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Why German households won’t cover their roofs in photovoltaic panels: And whether policy interventions, rebound effects and heat pumps might change their minds

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ABSTRACT

Rooftop photovoltaics in Germany generate around 15 TWh of electricity per year, and there is sufficient roof area to increase this many times over. Germany’s transition to renewable electricity requires large increases in rooftop and field-based photovoltaics. However, for household systems, each kWh fed into the grid pays only €0.0653, while households gain a marginal benefit of €0.334 for each kWh of their own electricity they consume. This deters households from installing large rooftop systems, where a large proportion of self-generated electricity is fed into the grid. This study uses cost-benefit analyses based on quarter-hourly electricity data, to estimate economically optimum sized photovoltaic systems, for a typical detached house. It finds that, for a range of battery sizes, optimal systems generate about the same amount as the household consumes, but use only about half of available roof space. Heat pumps and rebound effects increase this slightly. A subsidy of 10eurocents/kWh for grid feed-in would make the largest systems the most profitable, but this would bring further problems. Policymakers should aim for more households to adopt photovoltaics, rather than recommending larger systems for those who do. They should also promote the synergy between heat pumps and photovoltaics.

Introduction

In response to the climate emergency, Germany plans to decarbonise its electricity grid completely by 2050 [72]. Although electricity use has been falling in Germany since 2006, largely in response to increasing electricity prices [71,72], usage is expected to increase markedly as the share of electric vehicles increases and heat pumps replace fossil fuel for heating and are increasingly used for air cooling [72]. Studies estimate that electricity use would increase by 30% in developed countries such as Britain and the US if all conventional light vehicles are replaced by electric vehicles of about the same size and consumption as today’s electric vehicle fleets [11,51]. However, the average size of future electric vehicles is likely to be significantly larger than today’s, as firms such as General Motors and Volkswagen seek to gain market share by introducing larger, heavier and more powerful models [27–29,36,37]. It is therefore reasonable to expect developed countries’ electricity usage to increase by at least 50% in the coming decades just from vehicles and heat pumps. To this can be added large extra demands for renewable electricity to make green hydrogen via electrolysis for industry, public transport and seasonal electricity load-shifting [20].

Germany produced 41.8% of its electricity from renewables in 2020, from wind, photovoltaics, hydroelectricity and biomass [23]. To generate 150% of its current production entirely from renewables would therefore require more than a trebling of renewable electricity generation. Simply producing this much will be an enormous challenge, not to mention the difficulties of matching supply to demand in real time.

This paper is concerned with one aspect of this electrical energy transition: increasing the quantity of electricity production from rooftop photovoltaics. Photovoltaics in Germany produced 51.42 TWh in 2020, comprising 10.5% of Germany’s electricity production. This would need to increase to about 150 TWh by 2050 for photovoltaics to play a proportionate role in the energy transition, or at least 100 TWh if wind is seen as a better option. Around 31% of Germany’s photovoltaic production comes from small arrays of under 30 kWp (author’s calculation from data in Solaranlagen [59] and [48]), most of which are on rooftops. Current rooftop production is therefore around 15 TWh/y, but Mainzer et al. [47]

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estimated the technical potential for residential rooftop photovoltaics in Germany at 148 TWh/y, while Bódis et al. [9] estimated the economic technical potential from rooftops at 103 TWh/y.

Most south-facing roofs do not have photovoltaic panels, and of those that do, most have only small installations of around 5-6 kWp (author's calculation from [48]; see also [52]). Figure 1 shows the frequency distribution of photovoltaic panels of different sizes up to 30kWp. There is therefore very large potential for increasing the share of photovoltaic production substantially in the coming years.

There are two main obstacles currently inhibiting a rapid, seamless increase in rooftop photovoltaic capacity. First, Germany's regulatory regime, with high grid electricity costs and low feed-in tariffs, makes it uneconomical for a household to install significantly more photovoltaic capacity than it can use for its own consumption [8]. Figure 2 shows how the pricing structure for grid electricity and photovoltaic feed-in has developed in Germany since 2000. Households who installed photovoltaics prior to 2011 receive a 20-year guaranteed, heavily subsidised feed-in tariff of around 50 eurocents per kWh (c/kWh) for 20 years. However, households who install photovoltaics as in April 2022 will receive a feed-in tariff of only 6.53 c/kWh (see Figure 2). They pay the full price of around 33.4 c/kWh for electricity drawn from the grid but can consume their own-produced electricity tax-free if their installation is smaller than 30 kWp. With a feed-in tariff of 6.53 c/kWh it is not economical for a household with a system of <30 kW to install photovoltaics just to feed electricity into the grid. It would seem more economically sensible to install an array that produces

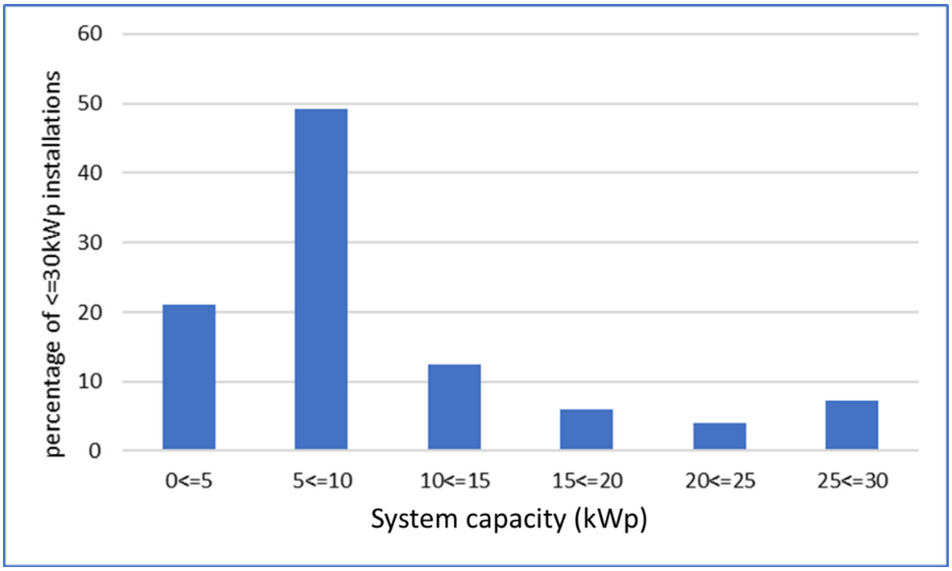

Fig. 1. Percentage of photovoltaic installations of capacity <=30 kWp, in different ranges. Author's calculations from Marktstammdatenregister [48].

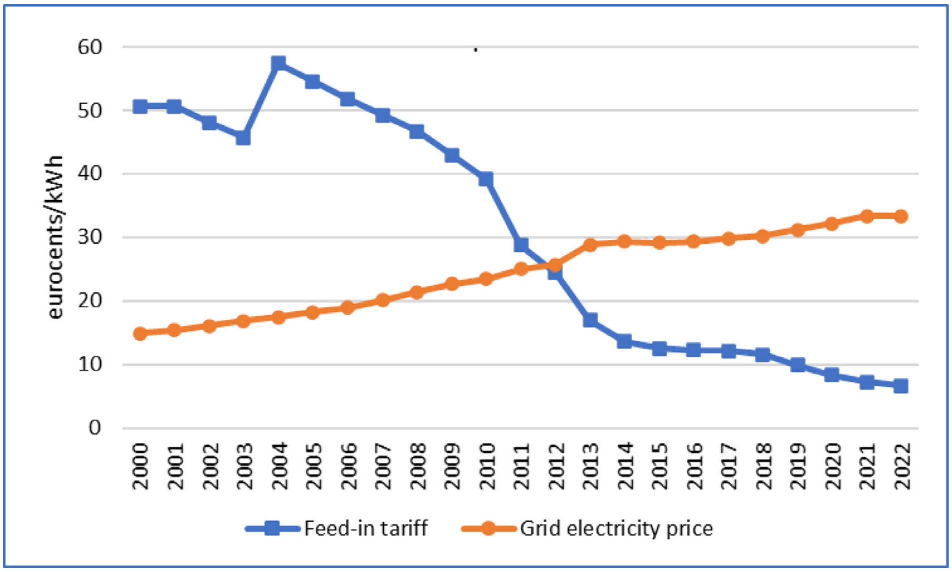

Fig. 2. Feed-in tariff for systems < 10 kWp, and grid-electricity price for households using up to 3900 kWh/a), years 2000-2020. Data sources: (Wirth et al. [77]; BMWi, 2021; ÜNB, 2021).

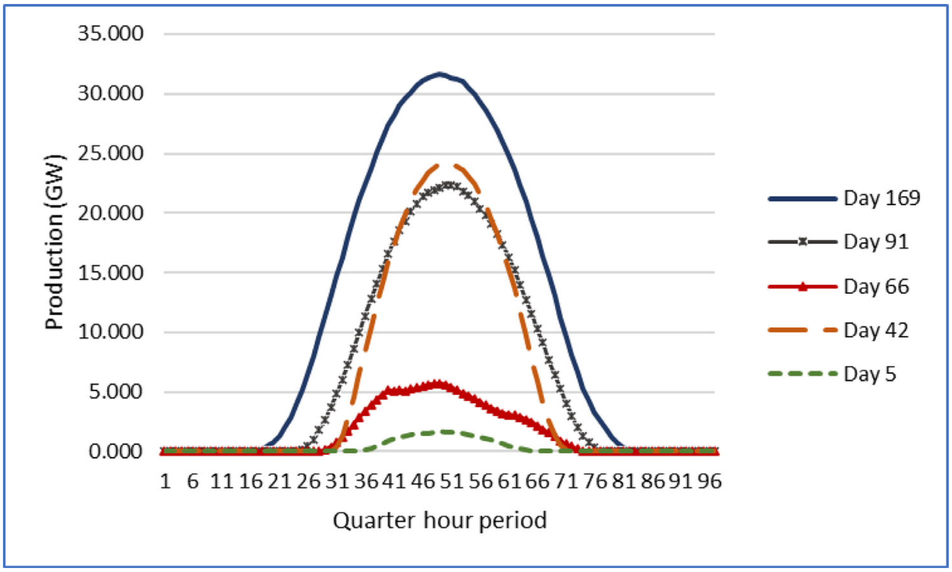

Fig. 3. Photovoltaic production on specific days of 2019 in Germany (author's calculations from Fraunhofer [21]).

about 20% more electricity than the household expects to use, since a household with a small photovoltaic array can never consume all it produces, nor produce all it consumes, due to the huge difference between summer and winter production. For a review of the impacts of different kinds of feed-in tariffs see Dijkgraaf et al. [16].

