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Net-zero-energy buildings or zero-carbon energy systems? How best to decarbonize Germany's thermally inefficient 1950s-1970s-era apartments

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ABSTRACT

A popular idea for reducing CO2 emissions from existing buildings is to renovate them to "net-zero-energy" standard. In Europe this usually involves increasing the energy-efficiency of the building envelope, replacing fossil fuel boilers with heat pumps, and installing photovoltaics to generate as much energy as the building uses over the course of a year. However, net-zero-energy consumption does not necessarily imply zero carbon emissions, since the carbon intensity of grid-based electricity is substantially higher in winter, when net-zero-energy buildings are consuming electricity from the grid, than in summer, when their on-site photovoltaic systems are feeding electricity into the grid. An alternative, emerging concept is that of "zero carbon energy systems" where a building is seen as part of a wider energy system, in this case the electricity grid, which aims to be carbon-neutral overall. This paper applies this concept to a typical case-study apartment from Germany's highly energy-inefficient 1950s-1970s-era apartment buildings. Using fine-grained data on national electricity generation and household-level consumption, it investigates costs and residual carbon impacts of a range of photovoltaic system sizes that would make the apartment "net-zero-energy" if the building envelope has been retrofitted to a high standard and an air-source heat pump installed. The study finds that (a) achieving net-zero-energy requires a 40% larger photovoltaic system than is technically optimal for the household; (b) achieving net-zero-energy fails to achieve net-zero-carbon by some 0.252 tCO2/y; (c) achieving net-zero-carbon would require a 60% larger than optimal photovoltaic system; and (d) it would be more economical to invest in remote wind power than in excess photovoltaic capacity. This strategy would accelerate decarbonization at the level of the energy system, i.e., the national electricity grid.

1. Introduction

This paper critically examines the rationale behind initiatives to retrofit thermally energy-inefficient dwellings in EU countries to "net-zero-energy" standard. In particular, it focuses on the need in Germany to substantially reduce CO2 emissions from the large cohort of extremely energy-inefficient 1950s-1970s-era apartments, which were built hurriedly after the Second World War to replace bomb damage and house a rapidly increasing population.

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In Germany residential buildings caused the emission of 206.9 MT of CO2e in 2018, the latest year for which accurate data is available, or 24.2% of Germany's total for that year [1]. This was largely because of the poor thermal quality of this cohort of buildings, with average annual heating energy use around 145 kWh/(m^2y). 62.8% of residential buildings' CO2 emissions were for space heating and a further 12.8% for domestic water heating [2].

The EU's Climate Target Plan "highlights the need to phase out fossil fuels in heating by 2040, when the direct emissions of the buildings sector will have to decrease by about 80%–89%." [3]. In parallel with this, the German government aims to reduce overall CO2e emissions to half their 2018 level by 2030 [1] and make buildings "nearly CO2-neutral" by 2050 [4].

As a major response to the need to reduce building-related carbon emissions, a number of "net-zero-energy" models for building renovation have emerged in the past decade (reviews in Refs. [5–8]). For Germany's 1950s-1970s-era apartments this requires three main refurbishment measures: retrofitting building envelopes to a high standard of energy-efficiency; using electrically driven heat pumps to replace fossil fuels for heating; and installing photovoltaics to provide part of the household's electricity demands and feed at least as much electrical energy into the grid as the apartment consumes from the grid annually.

"Net-zero-energy" usually means that over the course of a year, the amount of energy a system demands from outside its bounds is equal to the amount it feeds into the common energy pool, though there are nuances in different scholars' definitions (see reviews in Refs. [7,9]). In the case of a dwelling using only electricity, the simplest definition is that over the course of a year a household feeds the same amount of electricity into the grid as it takes from the grid [10–12]. In the words of Voss et al. [13], by the early 2010s the expression "Net Zero-Energy Building" had "become a popular catchphrase to describe the synergy between energy-efficient building and renewable energy utilisation to achieve a balanced energy budget over an annual cycle."

However, net-zero-energy does not necessarily imply net-zero carbon emissions. Climate change is driven by greenhouse gas emissions, not energy consumption directly. The CO2 emissions associated with grid-based electricity vary over time depending on the carbon content of the fuels used to generate the electricity at that moment. Thousands of net-zero-energy apartments would feed excess electricity from their rooftop photovoltaics into the grid in summer, when it is little needed, and demand large amounts from the grid in winter, when renewable electricity can be scarce. The CO2 emission content of electricity varies both seasonally and from moment to moment. EUPD Energy Research found a range from 664 g of CO2 per kWh (gCO2/kWh) of grid electricity consumed in mid-winter, down to 87 gCO2/kWh for electricity consumed in the sunniest hour of summer, a ratio of 7.6:1 [14]. Further, because feed-in to the grid tends to occur on the sunniest days and when there is the least household demand, the ratio in respect of photovoltaics is much higher. A net-zero-energy building therefore does not produce net-zero carbon emissions in the German context.

A further issue is the effects of net-zero-energy standard on the economic welfare of occupants, who may be tenants or owner-occupiers. German 1950s-1970s-era apartments are notoriously thermally inefficient. A large proportion are in energy class F–H [15], requiring 175–250 kWh of space heating energy per square metre of floor area per year (kWh/(m^2y)) to be comfortably warm [16]. Retrofitting these apartments to a high standard is expensive, so Germany's Energy Building Law (*Gebäudeenergiegesetz* – GEG) demands that, when older dwellings are retrofitted, they achieve only a modest standard equivalent to about 100 kWh/(m^2y) for space heating. This is intended to ensure that the costs of the energy-efficiency retrofit measures pay back over their 25-year lifetime through energy savings [17]. The marginal costs of retrofitting to higher standards increases sharply for every further kWh/(m^2y) reduction, and it is prohibitively expensive to retrofit to a standard better than about 40 kWh/(m^2y),[1] which is equivalent to the "KfW55" standard, for which subsidies are available from the German Development Bank (*Kreditanstalt für Wiederaufbau*). To achieve net-zero-energy using electricity requires a heat pump to reduce this load further, and photovoltaics to generate sufficient electricity to cover this heating load plus the domestic water heating load plus the demand from household electrical appliances [18]. Other renewable alternatives for heating are biomass or gas hybrid, but as of 2021, 52% of all attempts at "net-zero-energy" dwellings in Germany used heat pumps [19].

There is therefore a balancing act between costs, CO2 emissions and seasonal fluctuations in consumption and production. The building envelope and heating system need to be retrofitted to as high a standard as possible, to reduce energy demand in winter, when the CO2 content of grid electricity is high. On-site photovoltaics can reduce the load on the grid, but they produce very little electricity in winter, when it is most needed. Meanwhile, it is uneconomic to install a large photovoltaic system because, as shown below, the marginal economic benefits of photovoltaics tend to be highest for relatively low-capacity systems and to reduce sharply for higher capacities.

Further, for rented apartments, the economic effects on tenants with low incomes need to be considered. In German law a landlord/landlady can increase the annual rent by up to 8% of the costs of energy-efficiency improvements [20], and this can be crippling for tenants [21]. For owner-occupiers, a renovation to net-zero-energy can also be economically unachievable.

In view of these issues, this paper critiques the logic and rationale of the net-zero-energy quest and suggests the need for two alternative aims that need to be optimized in relation to each other: tracking towards net-CO2-emissions on the level of the wider energy system; and maximising the economic return on investment (i.e., minimising the economic burden). A case study of a typical 1950s–1970s era apartment is used to illustrate these points. The relevant parameters vary from building to building, but the paper argues that their general shape is fairly universal for the large cohort of 1950s-1970s-era German apartments.

Section 2 reviews relevant literature on net-zero-energy buildings and renovation, asking what the value of this concept is and how it relates to aims for zero carbon systems. Section 3 outlines the method used for the case study, and Section 4 presents the results. Critical discussion is offered in Section 5, and Section 6 offers conclusions and recommendations.

[1] The German standard of 40 kW h/(m^2y) is based on the assumption that all rooms in the apartment are heated to 19° Celsius through the entire winter, and total annual space heating consumption is 40 kWh multiplied by the useable floor area.

2. Literature review: from net-zero-energy buildings to net-zero emissions energy systems

A very large literature on net-zero-energy buildings has arisen over the last 20 years. By tracking some of the trends in this literature it can be seen that the aspiration to make buildings net-zero-energy continues to arise, despite clear evidence that it may be impractical. An important response to this is a shift of focus toward zero *carbon emissions* energy *systems*, which has arisen in recent literature.

Belussi et al. [7] offer a recent review of literature on the technical efficacy of net-zero-energy buildings. They set this within the framework of two alternative, broad definitions of a net-zero-energy building: one which produces as much renewable energy as it consumes in operation, and one which produces as much renewable energy as the sum of its embodied energy and its operational energy consumption. They highlight the challenges and progress to date in attempting to reach these goals, along with the variety of technologies employed. They find that most literature describes or advocates a two-pronged approach: increasing the energy efficiency of the building envelope and appliances; and installing a source of renewable energy. This is most often solar photovoltaics, but Belussi et al. [7] also review discussion of on-site wind power, or wind power installed close to the building, as a possible source of renewable electricity. Referring to earlier work by Dayan [22] they note the difficulties of getting sufficient airflow near buildings to power effective wind turbines. Nevertheless, they do not critique the notion of installing wind power locally.

D'Agostino and Mazzarella [9] offer a recent review on "*nearly* zero energy buildings", focusing on definitions of the term. Important differences between definitions hinge on whether energy *end*-use or *primary* energy is being considered, and whether the concern is energy *sources* (such as solar versus fossil fuels), or energy *carriers* (such as electricity versus gas). In a further recent review, Taherahmadi et al. [12] highlight that the word "zero" in definitions of "net-zero" buildings can refer to quite different things: annual energy in-out balance; the CO2 emissions impact of the energy flows; exergy; or energy-related running costs. Again, however, the main concern is with energy in versus energy out, while CO2 emissions play a minor role.

