 €/kW$_p$ for the analyses below. As described in section 3 above, the range of electricity consumption profiles in 3 and 5 person households in Germany and Ireland is represented by 100 electricity load profiles in a 30-minute resolution in each category (i.e. combination of country and household size). For the analyses in sections 5.1 and 5.2, we use the corresponding 'median profile' within each category. For the analysis in section 5.3, we use the full set of load profiles.

5.1 PV stand-alone systems

We begin by comparing the internal rates of return (IRR) of PV stand-alone systems for different PV capacities in Germany and Ireland under current legislation in each jurisdiction respectively, i.e. assuming a feed-in tariff (FIT) of 12.3 cent/kWh for Germany and no FIT in Ireland. For comparison purposes, we also include a case for Germany without any FIT. As expected, Figure 5 shows that the current legislation in Germany provides clear incentives for investments into residential scale PV with IRRs of approx. 7-10%, where the returns are slightly higher for larger households (5 persons compared to 3 persons). In Ireland, however, there are no incentives for households to invest into PV under current legislation. For all considered PV capacities the resulting IRRs are negative. Considering the German case without a FIT, we find that the IRRs are, as for Ireland, mostly negative. The only exceptions are very small PV systems for larger households but also in this case, the IRR does not exceed 2%. However, the IRRs for the German case without a FIT are still higher than those for Ireland, which can be mainly explained by different solar radiation characteristics (1,200 full load hours for the location in Southern Germany vs. 900 full load hours in Ireland). Moreover, the higher electricity retail price in Germany drives this result. It is also interesting to see that difference in profitability between 5 person and 3 person households is larger when no FIT is assumed. The reason for this observation is that, as a result of the generally higher power consumption of larger households, the natural self-consumption is higher for these. In the case with a FIT, the electricity generated by PV can always be sold at the FIT so that the self-consumption plays a less important role for the profitability.

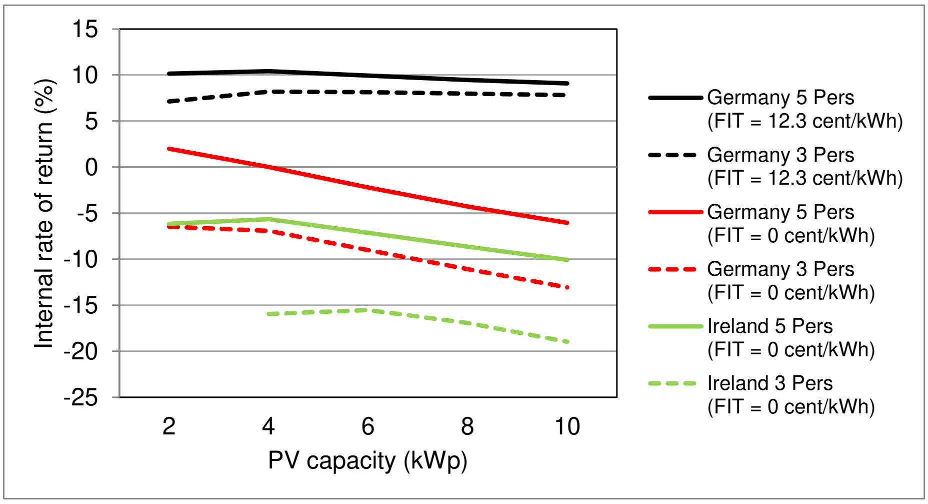

Figure 5: IRR for PV stand-alone systems in Ireland (ROI) and Germany (GER) under current legislation and comparison of GER with no FIT

Next, we analyse how different levels of FIT and different developments of PV system costs would affect the profitability of PV stand-alone systems in Germany and Ireland. Figure 6 shows the corresponding results for 5 person households. For Germany, we find that only a combination of a very low or no FIT with high (current) PV system costs would lead to a negative IRR. If the PV system costs decrease over time as anticipated by a number of studies (e.g. IEA (2014); IRENA (2016); Fraunhofer ISE (2015)), we find that even at much lower FIT levels or in a world without any FIT, reasonably positive IRRs can be achieved. For Ireland, the results are broadly similar but a higher FIT or lower PV system costs would be required compared to Germany to achieve the same profitability. The main reason for this difference is again the different situation in terms of the solar radiation. In addition, the residential electricity retail prices differ strongly between Germany (around 28 cent/kWh) and Ireland (around 18 cent/kWh), which has a big impact on the attractiveness of self-consumption. Nevertheless, Figure 6 does show that a FIT at the current level of the REFIT for wind (6.63-6.87 cent/kWh depending on the installed capacity) would be sufficient to incentivise household PV investments if the PV system costs came down from today's levels at the same time. However, at today's costs of PV systems, Figure 6 shows that a solar PV FIT of approx. 200% of the current REFIT level for wind would be required to achieve an IRR of 5%, which reveals the dominance of wind (onshore) in relation to a least cost RES expansion in Ireland.