Figure 3 highlights the further problem that the day-time curve of photovoltaic generation is not likely to match household consumption routines, since generation follows a cosine-like curve while consumption tends to be substantial in the early morning, low around midday and high in the early evening. Battery storage can smooth out this mismatch, enabling a household to consume much more of its own-produced electricity on a day-by-day basis, but battery storage is expensive despite persistent falls in prices [61,78].

Clearly, then, there is a policy problem with rooftop photovoltaics. Each kWp of photovoltaic capacity takes up about 5 m^2 of roof area. A typical detached house in Germany has about 60-75 m^2 of roof area per side, enough for 12-15kWp of photovoltaic capacity, capable of producing around 12,000-15,000 kWh/y. But a typical household of 2 adults and 2 children consumes around 4,500 kWh/y of electricity [65] or 7,500 kWh/y with a heat pump, so a system of about 6-8 kWp capacity would appear to be far more economically viable than a larger system.

A second problem is the technical limitations of the local low-voltage electricity grids which connect households to medium-voltage sections of the national grid. The quality, topology, state of repair and carrying capacity of Germany's local grids vary considerably from district to district. As Bayer et al. [5] show, grids in some local areas, and the transformers between these and medium voltage sections, are already at capacity and are hard-pressed to accommodate input from more photovoltaic panels than are already installed.

The government's response to this problem is currently the "70% curtailment rule", enshrined in the German Renewable Energy Sources Act (Erneuerbare Energiegesetz). Local grid operators are allowed to limit electricity feed-in to 70% of a photovoltaic installation's theoretical capacity. Although at least one source claims this "only" curtails about 2-5% of total household feed-in [77], some local grids would hardly cope with a three or fourfold increase in new, large rooftop photovoltaic arrays. Although this would be a serious issue if households begin to install large arrays en masse, it is not explored in this paper but would need to be in future research[1]. Mainzer et al. [47] estimated that at least 30% of current technical potential for residential rooftop photovoltaics would not be feasible due to this issue.

A factor that could make large rooftop photovoltaic systems more attractive is the use of heat pumps for water and space heating. In Germany there is a drive to replace fossil fuel boilers with electric heat pumps over the next decades [35]. This paper is not concerned with the economic and practical issues for a household in deciding whether or not to install a heat pump (on which see Globisch et al. [79]; Jarre et al. [80]), but if a household already has a heat pump or has decided to install one, the question arises as to whether this makes a large photovoltaic array more economical.

A further factor that will affect the economic viability of large rooftop photovoltaic arrays is rebound effects, discussed in the next section.

The aim of the paper is to investigate whether there is an economically optimum size of rooftop photovoltaic system, with and without battery storage, for a typical four-person household in Germany, in an average sized detached house retrofitted to high energy efficiency standard, using a heat pump for water and space heating. Given the results, a policy intervention is suggested that could substantially increase the economic viability of rooftop systems of capacity greater than 8kWp, though drawbacks in this are also noted. The study fits within the broad scope of finding paths for optimum adoption and use of photovoltaics in the transition toward a zero-carbon economy [74], and uses a modified form of Galvin's [30] modelling methodology.

In the remainder of the paper, the next section reviews literature relevant to the economic viability of rooftop photovoltaics post-2011 in Germany. The following section develops a methodology for performing cost-benefit analyses of rooftop photovoltaic systems ranging from 0.5 kWp to 15 kWp. The next section presents the results and a brief sensitivity analysis. A further section discusses the results, and a final section concludes and makes suggestions for policy.

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[1] Despite considerable effort, I have not been able to find any empirical study supporting Wirth's [77] claim that the 70% curtailment rule leads to the curtailment of 2-5% of (rooftop) photovoltaic feed-in.

Literature review: do rooftop photovoltaics in Germany pay back?

Cost-benefit analyses of rooftop photovoltaic systems

Zsiborács et al. [78] offer cost-benefit analyses of flexible battery storage photovoltaic systems in Germany, Italy, Spain and France, for seven different types of batteries. The electricity these photovoltaic systems generate can be used, via DC-AC converters, for direct consumption, direct feed-in to the grid, or via an inverter for battery storage. Electricity stored in the battery can be used, again via an inverter, for consumption or feed-in to the grid. Zsiborács and colleagues estimate system costs according to battery type and accessories (inverter, etc.), for a system rated at 14.76 kWp, based on an actual installation in Kassel, Germany. Their preferred battery type is an Olivine-Type-LiFePO4. Although this is the second most expensive, it has a lifetime of 30 years (the highest), an efficiency of 98% (the highest), average maintenance costs of €247/y (the lowest), and a stability of 10,000 charges and discharges (by far the highest). Its worst-case total system efficiency is 80.4%, where electricity has to flow from photovoltaic panels to converter, inverter, battery charge, discharge, battery inverter and grid feed-in – a situation that occurs relatively rarely.

Zsiborács et al's. [78] analysis provides a model that is broadly suitable for the analysis presented here, though their calculation method is not explicitly presented. A further limitation is that their 30-year analysis is based on the generation, consumption and feed-in patterns of one month of operation, August 2017. This is likely to bias the results, even if the other months are modelled proportionate to each month's electricity production, since day-to-day volatility makes one month's patterns of self-consumption, feed-in and consumption from the grid very different from those of other months.

A more realistic cost-benefit analysis should take into account the full seasonal and day-to-day volatility of photovoltaic electricity production over an entire year, projected into future years. It also needs to consider each day separately and, better, moment-by-moment consumption and generation at as fine a grain as possible (as [46] do in their study of different photovoltaic system typologies battery configurations). This study therefore uses the patterns of actual, quarter-hourly electricity production and consumption over a full year as the basis for this cost-benefit analysis.

Including the rebound effect

An increasing number of studies reveal that households who install photovoltaics often increase their energy consumption as a consequence of the financial or other benefits these installations bring [18]. In cases where feed-in tariffs are high, households often increase their overall energy use, as the high feed-in tariffs increase their income – the so-called "income effect" [4]. Deng and Newton [13] found this among households in Sydney where feed-in tariffs were high, and Galvin [28] found strong qualitative evidence of the effect among households in Bavaria, Germany, who had installed photovoltaics prior to 2011 and who therefore still receive around €0.50/kWh for feed-in. These rebounds occurred in a range of energy carriers, not necessarily electricity. The income from the high feed-in tariffs appeared to simply increase a household's balance sheet, enabling them to consume more in general.

More relevant to this study are rebounds due to a "price effect". Toroghi and Oliver [68] found that US households who installed photovoltaics increased their electricity consumption by an average of 5.85 kWh for each 100kWh of electricity generated. Qiu et al. [53] found a small reverse rebound effect in electricity consumption when households in Phoenix, Arizona, were heavily incentivised to feed their photovoltaic electricity into the grid, presumably because consuming their own electricity represented a loss in income. Atasoy et al. [3] conducted a country-wide survey of households in Germany with and without photovoltaics and used a statistical "matching" method developed by Kupper et al. [41] and Rubin [54] to compare electricity consumption of households that were similar in all relevant respects except for the presence of photovoltaics. Households receiving low feed-in tariffs but paying high grid electricity prices consumed significantly more electricity than households without photovoltaics who were in all other respects "matched" with these. More recently, in a large, interdisciplinary study Galvin et al. [32] found rebounds of between 18% and 32% among photovoltaic adopters in Germany

These rebounds are consistent with studies on the price elasticity of electricity consumption. Studies such as Schulte and Heindl [57] have found that in Germany, on average, each 1% decrease in the electricity price is associated with a short-term increase in electricity consumption of around 0.2% and a long-term increase of up to 0.8%, representing elasticities of -0.2% to -0.8%.

Another effect that can lead to rebounds among households with photovoltaics is so-called "moral licensing" [17,49,50]. Here, householders feel they have done their duty to the environment by investing in a CO_2-reducing technology and are therefore justified in consuming more.

Whether due to a price effect or moral licensing, rebound effects are not necessarily harmful. For a household struggling to pay for necessary energy services, rebounds can be welfare-enhancing [25] as they enable essential energy services to be enjoyed which were previously out of reach [66,55].

Rebound effects have been taken into account in cost-benefit analyses of energy efficiency upgrades of existing homes [33] and in general studies of households with photovoltaics (see above), but not (to this author's knowledge) in cost-benefit analyses of rooftop photovoltaics. In studies of energy efficiency upgrades, rebound effects are seen as reducing the net present value of an energy efficiency investment, because a portion of the potential returns is lost due to extra energy consumption. For photovoltaics this is not so straightforward. Extra electricity consumption is free when the sun is shining sufficiently, and while this deprives a household of the very low return on feed-in to the grid, it can enhance the household's welfare while avoiding paying the high price of grid electricity. This study therefore considers rebound effects in this cost-benefit analysis as welfare-enhancing.

Heat pumps

A further issue to be considered is how a heat pump affects the economic viability of household photovoltaics. Litjens et al. [44] investigated the economic viability of installing heat pumps in 16 homes in the Netherlands with rooftop photovoltaics and, in some cases, battery storage. Although the economic viability of installing the heat pumps was marginal without subsidies, photovoltaics with battery storage reduced heat pumps' CO_2 emissions by around 80% over a 30-year equipment lifetime.

Beck et al. [8] used a mixed integer linear programming model to investigate the theoretical economic viability of the reverse scenario, namely installing photovoltaics and battery storage where there is already a heat pump installed. Their study used large ranges of different price structures and photovoltaic capacities. They found that for regimes with low feed-in tariffs, households with high electricity consumption benefited most from having a photovoltaic system, and that under these regimes heat pumps brought greater economic benefit to households with larger photovoltaic systems.