In a similar vein, Liu et al. [23] review efforts in China to define "net-zero-energy buildings" and report progress on these in various climate zones. While they state throughout that these buildings are an effective way to mitigate carbon emissions in the building sector, they do not offer evidence of the degree to which net-zero-energy implies any particular depth of CO2 emission reductions. In contrast, Zhang et al. [24] examine the relationship between net-zero-energy buildings and net-zero carbon emissions in China. They conclude that to achieve carbon neutrality in respect of the building sector, "improving the building energy efficiency accounts for 50.1% while building electrification and zero carbon emissions from the grid account for 49.9%" ([24]: 741). This suggests that it is unrealistic to expect to be able to reduce emissions-related energy consumption in buildings by more than about half, so that the remainder would have to be supplied by a decarbonized electricity grid.

Up to a decade ago some scholars were already considering the limitations of the net-zero-energy concept for buildings. Voss et al. [13] investigated the German government's definition of a net-zero-energy building, in which monthly balances of energy in and energy out must sum to zero over the course of a year, and energy sources at or "in the immediate vicinity of" the building are credited to the building. There is no explicit rationale as to how net-zero-energy in this type of constellation would benefit society or the environment, nor is the degree of emission reduction taken into the calculation. The authors insightfully note that "The zero-energy building is often presented as a maximum goal in the political context" (p. 55).

Following this early lead of Voss et al. [13], and building on the work of Sartori et al. [25], Salom et al. [26] discuss the concept of load matching for net-zero-energy buildings. Here, energy consumed from outside the building is compared with energy generated by the building, energy consumed from self-generation, and energy supplied by the building to outside consumers, such as by feed-in to the grid. A useful metric they proposed is "loss of load probability", namely "the percentage of time that the local generation does not cover the building demand, and thus how often energy must be supplied by the grid." Generally, the smaller the time interval, the higher the probability of loss of load. A building that is net-zero-energy on an annual basis may be far from that in a particular month, week or day, with serious implications for carbon emissions, since the carbon intensity of grid electricity varies from month to month, week to week and day to day.

Some recent studies have taken up this critique of the concept of net-zero-energy for buildings. Moghaddasi et al. [8] survey the many definitions of a "net-zero-energy building" as used in regulations, awards and building standards, drawing on historic trends in academic discussion via researchers such as Torcellini et al. [11]; Crawley et al. [27]; Marszasl et al. [28]; Deng et al. [5], Peterson et al. [29]; Lu et al. [30]; Wells et al. [31]; Attia [32]; Wu et al. [33]; and Black et al. [34]. Among other inconsistencies, they find confusion between the notion of reducing net *energy* consumption for its own sake and reducing *CO2 emissions* as the main goal. Following Wu et al. [33], they note that net-zero-energy risks "becoming a status symbol for building owners rather than a practical goal in alleviating environmental, social or ethical issues." Here there are parallels with the comments of Voss et al. [13], that net-zero-energy buildings are more a political goal than a useful goal for society.

The idea of focusing on net carbon emissions, rather than net energy, can also be traced to work of a decade ago. In view of the mismatch between net-zero-energy and zero CO2 emissions, Kibert and Mirhadi Fard [35] proposed to "focus on carbon neutrality as the metric for net-zero buildings", "decouple the definition of net-zero energy, carbon-neutral and low-building-energy concepts", and "include all on- *and off-site* locations for renewable and low-carbon energy" (italics added). This could be seen as opening the way for a range of more economically and technically feasible solutions on a national, regional or systems level rather than just those at the level of the building.

Nevertheless, there still tends to be a focus on individual buildings, even where net-zero emissions are the guiding principle. Panagiotidou and Rismanchi [36] investigate the possibility of zero-carbon emissions buildings, using computer simulations based on market costs and typical energy performance of building components. Considering building performance only (not including embodied carbon), they find that even in "climate zone A", the warmest in Greece, it is not technically possible to achieve zero carbon emissions on-site. A cost-optimal retrofit brings a 60% reduction in greenhouse gas emissions, while a reduction of 87%–95% is possible only with high-end, expensive technology including extra-thick insulation, a biomass boiler, air-to-air heating and cooling systems, photovoltaic panels, solar-thermal panels, and facade-integrated photovoltaic systems.

Since it is technically and economically unrealistic to aim for on-site carbon neutrality, there is increasing interest in what are labelled "net-zero energy *systems*". Here, buildings are seen as only part of a larger constellation of energy consumers, producers, sources and carriers. The emphasis is on zero CO2 *emissions* on a national scale rather than an *energy* balance in a particular building. In this vein, Azevedo et al. [37] recently introduced a special issue of the Journal *Energy and Climate Change* on the topic "net-zero energy systems". Their definition of "net-zero-energy" effectively means "energy systems that produce net-zero greenhouse gas emissions". They state: "Net-zero energy systems—where anthropogenic CO2 emissions are balanced by removals—are likely to be central to such decarbonization efforts."

In the same special issue, Azevedo et al. [38] offer a review of literature on what they call "net-zero emissions energy systems". They state, "Here, we use 'net-zero energy systems' to denote energy systems that emit no net CO2, encompassing energy and industrial processes." They briefly survey the factors needing to be addressed to work toward this, namely: decarbonized electricity generation; a shift to electrification of energy services; the use of green fuels in sectors that are difficult to electrify; more efficient use of materials; better integration of energy use; and CO2 removal technologies.

An integral part of a "net-zero-emissions-energy-system" with respect to buildings is therefore the electricity grid. Authors such as Baik et al. [39] investigate possibilities of decarbonizing the grid, an essential feature if a building stock powered entirely by electricity is to be net-zero in terms of CO2 emissions. They use the phrase "firm technologies" to mean low-carbon electricity generating sources that are not compromised by fluctuations in solar or wind power and can be called upon at short notice to make up the gaps in these. The three they highlight are: fossil fuels with carbon capture and storage; nuclear power; and the combustion of zero-carbon fuels such as hydrogen produced by electrolysis from renewable electricity. A similar list is given by Bistline [40], who emphasises how the choices will vary depending on the energy-relevant characteristics of countries and regions.

This concern with net zero emissions energy systems lies at the heart of this paper. It aims to suggest a broad set of aims for renovating Germany's huge stock of energy-inefficient 1950s-1970s-era apartment buildings in line with the country's ambitious goals for CO2 emissions reduction. This renovation goal is currently being pursued amidst a resurgence of discourse on "net-zero-energy" buildings, and firms such as Energiesprong[2] are gaining large government subsidies to renovate these buildings to net-zero-energy standard, regardless of what this actually means for CO2 emissions. The paper sets out to critique this kind of approach and examine how an approach at the level of energy systems would be a better way to achieve Germany's CO2 emissions goals.

3. Method

3.1. Rationale

The study uses a third-floor apartment of 70 m^2 floor area, in a four-storey building of four apartments, three of which have floor area 70 m^2 and the other 50 m^2, built in 1960 in a medium-sized city in the German state of North Rhine-Westphalia (see details in the Supplementary Material, www.justsolutions.eu/DataInBrief). This is very typical of Germany's 1950s-70s-era housing. The apartment has three occupants, which is about average for this type of apartment. As is also typical, the roof area of the building is large enough to accommodate photovoltaic panels of up to about 15 kW-peak (kWp).

The building envelope has been retrofitted to a standard of 40 kWh/(m^2y) for space heating, which is about the limit of what is technically and economically feasible for this class of building, and the apartment's gas boiler has been replaced by an air-source heat pump. The analysis focuses on the question of what would be needed to bring this to net-zero *energy* standard using rooftop photovoltaics, and how close this would bring it to net zero *CO2 emissions* standard. If it does not reach net-zero emissions standard, the subsequent question is, would an energy systems approach (as outlined above) be useful here. All these questions have practical, technical and economic dimensions.

The costs of the building envelope refurbishment and heat pump are not included in the cost-benefit calculations used in this paper, as this investment was required simply to bring the building up to a relatively high energy efficiency standard. Instead, the emphasis is on attempts to move this building toward net-zero-energy standard through the installation of a rooftop photovoltaic system.

With a heat pump installed, all the energy used in the building is in the form of electricity. The energy system in which the building is embedded is therefore the electricity grid. The study therefore not only considers the energy and CO2 balance at the level of the apartment, but also how this plays out at the level of the grid.

The remainder of the Methods section first describes the data sources used in the study and how these were normalised for the case study apartment. This includes a brief discussion of rebound effects. It then explains the micro-methodology which is used in the study to estimate energy flows, CO2 emissions, costs and benefits, for an estimated 25-year lifetime of the photovoltaic system. It then outlines the series of steps taken, using the data and the simulations, in pursuing the research questions. Note that this is a set of simulations rather than the use of measured data, as the estimates refer to future energy flows and must therefore be made in advance of the decision as to which size and type of photovoltaic system to install.

3.2. Electricity production and consumption data

Three main datasets were used. First, the study used the quarter-hourly photovoltaic production for the whole of Germany for 2019,

[2] https://energiesprong.org/.

to give a profile of photovoltaic electricity generation over a complete year. Data readings of Germany's electricity production and consumption were available for every 15-min interval, giving 35,040 observations, in GW, of electricity generated by all electricity sources (hard coal, nuclear, wind, photovoltaics, etc.), and all electricity consumed (provided by Ref. [41]). Dividing each reading of power generated (GW) by 4 gives a very close approximation to the electrical energy (GWh) produced or consumed during each quarter-hour period. This gives the profiles of Germany's electrical energy generation and consumption over the course of the year from all sources.

To model the profile of electricity production from the apartment's photovoltaic system, the profile of national photovoltaic electricity production data was adjusted to take account of the increase in photovoltaic adoption over the year. It was then normalised to a total year's production of 1000 kWh to represent the production profile of each 1kWp of photovoltaic capacity, since production of 1000 kWh/y for each 1 kWp of photovoltaic capacity is about average for Germany. The data thereby gives the amount of electrical energy (kWh) produced in each quarter-hour for each 1 kWp of photovoltaic capacity installed on the building that contains the case study apartment.

Second, the study used the quarter-hourly profile of electricity consumption for energy services (apart from heating and domestic hot water) of a typical German household, over a whole year (provided by Ref. [42]). This was normalised to a total of 2600 kWh for the full year, as this is an "optimal" electricity consumption of a household of three persons [43]. There is of course a very large range of electricity consumption for a household of any particular size [43–45]. The average for German households is 3332 kWh/y, much higher than the "optimum" [44]. Using the lower, optimum level avoids over-estimating the financial benefits of rooftop photovoltaics, since a high-consuming household will gain more economic benefit from rooftop photovoltaics than a low-consuming household.

