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# Novel load matching indicators for photovoltaic system sizing and evaluation

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## HIGHLIGHTS

- Classical load matching indicators are incapable of advising photovoltaic capacity.
- Novel indicators with technical optima are introduced for PV sizing.
- Self-production can be a useful metric for maximizing renewable share on-site.
- Grid-liability indicator is practical when planning off-grid sites.

## ARTICLE INFO

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## ABSTRACT

Integration of renewable energy sources in energy systems is crucial in achieving climate goals. Transformation of the power system – decentralization and prosumerism has led to the spread of domestic power plants taking part in the process. Mismatch problem of these predominantly grid-connected systems are typically described with load matching indicators. Most commonly used self-consumption and self-sufficiency metrics, though come with limits. One of the greatest is that they are monotone as the function of the capacity of photovoltaics implemented, making them uncapable of suggesting a technical optimum for system size. The scope of this study is to introduce two novel indicators with technical optima those can serve as a sizing principle for domestic photovoltaic plants for different approaches. First, self-production metric is introduced which allocates photovoltaic capacity that delivers maximum renewable utilization on-site and second, grid-liability reveals an optimum from the perspective of minimizing grid usage.

A reference building is studied with two control approaches to observe both the existing and indicators. As a base scenario, a water heater with classical control is simulated, while in the second case, demand side management is achieved via improved rule-based control, aiming to store surplus photovoltaic power production. Simulations reveal that the optimum capacity of the photovoltaics from the perspective of both self-production and grid-liability is much lower than the capacity (of 6.57 kWp) that would cover the annual electricity demands of the observed household. In case of the traditional control, self-production leads to an optimal photovoltaic capacity of 4.38 kWp, while grid-liability to a 0.73 kWp. With improved control, optimal capacities are much closer, 2.92 and 2.19 kWp respectively.

## 1. Introduction

Residential buildings account for a significant part of both energy consumption and greenhouse-gas emissions [1]. Consequently, dwellings are often considered in regulations aiming to mitigate environmental effects [2]. Aligning with the goals of minimizing energy consumption and enhancing the use of renewable energy sources, there is a rapid increase in technologies like heat-pumps and photovoltaic (PV) systems in the residential sector [3]. Intermittence of PV production leads to a mismatch between the generated power and the loads [4]. Hence, there is an increasing focus on the possibilities of matching the electricity generation and consumption and pushing the integration of PV further and further, especially, in case of electric heating and cooling appliances [5]. Efficacy of the different tools are most commonly

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described with load-matching and grid-interaction indicators. These metrics focus on the quantification of the simultaneity of the load and the on-site power generation. Various indicators exist to describe the behavior of the system. Predominantly, self-consumption (SC) and self-sufficiency (SS) metrics are used, comparing the on-site utilization of the PV to either the PV production or the total load of the household [6,7].

Most of the studies seek the improvement of SC and SS indicators through storages and control strategies for fixed PV capacity. A group of studies focus on the utilization of storage and its sizing to enhance matching of production and consumption pattern for fix PV capacities and a selected control strategy. Thür et al. has investigated the effect of water storage size from 0.5 $m^3$ to 2 $m^3$ for PV capacities of 2.5 and 5 kWp [8]. Thermal mass activation has been in the focus of the paper from Pinamonti et al., conducting research for the behavior of three levels of thermal inertia activation under different climates with a capacity of 3.24 kWp domestic PV plant [9]. Ren et al. have highlighted the efficacy of the usage of phase change materials (PCM) for a Solar Dechatlon house with 5 kWp photovoltaics besides many possible design alternatives [10].

Another approach is reversing the question: sizing photovoltaics and selecting control methodology for a specific system to cover. Hassan has compared a fixed PV system and a two-axis tracking system for a selected household in Iraq [11]. Aiming to maximize the self-consumed energy, PV capacities have been observed as variables. Simulations based on the measured weather data and electric consumption have revealed that the maximum amount of annual self-consumed energy for the fixed system comes at a capacity of 7.15 kWp, while for the two-axis tracking system at 4.4 kWp. However, when comparing self-consumption and self-sufficiency metrics, the former yields better values for the fixed system, while the latter is more favorable for the two-axis tracking system.

Heinz and Rieberer have highlighted the effect of control strategies on load matching metrics [12]. Simulations with different control approaches have been carried out for a household equipped with an air-to-water heat pump and radiator heat emission system show that all the tested controls improve SC and SS. The most improved control strategy of theirs has been tested for various PV capacities, and it was concluded that a proper control strategy could enhance both indicators regardless of the PV size. Nevertheless, values are highly dependent on the peak capacity of the PV system. For peak capacity between 2 and 10 kWp, SC ranges from approximately from 0.4 to 0.18, while SS from 0.38 to 0.75 respectively. Renovation level and thermal energy storage (TES) size have minor effect compared to the PV size.

Reis et al. has focused on confirming the effectiveness of demand aggregation when observing self-consumption [13]. Authors found that demand aggregation is clearly an attractive investment for more than 6 dwellings, from the perspective of internal rate of return. More than that, self-consumption rates increase remarkably, from an approximate of 0.45 to 0.65, when appropriate building types are combined (a restaurant alone compared to a combination with a condominium and a bank), even without a storage. This can be pushed further with the use of battery storage, though this negatively impacts economic indicators. An important notice of the analyses of the measured load data is that load aggregation reduces self-sufficiency rates, while seeking the improvement of self-consumption.

Cao et al. have depicted that self-consumption and self-sufficiency (referred as on-site energy matching and on-site energy fraction in the study) curves flatten as a function of installed PV capacity. Furthermore the impact is more significant in case of an office building, where the available area for PV is relatively low compared to the electricity consumption [14]. For instance, saturation of SS at about 0.6 is visible on a range of 0 to 250 kWp (0 to 2000 $m^2$ PV area), of which at an area of approximate 200 $m^2$ SS = 0.3 is reached. Consequently, PV sizing has a dominant impact on SC and SS metrics as for the available roof area of maximum 200 $m^2$, in the range where self-sufficiency is almost linear with the PV area.

Similar findings have been revealed by Liu et al., investigating the effect of climate zones and PV orientation as a function of PV size for large 4 – 15 storeys high residential buildings, with floor area of 1000 $m^2$ each floor. PV area has a significant influence on the load matching indicators in the observed range, as also the orientation when the preferred south orientation is changed to east and west [15]. On the other hand, tilt angle modification within a reasonable range around the optimum has moderate effect. Further studies also involve variable size of battery to investigate the impact of various equipment sizes [16,17].

Mentioned studies examining PV capacity as parametric reflect in all cases that the capacity has a considerable effect on SC and SS metrics. However, these indicators show an anti-correlation as a function of PV size While from the perspective of SC a smaller capacity is more favorable, SS is enhanced for the larger capacities [13].

Alternatively, there are two frequent considerations for PV sizing. One is selecting a capacity which generates as much electricity as necessary to cover the needs of the case on an annual basis, creating a net zero energy building (ZEB). When sketching SC and SS as the function of PV capacity, this point comes as the intersection of the curves [18]. Though this kind of sizing does not consider impacts on the electricity grid and could result in large amount of feed-back to the grid when there is no electricity demand to be met at the building [19]. Various other indicators aim this exact problem, such as capacity factor, relative grid interaction index, dimensioning rate and others, which are quite helpful from the perspective of interpreting the interaction with the grid, though from the perspective of PV sizing are less handy as usually compared to the nominal connection values of the household [6,20].

Another quite common approach is providing economic evaluation for calculating PV size or other equipment [21,22]. This is more common and found in most of the previously mentioned studies where PV capacity is selected by some profit-orientated indicators. Nonetheless these calculations are prepared in distinctive economic environments, considering different tariffs, thus results vary remarkably.