Aguilar et al. [1] monitored heat pump performance with a photovoltaic system without battery storage, in a laboratory setting simulating a 4-person household in Alicante, Spain, for a full year. Energy storage was provided by a large water tank rather than a battery. They found the heat pump's coefficient of performance averaged 3.5 for the year. In a more theoretical study, von Appen and Braun [75] developed a model to optimize the sizing and grid integration of a household photovoltaic system with battery and heat pump. An increasing number of studies investigate this type of optimization, either empirically or with modelling (e.g., [2,45,58]; and see review in Gaur et al. [35]).

To date, however, no studies appear to have performed a cost-benefit analysis using a full year's day-to-day electricity production data, and especially not with quarter-hourly data, for a typical household in Germany (or any other country) who install photovoltaic systems of a range of sizes, with and without rebound effects, and with and without a heat pump. This paper makes a novel contribution by offering a first attempt at this.

Electric vehicles

A further factor that could greatly enhance the economic viability of large rooftop photovoltaic systems is the transition to electric vehicles. This brings several unknowns: to what extent these will be charged at home [38] how large they will be [26–29]; and how fast the transition will be [29]. This would represent an extra layer of uncertainty and volatility over what is already a multi-layered study, and it will not be considered here except for comments on its likely broad-brush effects. Ironically, the transition to electric vehicles is much easier than the transition to energy-efficient buildings, but the speed of this transition is likely to rapidly increase the demand for renewable electricity [27–30].

Method and data

Overview

The study investigates whether there is a maximum photovoltaic capacity beyond which economic viability reduces, using a 2-adult 2-child household in a detached house, for different sized batteries and no battery, with and without rebound effects, and with and without heat pumps, and taking photovoltaic performance at a typical level for Germany. Germany-wide average photovoltaic electricity production data over the course of the year 2019 is used as the basis for the analysis, repeating the 2019 patterns in future years. A sensitivity analysis repeats some of the modelling runs using 2020 radiation patterns.

te Heesen et al. [67] found total annual yield (kWh/kWp) of Germany's photovoltaics in 2012-2018 varied by +/-6.5% about a mean of 969 kWh/kWp, while Zsiborács et al. [78] estimated average annual yield for Munich at 1122 kWh/kWp. For simplicity the figure of 1,000 kWh/kWp is used in this study, as this is about the average for the "Fränkische Trockenplatte", the region of Bararia, Germany where the case study house is located.

Data and sources

Table 1 lists the parameters and their data values used in the analysis. Data of Germany's photovoltaic production for 2019 and 2020 was provided by Frauhofer [22]. The data for each year is given as GW of power produced each quarter-hour, a total of 35,040 readings. Dividing each reading by 4 gives an estimate of the electrical energy produced in each quarter-hour period. This was adjusted to take account of the steady increase in photovoltaic installed capacity throughout the year, then normalised to a total annual production of 1,000 kWh, to represent the quarter-hourly

Table 1
Summary of parameter values used in analysis.

Parameter	Units	Symbol	Comment	Value where constant in analysis
Annual baseline electricity consumption	kWh	A	Assume 4,500kWh as typical for household of 2 adults and 2 children	4500kWh
Annual consumption for heat pump	kWh	H		2133kWh
Annual electricity production	kWh	P	Used in above equations to estimate self-consumption, etc. 1,000 x kWp	
Annual self-consumption	kWh	S	Calculated within the program	
Annual feed-in	kWh	F	Calculated within the program	
Annual grid electricity consumption	kWh	G	Calculated within the program	
Rebound factor	number	R	1 + proportionate increase in consumption over baseline	1.2
Grid electricity price in year 1	Euros/kWh	Q	As in March 2022	0.33 €
Grid feed-in price in year 1	Euros/kWh	V	As in March 2022	0.0653 €
Annual electricity price increase factor	number	W	As forecast by the BMWi	1.054
Inflation rate factor	number	X	1+ inflation rate (%/100) as forecast by the European Central Bank	1.05
Discount rate factor	number	D	1 + discount rate (%/100) based on typical net rate of return for real estate investment, taking inflation into account	1.05
Annual system maintenance cost	Euros	M	1% of upfront costs. See discussion in Zsiborács et al. [78]	
Capacity of battery storage system	kWh	Z	Used to estimate annual maintenance costs, used in estimating system costs.	0, 3 and 5kWh
Upfront costs (itemised below)	Euros	U	Estimated from actual quote on 08/02/2022, and Solaranlagen [59] and other photovoltaic providers' websites.	
Modules (ncluding VAT)	€/kWp			919 €/kWp
Mounting	€/kWp			167 €/kWp
CDC-AC Converter etc.	€/kWp			200 €/kWp
Battery and related components	€/kWh			1,714 €/kWh
Cabling, fixtures and grid connection	€			950 €

patterns of photovoltaic production from each 1 kWp of installed capacity. A limitation of this method is that the profile is for Germany as a whole, not for a specific area of Germany where a case study photovoltaic array is located.

Data of a typical profile of a German household's electricity consumption (apart from heating and hot water) was provided by BDEW [7]. This is also given in quarter-hour timeslots. This was normalised to a total consumption of 4,500 kWh/y, which is typical for a 4-person household.

A data profile of water and space heating consumption, again at quarter-hour intervals, was obtained from E-Control [19]. This was normalised to 2,133 kWh/y, as follows. The house is assumed to have been retrofitted to Germany's so-called "KfW55" standard, which has theoretical heating energy consumption of around 30 kWh/m^{2}a (KfW [39]). For a total floor area of 120m^2 this gives 3,600 kWh/y. In Germany, water heating for a 4-person household consumes around 2,800 kWh/m2a [14], though this can vary widely. This gives a total of 6,400 kWh/y. Assuming the house is fitted with a heat pump achieving a coefficient of performance of 3.0, total annual heating energy consumption is 2,133 kWh/y.

Data was obtained for electricity costs, feed-in tariff, and estimates for inflation, electricity price inflation and the discount rate pertaining to the next 25 years [15,64]. The most up-to-date values at the time of writing were used for grid electricity price (33.4 eurocents/kWh) and feed-in tariff (6.53c/kWh).

All electricity consumption and production data, at quarter-hour intervals, is available in the supplemental material, at http://justsolutions.eu/PV_Info/.

Regarding the household discount rate, estimating this is very much a subjective judgment [56], as it represents the rate of income a household could have received if its money had been invested somewhere other than in rooftop photovoltaics. Zsiborács et al. [78] use the yield rates on government bonds as a basis, as this is the safest possible cash investment. However, this has long been negative [69], and is unlikely to attract a household who may be considering an investment. The net return on real estate is currently around 2.5% (Immobilenscout24, [42]), but unlike real estate, photovoltaic systems generally reduce in value from year to year, so a comparison here is difficult.

The inflation rate is a further consideration in estimating discount rates. The European Central Bank's target inflation rate is 2% and the rate in the third quarter of 2021 was 1.9%, with a five-year expectation of 1.8% [12]. However, inflation reached 4.9% for the year to January 2022 and 5.1% for the year to February 2022 [14,70]. This does not take into account the possible economic effects of the war in Ukraine, though this is unlikely to persist for the entire 25-year lifetime of a photovoltaic system installed in 2022. Since the discount rate is closely related to long-term inflationary expectations, this study uses a discount rate of 5%.

Regarding future increases in the electricity price, the Bavarian Chamber of Commerce's [73] estimated an increase of 50% over the next 9 years, representing an annual cumulative increase of 4.6%. Electricity prices are likely to rise steeply in the near and perhaps mid-range future due to Germany's attempts to move quickly away from Russian oil and gas imports, but this is unlikely to persist for the entire 25-year lifetime of a photovoltaic system installed in 2022. This paper therefore uses an estimate of an average price rise of 5% per year over the next 25 years.

The feed-in tariff for households' photovoltaic electricity fed into the grid has been falling since 2005 and continues to fall by approximately 0.1 c/kWh each month. For systems <10kWp this fell to 6.53 c/kWh in April 2022, while for systems of 10kWp or greater the tariff tends to track a further 0.2 c/kWh lower. Due to recent radical changes in Germany's energy transition the study assumes that the rates for April 2022 will stay stable.

Cost and performance of photovoltaic system

The costs of the components and installation of a rooftop photovoltaic system were obtained from an actual quote received on 08 January 2022 from the firm Rottmann[2] for a system on a detached house in Bavaria. These were compared with examples of costs from the portal Solaranlagen [59], which gives details and overviews of up-to-date pricing of solar installations in Germany. This enabled a reasonably generic set of prices to be estimated for a typical photovoltaic installation on a detached house. These prices, including value-added tax, are 919 €/kWp for monocrystalline photovoltaic panels; 167 €/kWp for their mounting; 200 €/kWp for the DC-AC converter and related components; 8,570 € for a 5 kWh battery and related components (or 1,714 €/kWh), plus fixed costs of 950€ for cabling, fixtures and grid connection. Annual maintenance costs are estimated at 1% of total costs (and see discussion in Zsiborács et al. [78]).

Finally, a factor was derived for annual deterioration of the photovoltaic panels. The quote from Rossmann included a guarantee of deterioration to no worse than 80% of performance in 25 years, representing an annual cumulative deterioration of 0.89%. This figure is used in the analysis.

Calculation strategy

A desktop computer program was written for estimating the energy and economic performance of rooftop photovoltaic systems of a range of capacities from 0.5 kWp to 15 kWp, using battery capacities of 3 kWh, 5 kWh, and no battery, with and without heat pump and rebound effects, and with and without a feed-in subsidy. The core of the program consisted of three loops. The inner loop mapped parameter values each quarter-hour timeslot through a full year, based on the above-mentioned data. For each quarter-hour timeslot, the household consumed its own-produced electricity as first priority. If there was excess production, the priority was to use this to charge the battery. If the battery was full or became full during this timeslot, the excess was fed into the grid. If there was insufficient own-produced electricity for the household's consumption, the first priority was to take this from the battery. If the battery was empty or became empty in this timeslot, the electricity was taken from the grid. All the parameter values were stored in arrays. The state of charge of the battery was carried over into the next timeslot.