Third, the study used an annual data profile, again by quarter-hour, for a heat pump providing space and domestic water heating consumption for a typical German household, provided by Ref. [47]. This was normalised to an annual total of 1470 kWh as follows. An apartment of 70 m^2 retrofitted to 40 kWh/(m^2y) will consume 2800 kWh/y for space heating (assuming optimal heating behaviour by the occupants). Domestic hot water (DHW) energy demand for a 3-person household is typically around 2100 kWh/y [48]. This gives a total heating consumption of 4900 kWh/y. For an air-source heat pump with an average coefficient of performance of 3.0 this gives annual electricity-driven heating consumption of 1470 kWh/y. The quarter-hour-by-quarter-hour profile for the year was set by normalising the total to this figure. In the remainder of the paper, "heating" includes both domestic water heating and space heating unless otherwise mentioned. Normally the DHW tank is heated at night, usually to about 55 °C.

3.3. Rebound effects

A further important input factor is rebound effects. A recent study found average direct rebound effects in the range 14–33% for households who install photovoltaics [44], meaning these households tend to increase their electricity consumption by 14–33% of the amount they generate. This appears to be a "price-effect" [49]: because the marginal cost per kWh of their own-produced electricity is close to zero [50], households tend to consume more. On average in Europe, each 1% decrease in electricity price is associated with an increase in electricity consumption of 0.53%–0.56% among households [51]. As a rule of thumb for the case study, it is assumed that installing photovoltaics leads to an increase in electricity use for appliances (excluding heating) of 20%, since the electricity which they no longer need to consume from the grid is effectively free. Galvin et al. [44] call this a "rebound factor" of 1.2. This increases the household's general electricity consumption to 3120 kWh/y. The household's general electricity consumption profile was then re-normalised to this annual amount. Their heating consumption, however, remains at 1470 kWh/y.

Note that these rebound effects are considered to be welfare-enhancing, in that they enable the household to benefit from a level of energy services that it would not otherwise enjoy. The extra costs due to the rebound are therefore not added to the debit side of the cost-benefit calculation.

3.4. Data for costs and benefits

The most up-to-date figures at the time of writing (April 2022) were used for the costs of the photovoltaic system and financial returns on its use. Costs of components and installation of the photovoltaic system were obtained from an actual quote from an installation firm[3] and compared with cost averages [52]. The figures used in the study are 919 €/kWp for monocrystalline photovoltaic panels; 167 €/kWp for mounting; 200 €/kWp for the DC-AC converter and related components; 1714 €/kWh for the battery and related components, and fixed costs of 950 € for cabling, fixtures and grid connection. Following [53], annual maintenance costs are estimated at 1% of total costs. The quote from the installation firm guaranteed the performance of the photovoltaic panels not to fall below 80% within the first 25 years of operation, representing a cumulative annual deterioration of 0.89%/y.

Households who install photovoltaics in April 2022 receive a feed-in tariff of 6.53 eurocents per kWh (c/kWh), guaranteed for 20 years [53]. The current price for household electricity consumed from the grid is 33.4 c/kWh. Following Galvin's [54] discussion of estimates by industry and the possible effects of the war in Ukraine on energy prices, together with Germany's energy transition plans, the average future annual increase in the grid electricity price is estimated at 5%/y. The discount rate is very difficult to estimate due to current volatility in inflation rates. Germany's inflation rate reached 4.9% for the year to January 2022 and 5.1% for the year to February 2022 [55], but the European Central Bank's long-term target is 2%, and volatility is not expected to continue indefinitely. In light of these figures the study uses a conservative discount rate of 5%/y, acknowledging that household discount rates are very much set by household perceptions of future price trends and are always subject to dispute. All the above figures are listed in Table 1.

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

3.5. The model and the steps of the analysis

A computer model was designed to simulate the future energy and economic performance of the photovoltaic system on the case study apartment. The model uses a similar strategy to that of Galvin [56] but with modifications to suit the case study dwelling, and an extension to consider net-zero energy, net-zero emissions, and energy system level impacts. It tracks household electricity consumption, feed-in to the grid, consumption from the grid, consumption of own-produced electricity, and battery state of charge, for a year, in quarter-hour steps. It does this over a 30-year period and repeats the simulation for 30 different photovoltaic system sizes, from 0.5 kWp to 15 kWp, in steps of 0.5 kWp. Examples of micro-level profiles of grid-consumption, feed-in, battery state of charge, etc., are given in Appendix 1. A description of the logic of the programming is given in Appendix 2. The full dataset and computer program code are available in the Supplementary Material.

Using this simulation tool, the analysis proceeded with the following steps.

First, the optimum-sized photovoltaic capacity was found for achieving net-zero-energy. This is the point where, in a year of average system performance, the total amount of electricity fed into the grid is at least equal to the total amount consumed from the grid. Because of the gradual deterioration of photovoltaic panels and battery over 25 years, this average is reflected in performance in the 12th year of operation. Note that this calculation is only marginally affected by battery size. A battery stores electricity only for short periods, between which there may be small differences in the CO2 intensity of the electricity available on the grid. A battery does not enable energy to be transferred between the large highs and lows of renewable energy production between summer and winter or between a windy week and a calm period. A 5 kWh battery was assumed for the simulations, but other battery sizes and a system with no battery were also tried, and the latter reported on below.

Second, the level of CO2 emissions per year produced by the net-zero-energy case were calculated. These net emissions arise because of the different mix of electricity sources between summer and winter. For this analysis, the CO2 intensity of Germany's electricity production in each quarter-hour over the course of a year was calculated.

Third, along with the above steps, simulations were run to see whether it might be more economically and technically feasible, from an energy systems point of view, to install a smaller photovoltaic system that does not enable the dwelling to reach net-zero-energy. This led to broader comments on the apartment as part of a net-zero emissions energy system, a theme taken up further in the Discussion section. A schematic of the method is given in Fig. 1.

4. Results

4.1. Finding the photovoltaic capacity for net-zero-energy energy consumption

As noted above, to achieve net-zero-energy over the system's 25-year lifetime, the photovoltaic capacity must be found for which feed-in to the grid is about equal to consumption from the grid in the 12th year of operation. This is achieved most closely by a system

Table 1
Summary of parameter values used in analysis.

Parameter	Units	Comment	Value where constant in analysis
Annual baseline electricity consumption	kWh	Assume 2600 kWh as optimal for household of 3 persons	2600 kWh
Annual consumption for heat pump	kWh		1470 kWh
Annual electricity production	kWh	Used in above equations to estimate self-consumption, etc. 1000 x kWp	
Annual self-consumption	kWh	Calculated within the program	
Annual feed-in	kWh	Calculated within the program	
Annual grid electricity consumption	kWh	Calculated within the program	
Rebound factor	number	1 + proportionate increase in consumption over baseline	1.2
Grid electricity price in year 1	Euros/kWh	As in April 2022	0.334 €/kWh
Grid feed-in price in year 1	Euros/kWh	For installations in April 2022, fixed for 20 years	0.0653 €/kWh
Expected annual electricity price increase	number	Long-range estimate based on forecasts by BMWi and others	5%
Inflation rate	number	Long-range estimate based on range of scenarios by the European Central Bank and others	5%
Discount rate	number	Based on inflation rate, but varies depending on investors' needs and perceptions	5%
Annual system maintenance cost	Euros	1% of upfront costs. See discussion in Zsiborács et al. [56]	
Capacity of battery storage system	kWh	Used to estimate annual maintenance costs, and used in estimating system costs.	0 and 5 kWh
Upfront costs (itemised below)	Euros	Estimated from actual quote on February 08, 2022, and photovoltaic providers' websites.	
Modules (including VAT)	€/kWp		919 €/kWp
Mounting	€/kWp		167 €/kWp
DC-AC Converter etc.	€/kWp		200 €/kWp
Battery and related components	€/kWh		1714 €/kWh
Cabling, fixtures and grid connection	€		950 €

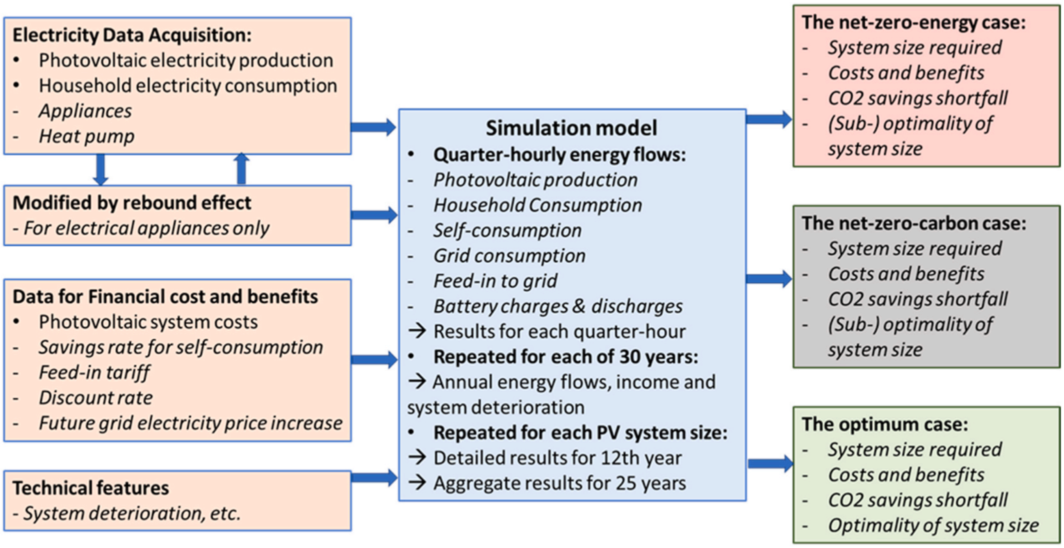

Fig. 1. Schematic of method used in the analysis.

of 7.0 kWp. This is illustrated in Fig. 2a and Fig. 2b, which show feed-in and grid consumption in the 12th year of operation of systems ranging from 0.5 kWp to 15.0 kWp, with a 5 kWh battery and no battery respectively. For the case with a 5 kWh battery, in the 12th year of operation a 7.0 kWp system feeds 1983 kWh/y into the grid and takes 1884 kWh/y from the grid, making it 99 kWh/y better than net-zero. A slightly smaller system, 6.5 kWp, feeds in 1636 kWh/y and takes 1962 kWh/y, failing to reach net-zero-energy by 325 kWh/y, while a slightly larger system, 7.5 kWp, over-achieves net-zero-energy by 526 kWh/y.