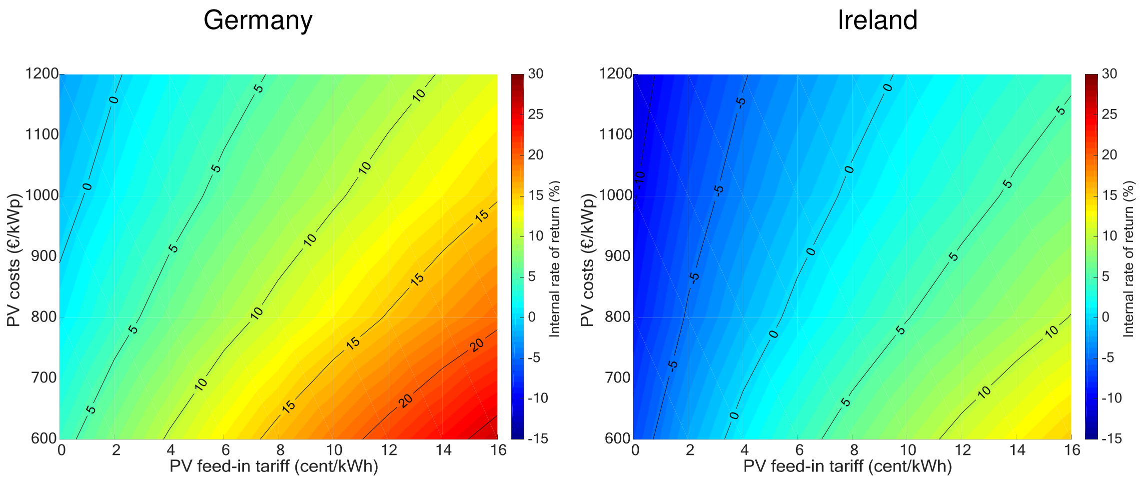

Figure 6: Impact of feed-in tariff (FIT) and PV system costs on IRR of a 6 kW_p PV stand-alone system for 5 person households

5.2 Combined PV-storage systems

We now turn to combined PV-storage systems and explore what drives their profitability. For these analyses, we generally assume that no FIT is in place, which reflects the status quo in Ireland and a topic of current debate in Germany. We first analyse which combinations of PV capacities and storage capacities are most profitable. For this purpose, we initially assume 500 €/kWh as battery storage system costs (on the basis of Kaschub et al. (2016)) and hypothesise an electricity price of 30 cent/kWh in both countries for comparison purposes knowing that this deviates from today's price levels particularly for Ireland. Both assumptions will be varied below to understand their impact (see Figure 8 and Figure 9). For the above initial assumptions, however, Figure 7 shows that 6 kW_p turns out as best possible PV capacity for 5 person households for both countries. In terms of the storage capacity, we find 10 kWh to be the most profitable size for Ireland and 12 kWh for Germany. However, should a PV capacity of 6 kW_p not be possible (e.g., for rooftop size or other technical reasons), further analyses show that one would prefer to build no storage for a smaller 2 kW_p PV system.