This process was repeated for all 35,040 timeslots in the year. At the end of each year, summations were made to calculate, for that year, the cost of electricity taken from the grid, and the monetary gain from electricity fed into the grid and from avoidance of having to pay for electricity due to consumption of own-produced electricity.

This loop was embedded in a further loop representing 30 years of the system's performance, taking into account maintenance costs and the annual deterioration in system performance. The costs and financial gains were adjusted annually according to the discount rate and assumed changes in electricity price.

These two loops were embedded in an outer loop which stepped the entire process through the range of installed capacities of photovoltaic panels. It ran 30 times, covering 0.5 kWp to 15 kWp in steps of 0.5 kWp.

The program was run multiple times for a range of battery sizes, with and without heat pump and rebounds, and for different levels of subsidy for electricity fed-in to the grid. The latter was to find

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[2] https://www.firmenwissen.de/az/firmeneintrag/97440/8310278156/RUDI_ROTTMANN_PHOTOVOLTAIKANLAGEN.html

how much the feed-in tariff would have to be increased, to make larger rooftop photovoltaic systems economically viable.

The coding of the program and a flow chart of the logic are available to readers in the supplemental material.

Rebound effects

Galvin et al. [32] define the rebound effect for photovoltaic households as:

$$\textit{rebound effect} = \frac{\textit{increase in consumption (of electricity)}}{\textit{increase in production of renewable electricity}} \tag{1}$$

This is compatible with definitions of rebound effects in the energy efficiency domain [31], but less useful when considering different sized photovoltaic systems for the same household.

A more useful rebound parameter for this type of analysis is the increase in household electricity consumption compared to electricity consumption prior to installing photovoltaics. This enables cost-benefits to be compared for the same household over a range of different sized photovoltaic systems but the same absolute increase in consumption due to rebound. Hence the rebound effect R is defined here as:

$$R = \frac{\textit{increase in electricty consumption after installing PV}}{\textit{electricty consumption prior to installing PV}} \tag{2}$$

This figure is included in modelling the household's daily consumption. The study uses an estimate of 0.2 for the rebound effect, thereby assuming that baseline consumption (apart from that for the heat pump) increases by 20% after installing the photovoltaic system. This is compatible with electricity price elasticity estimates for Germany (see discussion in Section 2).

Payback times

Income arises from two sources: self-consumption, where the household saves the grid price per kWh; and from feed-in to the grid. This income is reduced each year by annual maintenance costs. Income is reduced by the discount rate factor and increased by the annual electricity price factor, both raised to the power of the year being considered (y, where y = 1 in the first year).

The accumulated financial benefit B_Y after Y years of operation is given by the sum of the geometric sequence of annual financial benefits:

$$B_Y = \frac{(S_y \cdot Q + (P_y - S_y) \cdot F - M) \cdot (1 - (\frac{W}{D})^y)}{(1 - \frac{W}{D})} \tag{3}$$

where the variables S, Q, etc. are those in Table 1.

The above equation can be inverted to give the number of years Y after which the system pays back, i.e., when $B_Y = U$:

$$Y = \frac{ln\left(1 - \frac{U(1-(\frac{W}{D})}{S \cdot Q+(P-S) \cdot F-M)}\right)}{ln(\frac{W}{D})} \tag{4}$$

Note that equation (3) shows that the higher a household's self-consumption, the higher the financial benefit of having photovoltaics, provided the price of electricity from the grid is substantially higher than the feed-in price. Self-consumption is increased by having a heat pump and a rebound effect, hence these increase the beneficial effect of having photovoltaics. Equation (4) was embedded in the computer program.

Results

Consumption patterns

To illustrate the complexities involved in automatically optimising the use of a household system, Figure 4 displays the patterns of electricity consumption and production for a specific day, here 20 May, in the first year of a 5 kWp system's operation using a 5 kWh battery. Electricity production follows a roughly co-sinusoidal curve, peaking at midday but with dips due to intermittent cloud cover. Consumption is high in the morning waking hours, and erratic but mostly high during the day, with a dip in the afternoon and the highest peak in the early evening. Consumption from the grid is steady from midnight until about 06:00, falls to zero as the sun rises, then rises rapidly in the evening as the battery runs down to empty. The household uses its own electricity

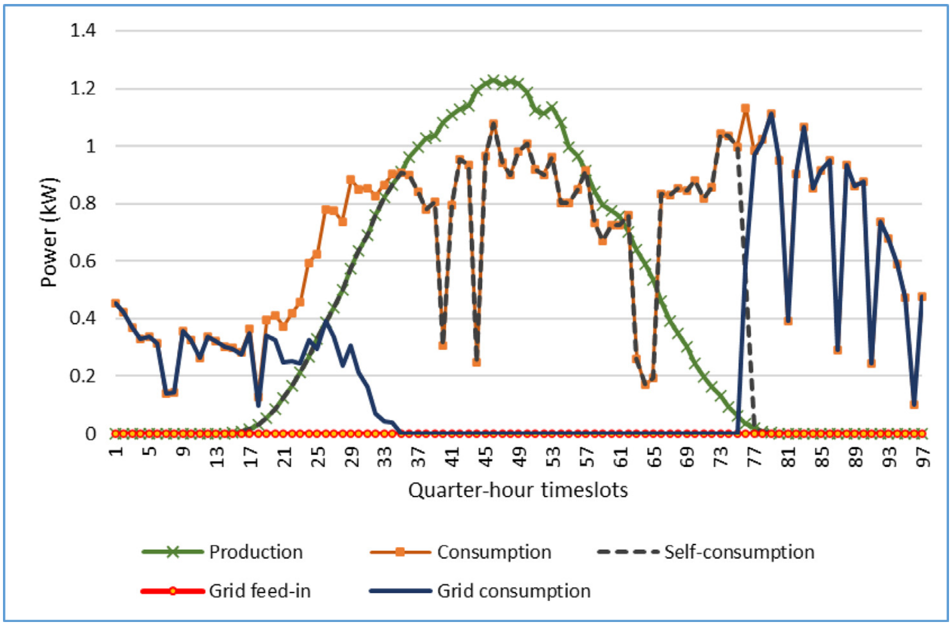

Fig. 4. Patterns of household electricity production, consumption, self-consumption, grid feed-in and grid consumption modelled fo r20 May in first year of a 5 kWp system operation, with 5kWh battery.

(self-consumption directly and from the battery) from about 09:15 until 19:15. No electricity is fed into the grid. This is a near-optimal situation since self-consumption saves the grid electricity price of over 33 c/kWh while feed-in would earn only 6.53 c/kWh.

Note, however, that 20 May was not typical of that time of year. Figure 5 shows the battery charge patterns for 15-30 May, for the same 5 kWp system but with a 3 kWh and a 5 kWh battery. The solar irradiation on 20 May (around timeslot 13,469-13521) was exceptionally poor compared to most days in that 16-day period. On most days, the batteries charged to their full capacities, but the charge for the larger battery lasted 2.5 hours longer in the evening than that for the smaller battery. This strengthens the case for a larger battery, though the cost per kWh of battery storage, at 1,714 €/kWh adds a caution to this.

Figure 6 provides an overview of the dimensions of the differences in self-consumption and grid consumption for a 5 kWp system with a 3 kWh and 5 kWh battery. Both have high grid consumption and low self-consumption in the winter months, but in the shoulder seasons and summer months, grid consumption is significantly lower while self-consumption is higher. The question of whether to use a smaller or larger battery is further investigated in the cost-benefit analysis below.

Payback times and financial returns

Figure 7 gives the payback times for systems of 0.5-15 kWp capacity with no battery, a 3 kWh battery and a 5 kWh battery. The system with the 5 kWh battery has the longest payback times for all photovoltaic capacities. The shortest for this is 14.9 years, with a capacity of 8.5 kWp, but a smaller, 7.5 kWp system gives an almost identical payback time of 15.1 years. For systems larger than 8.5 kWp the payback times increase.

The shortest payback time for the system with 3 kWh battery is 12.9 years, with a 7 kWp system, but a 6kWp system gives a similar payback time, of 13.1 years. For systems larger than 7 kWp the payback time increases.

The system with no battery has the shortest payback time, of 7.6 years, for a 1.5 kWp system. The payback time increases almost linearly after that to match those of the systems with batteries for large photovoltaic capacities.

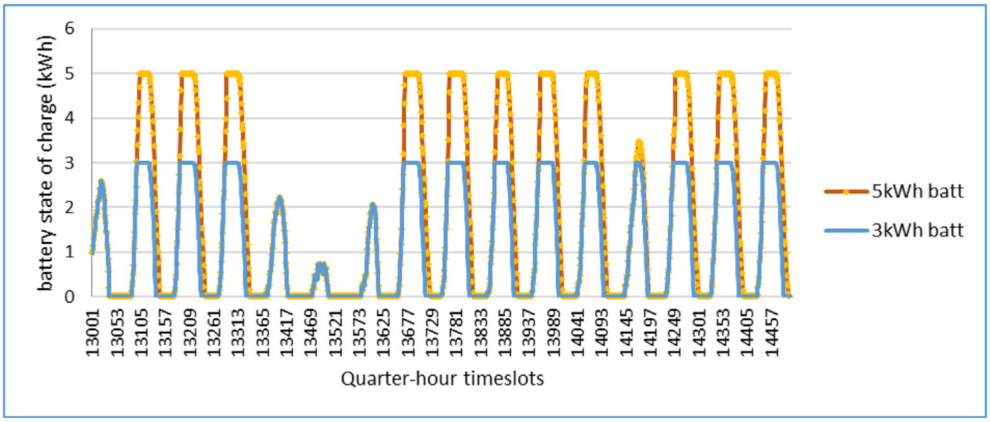

Fig. 5. Charging profile of 3 kWh and 5 kWh battery in 5 kWp system, 15-30 May, first year of operation.