The main objective of this paper is providing novel indicators those first, provide a better understanding of the effect of PV sizing regarding energy flows with the electricity grid, furthermore, are more expressive when comparing different control approaches. To do so, a short description is provided for the Classical load-matching indicators (2.1) and explained why Suggested metrics (2.2) are necessary. This is followed by the detailed Specification of the testing environment (2.3) which helps evaluating the Results (3) through the existing and novel indicators. A Discussion (4) is also contributed demonstrate applicability of the novel metrics with existing examples of the literature. Finally, Conclusions (5) are drawn, including an outlook for Future research (5.1).

| | |
|---|---|
| **Abbreviations** | |
| BEPS | building energy performance simulation |
| DHW | domestic hot water |
| DSM | demand side management |
| GL | grid-liability |
| PCM | phase change material |
| PV | photovoltaic |
| RES | renewable energy source |
| RBC | rule-based control |
| SC | self-consumption |
| SP | self-production |
| SS | self-sufficiency |
| TBS | technical building system |
| TES | thermal energy storage |
| ZEB | zero energy building |
| **Notations in equations** | |
| $A$ | load covered from the grid in a specific period |
| $B$ | surplus production of the photovoltaics in a specific period |
| $C$ | load covered directly on-site by the photovoltaics in a specific period |
| $L(t)$ | instantaneous load of the building |
| $P(t)$ | instantaneous power generation |
| $S(t)$ | instantaneous storage |
| $t_1$ | start of the observation period |
| $t_2$ | end of the observation period |

## 2. Methods and data

### 2.1. Classical load-matching indicators

Self-consumption and self-sufficiency are undoubtedly the most commonly used load matching indicators comparing the match or mismatch of electricity generation of grid-connected PV system and the load of the specific site [7,18]. However, as implicated by numerous research, they have a monotone trend as a function of PV capacity. Furthermore, while self-sufficiency is increasing, self-consumption is decreasing, hence it is impossible to optimize PV capacity aiming to maximize both. The reason is that these indicators either consider the amount of energy imported from, or the amount fed to the grid over a period of time [7,23,24]. In case of self-consumption, power generation utilized on-site is compared to the overall PV generation, while in case of self-sufficiency to the overall load of the household.

Denoting the instantaneous electrical load of the building with $L(t)$, instantaneous power generation with $P(t)$ and instantaneous storage with $S(t)$, PV generation utilized at any moments on-site can be expressed as $\min[L(t), P(t) + S(t)]$. $S(t)$ is positive for discharging, negative for charging, $t$ is any moment of time between the start and the end of the observed period $(t_1, t_2)$. Equations for self-consumption and self-sufficiency metrics are well detailed in many papers [6,14,18].

As explained, in case of self-consumption this utilized amount is compared to the total PV generation, which is written with the first Eq. (1).

$$SC = \frac{\int_{t_1}^{t_2} \min[L(t), P(t) + S(t)]dt}{\int_{t_1}^{t_2} P(t)dt} \tag{1}$$

While self-sufficiency is described with Eq. (2).

$$SS = \frac{\int_{t_1}^{t_2} \min[L(t), P(t) + S(t)]dt}{\int_{t_1}^{t_2} L(t)dt} \tag{2}$$

For better understanding, a visual representation is often suggested. Layout of the possible energy streams (Fig. 1) and the schematic outline of energy consumption and production (Fig. 2) provide a simple graphical explanation of the possible states of a grid-connected PV system, with $A$ being the load directly covered from grid, $B$ meaning surplus production injected to grid and $C$ standing for the on-site consumed PV production, $(A + C)$ describes load, $(B + C)$ describes PV production.

With the help of (Fig. 2), self-consumption can be expressed as:

$$SC = \frac{C}{B + C} \tag{3}$$

while self-sufficiency can be written in the form of:

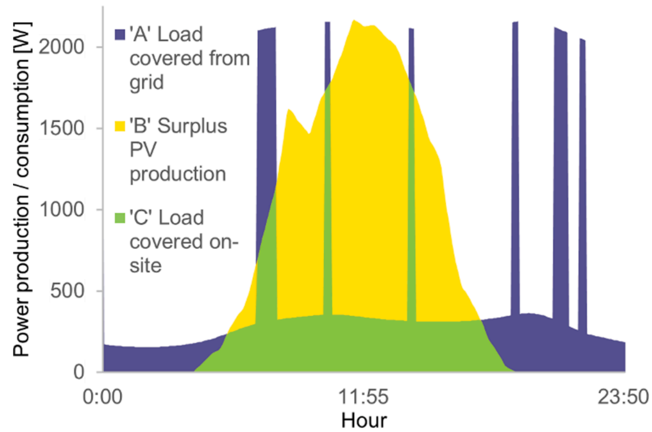


**Fig. 2.** Schematic outline of daily loads of a household with grid-integrated PV.

$$SS = \frac{C}{A + C} \tag{4}$$

[18].

The opposite trend of these metrics as a function of PV capacity makes evaluation hard in many cases (see Fig. 8 for the trends of SC and SS). There are suggestions resolving this, for instance, energy matching chart, visualizing both the metrics of SC and SS and the total load on an energy matching chart, sizing the points to the load of each cases [25]. Yet, this solution as well lacks defining an optimum from the perspective of suggested PV capacity.

### 2.2. Suggested metrics

#### 2.2.1. Self-production indicator

SC and SS indicators either involve the total load of the household or the production of the PV system as a base of comparison. In case of grid-connected systems, however, both are meaningful. Hence, self-production (SP) aims to merge these in one single indicator and express whether PV production enhances the on-site utilization or the feed-back in a larger extent. Comparing the on-site utilized ratio to the total energy flows of the case (sum of grid-covered, feed-back and on-site utilized amounts) self-production can be calculated as follows:

$$SP = \frac{C}{A + B + C} \tag{5}$$

The equation is restricted between the minimum of zero, when there is no PV production, therefore $C$ is zero, and a maximum of one, when the system is capable of perfectly matching the load at all times, without any interaction with the power-grid.

As any moment, $A$ and $B$ are mutually exclusive, self-production in a

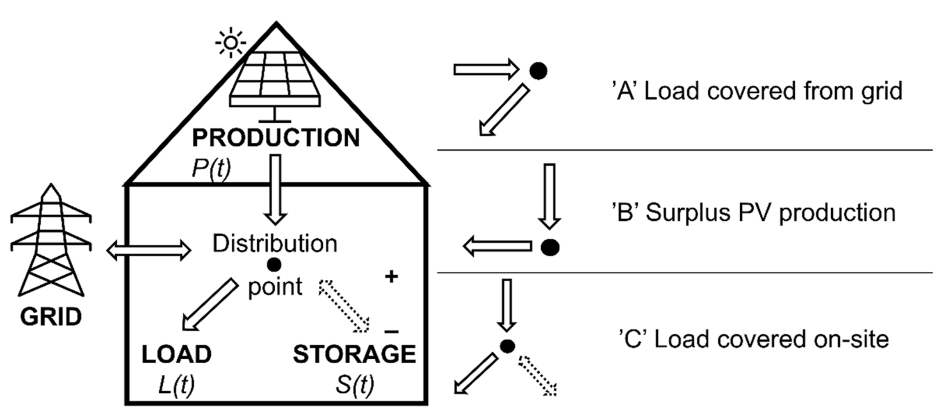


**Fig. 1.** Possible energy streams for a grid-connected PV system, storage with dashed as an optional energy stream.

more accurate mathematical form appears as the follows:

$$SP = \frac{\int_{t_1}^{t_2} \min[L(t), P(t) + S(t)]dt}{\int_{t_1}^{t_2} \max[L(t), P(t) + S(t)]dt} \tag{6}$$

Self-production indicator has a motive of preferring the integration of high-capacity intermittent renewable energy sources (RES) with the maximization of the on-site utilized ratio. Until the pace of on-site utilized fraction is more significant than the increase of feed-back, for example, SP will increase. However, these feed-back periods must be managed.