When annual feed-in and grid consumption are each added up over the 25 years, the result is similar: a 7.0 kWp system feeds 48,637 kWh into the grid and takes 47,545 kWh from the grid, an over-achievement of 1091 kWh. In contrast, a smaller system, of 6.5 kWp, under-achieves by 14,539 kWh.

The system with no battery also needs 7.0 kWp to achieve net-zero-energy, but the energy flows are substantially higher. Here, 3119 kWh/y are fed into the grid while 3020 kWh/y are taken from the grid. This is because electricity generated during the day is not being stored for use in the evenings. This brings the economic disadvantage that the household must pay the high cost of grid electricity in the evenings and earns only the low feed-in tariff during the day.

There is a further economic disadvantage with the net-zero-energy situation, regardless of whether there is a battery. For net-zero-energy the household feeds at least the same amount of electrical energy into the grid as it takes from it, namely around 1900 kWh/y for the case with a 5 kWh battery. Since the household's total consumption is 5214 kWh/y, this means that the household is only consuming 3314 kwh/y of its own-produced electricity, or just over half of the 6300 kWh/y it is producing. Hence it gets nowhere near

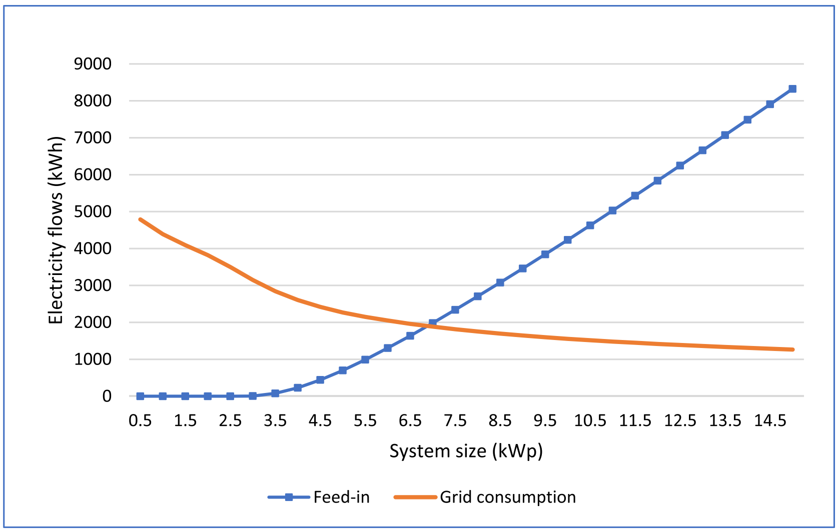

Fig. 2a. Feed-in and grid consumption in 12th year of operation, 70 m^2 apartment with heat pump and 5 kWh battery.

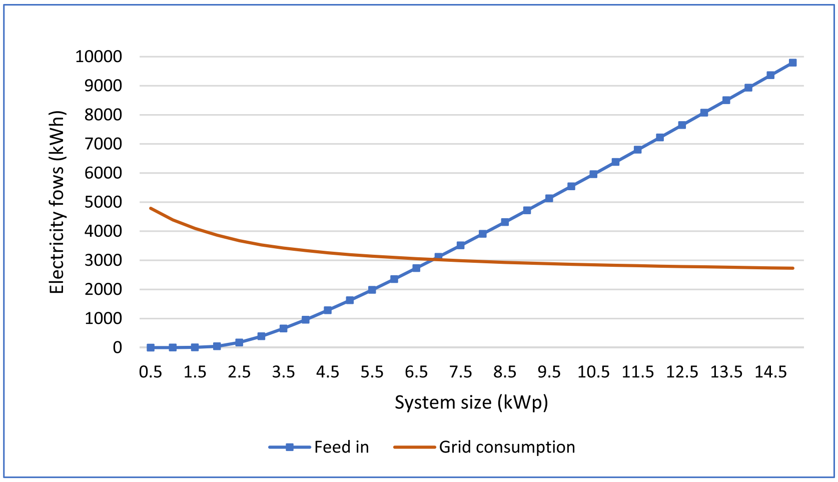

Fig. 2b. Feed-in and grid consumption in 12th year of operation, 70 m^2 apartment with heat pump and no battery.

the full economic potential of its photovoltaic system, since the advantage of saving 33.4 c/kWh only applies when consuming one's own-produced electricity.

4.2. The summer-winter CO2 emissions dilemma with net-zero

A further problem for net-zero-energy buildings is the mismatch between high electricity production in summer and high electricity use in winter. This is illustrated in Fig. 3, which shows the day-by-day patterns of feed-in to the grid and consumption from the grid, for the 7.0 kWp system with a 5 kWh battery in its 12th year of operation. Fig. 4 gives the net feed-in, i.e., the feed-in minus grid consumption. These plots show how strongly seasonal these flows are. There is excess electricity production in summer and a severe shortage in winter.

Fig. 5 gives the profile of day-by-day consumption and production in the 12th year, showing that there are hardly any days when the household's electricity production and consumption make a near match, and on most days, one is substantially lower or higher than the other. The household loses financially with both types of mismatch. When it over-produces, it gets only 6.53 c/kWh for the excess. When it under-produces, pays 33.4 c/kWh for grid electricity. The battery smooths out fluctuating discrepancies within a 24-36-h period, but not over several days or weeks.

Aside from economic issues, there is the important question of CO2 emissions with net-zero-energy. In Germany almost all renewable electricity is produced by photovoltaics and wind turbines. In 2019 photovoltaics produced 186,529 GWh and wind 507,586 GWh, while hydro produced only 80,375 GWh and fossil fuels 825,412 GWh [41]. The profiles of wind and photovoltaic power production (GW) in 2019 are given in Fig. 6 and Fig. 7, and comparisons between their different levels of total production for January–February and July–August 2019 are displayed in Fig. 8. For photovoltaics, production in July–August was 7.6 times that of production in January–February, whereas for wind, production in the two periods was almost identical. Although wind gusts are

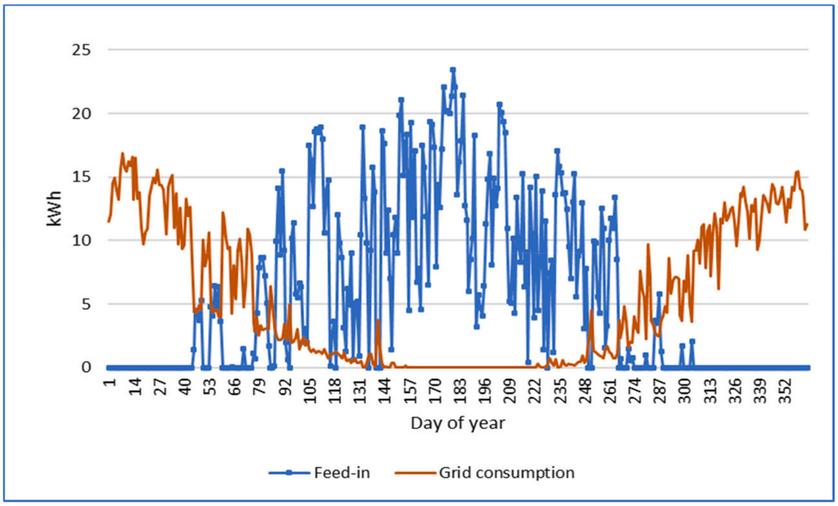

Fig. 3. Daily feed-in and grid consumption for apartment with 5 kWh battery and 7.0 kWp photovoltaic system in 12th year of operation.

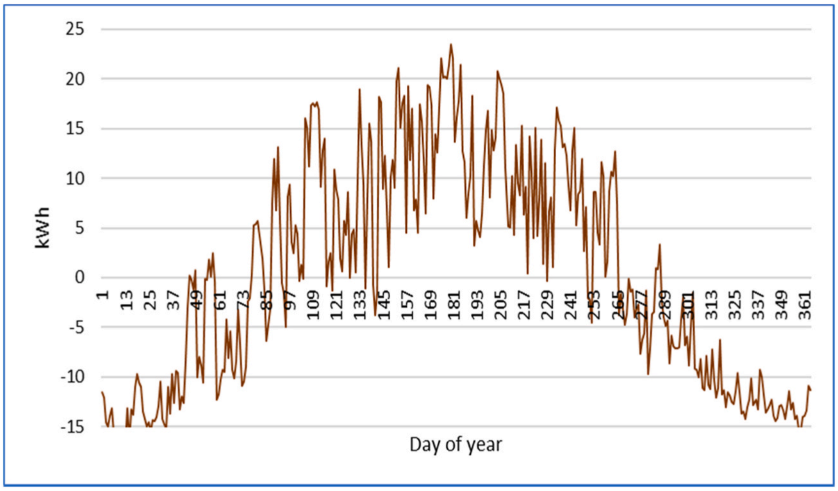

Fig. 4. Daily net feed-in to grid (feed-in less grid consumption), apartment with 5 kWh battery and 7.07.0 kWp PV system, 12th year of operation.

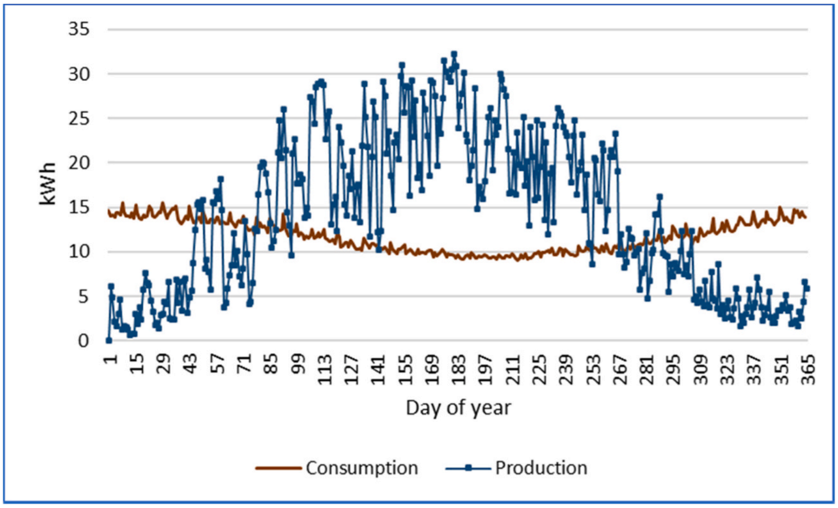

Fig. 5. Daily electricity consumption and production, apartment with 5 kWh battery and 7.0 kWp PV system, 12th year of operation.

heavier in winter, the wind is less steady and there are periods of relative stillness, as seen in Fig. 6. Another difference is that although the day-to-day profile of photovoltaic production can vary substantially, its seasonal profile is very predictable, whereas the seasonal profile of wind power is highly unpredictable, as are its weekly and even daily fluctuations.