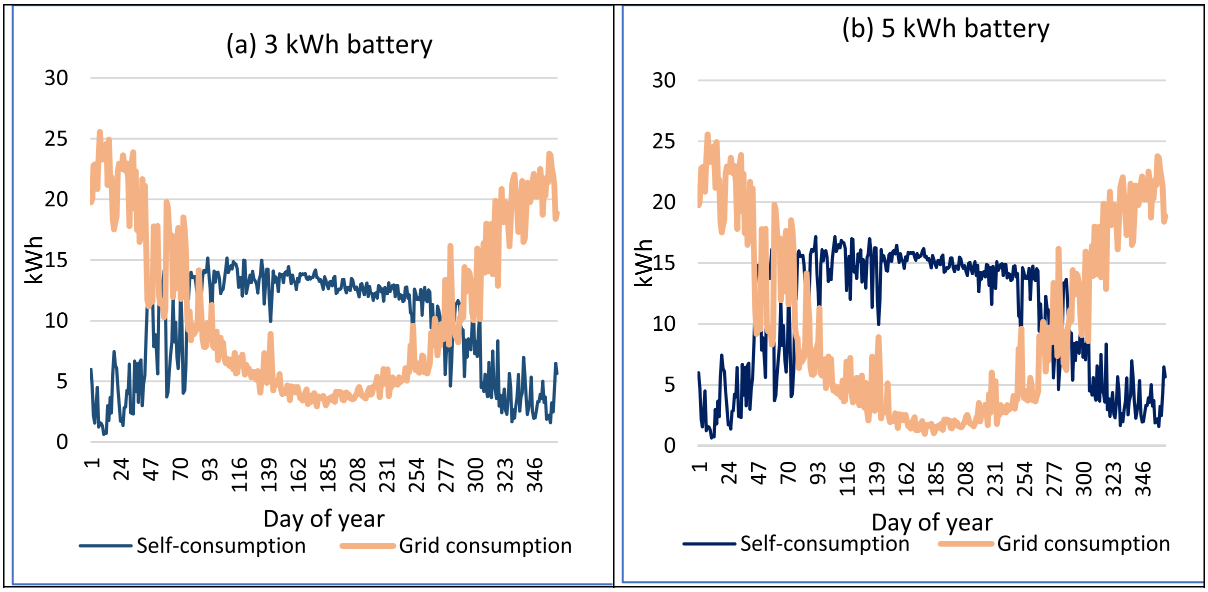

Fig. 6. Self-consumption and grid consumption by day for 5 kWp system with (a) 3 kWh battery and (b) 5 kWh battery, in first year of operation.

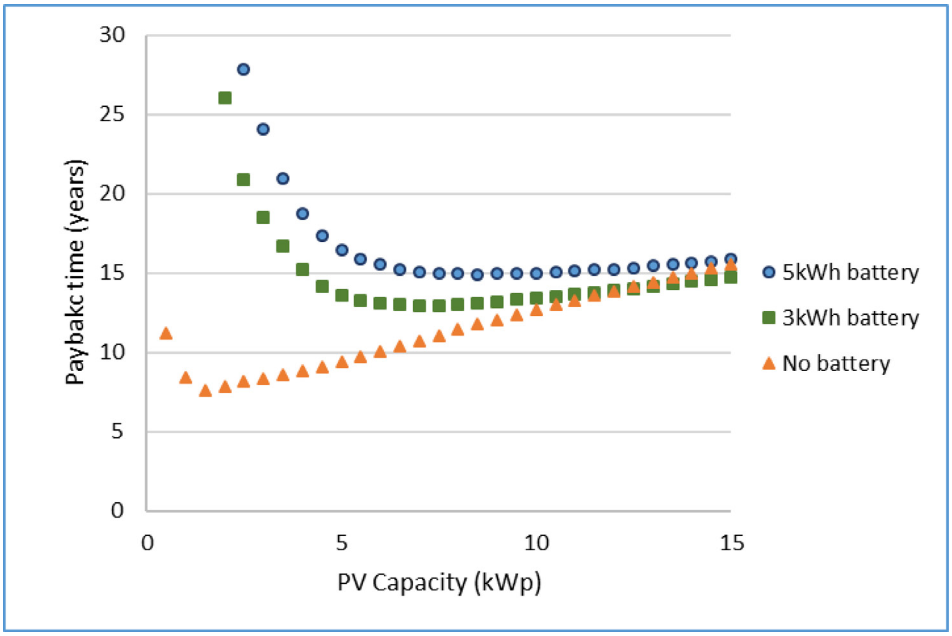

Fig. 7. Payback time for range of capacities (kWp) for rooftop photovoltaic system with various battery capacities, and no battery.

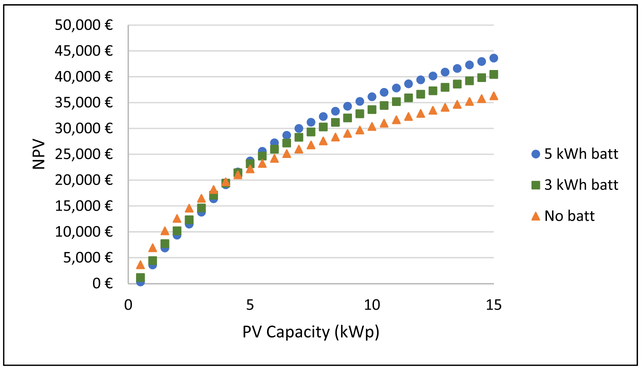

Fig. 8. Net present value of return after 25 years, for range of PV capacities, various battery sizes and no battery.

On the basis of payback times alone, then, it would be hard to make a case for covering a roof with photovoltaic panels, since payback times increase as capacity increases. However, Figure 8 gives the net present value of the financial return after 25 years of operation for the three cases, for photovoltaic capacities up to 15 kWp. In all three cases, the financial return increases relatively steeply up to 5 kWp capacity and then less steeply but persistently, at the rate of about 1,600€ per extra kWp. This might appear to be a good marginal return, since each extra kWp costs in the region of 1,300€.

Nevertheless, Figure 9 indicates that profit margins per euro invested are falling for installations above about 8 kWp. Figure 9 gives the ratio between net present value of return after 25 years, and upfront costs. For a system with a 3 kWh battery the ratio peaks at 1.88 for 6 kWp, for a 5 kWh battery it peaks at 1.83 for 8 kWp, and for no battery it peaks at 3.14 for 2 kWp. For larger systems it falls steadily as photovoltaic capacity increases.

It is difficult, then to make a case for maximising the number of photovoltaic panels to fit the roof area. Profitability simply reduces with each extra kWp of installed capacity, above an optimum level.

The effect of a feed-in subsidy

The underlying problem with large capacity household rooftop photovoltaic systems is due to the high ratio between the grid electricity price and the feed-in tariff [32]. The marginal cost of each extra kWp of capacity is 1,607€, including 919€ for the photovoltaic panel, 200€ for the marginal DC-AC inverter costs, 167€ for the panel mounting and 1% of the total of this per year for maintenance. Each extra kWp gives an average yield of 900 kWh/y over 25 years (taking deterioration into account), giving a marginal cost of 7.14 c/kWh generated. However, the marginal gain for each kWh fed into the grid is lower, at 6.53 c/kWh. This means that, beyond the level required for household consumption, each extra kWp brings a negative return of 0.61 c/kWh fed into the grid. Meanwhile, optimising the system size to maximise the amount of self-produced electricity consumed by the household takes full advantage of the high price of grid electricity. Each kWh of avoided grid electricity represents a saving of 27c, i.e., the grid price less the feed-in tariff.

A possible solution would be to subsidise the feed-in tariff for household photovoltaics. A series of model runs indicated that a subsidy of 10 c/kWh would be sufficient to reverse the downward trend in the marginal return per extra kWp. Figure 10 shows payback times for systems with a 3 kWh battery, with and without the subsidy, and Figure 11 shows this for a 5 kWh battery. In both cases the payback time reduces for each extra kWp added. For the 3 kWh battery system, payback time reduces to just above 10 years for the largest system (15 kWp), and for the 5 kWh battery system it reduces to just under 12 years for the largest system.

Further, the net present value of the financial return after 25 years increases, for the 3kWh battery, from 40,458€ to 51,323€ for a 15 kWp system. For the 5 kWh battery the increase is from 43,621€ to 53,718€. Also, for the 5 kWh battery the ratio between net present value of return after 25 years and upfront costs does not fall for larger system capacities but rises very slightly. For the 3 kWh battery it rises for medium-sized system, then falls slightly for systems >13.5 kWp. All other things being equal, then, a subsidy of 10 c/kWh would solve the problem of non-profitability of large rooftop photovoltaic systems. It would lead to further problems, however, as explained in Section 5.

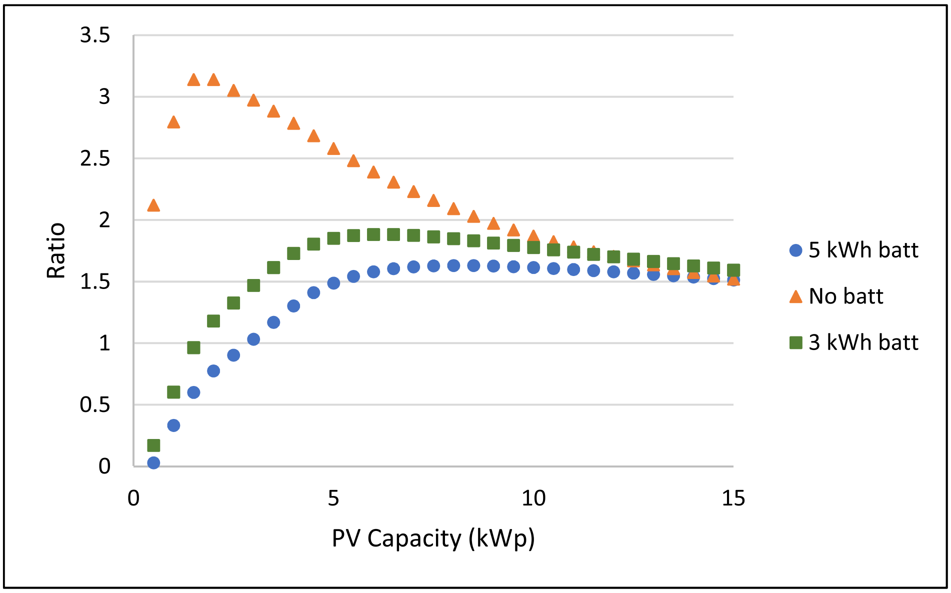

Fig. 9. Ratio of net present value of return after 25 years and upfront costs, for range of PV capacities, various battery sizes and no battery.