As a result, SP is suggested to be used for grids that are expanded enough to manage the surplus production of the observed cases for example sizing the PV for a specific case with the aim of covering the loads in the greatest extent directly on-site from solar friction or selecting a control strategy that could maximize on-site utilization of intermittent PV production.

#### 2.2.2. Grid-liability rate

Management of feed-back periods leads to a need for an indicator that focuses on the change in grid-interaction as well. Grid-liability rate aims to describe the variation in the amount of energy transferred through the grid-connection point no matter what the flow direction is. This can be done by setting the load as the base of reference and comparing the sum of grid-covered and feed-back amounts to that $(A + B)/(A + C)$.

To highlight the deviation in energy transferred via the grid, compared to the base case of no photovoltaics, one is subtracted, therefore zero means the base case, negative values suggest a decrease, positives an increase in the grid-transferred rates. Grid-liability can be described by the following equations:

$$GL = \frac{A + B}{A + C} - 1 \tag{7}$$

Furthermore, GL is again zero when as much energy is fed to the grid that is directly utilized from PV on-site $(B = C)$. That means the exact amount of grid-liability as for no PV, but with opposing direction – feed-ins instead of grid-coverage.

In the form of describing loads and powers it can be expressed as:

$$GL = \frac{\int_{t_1}^{t_2} |L(t) - \{P(t) + S(t)\}|dt}{\int_{t_1}^{t_2} L(t)dt} - 1 \tag{8}$$

The form comes with the lower limit of −100 %, which describes the ideal case of no interaction with the grid; all loads are exactly covered with the PV system at all times. This is also the optimum of the function, a minimum value, expressing a fully off-grid operation (consequently, $A$ and $B$ are mutually zero).

There is no upper limit for grid-liability, which practically expresses that with an increasing amount of PV the grid is more-and-more involved in managing the power balance of the specific case, as the energy exported to the grid diverges to infinity.

The significance of GL is that it truly reveals whether the grid is eased by adding photovoltaics to a certain site, or in fact, it is responsible in managing increased amounts of feed-ins as the result of the mismatching production and load. Accordingly, it is most useful when only limited grid is available (like in case of energy-communities) or when off-grid operation is in the focus. With the help of GL, PV size could be appointed to minimize the need for the grid-connection or to select appropriate control strategies. Table 1 summarizes the description of the indicators.

### 2.3. Specification of the testing environment

#### 2.3.1. Building data

Dynamic building energy performance simulation is the most common way of testing load matching indicators for different scenarios [26]. In the present study, a single-floor detached house was simulated with the net floor area of 98 $m^2$, volume of 283 $m^3$, compactness ratio of 1.19 $m^2/m^3$ and glazed surface area of 36 $m^2$. Thermal transmittance of the structural elements were set to meet the national nearly zero energy building threshold values of Hungary (external wall of 0.24, ground slab of 0.26, roof slab of 0.17 and glazed surfaces with 1.15 $W/(m^2K)$ respectively). Internal gains and ventilation rates were considered by the national standard [27].

Simulations were run with the Typical Reference Year of Budapest, setpoint temperatures of 20 °C for heating and 26 °C for cooling and resulted in net energy needs of 85.5 $kWh/m^2a$ and 4.67 $kWh/m^2a$ respectively [28]. Domestic hot water (DHW) consumption was considered by the profile suggested by the European Standard and the average amount of a Hungarian household of 126 l/day [29,30].

Typical electrical load profile curve, generated by a distribution system operator (based on the averaged profile of the distribution area of the operator, for the year of 2021) was used with an assumption of 2.500 kWh/year annual electricity consumption for the electrical appliances excluding the consumption of the technical building system (TBS) [31,32].

Geometric model of the building was set up in SketchUp [33]. The model was imported in TRNSYSv18, where further data (gains, weather conditions, technical building system layout and elements) were added to the model [34].

#### 2.3.2. Technical Building System

Most of nearly ZEBs are equipped with heat-pump systems for heating and cooling [35]. Vast majority of research consider heat pumps (either air-source or ground source) with water sink, as this provides an opportunity of utilizing TES either in the form of water tanks or building mass activation. In the meanwhile, air-to-air heat pumps could also provide an alternative for heating and cooling in residential sector, especially in case of building renovation scenarios [36,37]. The number of studies with air-to-air heat pumps is much more limited. A possible explanation of this is that the relatively low thermal capacitance of air requires the involvement of more complex technologies (such as phase-

**Table 1**
Summary of load matching indicators.

| Indicator *(also known as)* | Trend as a function of installed PV capacity | Equation | Min | Max | Optimum | Optimum at |
|---|---|---|---|---|---|---|
| Self-consumption *(Supply cover factor, On-site energy matching* [6,14,41] *)* | a decreasing curve | (1),(3) | 0 % | 100 % | 100 % | minimum or no PV |
| Self-sufficiency *(Self-generation factor, Load cover factor, On-site energy fraction* [6,14,41]*)* | an increasing curve | (2),(4) | 0 % | 100 % | 100 % | maximum PV capacity available |
| Self-production | provides an extremum in the form of a maximum | (5),(6) | 0 % | 100 % | 100 % | a specific PV capacity appointed by the optimum of the curve |
| Grid-liability | has a minimum as extremum | (7),(8) | −100 % | + ∞ | −100 % | |

change materials), to provide reasonable storage capacity for demand side management (DSM). [10,38]. On the contrary, electric resistance boilers that are often matched for DHW production when having and air-to-air heat pump systems, offer a high potential in on-site utilization of PV capacity [39]. Consequently, a combination of air-to-air heat pump for heating and cooling, and an electric water heater, covering DHW needs was considered in the simulations. TRNSYS component Type 786, variable speed compressor air-to-air heat pump was used with a rated heating capacity of 6.0 kW and rated cooling capacity of 5.0 kW. For DHW generation and storage, Type 156 storage tank with parameters of a typical electric water heater, a capacity of 0.12 $m^3$ and electric resistance heating of 1800 W was used.

In case of the grid-connected PV, panels of 365 Wp were oriented as optimal for the region, south facing, tilt angle of 35° [40]. PV array was simulated using Type 103, considering an overall system efficiency of 0.92. To determine the optimal PV capacity based on the introduced self-production and grid-liability indicators, simulations had been run from no PV to 11.68 kWp (32 panels) PV capacity. There was no battery storage simulated in this study.

#### 2.3.3. Control strategies

Operation of the air-to-air heat pump was common for both strategies. From the perspective of DHW generation control, two scenarios were considered. First, a conventional control for the appliances was analyzed and second, DSM was applied in order to assess surplus PV production - resistance heating of the water tank was modulated to the excess power [41]:

a) Standard control strategy: DHW tank with a setpoint temperature of 50 °C, temperature dead-band of 4 °C. Electric resistance heating with a capacity of 1800 W, on–off control strategy. (Setpoint of 50 °C is the favorable from the perspective of energy losses and calcium-carbonate remains – scaling, though a minimum requirement from the perspective of avoiding legionella growth [42,43].)
b) Improved rule-based control (RBC) for DHW production: DHW setpoint temperature is based on the power balance of the household. Until the tank has not reached 50 °C, DHW control is the same as in the standard scenario. After reaching 50 °C and in case PV production exceeds the accumulated load of the household, setpoint is increased to 70 °C and resistance heating is modulated in the range of 0–1800 W to store surplus power of the PV instead of grid-injection (Fig. 3).

