

RESIDENTIAL LOAD MATCHING INDICATORS ACROSS EUROPE

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Abstract

This research uses load-matching indicators to investigate the relationship between PV generation and residential electricity consumption. It analyses how climatic conditions and various photovoltaic generation profiles influence these indicators across European countries and the effects of residential community size. The findings can serve as a baseline for evaluating the load on low-voltage networks, and for testing different demand-side management strategies.

Keywords

Load matching indicators, PV systems, Energy Communities, Demand Aggregation

1 INTRODUCTION

The installation of PV systems worldwide is still growing reaching a total of 1589 GW peak power in 2023 [1]. In the EU the installation of PV systems on buildings is incentivised by the 2024 EPBD directive [2]. While the installation of the PV systems is still supported by the legislation it poses a significant challenge for the electrical grid operation even in the developed countries [3]. Due to the challenges for grid stability, a strong focus has been set on motivating prosumers to increase the share of directly utilised photovoltaic generation. This can take various forms, involving technical aspects, like demand side management, or less technical approaches, like transforming the billing schemes to motivate prosumers. The latter can trigger two main different branches. One is the improvement of individual self-consumption (SC), as the prosumers become motivated by bills to do so. The other is forming energy communities and sharing the produced energy amongst the members (again, either in a technical or a less technical and simply accounting-focused system) [4].

Consequently, the SC of residential buildings is an actively researched field across Europe. SC highly depends on key factors, like photovoltaic system size and climatic conditions. To find common ground, the photovoltaic system sizing can be approached from the perspective of Net Zero Energy Buildings (NZEB), in which case PV systems are sized for an annual generation-to-demand ratio (GTDR) of 1, meaning these buildings generate as much energy over the year as they consume. Gjorgievski et al. examined SC rates for Cyprian households and found by analyzing measurement data that NZEBs have an average SC of 0.373. Similarly, for a warm, Spanish context Miranda et al. found SC values between 0.35-0.45 for NZEBs [5]. For colder climates with less irradiation, SC values are reasonably lower, for the Netherlands Litjens et al. calculated an average SC of 0.32 [6]. The above examples reflect the effect of individual climates on SC – regions with increased irradiation and warmer climates, in general, show higher SC at an NZEB PV sizing [7]. While there is a relatively wide body of literature on specific countries' contexts, comparative analysis of SC across different climates and regions is more challenging to find.

The focus of the present paper is to extend knowledge on how different climates and prosumer aggregation into energy communities affect the level of SC. The rest of the paper is organized as follows. The assumptions related to generation and load profiles, the specific countries examined, and the metrics utilised for evaluation are outlined in detail in the Methodology section. This is followed by the Results and Discussion, detailing the paper's findings. In the end, the Conclusion section summarises the key findings and the limitations set to be addressed by future work.

2 METHODOLOGY

Electricity consumption profiles

To evaluate the effect of different climates, the present study selected countries from different climate zones. We selected countries for which PV system orientations were publicly available [8], [9]. As a result, Denmark, France, Germany, Hungary and Italy were selected. For each of the countries weather data of the capital city was used, gained from System Advisor Model (SAM) [10].

When analyzing load matching of different regions, the load profile of the buildings observed is a crucial input in the analysis. However, there is a notable scarcity of publicly accessible measured load profiles, and the utilisation of varying load profiles may obscure the inherent effects of distinct climate zones.

The uptake of smart meter installations has enabled us to access accurate and high-resolution data electricity consumption profile data for the present study. In Hungary, more than 120,000 smart meters were installed in a pilot study led by KOM Kft [11]. These included electricity and gas meters. The measurements took place in 2018, which Czétány analysed in detail in his previous study focusing on electricity consumption [12]. For the analysis, 316 individual residential electricity profiles that do not have PV or a special tariff system were selected. A cluster analysis was performed on the filtered profiles to identify three diurnal profiles, representing the daytime consumption of residents, and three seasonal profiles, representing the consumption characteristics of different HVAC systems. Combining these classes can divide the profiles into nine categories considering daily and seasonal trends. Tab. 1 summarises the distribution of the 316 profiles between the different categories.