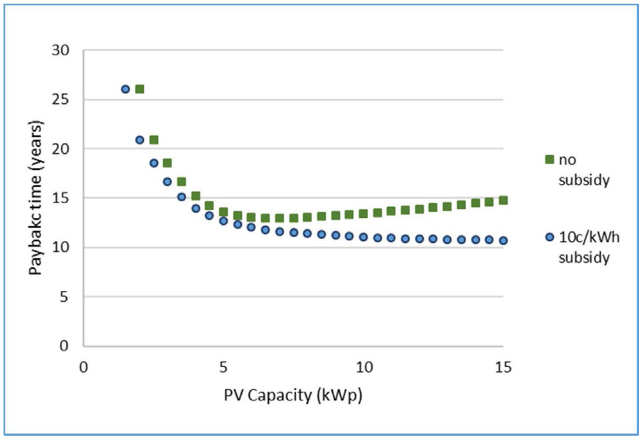

Fig. 10. Payback time with and without 10c/kWh feed-in subsidy for range of capacities (kWp) for rooftop photovoltaic systems with 3 kWh battery.

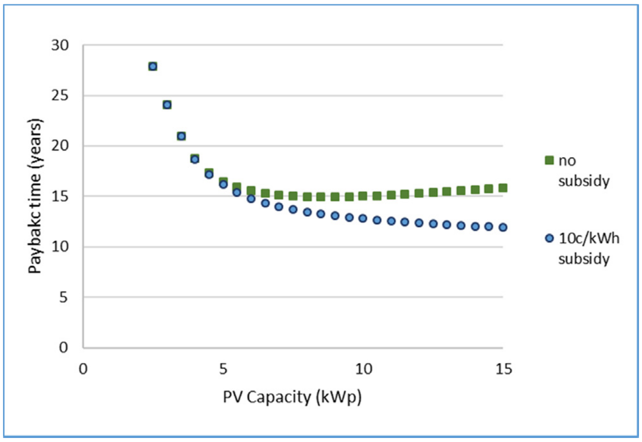

Fig. 11. Payback time with and without 10c/kWh feed-in subsidy for range of capacities (kWp) for rooftop photovoltaic systems with 5 kWh battery.

Consumption, self-consumption and grid load

One of the difficulties of ramping up photovoltaic production in residential areas is the increased load on the grid due to increasing feed-in (see Sections 1 and 2). On the other hand, an advantage of household photovoltaics is reducing the load on the grid through self-consumption of own-produced electricity. Figures 12 and 13 illustrate the effect on these parameters of increasing photovoltaic capacity, with a 3 kWh and 5 kWh battery respectively. Both cases show how the magnitudes of self-consumption, feed-in and grid consumption vary according to system capacity in the 12th year of operation - the half-way point in the system's technical lifetime, which gives about the average magnitudes for each parameter.

For the system with a 3 kWh battery, Figure 12 shows that, as system size increases, grid consumption reduces fairly steeply for small systems, then more gradually for larger systems from about 6.5 kWp upwards, and never gets below 3,225 kWh for the year. Meanwhile, feed-in is zero for low-capacity systems, then increases steeply for systems >4.5 kWp, to reach 7,573 kWh for 15 kWp. This means that the highest capacity systems not only fail to relieve the grid of more than about half the load of grid-to-household electricity, but concurrently add a load of household-to-grid electricity, in this case about equal to total household consumption. Looking more closely at the figure, the optimum system size for a local grid seems to be around 5.5-6.5 kWp, which generates an amount equal to about 50% of household electricity consumption. Here, grid consumption is markedly reduced but feed-in has not ramped up substantially.

A similar pattern is seen for the 5 kWh battery system, except that feed-in is slightly lower and the optimum size for reduced grid consumption and not-too-high feed-in is slightly higher, at around 6.0-7.0 kWp. As these displays indicate, even if households were to accept the economic disadvantages of covering their roofs with photovoltaics, in districts with limited grid capacity it might be sensible to discourage them from installing large systems.

A further important observation from Figures 12 and 13 is that there is a limit to how much of household electricity consumption can be covered by rooftop photovoltaics. For the system with a 3 kWh battery this is under 4,500 kWh, even with a 15 kWp capacity that generates some 13,474 kWh/y (in year 12). For the case of a 5

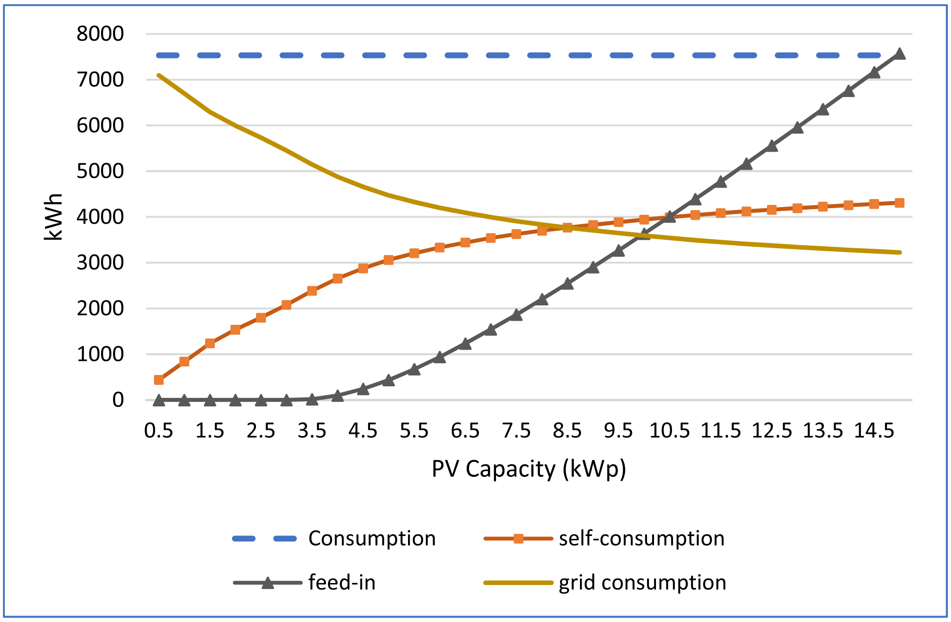

Fig. 12. Consumption, self-consumption, feed-in and grid consumption, for PV system capacities 0.5-15 kWp with 3 kWh battery, in 12th year of operation.

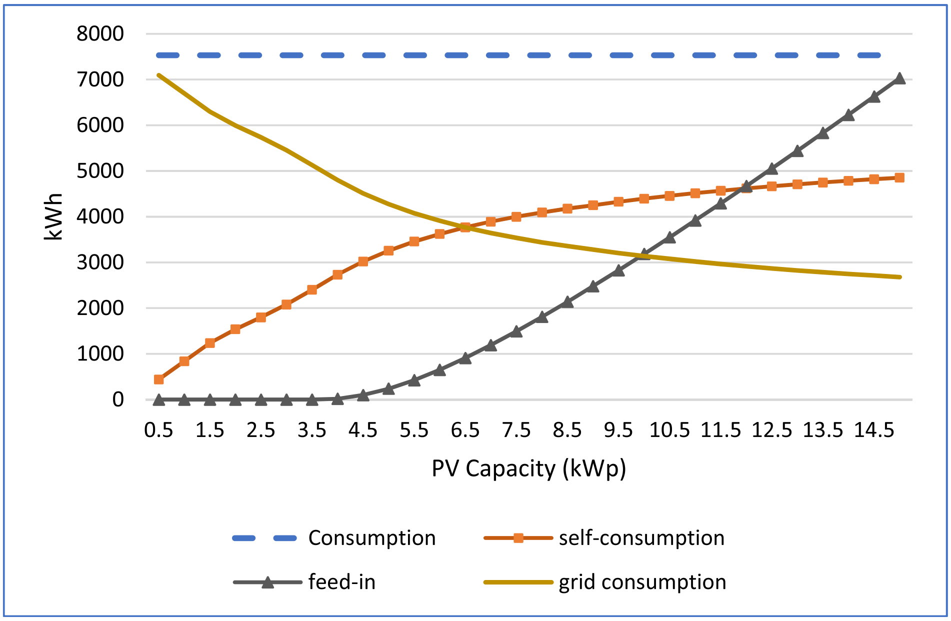

Fig. 13. Consumption, self-consumption, feed-in and grid consumption, for PV system capacities 0.5-15 kWp with 5 kWh battery, in 12th year of operation.

kWh battery the limit is under 5,000 kWh. The reason for this is seen in Figure 6, above. Grid consumption is inevitably high in the winter months regardless of photovoltaic system size, because of low solar radiation in winter.

This resonates with the finding of Lawaczeck et al. [43] that the level of self-consumption (which they call the "degree of autarky" - Autarkigrad) rises steeply as capacity increases initially, then begins to taper off at about 50% for capacities of 4 kWp and thereafter rises only very gradually, reaching only 67% for a 15 kWp system with 5 kWh battery. Further technical (non-peer-reviewed) articles and reports in a similar vein may be found at Solarspeichersysteme [60].

Sensitivity analysis

The analysis was extended to see how sensitive the results are to a change of base year patterns of solar radiation, the presence or absence of a heat pump, and the presence or absence of rebound effects.

Solar radiation

Quarter-hourly data for 2020 was derived from Fraunhofer [21]. As with 2019, this was adjusted to take account of the increase in installed capacity during the year, then normalised for a system producing 1,000kWh per kWp of installed capacity, and finally re-normalised within the computer program for the different capacities of photovoltaic systems. This puts the focus entirely on the fluctuations in electricity production: would the differences in these fluctuations make a significant difference to payback time and profitability?

The intricate, quarter-hour by quarter-hour differences between the two years' profiles are extremely difficult to display for an entire year. However, Figure 14, gives the profiles on a day-by day basis, while Figure 15 gives a 32-day section on a quarter-hourly basis. These show that there is considerable instantaneous volatility between the two profiles as well as some notable medium-term differences, though they have the same general shape over the year.