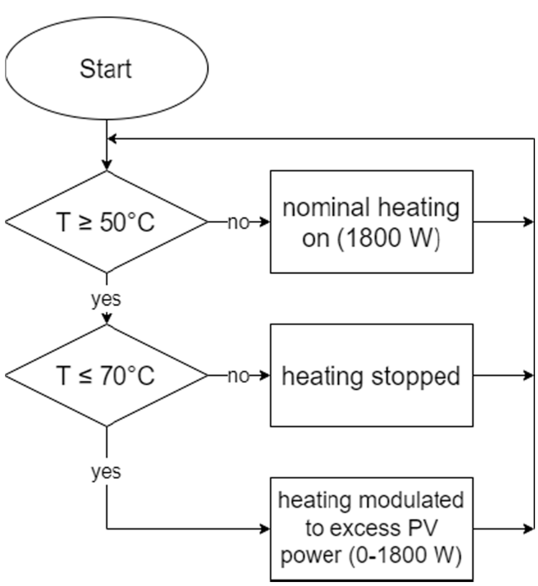


**Fig. 3.** Improved rule-based control strategy for demand side management of domestic hot water generation with the electric water heater.

In Section 3, synchrony of the possible PV production with both air-to-air heat pump operation and simple DHW generation (a) and air-to-air heat pump and improved DHW generation (b) is analyzed and compared.

## 3. Results

### 3.1. Qualitative analysis of the control strategy

Heatmaps of PV production (Fig. 4) and electric loads (Fig. 5) of the simulated case clearly reveal the difficulty of intermittent renewable energy source integration. Expectedly, PV production shows a peak in the middle of the year and the middle of the days (Fig. 4).

In contrast, on the demand side, electric load of the household appliances, the heat pump, and the classical DHW generation approach, peaks are mostly out of this timeframe. 15-minute averaged electric load of the household shows clear evening peak (Fig. 5). Though deviations are assumably higher with improved resolution, it is considered to have moderate effect from this order of magnitude [44]. Furthermore, compared with heat pump power and resistance heating power, electrical load of appliances is much lower.

In case of the heat pump operation, cooling provides a match with the PV generation as a result of increased irradiation. While for the summer period this provides the opportunity of direct on-site utilization of the PV for cooling, it is the opposite for the winter period. PV production is during the day, however solar gains reduce heat-needs in this period, meaning that electricity needs for heating appear at night, leading to a mismatch.

DHW production comes with the same level of loads as the heat pump, but in a more patterned way, aligning with the domestic hot water consumption of the household. Comparison of PV production and DHW power reveals, that most of the electricity consumption of hot water generation is also out of the high peak PV periods. Regardless of the day of the year peak DHW loads appear once early in the morning at around 7–8 am., and once at night, in the period of 7–10 pm. Only a minimal DHW generation appears during the day when there is PV peak production. Improved RBC of DHW generation aims to balance this mismatch, shifting electric load of hot water production to periods with surplus PV production.

Fig. 6 sketches the efficacy of the improved RBC of DHW production for a spring day. This clearly suggest that there are periods when DHW generation can completely be achieved with the use of PV. This type of control strategy is the most effective during spring and fall periods,

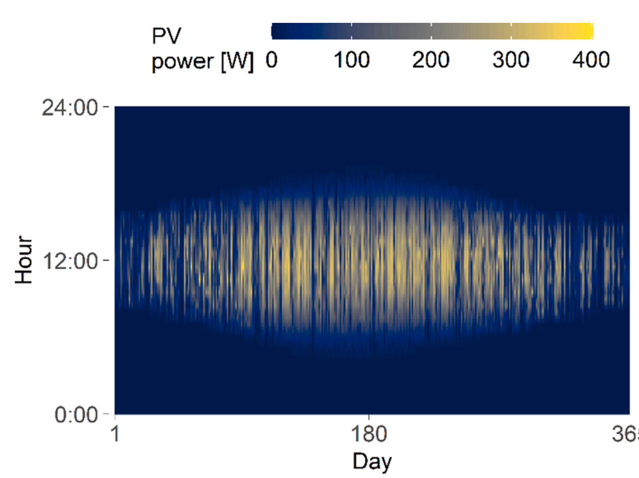


**Fig. 4.** PV production of a south faced, 35° tilted 365 Wp module.

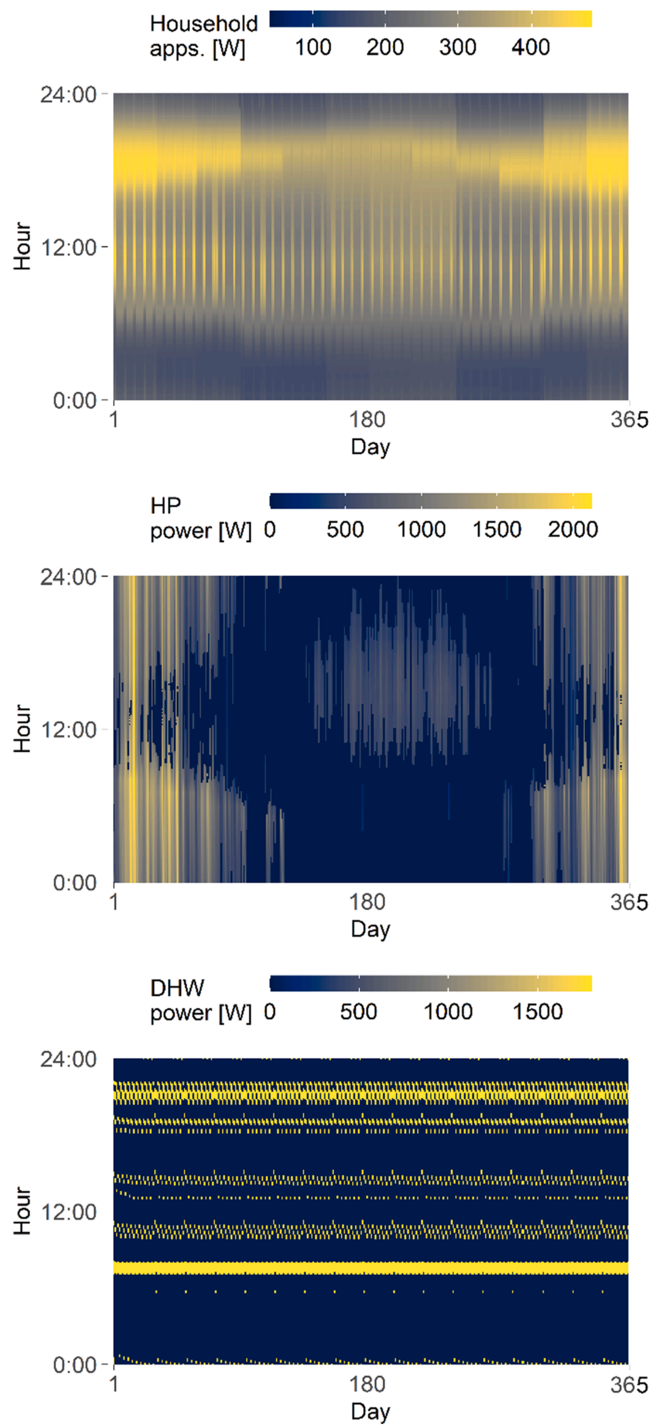


**Fig. 5.** Electric load of household appliances, heat pump and domestic hot water production across the year.

when there is enough radiance for high amount of PV production and relatively low or no need for heating or cooling (Fig. 7).