4.3. *Quantifying the patterns of CO2 emissions*

It is important, therefore, to quantify the CO2 intensity for each quarter-hour timeslot in which the apartment is feeding electricity into or taking electricity from the grid. The CO2 emissions per kWh of electricity generated in Germany from non-renewable sources are given in Table 2. The profile of CO2 intensity, I (tCO2/GWh) for each quarter-hour time-slot q can be calculated:

$$I_q = (A_{1q}.E_{1q} + A_{2q}.E_{2q} + A_{3q}E_{3q} + A_{4q}E_{4q} + \ldots)/D_q \quad (1)$$

where A_1, A_2, etc. are the CO2 intensities (tCO2/GWh) of each of the different electricity sources, E_1, E_2, etc., are the magnitudes of electricity (GWh) produced by these respectively, and D is electricity demand. A graph of this intensity profile, aggregated to 24-h periods, is given in Fig. 9. Clearly, CO2 emissions per kWh of electricity demand are substantially higher in winter than in summer, and there are large fluctuations in all seasons.

The profiles of tonnes of CO2 saved and caused by the apartment are obtained by multiplying the grid's quarter-hourly carbon intensity by the quantities of electrical energy which the apartment feeds into the grid and takes from the grid in each quarter-hour timeslot in its 12th year of operation. Fig. 10a displays the profiles of CO2 saved and caused by the apartment respectively. Fig. 10b gives the quarter-hourly net CO2 emissions. For both graphs the apartment has a 7 kWp system (to achieve net-zero-energy) and a 5

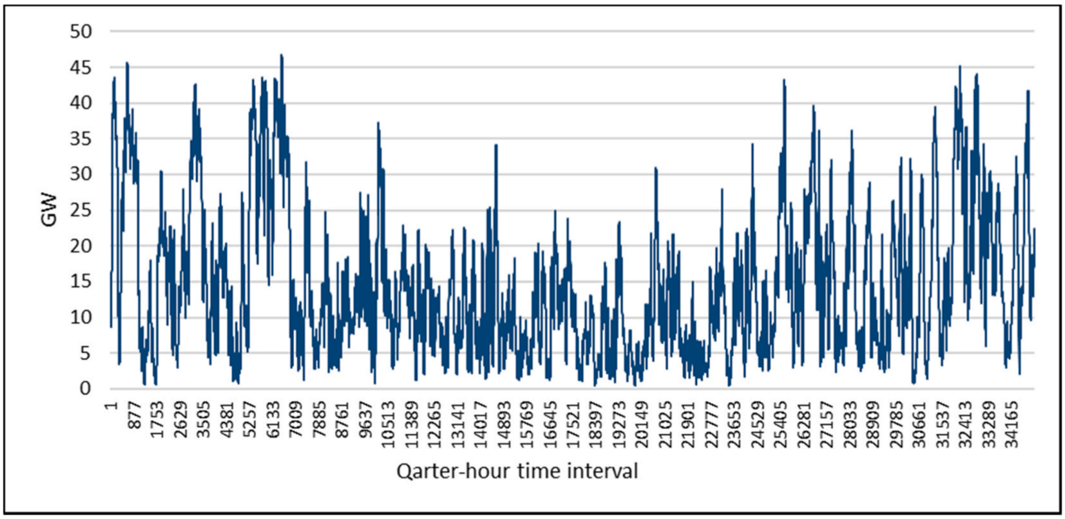

Fig. 6. Wind electricity production in Germany, 2019, power produced at beginning of each quarter-hour time interval.

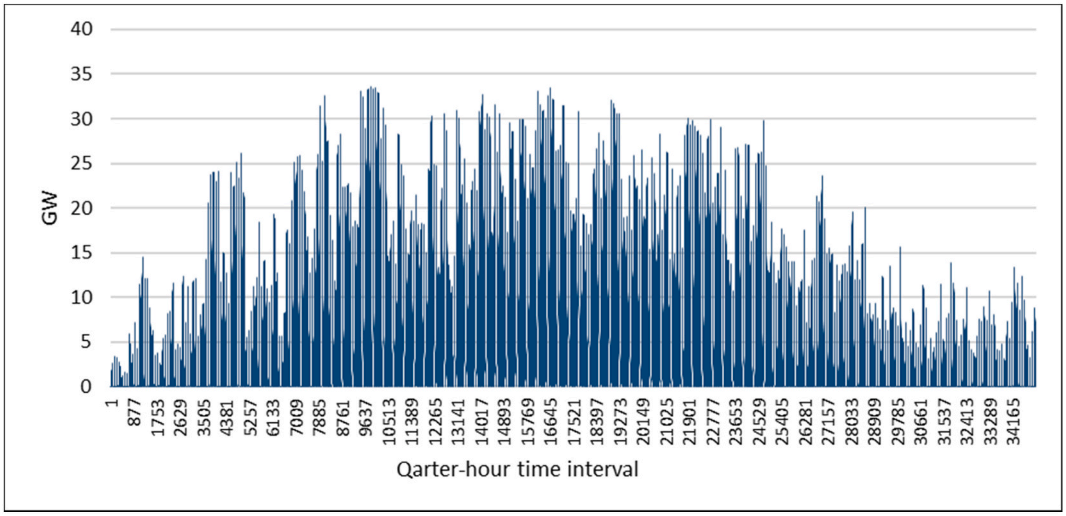

Fig. 7. Photovoltaic electricity production in Germany, 2019, power produced at beginning of each quarter-hour time interval.

kWh battery.

As Figs. 10a and b show, the profile of CO2 emissions *caused* by the apartment is fairly consistent throughout the year, with larger peaks in winter, while the profile of CO2 emissions *prevented* is much more sporadic, with large intermittent peaks in summer, spring and autumn. Looking at the data behind Fig. 10a and b, the total CO2 emissions saved by feed-in over the year is 891,657 g (0.0.892 t), while the total caused by grid consumption is 1,143,9375 g (1.144 t). The difference between these, 0.252 t, is the net CO2 emissions caused by the net-zero-energy dwelling in its 12th year of operation. *The net-zero-energy dwelling thereby misses the goal of net-zero emissions by 28%.*

A multivariate analysis of the correlation between photovoltaic feed-in and carbon intensity of the grid also highlights this summer-winter discrepancy (see details in Appendix 3). Each increase of 1 GWh of photovoltaic production in summer (controlling for all other sources of electricity) is associated with a reduction in carbon intensity of 0.93 tCO2/GWh, but in winter the reduction is 1.42 tCO2/GWh. Renewable energy production in winter therefore has a 53% higher carbon-reducing potential per GWh than in summer – but most photovoltaic production happens in summer and hardly any in winter.

Using these figures it can therefore be asked, what sized photovoltaic capacity would be needed to produce net-zero carbon emissions? Further runs of the model showed that a capacity of 8.0 kWp would be needed to reach net-zero-carbon. In the 12th year of operation, feed-in would reduce CO2 emissions by 1,124,694 g while grid consumption would increase emissions by 1,121,278 g, providing a small net CO2 emission reduction of 3416 g.

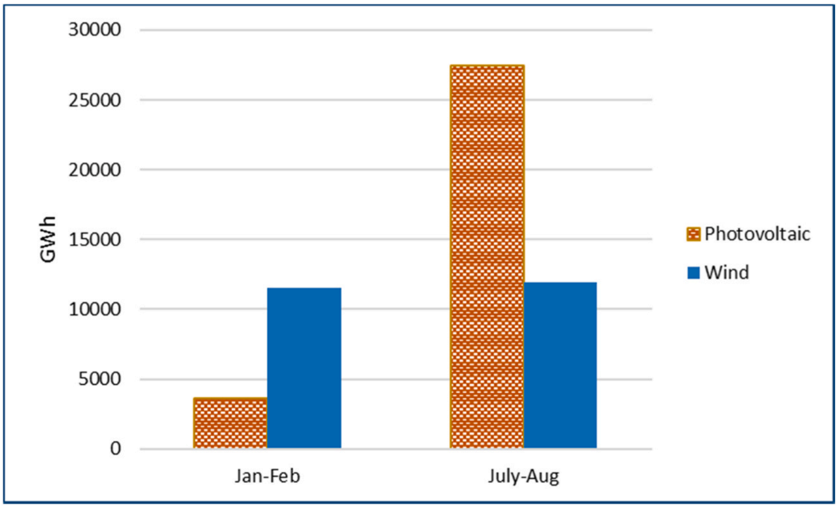

Fig. 8. Comparisons of photovoltaic and wind electricity production (GWh) during January–February and July–August 2019.

Table 2
Gram of CO2 emitted per kWh of electricity generated from non-or partially renewable sources. Data source: UBA [57].