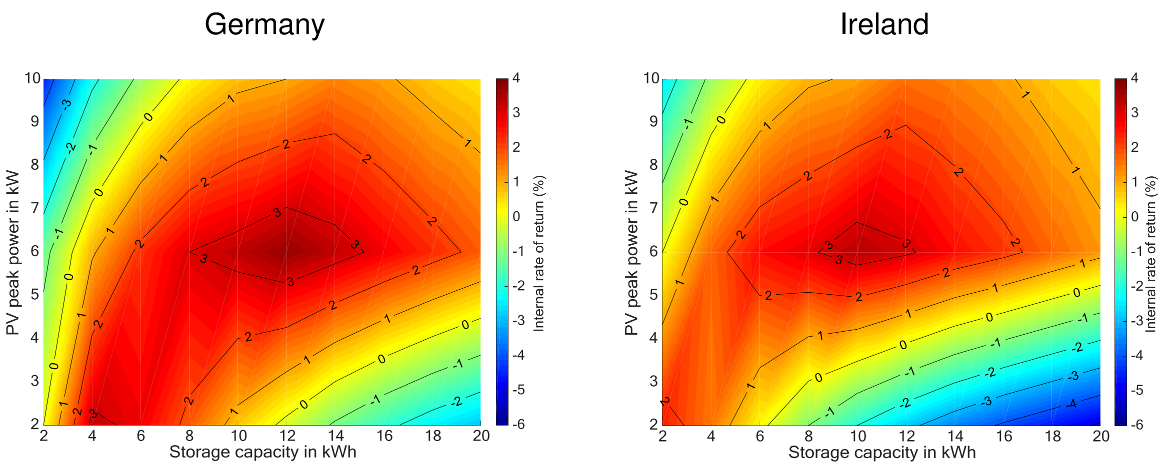

Figure 7: Impact of PV capacity and battery storage capacity on IRR for 5 person households, assumed battery storage costs: 500 €/kWh

For the next analysis, we assume, again, an electricity price of 30 cent/kWh in both countries but we now vary the battery storage costs. Figure 8 shows the IRR for different storage costs and capacities and also allows for deriving the most profitable storage capacity for different battery storage costs. While it is obvious that the IRRs increase with decreasing storage costs, it is interesting to see that the optimal storage capacity is the same for all considered storage system costs. The main reason for this observation is that the marginal increase of self-consumption and self-sufficiency for storage sizes increasing beyond the most profitable levels of 10 kWh and 12 kWh respectively is very small (see Figure 10 and Figure 11 below). This means that larger storages would mainly come along with higher costs while the benefits would be very limited. Altogether, this analysis shows that the most profitable storage size is robust with respect to storage cost changes within the considered range. We also find that the optimal storage capacity in Ireland is slightly smaller than in Germany. This can be explained by the higher natural self-consumption in Ireland resulting from (i) a generally higher electricity demand in Irish households and (ii) lower amounts of electricity generation from the same installed PV capacity. As a result there is less need to store self-generated electricity. We find 10 kWh for Ireland and 12 kWh for Germany as optimal storage capacities. For battery storage system costs of 500 €/kWh (as assumed in (Kaschub et al. 2016)), these storage capacities would lead to IRRs in a range of 3-4%, which might be a sufficient investment incentive for private households under the assumption that the required capital is available or can be accessed.

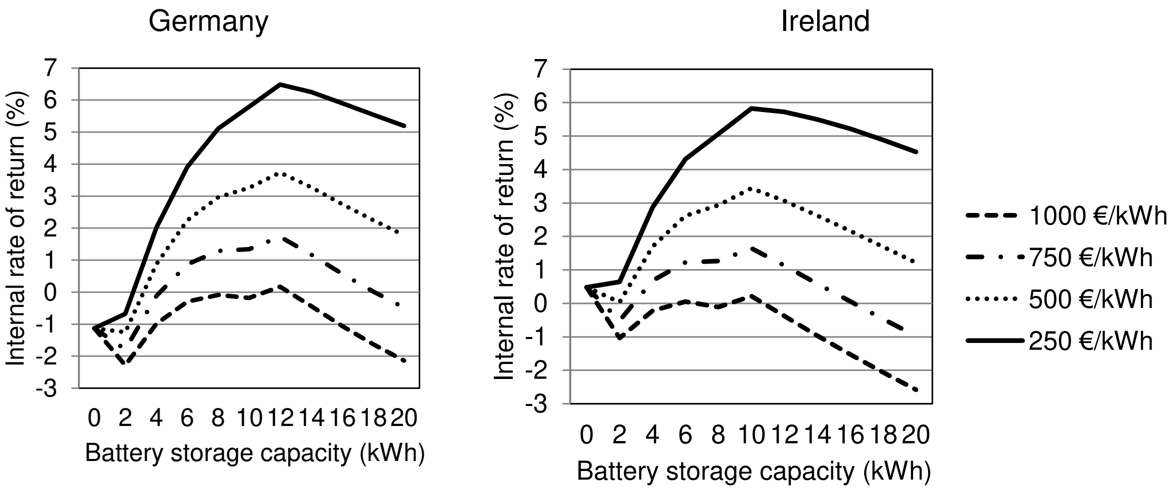

Figure 8: Impact of battery storage costs on optimal battery storage capacity assuming a 6 kW_p PV system for 5 person households