Comparison of the accumulated load diagrams of the original case and the improved RBC case assuming PV capacity of 2.92 kWp suggest, that when there is available excess power, from spring to autumn, RBC helps managing DHW generation to morning periods with an extended timeframe as of setting a higher temperature to the boiler to assess PV surplus power.

Furthermore, night-time DHW generation becomes unnecessary, as the higher temperature is enough to mostly cover these periods as well, starting the cycle the other morning again. This also highlights the improvement of matching the load to excess PV. Use of the control strategy comes to a limit in winter period when PV production is moderate and consumed also by the heat-pump for heating.

### 3.1.1. *Effect on self-consumption and self-sufficiency*

Self-consumption and self-sufficiency also reflect, that even in case of such a layout, on-site PV use can be successfully increased with proper control of the DHW generation. Evaluation of the improved RBC through the classical load matching indicators for PV capacities in the range of 0 – 11.68 kWp can be seen in Fig. 8. For the capacity of 2.92 kWp, it is shown that SC can be pushed from originally 46.0 % to 62.9 % while SS is increased from 21.1 % to 33.6 %.

Furthermore, intersection of curves SC and SS are approximately at the same PV capacity, 6.57 kWp for both controls. As this point stands for the net ZEB PV capacity [18], this implicates that the change of overall energy consumption due to the different control strategy is insignificant. DHW generation data justifies this assumption, as comparing no PV scenario with 11.68 kWp, the difference is only 5 % (1,936 and 2,032 kWh/year respectively), which aligns with the results of similar studies [39].

Classical load matching indicators successfully highlight the improvement of on-site utilization that can be achieved by a specific control strategy. However, SC and SS are uncapable of suggesting a specific capacity to install, as the metrics show an opposite monotonicity as a function of PV capacity. Novel self-production and grid-liability rate indicators aim filling this gap.

### 3.1.2. *Effect on self-production and grid-liability*

Introduced self-production and grid-liability indicators are useful from the perspective of PV sizing. As described earlier in Table Table 1, both metrics have an optimum for the PV capacity suggested for the TBS. In case of self-production, the optimum is a maximum. The higher the value, the more amount of energy is covered directly by the PV.

Fig. 9. Reveals, that originally, the amount of energy need provided directly on-site from the PV comes mostly at in the range of 10–20 %. With the improved RBC this can be increased significantly, even up to 30.0 % (II.rbc). The trend of the curve reveals that in case of relatively small PV capacities the increased power output of PV panels is consumed by the household mostly. However, a further push in peak capacity increases periods, when feed-in is necessary to manage PV power, as RBC cannot handle increased amounts. The share of the PV is getting fed to the grid will be greater than the amount utilized on-site.

As the consumption, $A + C$, is almost the same for all PV sizes, even the improved RBC cases, SP expresses the change in on-site utilized PV production ($C$) and electricity fed back to grid ($B$). Thus, it successfully highlights that when increasing the amount of renewable energy, after a certain point electricity is produced more to the grid ($B$) than for self-usage ($C$).

This also leads to the fact, that the PV capacity that would achieve net ZEB system (6.57 kWp, Fig. 8.) is not the best from the perspective on-site utilization of photovoltaics, because high amount of feed-ins have to be considered due to the mismatch of PV generation and the loads of the household (Fig. 5).

Like classic metrics, self-production also reflects the efficacy of the improved control, as its value is notably higher for all PV capacities, meaning that the improved RBC is working properly. However, it contains the surplus information about the advised PV capacity in case of aiming to maximize RES share for a site with accounting the feed-backs also. From this perspective, Fig. 9 highlights that there is a shift in the capacity of the suggested PV size when applying different control strategies. To assess a notable increase in SP, from 17.3 % in the original case (II.o) to 30.0 % (II.rbc) in the improved RBC case, a PV capacity reduction is advised from 4.38 kWp to 2.92 kWp.

Grid-liability focuses on the change in grid-usage. It has a minimum point as an optimum (III.o and III.rbc), expressing the reduced amount of energy transfer via the grid, to a base of no PV. For small capacities of

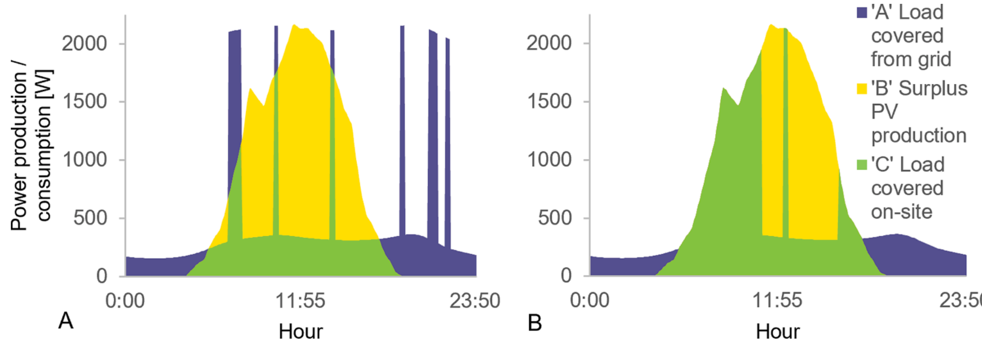


**Fig. 6.** Hot water production with original control (A) and effect of improved hot water production control (B) on the load diagram of the household for 14th, May, assuming PV capacity of 2.92 kWp.

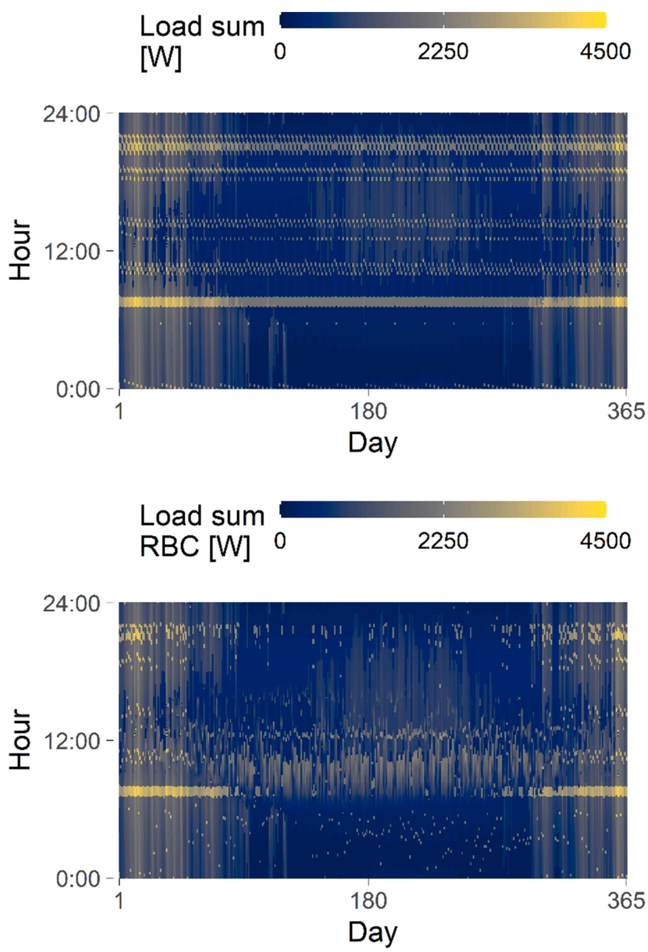


**Fig. 7.** Heatmap of accumulated electrical load of the household with the original control, and the improved rule-base controlled hot water production, for 2.92 kWp PV.