	Gram CO2/kWh of electricity
Brown coal	**1093**
Lignite	**1001**
Natural gas	**433**
Oil	**789**
Pumped Storage	**50**
Imported	**500**
Other	**300**

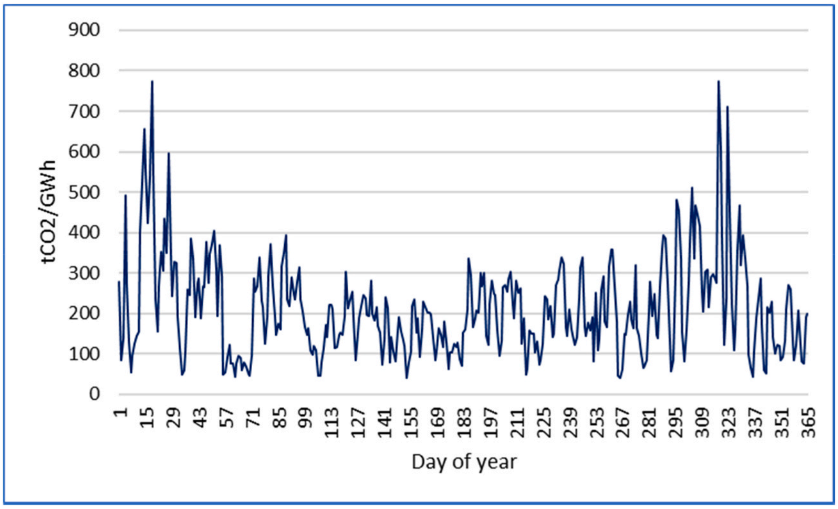

Fig. 9. Carbon intensity of electricity (tCO2/GWh) consumed each day in Germany in 2019.

4.4. Costs and benefits

An important question is whether it pays, financially, for the household to install a photovoltaic system large enough to achieve net-zero-energy or net-zero-carbon. A series of cost-benefit calculations shed light on this. Fig. 11 compares photovoltaic system costs with the net present value of the sum of financial gains after 25 years of operation, for different capacities of photovoltaic systems, with a 5 kWh battery. It also displays the net present value of the overall profit. This shows that payback is achieved with a system of just 3.5 kWp, and profit reaches just under 8600 € with a system of 5.5 kWp but is hardly higher than this for larger systems, and in fact falls for

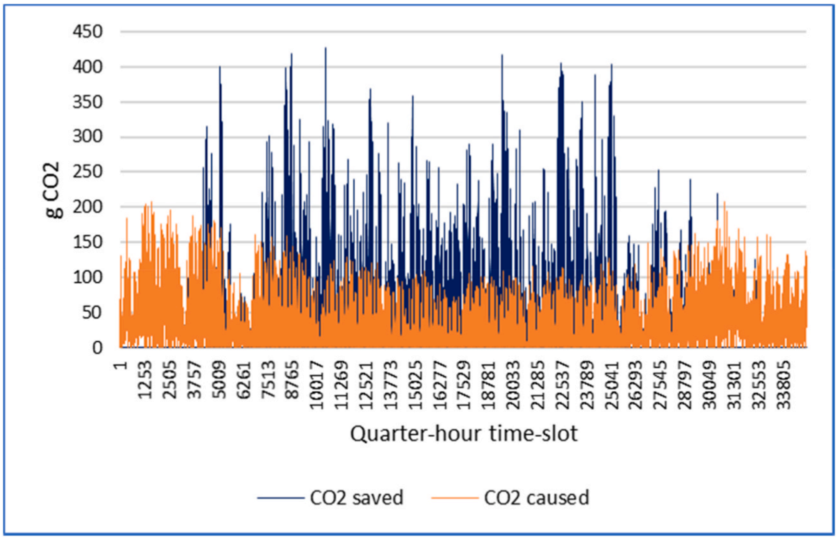

Fig. 10a. CO2 saved by feed-in and CO2 emissions caused by consumption from the grid, net-zero-energy apartment in 12th year of operation, 7 kWp system with 5 kWh battery, by quarter-hour time-slot.

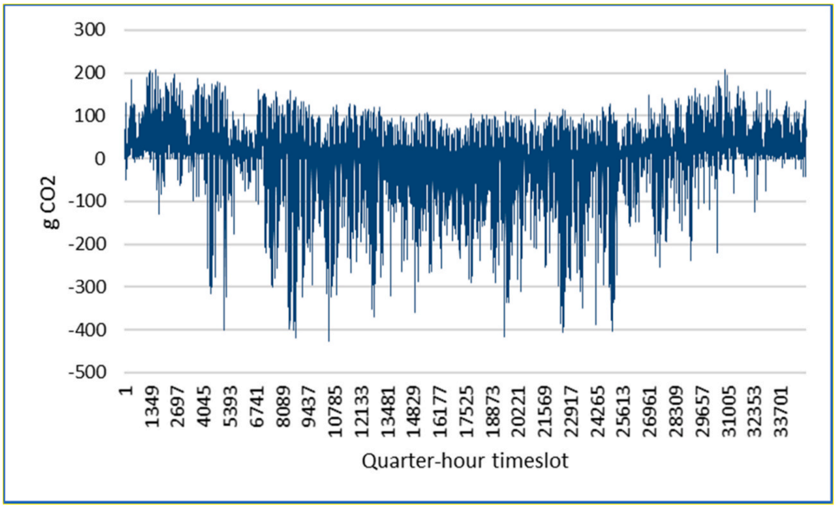

Fig. 10b. Net CO2 emissions caused by net-zero-energy apartment in 12th year, by quarter-hour timeslot.

systems over 12.5 kWp. Clearly, then, there is scarce financial advantage for the household in reaching net-zero-energy or net-zero-emissions. A net-zero-energy system (7.0 kWp) would cost 2000€ more than a 5.5 kWp system but bring only 1200 € more profit. A net-zero-emissions system would cost 3200 € more but bring only 1746 € more profit.

Fig. 12 extends the analysis to show the *percentage* profit achieved after 25 years, and the percentage of the apartment's consumption covered by the photovoltaic panels in the 25th year. Percentage profit reaches 52% for a 5.5 kWp system and is only marginally above this for systems up to 8kWp. It then falls for larger systems. Meanwhile, the percentage of electricity consumption provided by the photovoltaic panels rises steadily to just over 50% as capacity increases up to 5 kWp, then starts to level off, reaching 74% for a 15 kWp system.

The optimum system size could therefore be judged to be around 5.0 kWp. With such a system the household can almost maximise its percentage profit within the lifetime of the photovoltaic system while contributing to society by relieving the grid of half the load it would otherwise have taken.

Key results from the above analysis are given in Table 3.

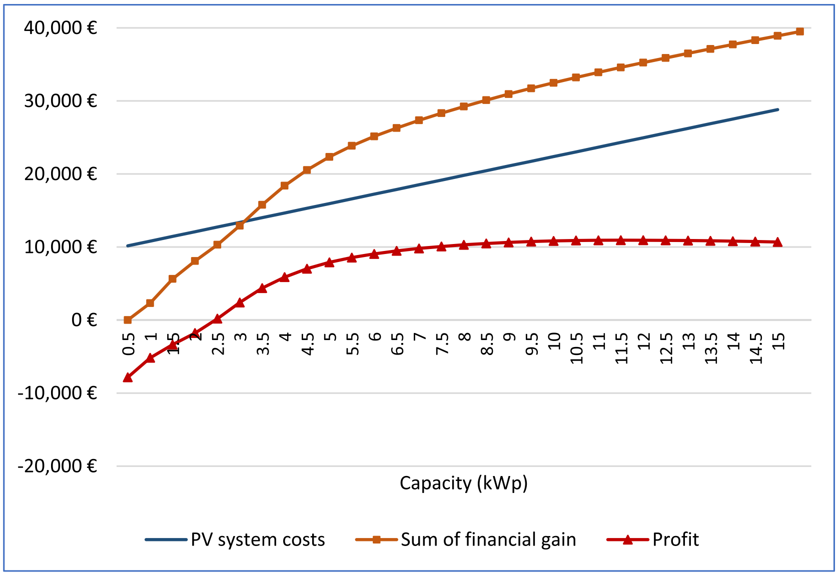

Fig. 11. System costs, sum of financial gain, and net present value of profit, after 25 years of operation, for different capacities of systems, with 5 kWh battery.

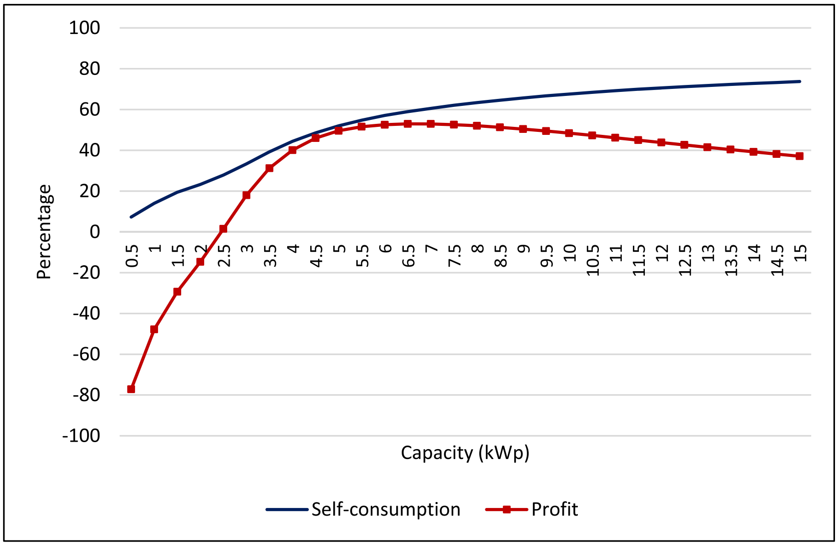

Fig. 12. Percentage profit after 25 years and percentage of consumption from own PV generation, for different PV capacities.

5. Discussion

5.1. *Problems with net-zero-energy*

The analysis has shed light on some of the shortcomings of a net-zero-energy approach. To reach net-zero-energy, the apartment needs a photovoltaic system of 7.0 kWp capacity, which is 2.0 kWp higher than the 5.0 kWp that is needed for optimising the ratio between the level of consumption of own-produced electricity and the amount of electricity fed into the grid. Further, achieving net-zero-energy does not imply achieving net-zero-emissions. For this, the photovoltaic system needs an even higher capacity, of 8.0 kWp.

This raises the question of roof area. Each kWp of photovoltaic capacity covers just over 5 m.[2] Since there are four apartments in the building (as is typical for hundreds of thousands of 1950s-1970s-era apartment buildings in Germany), there would not be enough roof area for four 7.0 kWp systems, and certainly not for four 8.0 kWp systems. It would even be challenging to fit four 5.0 kWp systems on such a roof. These problems are likely to be encountered for most typical 1950s-1970s-era apartments in Germany.