Tab. 1 Clustered residential consumption profiles.

Seasonal Characteristics \ Intraday Characteristics	A: Summer Peak	B: Winter Peak	C: Even Profile	Total
I: Morning and Evening Peaks	16	8	63	87
II: Evening Peaks	17	11	67	95
III: Even Daily Profile	49	20	65	134
Total	82	39	195	316

In our research, due to the lack of other available data with similar level of detail, we used the Hungarian profiles for each of the countries studied: Denmark, France, Germany, Hungary and Italy. These profiles do not fully represent these countries, but they suffice for load matching calculations, and they are sufficient for highlighting the impact of the solar production profiles discussed in the following sections. Furthermore, the focus of the research is on climatic conditions, thus ignoring the fact that some countries have different energy pricing (e.g. ToU), which may influence users' energy consumption behaviour.

PV generation profiles

PV production profiles were created in SAM for the above-mentioned countries based on 2018 weather data. In the program, solar panels with different azimuth and tilt angles were defined, with a module capacity of 4.14 kW. This was used to define the solar PV production profiles for the country and PV orientation.

Jamie M. Bright et al. [8], [9] studied the installed solar PV capacity in different countries. In this study, they examined the tilt angle, orientation, capacity and yield of solar panels, determining their various distribution functions. In our study, the buildings selected for solar PV production were individually assigned a country-specific PV orientation, which was determined using the distribution functions obtained as a result of previous research, thus representing the solar PV characteristics of the country. In the case of Hungary, where no such data is available, the orientations typical of the Austrian PV systems, the country closest to Hungary, was used.

The simulated solar profile was scaled to the solar capacity selected based on the orientation and tilt angle achieving the NZEB generation based on the consumption profile selected. This means that in the examination, households were either NZEBs or had no PV systems.

Profile aggregation method

The effect of profile aggregation was considered by forming different sizes of “energy communities”, which in this case, is simply a combination of consumer and prosumer profiles. Energy communities were expanded along two key parameters. Firstly, we increased the number of buildings from 1 to 300 by randomly selecting from the Hungarian consumption profiles. Secondly, for each residential community size, we randomly chose N buildings to which we assigned a solar PV capacity following the previously mentioned national distribution function, while the remaining buildings were designated as having no PV system. The latter was repeated 50 times to map the full PV penetration scale (resulting in a scale of 0 to 1, where 0 is no PV, 1 is a community where the demand is fulfilled with local PV generation on an annual base) per energy community with the number of NZEB buildings randomly chosen several times for a given energy community size.

The steps outlined above were utilized to determine the size and composition of the energy community, enabling us to summarize the consumption and production data for each community at each step. Network parameters in the study were not considered, thus the buildings can be thought of as lumped together in a common connection point, without any internal resistances or impedances. Simply the power and energy flows of the households are aggregated. This gave an aggregated annual production and consumption data set, which was analysed in detail in the next section.

Indicators evaluated

Load matching and performance indicators are used to evaluate the different PV penetrations. For these, the energy flows can be divided into three groups:

- Energy taken from the grid (A).
- Excess PV energy fed back to the grid (B).
- Energy produced and consumed on site (C).

This is illustrated in Fig. 1 for a sample day.

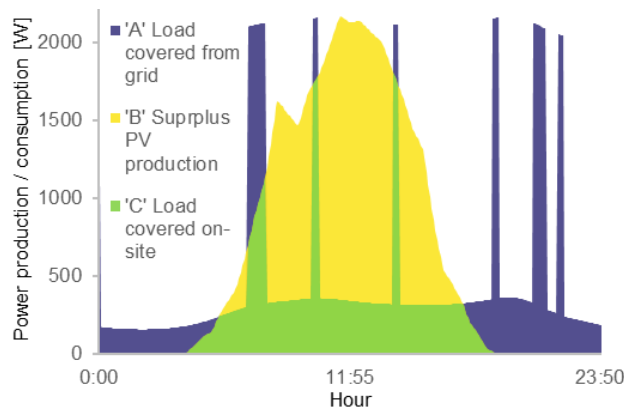


Fig. 1 Interpretation of energy streams on an example day [13].