PV, on-site utilization of the panels can be fully reached (as expressed with SC = 100 %). Though after a certain point, the increased amounts of feed-ins are more significant than the production for self-usage. For the standard control case the maximum modification in grid-liability is −8.5 % (III.o). The improved RBC provides much better result, as anticipated, with an optimum of −26.3 % (III.rbc) energy transfer via the grid compared to the base scenario.

Again, improved control has not only an effect on providing a decreased minimum for GL, but also on the preferred PV size as well. It can achieve the same amount of interaction with the grid as the

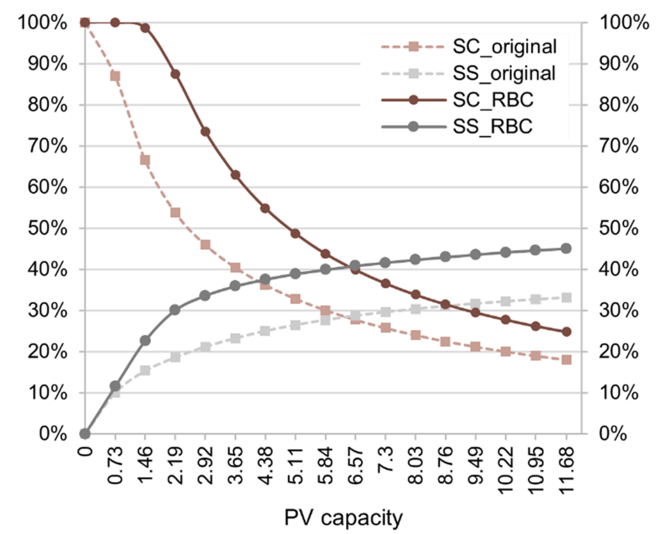


**Fig. 8.** Self-consumption (reddish) and self-sufficiency (greyish) curves as a function of PV capacity, with the original (dashed) and the improved rule-based control (continuous).

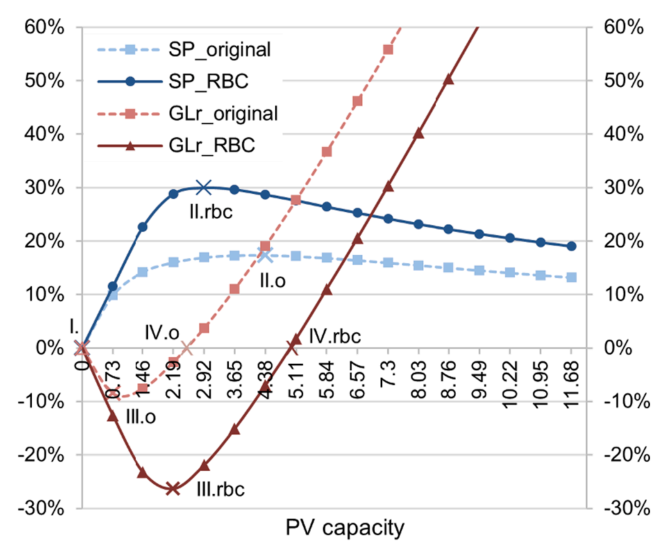


**Fig. 9.** Self-production (blueish) and grid-liability (reddish) indicators as a function of photovoltaics capacity for the different control strategies of the technical building system, original (dashed) and improved (continuous).

reference base, up until the capacity of 5.11 kWp (IV.rbc) (instead of the 2.19 kWp (IV.o), when no improved control is used). This means that with improved RBC and capacity of 5.11 kWp PV the same amount of energy is transferred via the grid as when no PV assessed. Though this case, feed-backs also appear in the transfer. It should be highlighted, that similarly to self-production, minimal grid-liability can be achieved with a much lower capacity of PV than it is needed for the net ZEB energy balance.

## 4. Discussion

### 4.1. Potential of self-production and grid-liability curves

As an extent to the interpretation of the quantitative and qualitative results, a general overview is suggested for the introduced self-production and grid-liability metrics. Unlike self-consumption and self-sufficiency indicators, self-production and grid-liability come with optima – a maximum and a minimum respectively, when sketched as a function of PV capacity. Hence, they suggest a capacity for the photovoltaics when sizing for a specific application. Self-production metric has a preference of selecting the capacity for the photovoltaics, that provides the maximum available PV utilization on-site. Either loads covered from grid and surpluses fed back worsen the results. After reaching the maximum utilization, the curve of SP is slowly decreasing, reaching the limit of using PV production on-site thus producing electricity for the grid. SP thereof is suggested when extensive grid network is available for the user and rapid integration of renewables is a priority, while having regards that other participants will also consider implementing such technologies. Consequently, self-production is a suggested metric in such cases as the nearly ZEB regulations for the residential sector.

If the priority is given on a higher independency from the grid, grid-liability could be the useful metric to select the size of PV installed. This expresses that compared to the reference load, what is the reduction that can be achieved with a certain layout and control strategy. Fully off-grid utilization is described with a grid-liability rate of −100 %, expressing that to the reference, the proposed scenario is capable of totally being independent from the grid. Such metric can be useful when the aim is to create off-grid sites or communities with limited uptake of surplus renewable energy.

### 4.2. Outlook with novel metrics

Results shown in Section 3.1.2 highlighted that both self-production and grid-liability indicators can allocate a recommended PV size for a selected TBS layout and control strategy. However, as the metrics could be practical in many other comparisons, an outlook is provided from other perspectives found in the literature.

For instance, both self-production and grid-liability could be used even in case of comparing various control strategies. Heinz and Rieberer compared control strategies for an Austrian residential house, to judge the efficacy of different control strategies from the perspective of PV integration [12]. Regardless of detailing the specific strategies, results for eight different approaches can be seen in Fig. 10. SC and SS metrics can be reproduced with the data provided for a 7 kWp photovoltaics and 1 $m^3$ hot water tank. In general, it can be concluded, that where SC and SS metrics are the higher, SP and GL are better. However, GL helps indicating that in all cases whatsoever, grid usage is increased with the control strategy compared to a no PV scenario. This is probably due to the size of the PV As even with the best control strategy ("fully integrated"), 7 kWp of PV is a capacity that in the context increases the need for the grid with 8 %. However, for this slight increase of grid-usage, there is a significant ratio of renewable usage as SP is the highest in this case with approximately 23 %. Anticipating a similar trend of curves GL and SP as in Fig. 9., it is suggested that reducing PV capacity could significantly decrease grid-liability.

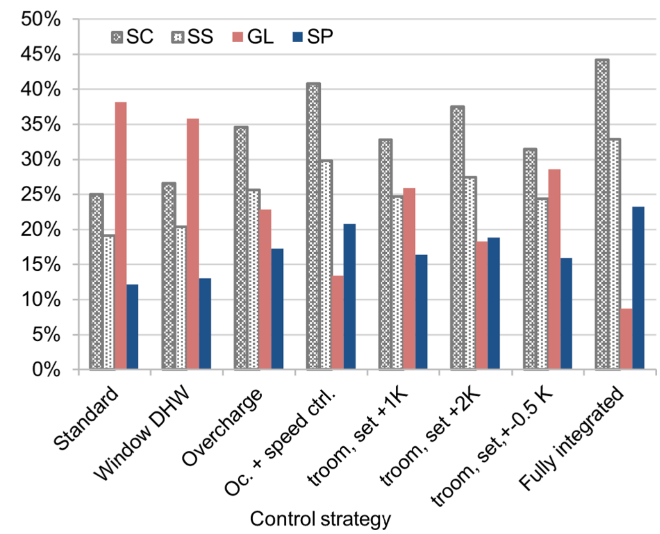


**Fig. 10.** Classical and novel indicators for different control strategies used by Heinz and Rieberer for 7 kWp PV integration for an Austrian household [12].