5.2. *Problems and solutions at the systems level*

As increasing numbers of households install heat pumps, the demand on the grid in winter will increase, and therefore the CO2

Table 3
Key results of analysis.

	System with 5 kWh battery	System with no battery
Net zero energy case		
Minimum capacity	7.0 kWp	7.0 kWp
Feed-in in 12th year	1983 kWh	3119 kWh
Grid consumption in 12th year	1884 kWh	3020 kWh
Own consumption in 12th year	3314 kWh	2189 kWh
Production in 12th year	6300 kWh	6300 kWh
Cumulative 25-year feed-in	48,637 kWh	
Cumulative 25-year grid consumption	47,545 kWh	
CO2 saved through feedin	891,657 g	
CO2 caused through grid consumption	1,143,937 g	
Net CO2 emissions for net-zero-energy	252,280 g	
Three main cases		
Optimum photovoltaic system capacity	5.5 k Wp	
System capacity for net-zero-energy	7.0 kWp	
System capacity for net-zero-emissions	8.0 kWp	

intensity of grid electricity will increase (for further insights into possible effects of and aspirations for heat pump adoption in Germany, see Bettgenhäuser et al. [64]). The equivalent feed-in to the grid in summer will not be sufficient to offset this, as the problem occurs in winter. Also, as more households install rooftop photovoltaics, the national share of photovoltaic electricity increases in summer, thereby reducing the carbon intensity of summer electricity, thereby reducing the marginal benefit of installing more photovoltaics.

Since achieving net-zero CO2 emissions is impractical at the level of the building, this has to be achieved at a systems level. Instead of investing extra money in larger photovoltaic systems to produce more electricity in summer, when the CO2 intensity of the electricity in the grid is low, more money needs to be invested in the types of renewable electricity that can be readily produced in winter, when the CO2 intensity is high. Since it is the grid that has to be decarbonized and not just individual buildings, this implies investing in the most economically efficient winter-effective renewables, namely coastal and hilltop wind power.

5.3. Energy storage

This implies the need for energy storage. An example is producing hydrogen by electrolysis from wind power, then using it to regenerate electricity during periods when renewables are insufficient. Hydrogen can be stored underground, for example in disused mines, or above ground in tanks and in piping distribution systems. Current advances in the technology are reviewed by Tarkowski [62]. There are of course losses in such a system, up to around 60% round-trip.

Although excess summer electricity from photovoltaics can also be used to produce hydrogen, the hydrogen would need to be stored for several months to re-generate electricity in winter, and the storage capacity would be used only once per year. It would be much more efficient to invest in wind power, as the main fluctuations in this are short-term rather than annual (see Fig. 6). Smaller storage capacities can therefore be used several times over during winter, with short-duration cycles [56]. Although the round-trip efficiency of such an approach is probably less than 40%, there may not be any better option. Further, the financial rate of return for onshore wind farms in Germany is greater than that of rooftop photovoltaics. In 2021 the average levelized cost of onshore wind power was 6 c/kWh [58] and the feed-in return was 8.8 c/kWh [59]. For rooftop photovoltaics the average cost was 7 c/kWh (without battery) and 12c/kWh with battery, while the feed-in return was 7.3 c/kWh (now fallen to 6.53 c/kWh). Hence the return on investment in wind power was about 130% greater than in rooftop photovoltaics with battery, or 41% greater than photovoltaics without battery. For an overview of issues involved in costs of hydrogen storage see Anderson and Grönkvist [63].

Wind power installed in remote areas also has the advantage of scale. Unlike photovoltaics, larger capacity wind farms usually have higher rates of electricity production per unit size. Also, the noise factor with wind power makes it more suitable for remote areas rather than near urban residences.

It might be argued, however, that the high CO2 intensity of winter electricity will put upward pressure on the wholesale price of electricity and that this would motivate industry to cut production when there is a deficit, while also attracting imported power from neighbouring countries at these times. Csereklyei [51] finds that the price elasticity of electricity is almost twice as large for industry in Europe as for households: each 1% increase in electricity price is associated with a reduction in electricity demand from industry of 0.75%–1.01%. But this will not fully solve the problem, as industry cannot always ramp its production up and down from day to day, and neighbouring countries may be just as hard-pressed as Germany for winter electricity, since weather patterns do not stop at international borders.

From a systems level perspective it would therefore seem appropriate for society to invest in wind farms and storage, as a complementary element to low-net-energy dwellings, rather than simply installing over-large rooftop photovoltaic systems which feed most of their electricity into the grid at times when it is little needed.

5.4. Household photovoltaics and local grid capacity

A further consideration is that summer excess photovoltaic production from dwellings might not all be able to be fed into the grid for technical reasons. Dwellings are connected to local low-voltage grids, many of which are already at or near the limit of their electricity carrying capacity [60]. In Germany the Renewable Energy Sources Act (*Erneuerbares Energiegesetz*) gives local grid operators the right to curtail feed-in to 70% of a photovoltaic system's theoretical capacity. Currently this curtails very little photovoltaic production, since German sunshine is seldom intense enough to drive photovoltaic outputs above 70% of capacity [61]. However, if net-zero-energy renovations become popular and widespread, as the European Commission and German government desire, this threshold might have to be lowered to prevent overloading. This would subvert net-zero-energy building projects because some of their excess electricity would not be able to be fed into the grid, thereby spoiling their net-zero energy balance.

There are, nevertheless, two advantages of rooftop photovoltaics. One is that the area they utilize is already available and costs nothing. The other is that they relieve pressure on the electricity grid, as there are no grid line losses or loads for the electricity that is generated by the photovoltaic panels and used by the household. If around half a household's annual electricity use comes from its photovoltaic system, as it does with the 5.0 kWp system, this reduces loading on the local grid in summer and for some periods during spring and autumn.

5.5. Limitations of the study

The apartment building used in the study, in a medium-sized city in North Rhine-Westphalia, is typical of 1950s–1970s buildings in Germany. Of course, within this building stock, floor area, roof design, number of apartments per building, orientation to the sun and therefore heating needs can vary significantly. Also, the values of parameters such as household consumption, cost of photovoltaic systems, rate of system deterioration, discount rate and annual weather patterns can vary. The results of the study are specific for the case study apartment and one set of parameter values. However, the interactions of all the different factors would likely be comparable for most 1950s-1970s-era apartments in Germany. Net-zero-energy would not imply zero carbon emissions; aiming for zero carbon emissions on-site would be a highly inefficient use of capital that could better be used at the energy system level for wind farms and storage; increasing the capacity of rooftop photovoltaic systems beyond a certain point leads to a fall in rate of return; and the roofs of apartment buildings are not large enough to accommodate more than about 5.0kWp per apartment.

A further limitation of the study is that the seasonal variations in the heat pump's coefficient of performance, which are incorporated into the heating profile, were those typical for Germany and Austria, and not specific to the ambient air temperature variations of the specific apartment. This was due to lack of data on local air temperature conditions around the building. This could have either exaggerated or lessened the magnitude of the difference between summer and winter electricity consumption.

Further, the case study apartment uses an air-source heat pump, as these are increasingly common, but many upgrades use ground-source heat pumps. Future research could investigate what difference a ground-source heat pump would make to patterns of electricity consumption from the grid and the photovoltaic system.

5.6. Recommendations

In view of the difficulties of associated with achieving net-zero-energy at the building level, this paper confirms the proposal of recent scholarship that we aim instead for net zero carbon emissions *systems*. Here, a building is part of a larger energy system – in this case the electricity grid - and its performance can be optimized such that other elements in the system can supply its energy deficits at a lower carbon intensity than can be achieved by the building itself. It is therefore recommended that the governments and the European Union refrain from promoting net-zero-energy building retrofits. Instead, they should promote deep but economically practical retrofits, support household photovoltaics inasmuch as they reduce electricity flows to and from the national grid, and encourage major investment in wind power and hydrogen storage to move toward the achievement of a net-zero-carbon electricity grid.

6. Conclusions

This paper was set in the context of renewed calls for residential buildings to be renovated to "net-zero-energy" standard in conjunction with the aim of decarbonizing the building sector. This usually means thermally retrofitting a building to a high standard, substituting a heat pump for fossil fuel-based heating devices and installing photovoltaics (or other on-site renewables) to offset residual energy consumption. Although the technical and economic feasibility of this aim has long been questioned, it continues to emerge anew in government policies and scientific and popular literature.

This paper explored this issue in relation to Germany's large stock of 1950s-1970s-era energy-inefficient apartments, using a typical example of such an apartment. The difficulties with aiming for net-zero-energy were found to be, first, net-zero-energy does not necessarily equate to zero carbon emissions and in fact can fall far short of this. Second, such a dwelling still demands large amounts of electricity from the grid in winter, when electricity is highly carbon-intensive, and feeds large amounts of electricity into the grid in summer, when it is much less needed. Third, reaching net-zero-energy is very expensive compared to other ways of transitioning to a low- or zero-carbon economy. Fourthly, as increasing numbers of dwellings adopt electrically driven heat pumps, increased demand for electricity in winter intensifies the carbon content of grid electricity, and this is not solved by adding more photovoltaics. Finally, the cost of installing a net-zero-energy system is far higher than that of the smaller-sized system a household needs for all practical purposes, and the money could be spent on projects such as coastal wind power and hydrogen storage. Some authors therefore comment that "net-zero-energy" is a political goal or a kind of badge of honour, rather than a rational route to zero carbon emissions.

Author statement

This article was entirely the work of Ray Galvin. Dr Galvin used existing publicly available data, wrote the software for analysing it, performed the analysis, gathered and read relevant existing literature and wrote the article.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1. Initial checks on the simulation model

The output of the simulation model was checked by recording and graphing the quarter-hourly outputs of photovoltaic production, electricity consumption, self-consumption, feed-in to the grid, and consumption from the grid for selected days. Day profiles for 10 January and 07 July for a 6.5 kWp system in its 12th year of operation, with a 5 kWh battery, are given in Figures A1 and A2. The photovoltaic system deteriorates at a small annual rate, and the 12th year of operation is used, as this is near to the half-way point in the system's lifetime.

As Figure A1 shows, for 10 January production reaches almost 0.17 kWh for the midday quarter-hour slot and is never sufficient to fully cover consumption. It does, however, reduce consumption from the grid until late afternoon, after which all consumption is fed from the grid. There is no feed-in to the grid.