For the most profitable combinations of PV and storage combinations derived from the above analyses, we now hypothesise the electricity prices to vary in a range from 15-40 cent/kWh for both countries in order to explore the impact of this driver. Figure 9 shows the impact of this variation and varying battery storage costs on the IRR of PV storage systems in Germany and Ireland. Since the profitability of self-consumption increases with increasing electricity prices, we observe higher IRRs with increasing electricity prices. Obviously, decreasing costs for battery storage systems also lead to higher IRRs. The effects are similar in both countries with slightly higher IRRs for Germany in comparison to Ireland. This is mainly a result of higher levels of self-sufficiency in Germany (see Figure 11 below) leading to higher savings.

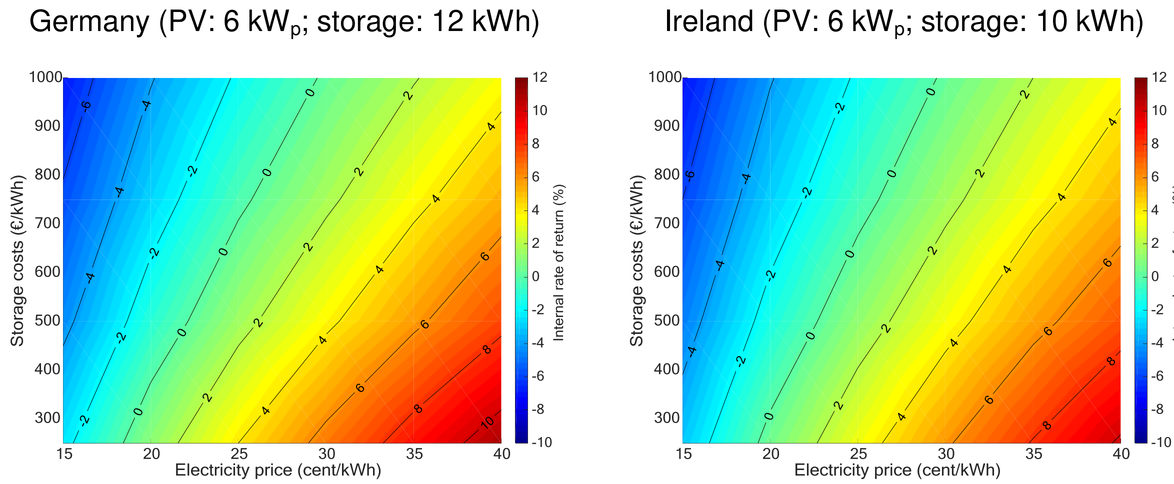

Figure 9: Impact of residential electricity retail price and battery storage costs on IRR of a PV-storage-system for 5 person households

For predefined ranges around the most profitable PV and storage sizes identified above, Figure 10 shows how the self-consumption rate varies within these ranges. For the identified system, the 5 person household in Germany would achieve a self-consumption rate of approx. 65%, while the corresponding Irish household would achieve a rate of almost 80%. It is interesting to note that, despite a smaller storage in the most profitable Irish system, higher self-consumption rates are achieved in Ireland. This is mainly driven by the higher electricity demand and the lower solar power availability.