Besides selecting among control strategies, could be other approaches when the new metrics are useful. Hassan evaluated SC and SS indicators for a household in Iraq. A fix and a two-axis tracking system were compared parametrically for the PV capacity [11]. Fig. 11. Helps revealing further anticipations about the proposed systems. While it is explained that the tracking system enhances PV production, GL clearly reveals that it can also significantly increase the need for feed-back to the grid with an increasing PV size. As in the meanwhile SP remains approximately the same, it can be concluded that the increase of feed-back is much more dominant, than the increased on-site utilization of PV production.

## 5. Conclusions

The urgent transition to a sustainable residential building sector is generally foreseen with the integration of renewable energy sources, especially grid-connected photovoltaics. The intermittence of power generation of these domestic plants leads to the mismatch problem of production and consumption, which is usually described by load-matching indicators, especially self-consumption and self-sufficiency. These metrics are effective in comparison of for instance control approaches, however as both are monotonic curves as a function of the

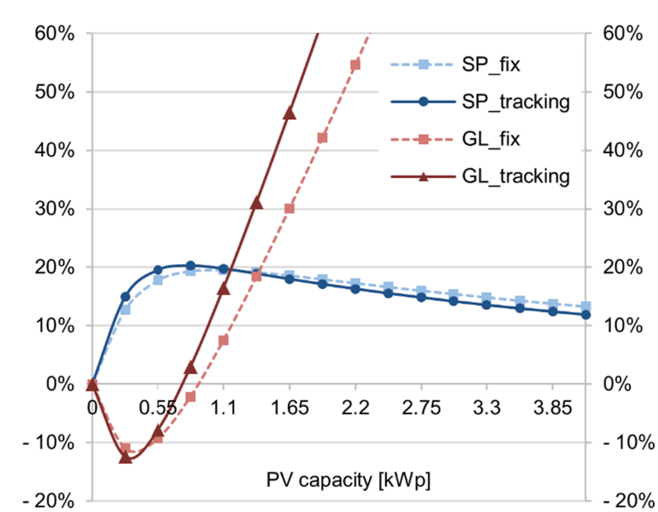


**Fig. 11.** Self-production and grid-liability metrics with the results of Hassan comparing a fix axis and a two-axis tracking system [11].

capacity of the photovoltaics, are limited when it comes to the sizing of PV. In this paper we suggested two novel indicators with optima that could resolve this.

One is the self-production indicator, that is to describe the amount of energy utilized directly on-site by the household, compared to the sum of load covered from grid, energy exported to grid, and energy utilized on-site. Self-production can be a useful indicator when aiming to maximize renewable share on a site that is connected to a grid which is sufficiently extensive for the management of feed-in periods.

The other proposed indicator is grid-liability rate, which expresses the change in grid-usage (either feed-in or from-grid periods) compared to the total load of the case. Grid-liability is advantageous when the connected grid is limited, or the goal is minimizing the interaction with the grid, such as in case of an off-grid operation or energy-communities.

Both the proposed indicators, also self-consumption and self-sufficiency metrics were tested with the help of building energy performance simulations in TRNSYS, with a technical building system of air-to-air heat pump for heating and cooling and electric resistance boiler for domestic hot water needs. It is proven that demand side management (with power modulation) of the electric boiler for storing surplus photovoltaic capacity is favorable for all the indicators.

The study justifies that when accounting grid exchange, the advised PV sizes are much lower than that of the net ZEB suggestions. Introduced metrics self-production and grid-liability provide simple and illustrative indicators to allocating the optimum capacity of the photovoltaic system to certain sites. With the original control strategy, compared to the approximate net ZEB providing capacity of 6.57 kWp, an approximate capacity of 4 kWp is suggested from self-production while 1 kWp from grid-liability perspective. While with the improved control, suggested capacities are much closer, approximately 3 kWp and 2 kWp respectively, but still much lower than of the 6.57 kWp capacity.

Besides the reduced capacities suggested, proper control indisputably improves both novel and classic metrics.

Eventually, demonstrating the applicability of the introduced metrics, an outlook is also provided with results of the scientific literature. It is suggested how self-production and grid-liability indicators could improve the interpretation of different control strategies and could help in the problem of selecting the photovoltaics for a specific site.

### *5.1. Future research*

The novel indicators bring up various questions that are necessary to answer. Most importantly, sensitivity analysis is to be carried out for the weather data, building specifications, technical building system layout (including PV orientation, use of batteries, etc.) and electric profile. Furthermore, the quantitative comparison of other load matching and grid interaction indicators (capacity factor, relative grid interaction index, dimensioning rate is planned to be carried out.

### *CRediT authorship contribution statement*

**László Zsolt Gergely:** Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Tamás Csoknyai:** Conceptualization, Resources, Writing – review & editing, Supervision. **Miklós Horváth:** Conceptualization, Resources, Writing – review & editing, Supervision.

## 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.

## Data availability

Data will be made available on request.

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## References

[1] International Energy Agency, 2019 Global Status report for Buildings and Construction, 2019.
[2] EPBD, Directive 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency, 2018.
[3] D'Agostino D, Tzeiranaki ST, Zangheri P, Bertoldi P. Assessing Nearly Zero Energy Buildings (NZEBs) development in Europe. Energy Strateg Rev 2021;36:100680. https://doi.org/10.1016/j.esr.2021.100680.
[4] Aszódi A, Biró B, Adorján L, Dobos ÁC, Illés G, Tóth NK, et al. Comparative analysis of national energy strategies of 19 European countries in light of the green deal's objectives. Energy Convers Manag X 2021;12. https://doi.org/10.1016/j.ecmx.2021.100136.
[5] Fischer D, Madani H. On heat pumps in smart grids: A review. Renew Sustain Energy Rev 2017;70:342–57. https://doi.org/10.1016/j.rser.2016.11.182.
[6] Salom J, Widén J, Candanedo J, Sartori I, Voss K, Marszal A, et al. 12th Conf. Int Build Perform Simul Assoc 2011;6(2011):2514–21.
[7] Al Dakheel J, Del Pero C, Aste N, Leonforte F. Smart buildings features and key performance indicators: A review. Sustain Cities Soc 2020;61:102328. https://doi.org/10.1016/j.scs.2020.102328.
[8] Thür A, Calabrese T, Streicher W. Smart grid and PV driven ground heat pump as thermal battery in small buildings for optimized electricity consumption. Sol Energy 2018;174:273–85. https://doi.org/10.1016/j.solener.2018.08.087.
[9] Pinamonti M, Prada A, Baggio P. Rule-based control strategy to increase photovoltaic self-consumption of a modulating heat pump using water storages and building mass activation. Energies 2020;13. https://doi.org/10.3390/en13236282.
[10] Ren H, Sun Y, Albdoor AK, Tyagi VV, Pandey AK, Ma Z. Improving energy flexibility of a net-zero energy house using a solar-assisted air conditioning system with thermal energy storage and demand-side management. Appl Energy 2021;285:116433. https://doi.org/10.1016/j.apenergy.2021.116433.
[11] Hassan Q. Evaluate the adequacy of self-consumption for sizing photovoltaic system. Energy Rep 2022;8:239–54. https://doi.org/10.1016/j.egyr.2021.11.205.
[12] Heinz A, Rieberer R. Energetic and economic analysis of a PV-assisted air-to-water heat pump system for renovated residential buildings with high-temperature heat emission system. Appl Energy 2021;293. https://doi.org/10.1016/j.apenergy.2021.116953.
[13] Reis V, Almeida RH, Silva JA, Brito MC. Demand aggregation for photovoltaic self-consumption. Energy Rep 2019;5:54–61. https://doi.org/10.1016/j.egyr.2018.11.002.
[14] Cao S, Hasan A, Sirén K. Matching analysis for on-site hybrid renewable energy systems of office buildings with extended indices. Appl Energy 2014;113:230–47. https://doi.org/10.1016/j.apenergy.2013.07.031.
[15] Liu C, Xu W, Li A, Sun D, Huo H. Analysis and optimization of load matching in photovoltaic systems for zero energy buildings in different climate zones of China. J Clean Prod 2019;238:117914. https://doi.org/10.1016/j.jclepro.2019.117914.
[16] Nyholm E, Goop J, Odenberger M, Johnsson F. Solar photovoltaic-battery systems in Swedish households – Self-consumption and self-sufficiency. Appl Energy 2016;183:148–59. https://doi.org/10.1016/j.apenergy.2016.08.172.
[17] Weniger J, Tjaden T, Quaschning V. Sizing of residential PV battery systems. Energy Procedia 2014;46:78–87. https://doi.org/10.1016/j.egypro.2014.01.160.
[18] Luthander R, Widén J, Nilsson D, Palm J. Photovoltaic self-consumption in buildings: A review. Appl Energy 2015;142:80–94. https://doi.org/10.1016/j.apenergy.2014.12.028.
[19] Cillari G, Franco A, Fantozzi F. Sizing strategies of photovoltaic systems in nZEB schemes to maximize the self-consumption share. Energy Rep 2021;7:6769–85. https://doi.org/10.1016/j.egyr.2021.09.117.
[20] Voss K, Sartori I, Napolitano A, Geier S, Gonçalves H, Hall M. et al. Load Matching and Grid Interaction of Net Zero Energy Buildings, in: EuroSun 2010, 2010: pp. 1–8. https://doi.org/10.18086/eurosun.2010.06.24.
[21] Pinamonti M, Baggio P. Energy and economic optimization of solar-assisted heat pump systems with storage technologies for heating and cooling in residential buildings. Renew Energy 2020;157:90–9. https://doi.org/10.1016/j.renene.2020.04.121.