The profile for 07 July, given in Figure A2, shows there is sufficient production to cover consumption as from 08:45 (timeslot 35). The battery is full by 13:15 (timeslot 53) and at that point, electricity begins to be fed into the grid. By 17:45 (timeslot 71) the battery charge has fallen drastically, and photovoltaic production has fallen to below the level of household electricity demand, so the household then begins to use electricity from the grid. Its grid demand then matches its consumption throughout the evening from 20:15 (timeslot 81), when the photovoltaic panels cease producing electricity.

The battery charge profile in Figure A3 shows the battery charging rapidly in the mornings, flattening out at its full charge of 5 kWh by about 13:00 as the household begins to feed electricity into the grid, then collapsing rapidly in the late afternoon.

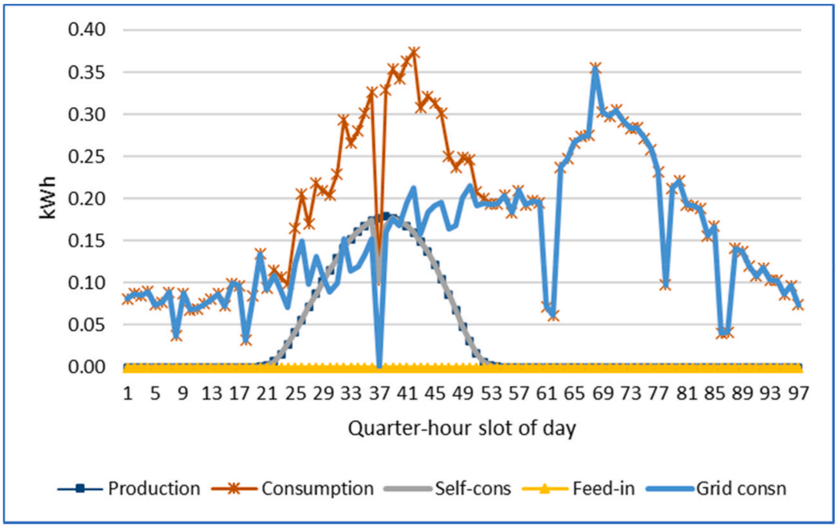

Fig. A1. Electricity production, consumption, self-consumption, feed-in and grid consumption, 10 January, for 6.5 kWp system with 5 kWh battery in 12th year of operation. The electricity flows are given in kWh for each quarter-hour timeslot.

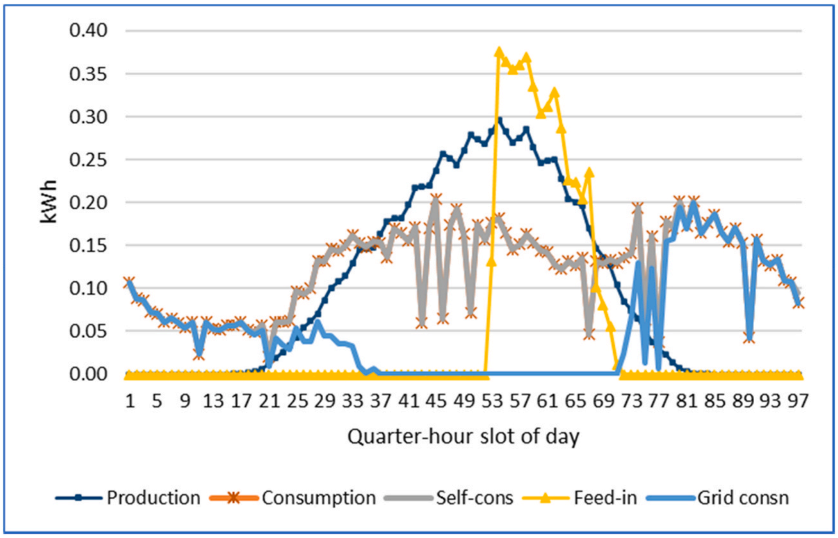

Fig. A2. Electricity production, consumption, self-consumption, feed-in and grid consumption, 07 July, for 6.5 kWp system with 5 kWh battery in 12th year of operation. The electricity flows are given in kWh for each quarter-hour timeslot.

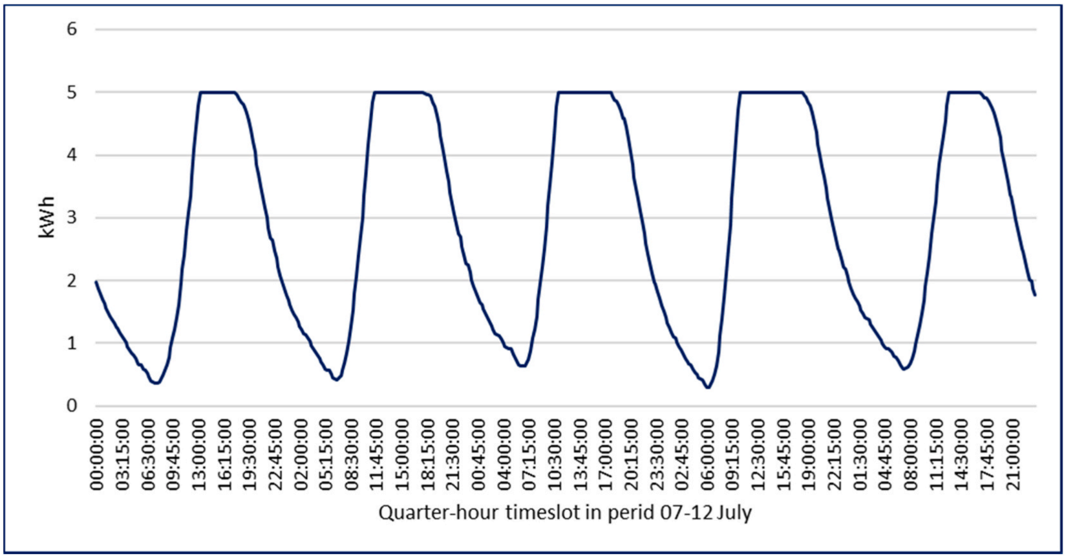

Fig. A3. Battery state of charge over the 5 days 07–12 July, 5 kWh battery with 6.5 kWp system (year's timeslots 17,949–18429).

Appendix 2. The simulation tool

The tool used to simulate and predict future electricity flows, costs and benefits is an adaption of the program used by Galvin [54], but using the specific data for the case study apartment in this study. The program estimates 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 heat pump and rebound effects. The core of the program consists of three loops. The inner loop maps parameter values in each quarter-hour through a full year, based on the quarter-hourly data for photovoltaic production and household electricity consumption. For each quarter-hour timeslot, the household consumes its own-produced electricity as first priority. If there is excess production, the priority is to use this to charge the battery. If the battery is full or becomes full during this timeslot, the excess is fed into the grid. If there is insufficient own-produced electricity for the household's consumption, the first priority is to take this from the battery. If the battery is empty or becomes empty in this timeslot, the electricity is taken from the grid. All the parameter values are stored in arrays. The state of charge of the battery is carried over into the next timeslot.

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

This loop is 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 are adjusted annually according to the discount rate and assumed changes in electricity price.

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

The program can be 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 coding of the program is available to readers as Supplementary Material in the Supplementary material (http://www.justsolutions.eu/DataInBrief/).

Appendix 3. Impacts of winter load on CO2 intensity of electricity grid

The CO2 intensity of electricity consumed from the grid can be correlated with the magnitudes of the different sources of electricity fed into the grid. An ordinary least squares multivariate analysis was performed using the net CO2 intensity of grid electricity as the dependent variable, and the main sources of generation as the independent variables. The unit of observation is days (24-h periods) rather than quarter-hour timeslots, as this avoids the distorting effect of there being no photovoltaic generation at night and very little consumption. The regression equation is:

$$I_q = \beta_{qP}.P_q + \beta_{qW}.W_q + \beta_{qF}.F_q + \beta_{qN}.N_q + \ldots + e + K \tag{A1}$$

where I_q is CO2 intensity I on day q, P_q, is the magnitude of Photovoltaic electricity (GW) produced on day q, W_q is the magnitude of Wind electricity (GW) produced on day q, F is the magnitude of Fossil-based electricity (GW) produced on day q, N is the magnitude of Nuclear-powered electricity (GW) produce on day q etc., are the magnitudes of electricity (GWh) produced by each different source on days q, β_{qP}, etc., are the regression coefficients, e is the error term and K is the constant. The regression results are given in Table A1.

The coefficients show that each extra GWh of photovoltaic input to the grid in summer ($91 < day < 273$) reduces its carbon intensity by 0.930 tCO2/GWh, whereas each extra GWh in winter ($day \leq 91$ and $day \geq 273$) has a much higher impact, reducing the grid's CO2 intensity by between 1.315 and 1.552 tCO2/GWh. Unfortunately, however, much less photovoltaic electricity is produced in winter than in summer.

The biggest positive impact on the grid's CO2 intensity is from fossil fuel sources. The regression coefficients indicate that each extra GWh of fossil-based electricity fed into the grid increases its CO2 intensity by between 2.284 and 2.957 tCO2/GWh. Nuclear-based electricity increases the CO2 intensity slightly in winter but reduces it markedly in summer. Wind-based electricity always reduces the CO2 intensity but by a greater amount in winter than in summer.

Table A1
Regression results: Electricity production of main sources, regressed against CO2 intensity of electricity consumed, by day totals, 2019.

Regressed against tCO2/GWh consumed	Coefficient (and p-value)	Coefficient (and p-value)	Coefficient (and p-value)
Production (GW) of electricity from:	**91<day<273**	**day> = 273**	**day<=91**
Photovoltaic	−0.9302575	−1.315042	−1.552149
	(0.000)	(0.000)	(0.000)
Wind	−0.2643044	−0.5815737	−1.353167
	(-0.013)	(0.459)	(0.003)
Fossil	2.283715	2.956628	2.587328
	(0.000)	(0.000)	(0.000)
Nuclear	0.6561269	−4.534841	−3.97624
	(-0.005)	(0.033)	(0.224)
Constant	767.7052	2104.649	2801.683
	(0.000)	(0.000)	(0.000)
Observations	181	93	91
F	0	0	0
Adj R-squared	0.9405	0.8675	0.8987

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