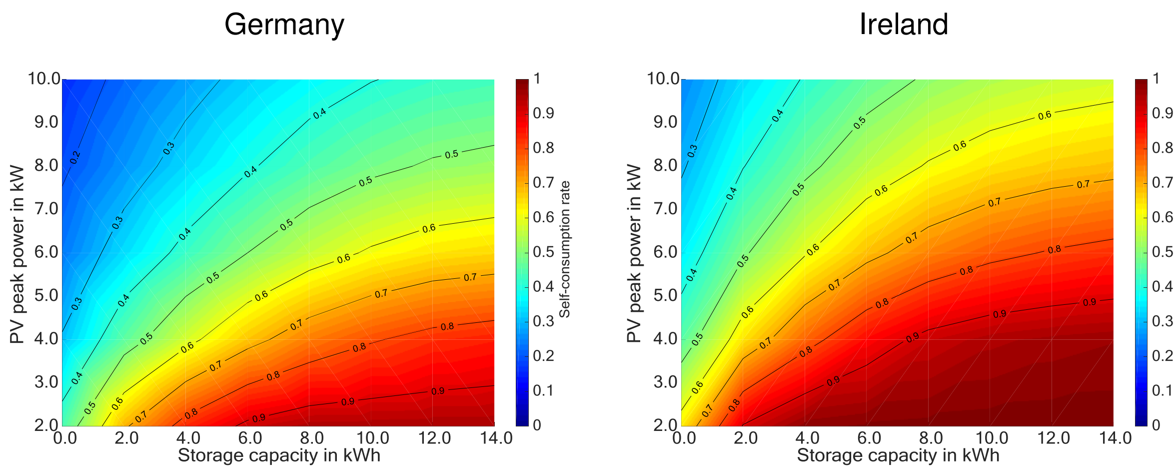

Figure 10: Impact of PV capacity and battery storage capacity on self-consumption rate for 5 person households

While Figure 10 shows self-consumption rates, Figure 11 shows self-sufficiency rates for the same ranges of PV and storage sizes. Having discussed the drivers of the differences in self-consumption between Germany and Ireland above, effects in the opposite direction could be expected for the self-sufficiency rate. While for the most profitable system configuration in Germany, a self-sufficiency rate of approx. 75% is achieved, the corresponding rate for the Irish household is approx. 65% only for the same reasons that are discussed above.

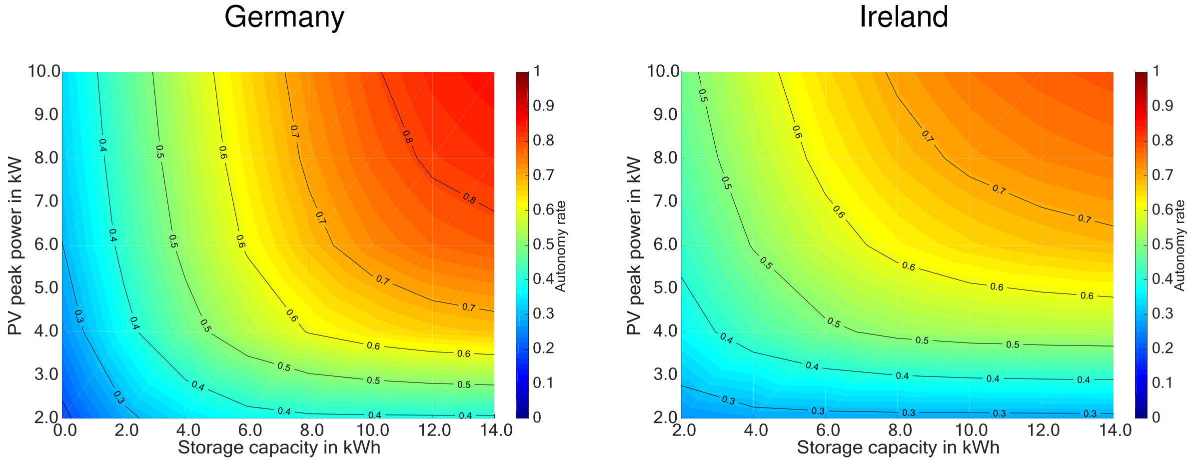

Figure 11: Impact of PV capacity and battery storage capacity on self-sufficiency rate for 5 person households

Figure 12 synthesises the findings from Figure 8 and Figure 11. However, while our analysis behind Figure 8 included varying battery storage sizes in a range from 0-20 kWh, we now expanded this analysis to investigate what levels of self-sufficiency are achievable (by increasing the storage size), and at what costs. Figure 12 shows our findings, again, for a 6 kW_p PV system. We already discussed above why higher levels of self sufficiency are achievable in Germany than in Ireland. However, it is very interesting to see that the profitability of self-sufficiency decreases rapidly for levels beyond approx. 75% in Germany and 65% in Ireland and that levels close to 100% are never achieved.