Using this allocation, the following load-matching indicators were investigated:

- Self-consumption (SC) is among the most widespread load-matching metrics. It describes the share of PV production consumed on-site.

$$SC = \frac{C}{C + B} \quad (1)$$

- Self-sufficiency (SS), another common metric, describes to what extent the photovoltaic system covers the consumption on-site.

$$SS = \frac{C}{A + C} \quad (2)$$

- Self-production (SP) also focuses on the share of on-site consumption. However, it considers all the energy streams, the sum of feedback, the grid covered amount and on-site consumption as the comparison base.

$$SP = \frac{C}{A + B + C} \quad (3)$$

- Grid liability (GL) on the contrary, focuses on the change in interaction with the grid. It shows how the electricity grid usage changes compared to when there is no photovoltaic system. A decrease in the indicator suggests a lower energy transfer through the connection point. At the same time, values above zero indicate increased grid transfer due to more intense grid feedback.

$$GL = \frac{A + B}{A + C} \quad (4)$$

In addition to these indicators, we examined the load on the energy network using additional indicators. The number of feedback hours shows how many hours of surplus generation we had each year that we did not use locally. Similarly, we looked at the number of hours when the fed-back power exceeded the maximum consumption power originally consumed. This will be referred to as excessive feedback hours in the following. In addition to the feedback periods, we also examined the magnitude of these periods, for which we implemented the peak feedback/demand ratio. This illustrates the ratio of the maximum feedback power to the maximum power consumption of the original case.

3 RESULTS

While numerous papers research load matching of residential buildings, there is relatively little knowledge on how these indicators come out for different countries compared under a unified framework, like the same consumption profiles applied. Results section compares load matching of individual buildings across the selected countries and aggregated building stocks.

NZEB LMIs across different countries

When comparing load matching on an individual level across NZEB designs, the best indicators appear for the Italian case, followed by France, Hungary, Denmark and Germany. The Italian indicators are very different from those of the other countries, while the other countries show minor differences compared to each other. While Italy reaches an SC of 0.335, in the case of Germany the mean value of SC is only 0.288.

GL also exposes major differences across these countries. While the Italian case is 0.330, meaning there is a +33% grid usage for energy transfer in this case, GL in case of Germany is much higher, 0.425. Findings highlight that achieving net zero buildings in climates less favourable for PV utilisation is a much higher challenge from the perspective of integrating these into the electricity grids. The data are shown in Tab. 1 and illustrated in Fig. 2.

Tab. 1 Mean and standard deviation values of load matching indicators for individual NZEB consumers with different profiles by country.

indicators	countries	DE	DK	FR	HU	IT
SC	mean	0.288	0.300	0.314	0.307	0.335
	std	0.041	0.043	0.044	0.041	0.045
SS	mean	0.288	0.300	0.314	0.307	0.335
	std	0.041	0.043	0.044	0.041	0.045
SP	mean	0.169	0.177	0.187	0.182	0.202
	std	0.028	0.030	0.031	0.029	0.032
GL	mean	0.425	0.399	0.372	0.385	0.330
	std	0.081	0.087	0.087	0.082	0.090