However, running the computer simulation using the 2020 profile indicates that the difference in results is trivial. This is illustrated in Figure 16, which gives payback times for systems 0.5-15 kWp with a 5 kWh battery, for the 2019 profile and the 2020 profile. The same closeness of results was found for the case of a 3 kWh battery, and also for comparisons of financial return (see Table 2).

It seems, then, that differences in instantaneous and medium-term profiles of solar radiation in at least these two different years do not affect the results significantly. Results will differ, however, if the total radiation for one year is different from that of another, but unless there are long-term changes in cloud cover this is unlikely to affect summations of financial benefits over a 25-year period.

Sensitivity to heat pumps

A factor that could affect payback times and economic viability is whether a household has a heat pump. On the one hand, this takes advantage of free electricity from the photovoltaic panels. On the other hand, heat pumps operate more in winter, when photovoltaics are least productive, than in summer, when they often produce more than is needed. Figure 17 displays this, giving the consumption profile of the heat pump. Consumption peaks are almost twice as high in winter as in summer, at around 0.15 kW

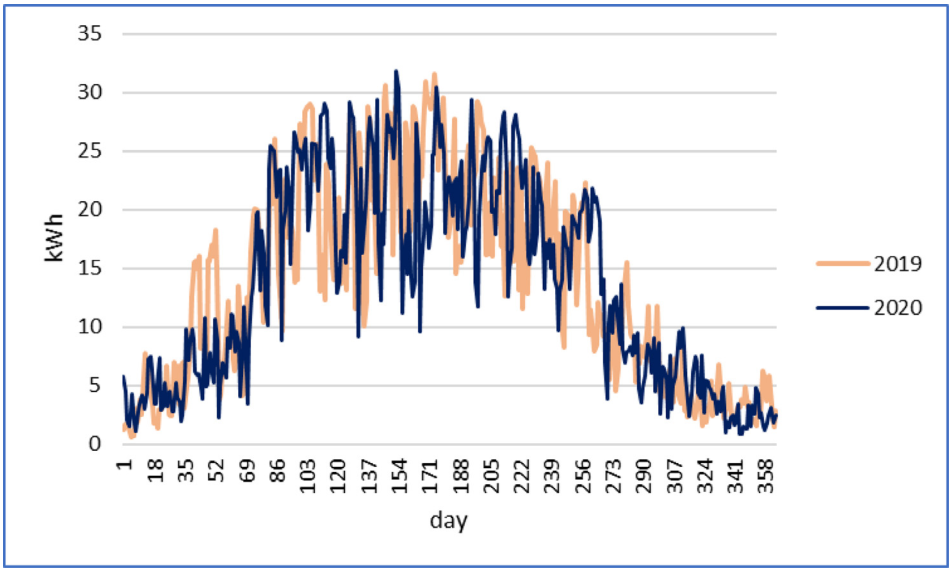

Fig. 14. Daily electricity production in 2019 and 2020 of standardized rooftop photovoltaic system of 5kWp and yield 1000kWh/kWp.

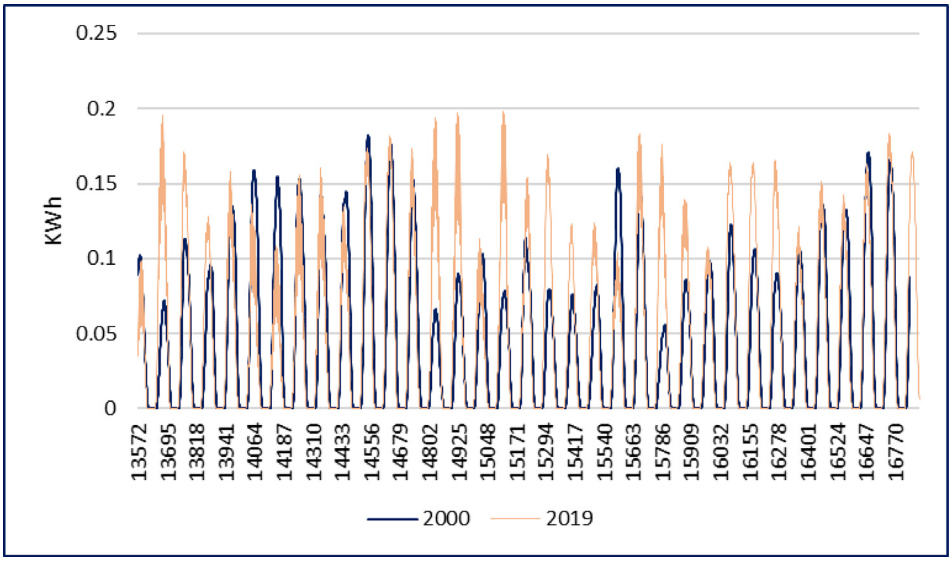

Fig. 15. Photovoltaic production profiles for 21/05-24/6 of 2019 and 2020, adjusted for growth during year and normalised to 1,000 kWh/y.

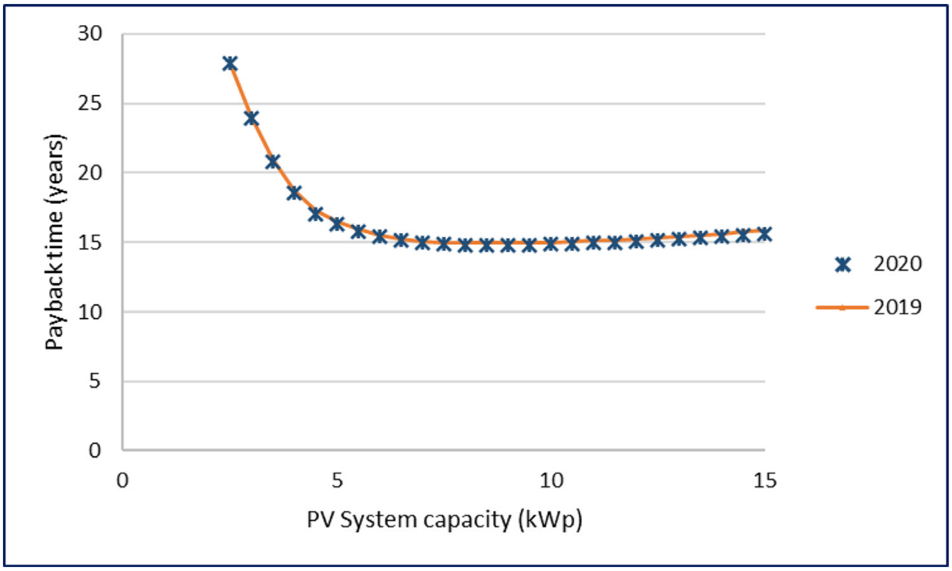

Fig. 16. Comparison of payback times for range of capacities 05-15kWp systems with 5kWh battery for 2019 and 2020 solar radiation profiles.

Table 2
Key results, ordered for easy comparison. "Payback ratio" is the net present value of financial returns after 25 years, divided by the upfront costs (not including annual maintenance costs)

Type of system					Shortest Payback		Best Payback ratio after 25 years	
Solar Profile	Battery	Heat pump	Subsidy	Rebound	Capacity (kWp)	Years	Capacity (kWp)	Ratio
2019	**None**	Yes	No	Yes	1.5	7.6	2.0	3.14
2019	**None**	No	No	Yes	2.5	9.1	2.0	2.81
2019	**3kWh**	Yes	No	Yes	7.0	12.9	6.0	1.88
2019	**3kWh**	Yes	**Yes**	Yes	15.0	10.7	10.0	2.05
2019	**5kWh**	Yes	No	Yes	8.5	14.9	8.0	1.63
2020	**5kWh**	Yes	No	Yes	8.5	14.8	8.5	1.64
2019	**5kWh**	Yes	No	**No**	8.5	15.7	10.0	1.54
2019	**5kWh**	No	No	Yes	8.0	16.9	7.5	1.44
2019	**5kWh**	No	**Yes**	**Yes**	15.0	11.9	15.0	1.86

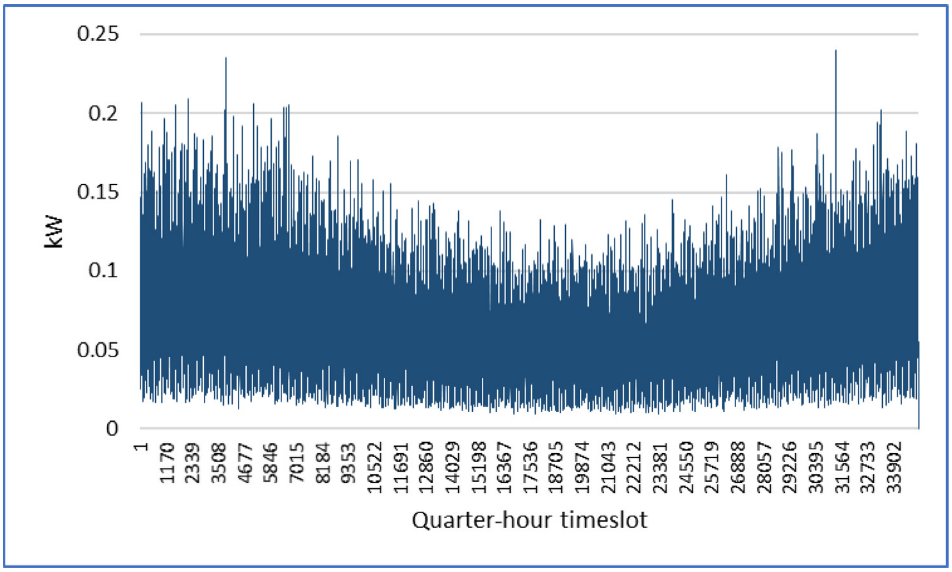

Fig. 17. One-year consumption profile of heat pump.