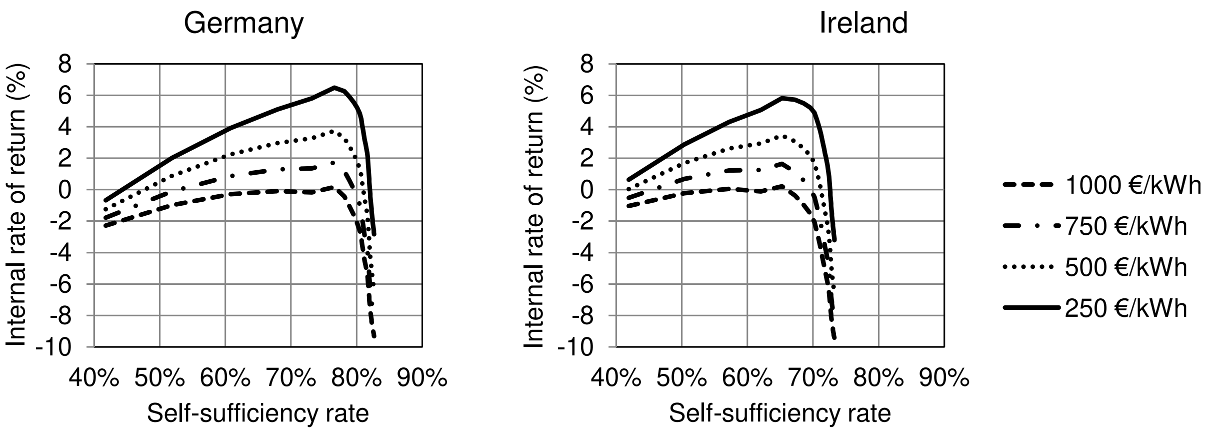

Figure 12: Relation between the IRR of a 6 kW_p PV storage systems and the self-sufficiency rate

As the analysis behind Figure 12 is based on a 6 kW_p PV system which has an impact on the results, we also conducted this analysis for a larger PV system. When increasing the PV peak power to 10 kW_p, we find that the shapes of the curves are generally the same, but shifted to the lower right, i.e. higher levels of self-sufficiency are achievable (84% instead of 73% in Ireland and 91% instead of 83% in Germany) but the profitability generally decreases.

5.3 Sensitivity analysis

As described above, the analyses up to this point are based on a 'median load profile', which was identified for Germany and Ireland respectively. To explore the impact of varying overall amounts of electricity consumption as well as varying load profiles, we now carry out a sensitivity analysis using 100 load profiles for each household size in each country. Again, we assume battery storage costs of 500 €/kWh and hypothesise electricity retail prices of

30 cent/kWh in both countries to focus on the impact of the electricity demand profiles. The results are shown in Figure 13. Note that, for this sensitivity analysis, the IRR is maximised for each load profile individually by varying the capacities of the PV and storage systems, i.e. the different dots in Figure 13 involve different storage and PV sizes. The sensitivity analysis shows that there are two main effects. First, the IRR generally increases with increasing annual electricity consumption. This could be expected as higher consumption generally leads to higher self-consumption and therefore higher profitability. Second, within the same levels of annual electricity consumption, the IRRs vary as well. This can be explained by different natural correlations between load profiles and PV generation resulting in different levels of self-consumption and profitability. Figure 13 shows results for 5 person households. We ran the same analysis for 3 person households. The IRRs are generally lower by around 2% but the overall picture is the same.

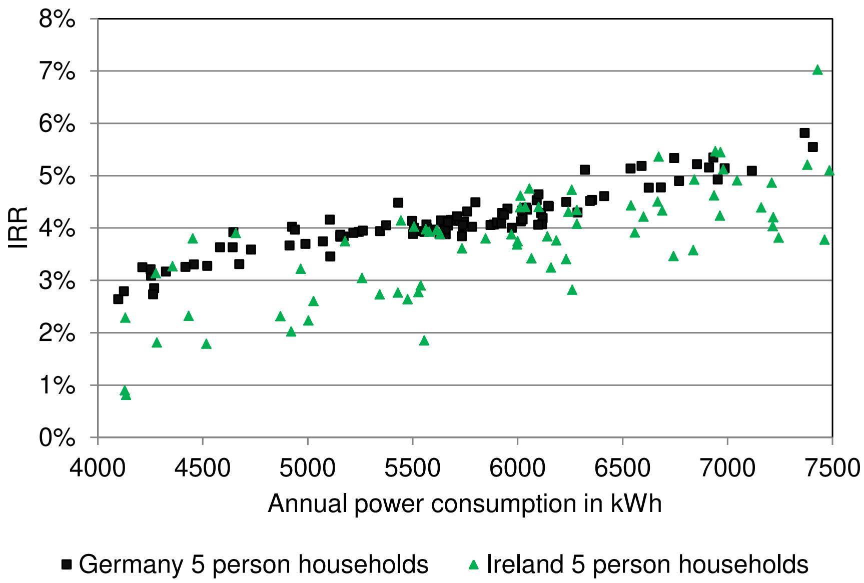

Figure 13: Sensitivity analysis exploring the impact of different load profiles on the IRR for 5 person households in Germany and Ireland