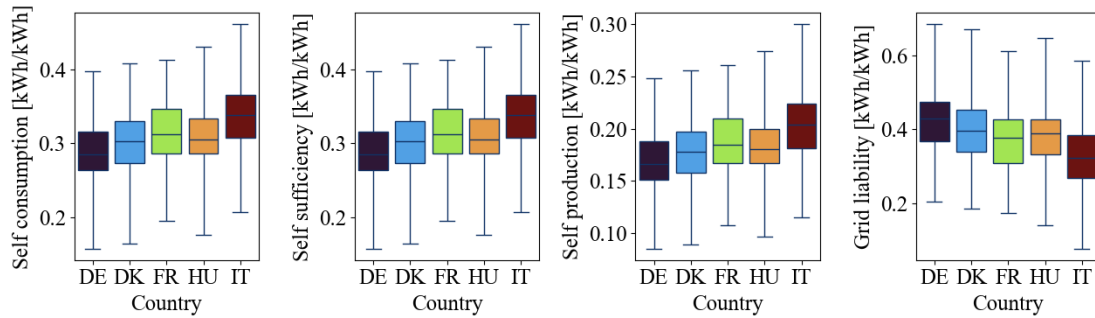


Fig. 2 Boxplots of load-matching indicators for individual NZEB consumers with different profiles by country.

Load matching of energy communities across countries

When evaluating indicators across larger communities, the most important note is the stationarity of the elbow points. For all the countries and LMIs, elbow points appear at relatively small communities with 20-30 participants, as shown in Fig. 3. This highlights that the portfolio effect of demand aggregation is the most effective in small communities; no further improvement can be expected under the same generation profiles.

As expected, lower PV penetrations produce a much lower load matching, except for the case of SS. From the perspective of GL, for example, a PV penetration of 0.5 exhibits a reduced grid usage (as compared to a no PV scenario). While PV penetrations of 1.0 highlight an increased grid usage.

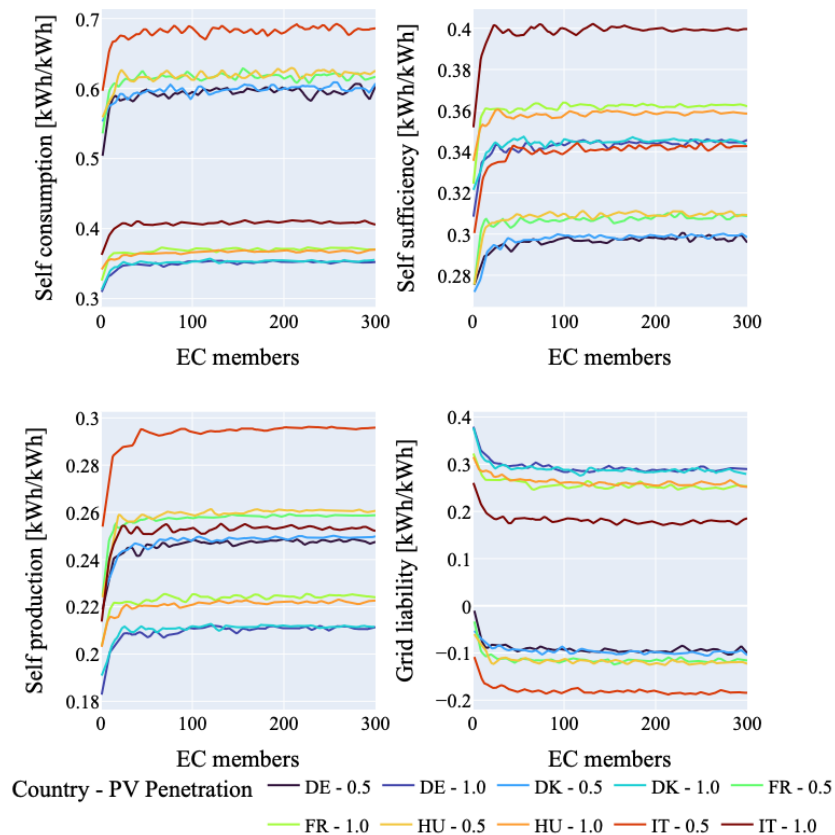


Fig. 3 Load matching indicators as the function of energy community size with 1.0 and 0.5 PV penetration in different countries.