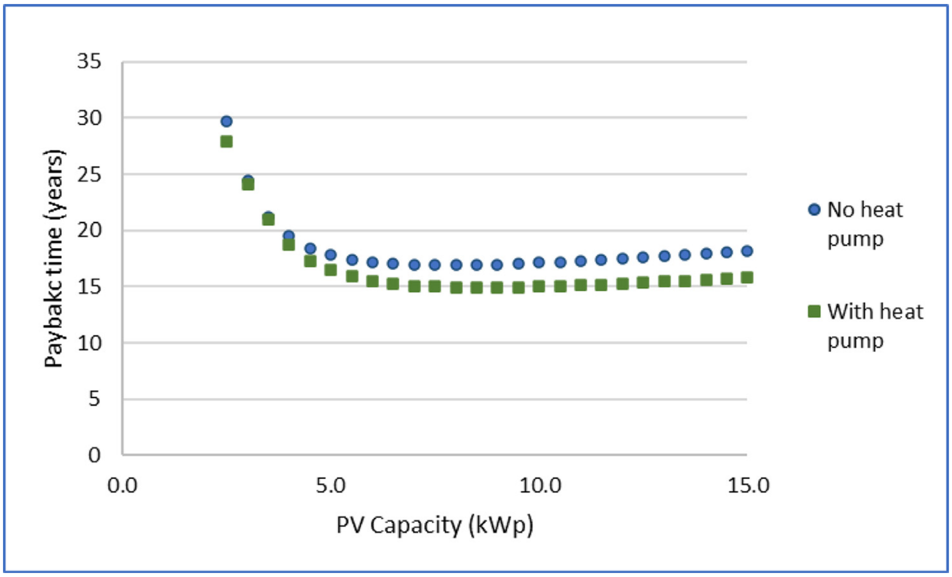

Fig. 18. Payback time for range of capacities (kWp) for rooftop photovoltaic systems with 5 kWh battery, with and without heat pump.

in winter compared to 0.08 kW in summer. The difference would be greater if the heat pump was used only for space heating and not for water heating, which is relatively steady all year.

Figure 18 compares payback times for a system with a 5 kWh battery, with and without a heat pump. Payback times are longer for the household without a heat pump, for example 17 years without a heat pump to 15 years with a heat pump, for a system of 8 kWp. The difference increases for high-capacity systems. The conclusion is that making use of photovoltaics for a heat pump reduces payback time and increases the photovoltaic capacity for which payback is optimum (see Table 2).

Sensitivity to rebound effects

A system with 5 kWh battery and a heat pump was simulated for the case of zero rebound effect. As shown in Table 2, the shortest time to payback was almost a year longer than its counterpart with rebound, at 15.7 years compared to 14.9 years, both for systems of 8.5 kWp. Also, its best financial return ratio after 25 years was lower, at 1.54 compared to 1.63, and it took a capacity of 10 kWp to achieve this compared to 8 kWp with a rebound effect. In this case, then, a rebound effect (i.e., a higher level of welfare-enhancing consumption) increases the profitability of the system and demands a lower capacity system for the best payback, but does not affect the capacity required for the shortest time to payback. In short, welfare-enhancing rebound effects improve system profitability and provide this improvement with slightly lower system capacities.

Discussion

Incentivising large rooftop photovoltaic systems

The feed-in tariffs of 2000-2010 were designed to achieve a 10-year payback, as an incentive to develop photovoltaics as a viable renewable energy source [34], though they laid a heavy burden on poor households by being funded via increased electricity prices [24].

However, there might now be a case for funding feed-in again, though at a substantially lower rate and certainly not by increasing electricity prices. The analysis suggests that a feed-in subsidy of 10 c/kWh would make the marginal return on each extra kWp larger than the marginal cost of installing each extra kWp. If we assume each kWh fed into the grid replaces 1 kWh of coal-fired electricity generation, a subsidy of 10 cents/kWh amounts to a cost of €54 per tonne of avoided CO_2 emissions. This is well within the range set by the German government for the emissions trading system for the coming years, as a Federal government statement declares:

> “The initial CO_2 price per tonne will be €25 as of January 2021. After that, the price will gradually rise to €55 in 2025. A price corridor of at least €55 and a maximum of €65 will apply for 2026.” [10].

There are, however, two main difficulties with this. First, a 10 c/kWh subsidy over 25 years amounts to a total of 2,250 €/kWp of extra installed capacity (assuming an average yield of 900 kWh/kWp due to system deterioration). This might not be the most economically efficient way to subsidise renewable energy, as it effectively trebles the cost per kWp.

Second, as noted above, many local electricity grids would not cope with the large quantities of feed-in from households which would ensue from large photovoltaic capacities, illustrated in Figures 12 and 13. It would be more technically effective to invest in large field-based photovoltaic arrays connected directly to medium voltage sections of the grid. Here, grid overloading is not such a problem, and the investment can be optimised for pure feed-in.

The issue of Germany’s large unused roof area therefore needs to be seen in a different light. The problem is not that roofs are getting too few photovoltaic panels, but that not enough roofs are getting photovoltaics. Referring again to Figures 12 and 13, the advantages for both the household and the grid are in synch for systems of about 5-8 kWp, which produce about the same amount as the household’s total annual consumption. Self-consumption cannot be increased substantially or linearly just by adding more modules, because winter consumption is out of phase with summer production. The policy aim should then be to increase the number of homes that have photovoltaics of sufficient capacity and design to enable a household to get at least half its electricity needs from its photovoltaic panels.

Heat pumps and rebound effects

The analysis showed that despite the electricity demand of heat pumps being seasonally out of phase with photovoltaic electricity production, having a heat pump puts downward pressure on the number of years to payback and upward pressure on the ratio of financial returns to initial investment. Further, heat pumps are highly likely to become more prevalent due to the shift away from fossil fuels (see Sections 1 and 2). The move toward heat pumps can therefore be used to increase the adoption of rooftop photovoltaics – but not necessarily to promote systems of excessive capacity.

Rebound effects reduce the time to payback and reduce the system capacity required for shortest payback time. They also increase the ratio of financial return to initial investment, while also increasing the photovoltaic capacity for optimal return. This is of course only if these rebounds are seen as welfare enhancing. This may be controversial, since rebounds are almost universally seen as negative. However, as Galvin et al. [31] point out, the sociotechnical factors in generating one's own electricity are very different from those in using a more energy-efficient appliance, so direct comparisons drawn from classical rebound literature are risky. Further, the promise of cost-free rebounds is often implied in photovoltaic providers' promotional literature, as Kratschmann and Dütschke [40] found.

The idea of being able to consume more electricity-powered energy services in the home can therefore be used as a lever to increase the number of photovoltaic panels on roofs, though these increases would only be marginal. Increases in capacity inevitably lead to more feed-in to the grid, because photovoltaic yield, even with batteries, is never fully in line with household consumption.

Limitations of the study

A limitation of the study is the volatility of financial and energy markets at the time of writing. The study has used conservative estimates for the discount rate and the long-term increase in electricity prices, and this might be proven wrong in the coming years.

Another limitation is that one particular, generalised profile of household electricity consumption was used, which might be substantially out of step with the profile of any particular household that is considering adopting rooftop photovoltaics. Further, this might vary from year to year as children become teenagers or leave home or if lifestyle changes, such as working from home rather than going out to work. A household that expects to spend a lot of time at home during the day could install a higher capacity system with lower capacity battery storage, and add more batteries if the their lifestyle changes to less time at home during the day and more at-home activity in the evening.

Another limitation is that only two years' data on quarter-hourly readings of Germany's photovoltaic production were available at the time of writing. For years prior to 2019, data was only available at one-hour intervals. More important, the same yearly total electricity production was assumed for each of the 25 years. For future studies an option might be to use recorded data of specific households' annual production over 10-20 years to set a pattern of annual production, and normalise the 2019 and 2020 quarter-hourly patterns according to these year-by-year totals.

Nevertheless, all cost-benefit analyses have to be made under conditions of uncertainty, as is also generally assumed with cost-benefit calculations of energy efficiency building retrofits [33].

Another limitation is that the study does not include a factor for reduction in photovoltaic electricity production due to roof inclination and orientation. The roof of the house for which the quote was obtained was almost ideal, with a 55% inclination and south-southwest orientation. Generally, orientation affects the timing and magnitude of electricity production, while inclination affects seasonal yield (a steep roof slope performs better in winter and poorer in summer). The computer simulation program could be easily modified to take these factors into account in future studies.

Finally, many of the points identified in this paper resonate with findings in recent technical, non-peer-reviewed articles on photovoltaic systems in Germany, collected by the website Solarspeichersysteme [60]. Readers are referred to this for pursuing specific points of interest.

Conclusions

This study addressed the issue that, under the current electricity pricing regime, German households tend to be reluctant to install rooftop photovoltaic systems that generate substantially more electricity than they themselves can use. This tends to cluster new installations around the 5-6kWp range, generating around 5,000-6,000 kWh/y, often covering less than the available roof space.

Using actual quarter-hourly data for Germany's photovoltaic electricity production, typical household electricity consumption and heat pump consumption, the study explored the effects of a range of factors on the optimum system size for shortest payback and highest long-term return. It found that, with a battery of 3 kWh or 5 kWh, a 4-person household in a typical detached house, with a heat pump and a modest, welfare-enhancing rebound effect, the optimum system for shortest payback time and highest rate of return was in the range 5-8 kWp. Without a heat pump or welfare-enhancing rebound effect, there was even less value in installing a larger system. A feed-in subsidy of 10 c/kWh would increase the marginal return per installed kWp, such that the larger the system, the shorter the payback time and the greater the rate of return. However, this would be equivalent to an up-front subsidy of about 2,200€ per kWp installed, effectively trebling the cost, where far better returns are available for this level of investment in other renewable electricity domains. It would also lead to upward pressure on local grids and shift the patterns of self-consumption and feed-in well outside the optimum zone.

Policymakers and the photovoltaic installation industry should refrain from narratives that encourage households to cover their roofs with photovoltaics, and instead promote the installation of optimum-sized systems on the roofs of more houses. Such a system produces an amount of electricity, about equal to the amount the household consumes, knowing that at the optimum about half of this will be consumed by the household and the other half fed into the grid. Policymakers should also strengthen the promotion of heat pumps as a complement to photovoltaic systems, promoting both together as a package. They should also develop positive narratives regarding welfare-enhancing rebound effects, along the lines that households who install sufficient photovoltaic capacity may be able to consume electricity a little more liberally.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declaration

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