6 Discussion and limitations

The above analyses show that the profitability of private household investments into solar PV and battery storage systems largely depends on a number of different drivers, which we broadly grouped into 'finance-related' and 'quantity-related' drivers (as illustrated in Figure 1). Within the group of finance-related drivers, we explored the impact of (uncertain) technological developments, mainly focussing on cost developments for solar PV and battery storage systems. While the development of technical parameters, such as efficiencies or lifetime, also plays a role, we did not focus on these in our analyses. We further analysed the impact of electricity retail price levels, which may be referred to as both a market-based and a political driver. While the share of the total price that is associated with electricity generation is obviously determined in the electricity wholesale market, there are a number of political and regulatory decisions that have an impact on the unit costs of electricity for consumers (e.g. what cost components are levied on a per unit (kWh) basis, per capacity (kW) basis or per household basis). In addition, we considered the availability of a FIT as a political driver. In terms of the quantity-related drivers, we explored the impact of the overall amounts and profiles of electricity demand and supply (by PV) on the profitability of the considered investments. These parameters are largely driven by geographical and meteorological characteristics (e.g. temperature and solar radiation availability) as well as household characteristics (e.g. household size determining overall amount and profile of demand, see Hayn et al. (2014)). In combination, the amounts and profiles of consumption and generation drive the so-called natural self-consumption.

For the combinations of solar PV system and battery storage capacities that turned out to be most profitable, we find that such systems would yield self-sufficiency rates of 75% in Germany and 65% in Ireland. Assuming that no FIT is in place, we also found that once the battery storage costs come down to a level of around 500 €/kWh (which others, e.g. Kaschub et al. (2016), assume as a realistic reference price), systems yielding such self-sufficiency rates would be profitable in Germany, while in Ireland, the costs would need to decrease further or electricity prices would need to increase to make such investments attractive. In other words, we can expect that, for an increasing number of German households, the electricity demand from the grid may decrease to around 25% of their total demand. This will bring about enormous changes and challenges for the electricity retail business. Moreover, in systems where consumers pay for costs to build and maintain the energy system infrastructure on a per unit basis (e.g., grid charges), this means (i) that the consumers that can afford to invest into PV-storage systems contribute less to maintaining the system while still benefiting from the security of supply from being connected to the grid and (ii) that a decreasing amount of households that don't or cannot invest into self-sufficiency bear the costs of the system (Khalilpour & Vassallo 2015), which brings about distributional problems. Moreover, one can expect that the per unit charges for system maintenance will increase over time as less and less kilowatt hours are extracted from the grid and contribute to paying the same overall pot. This results in a spiral where incentives for self-sufficiency and per unit charges continue to increase over time. This is not only worrying because of the distributional implications but also because of the overall system (in)efficiency. If self-sufficiency on a single-household basis is incentivised, this means that all potential efficiency gains from balancing supply and demand over smaller or larger areas (using the grid infrastructure that already exists) are omitted. Similar developments are possible for Ireland, though with a certain time lag. However, as it stands, the renewable support in Ireland is levied by the PSO on a per household basis rather than a per unit basis. While the distributional implications of this regulation are discussed by (Farrell & Lyons 2015), one of the effects of this system is that the per unit electricity retail price is lower under this regulation providing less incentives for self-consumption.

Several ideas to overcome the above effects are discussed in the literature. The German government decided to partially add the per unit renewable support levy on the kilowatt hours that are self-consumed for solar PV systems of a capacity that exceeds 10 kW_p or if annual self-consumption exceeds 10 MWh to 'address' this problem. However, this legislation does not address the source of the problem. Moreover, it reduces the incentive to invest into solar PV systems. We wish to emphasise that we do not want to advocate against incentives for self-consumption. Our concern is simply that the system maintenance costs should be levied in a distributionally fair way. This can be achieved, for instance, by introducing capacity-based price components, also called demand tariffs in the literature (Simshauser 2016; Kaschub et al. 2016). Opponents of such systems claim that these will produce undesirable distributional effects in their own right. Overall, this discussion shows that there is a need for further research in this area, particularly given the emphasis of the EU winter package on consumer empowerment and self-consumption (COM 2016).