Power metrics of energy communities across countries

Power indicators present some variations, yet consistent with the previous results, as shown in Fig 4. Across these metrics, again, the Italian case can be distinguished easily. For the Italian example, the amount of feedback hours is significantly higher than in all the other examples, reaching 2,600 hours (regardless of the community size) in case of PV penetration of 1.0. Meanwhile, the peak feedback per peak demand ratio remains the lowest and excessive feedback hours, that is, the aggregated number of periods when feedback is higher than the original peak demand appears to be the same as in other countries. Elbow points of the latter two indicators across the size of the EC is also influenced by the specific country.

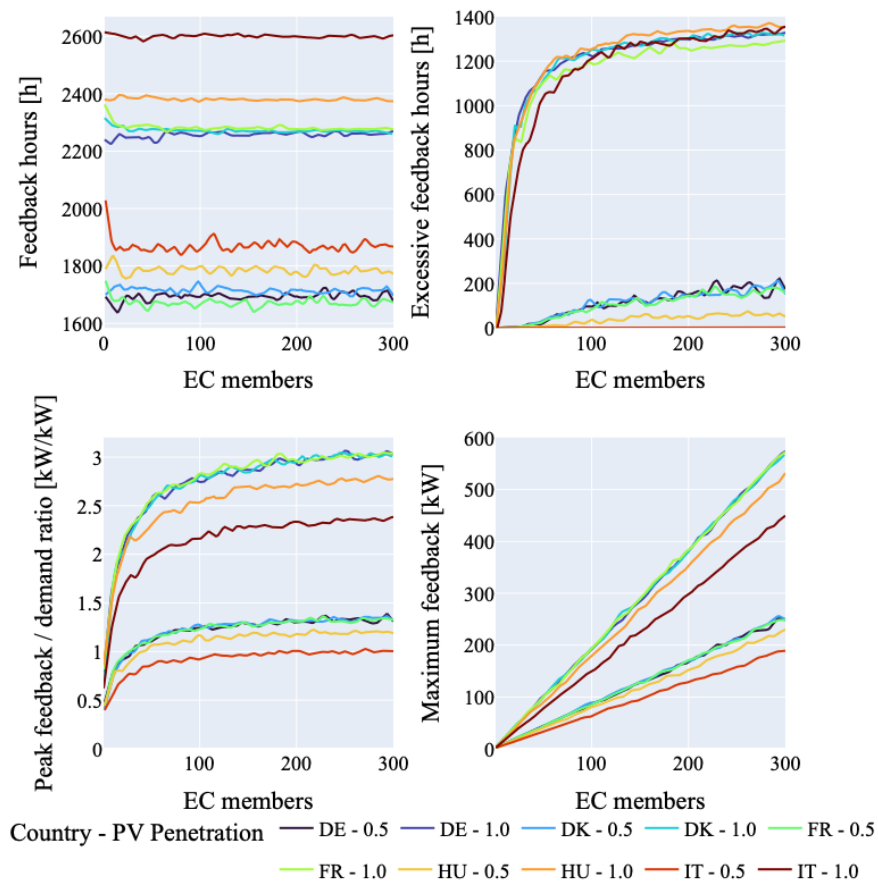


Fig. 4 Energy and power indicators as the function of EC size with 1.0 and 0.5 PV penetration in different countries.

A possible explanation for all this can be found in the size of photovoltaic systems. Countries with longer sunshine hours necessitate smaller PVs, which is favourable from the perspective of load matching as production peaks are relatively lower; thus, the same loads can cover a relatively higher ratio of the production peaks in the same periods. Meanwhile, the longer the period the wider the timespan when there is notable PV production. Consecutively, there can be more periods when the PV production is higher than the load of the building.