[22] Jiménez-Castillo G, Muñoz-Rodriguez FJ, Rus-Casas C, Talavera DL. A new approach based on economic profitability to sizing the photovoltaic generator in self-consumption systems without storage. Renew Energy 2020;148:1017–33. https://doi.org/10.1016/j.renene.2019.10.086.
[23] Salom J, Marszal AJ, Widén J, Candanedo J, Lindberg KB. Analysis of load match and grid interaction indicators in net zero energy buildings with simulated and monitored data. Appl Energy 2014;136:119–31. https://doi.org/10.1016/j.apenergy.2014.09.018.
[24] Finck C, Beagon P, Clauß J Péan T, Vogler-Finck PJ, Zhang K. et al. Review of applied and tested control possibilities for energy flexibility in buildings, 2018. https://doi.org/10.13140/RG.2.2.28740.73609.
[25] Luthander R, Nilsson AM, Widén J, Åberg M. Graphical analysis of photovoltaic generation and load matching in buildings: A novel way of studying self-consumption and self-sufficiency. Appl Energy 2019;250:748–59. https://doi.org/10.1016/j.apenergy.2019.05.058.
[26] Juntunen JK, Martiskainen M. Improving understanding of energy autonomy: A systematic review. Renew Sustain Energy Rev 2021;141:110797. https://doi.org/10.1016/j.rser.2021.110797.
[27] Ministry Without Portfolio of Hungary, Regulation 7/2006 determining the energy performance of buildings, (2020) 1–63. https://net.jogtar.hu/jogszabaly?docid=a0600007.tnm (accessed June 17, 2021).
[28] E.C. for S. CEN, EN 15251 (2012) - Indoor environmental input parameters for design and assessment of energy performance of buildingsaddressing indoor air quality, thermal environment, lighting and acoustics, 2012.
[29] European Committee for Standardization-CEN, EN 12381 - Energy Performance of Buildings - Method for Calculation of Design Heat Load - Part 3: Domestic Hot Water Systems Heat Load and Characterisation of Needs, 2012.
[30] Vámos V, Horváth M. Residential DHW consumption analysis for multifamily buildings supplied by district heating, (n.d.) 265–268.
[31] E.on, Statistical Load Profiles of Residential Consumers - 2021, (2022).
[32] Vámos V, Czétány L, Horváth M, Csoknyai T. Energy Consumption Cluster Analysis In Hungarian Buildings. Ondrej Sikula. Simulace Budov a Tech. Prostredi; 2020.
[33] Trimble, Google SketchUp 3D modelling programme, (n.d.). https://www.sketchup.com/.
[34] Klein SA. TRNSYS 18 - A Transient System Simulation Program, (2018). http://sel.me.wisc.edu/trnsys/.
[35] D'Agostino D, Mazzarella L. What is a Nearly zero energy building? Overview, implementation and comparison of definitions. J Build Eng 2019;21:200–12. https://doi.org/10.1016/j.jobe.2018.10.019.
[36] Xiao B, He L, Zhang S, Kong T, Hu B, Wang RZ. Comparison and analysis on air-to-air and air-to-water heat pump heating systems. Renew Energy 2020;146:1888–96. https://doi.org/10.1016/j.renene.2019.08.033.
[37] Gergely LZ, Csoknyai T. Parametric Analysis of Greenhouse Gas Emissions of the Technical Building System Alternatives in Detached Houses Retrofitted to nZEB Level, in: 2022: pp. 231-239. https://doi.org/10.5220/0011021600003354.
[38] Simko T, Luther MB, Li HX, Horan P. Applying solar pv to heat pump and storage technologies in australian houses. Energies 2021;14:1–18. https://doi.org/10.3390/en14175480.
[39] Clift DH, Suehrcke H. Control optimization of PV powered electric storage and heat pump water heaters. Sol Energy 2021;226:489–500. https://doi.org/10.1016/j.solener.2021.08.059.
[40] Mayer MJ, Gróf G. Techno-economic optimization of grid-connected, ground-mounted photovoltaic power plants by genetic algorithm based on a comprehensive mathematical model. Sol Energy 2020;202:210–26. https://doi.org/10.1016/j.solener.2020.03.109.
[41] Jensen SØ, Marszal-Pomianowska A, Lollini R, Pasut W, Knotzer A, Engelmann P, et al. IEA EBC Annex 67 Energy Flexible Buildings. Energy Build 2017;155:25–34. https://doi.org/10.1016/j.enbuild.2017.08.044.
[42] European Working Group for Legionella Infections, Prevention, Control and Investigation, of Infections Caused by Legionella species, Eur. Soc. Clin. Microbiol. Infect. Dis. (2017) 126. https://www.escmid.org/fileadmin/src/media/PDFs/3Research_Projects/ESGLI/ESGLI_European_Technical_Guidelines_for_the_Prevention_Control_and_Investigation_of_Infections_Caused_by_Legionella_species_June_2017.pdf.
[43] Kyritsi MA, Mouchtouri VA, Katsioulis A, Kostara E, Nakoulas V, Hatzinikou M, et al. Legionella colonization of hotel water systems in touristic places of Greece: association with system characteristics and physicochemical parameters. Int J Environ Res Public Health 2018;15. https://doi.org/10.3390/ijerph15122707.
[44] Elkholy A, Nafeh AESA, Fahmy FH. Impact of time resolution averaging analysis on integrated photovoltaic with office buildings and grid interaction metrics: Case study. Energy Build 2022;257:111818. https://doi.org/10.1016/j.enbuild.2021.111818.