Critically reflecting our findings, we wish to emphasise that the results need to be interpreted with some caution. Our analyses in this paper focus on household investments in Germany and Ireland. Our simulation model, however, is generic and transferrable to other countries and consumer groups. Moreover, on the demand side, measurement data were available from the control group of the large-scale time-of-use field trial in Ireland. In absence of such large-scale measurement data sets, modelled demand profiles were used for Germany. However, measurement data from individual households (rather than hundreds) were available and we carried out robustness checks showing that the main findings hold. Furthermore, while we considered the uncertainty on the demand side in terms of overall amount and profiles of electricity consumption through a set of 100 profiles for each household size, our consideration of the supply side uncertainty in relation to the overall amount and profiles of electricity generated from PV is limited to the comparison of Germany and Ireland. Further, our analyses focussed on standard electricity retail tariffs with a constant price in cent/kWh. Future analyses should also explore the impact of dynamic pricing schemes, which may have an impact on the optimal solar PV, battery storage capacities and its optimal operating strategy as well as their profitability. Finally, we quantified costs of self-sufficiency of individual households. Quantifying the societal costs of self-sufficiency of individuals is also a relevant topic for future research.

7 Conclusions and outlook

We use a techno-economic simulation model to analyse the profitability of private household investments into solar PV and battery storage systems. The profitability of such systems depends on a number of different drivers. Looking at the profitability of PV stand-alone systems, we find that the PV system costs and availability of a FIT are crucial drivers. Further, their profitability is driven by solar power availability and electricity retail prices. However, electricity retail prices become yet more important for combined PV storage systems, i.e. for higher levels of self-consumption. Storage system costs are obviously also a major driver of the profitability of such systems. Overall, we find that for current levels of costs, prices and FIT, household investments into solar PV are profitable in Germany. While for these current levels, investments into combined PV-storage systems with smaller storages would also be profitable in Germany, the IRRs would typically be lower than for PV stand-alone systems. For Ireland, we find that investments into solar PV or storage are not profitable under current market conditions and regulation. However, we also find that this may change soon as the PV and storage system costs are expected to fall over the coming years and electricity retail prices may further increase. Under these developments, our findings show that, even when assuming no FIT, there will be increasing incentives to invest into PV-(storage) systems in both countries.

For the most profitable combinations of PV and storage system sizes, we find that self-sufficiency rates of approx. 75% and 65% can be achieved in Germany and Ireland respectively. Increasing the self-sufficiency rate beyond these levels will decrease the profitability of PV-storage systems significantly. In line with this finding, we observe that the most profitable storage size does not increase with decreasing storage costs as the marginal increase of self-sufficiency beyond the identified levels of 75% and 65% respectively is negligible for increasing storage sizes. Self-sufficiency rates of 100% are never achieved for PV-storage systems. However, the achievable self-sufficiency rates imply that these households will only need to cover as little as 25% of their total electricity demand from the grid. This will create a huge challenge for electricity retail companies as well as policy makers. Electricity retailers will only be able to supply a small share of the households' total electricity demand, which will negatively affect their business model. Policy-makers will face distributional challenges. When an increasing number of households only cover a small portion of their electricity demand from the grid in a system where the costs for maintaining the infrastructure are levied on a per unit basis, a decreasing number of households will need to pay continuously increasing per unit charges. Policy makers and the society will need to discuss whether these developments should be addressed by introducing capacity-based charges (e.g., for the grid). The economic pressure will increase over the coming years.

Finally, the observed developments showing that self-sufficiency is or may soon be largely profitable and, willingly or unwillingly, incentivised for individual households should spark a discussion of the (in)efficiency of the system as a whole. First, harnessing efficiency gains from balancing supply and demand over areas of different size using the existing grid infrastructure should be ensured. Second, if governments wish to support solar PV, slightly larger, community-based PV assets would come along with economies of scale and therefore may be able to provide the same amount of renewable electricity at lower overall costs. Such solutions may be less favoured because of a lack of trust and legislation. Ultimately, however, consumers will pay for their electricity demand so they should choose a solution according to their preferences. It is therefore important that they are aware of all options and related (financial) consequences.

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