Load matching of large energy communities across countries

From the above described, we have seen that after the elbow points, the values of the load-matching indicators are nearly constant ($EC > 30$), and the power indicators also take on a linear character ($EC > 100$). Accordingly, the load-matching indicators can be evaluated as a function of PV penetration for larger energy communities

Fig. 5 shows that the load-matching indicator values for communities with more than 100 members, as a function of PV penetration take on a similar character as observed in other studies [13] for individual buildings. The different points per PV penetration (that would appear as a result of minor variation across the EC sizes)

are fitted curves applying the LOWESS method from *statmodels* package [14]. The Italian indicators are also outstanding in this case for the reasons already discussed. Comparing the functions with the data in Table 1, we can see that the data for PV penetration 1 shows an improvement of 10-20% in each case. Moreover, the optimum points of the SP and GL functions also take a more favourable value, which is achieved at higher PV penetration.

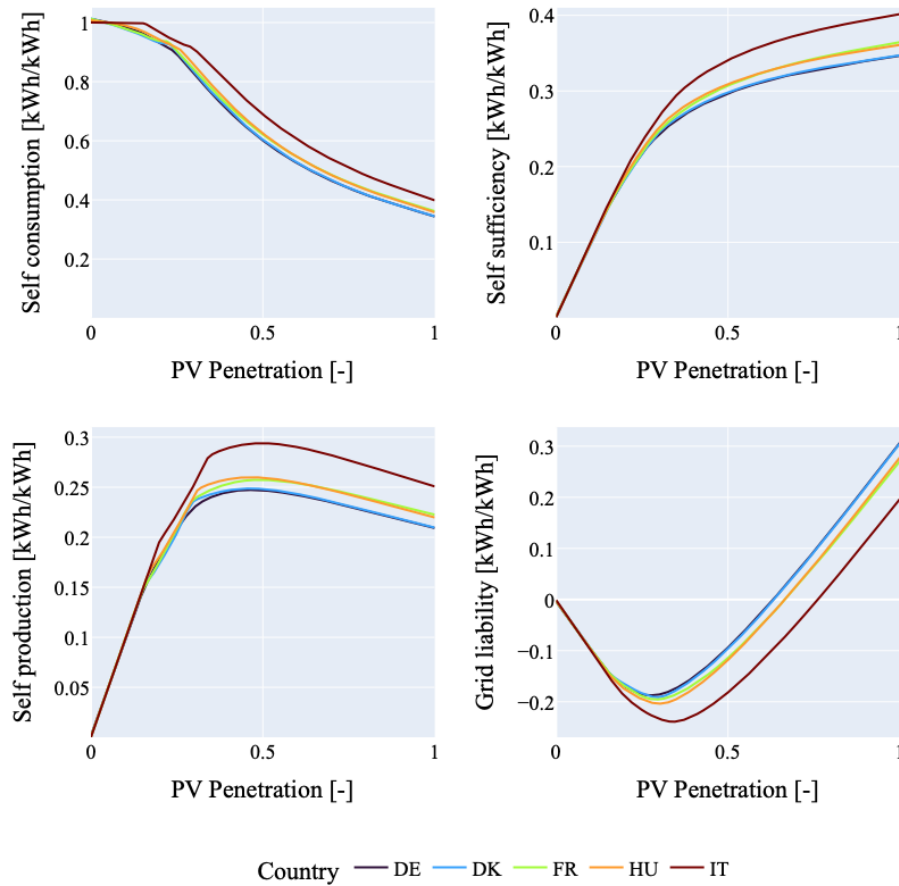


Fig. 5 Load matching indicators as the function of PV penetration with more than 100 energy community members in different countries.

4 DISCUSSION

The results show consistent trends across individual buildings and energy communities. Italy's superior performance in both LMI and power indicators suggests a strong link between geographical PV potential and load matching effectiveness. Smaller PV systems in sunnier climates yield better performance due to more consistent production spread across time and lower production peaks relative to demand.

The findings also demonstrate that the portfolio effect in load matching is maximized in smaller energy communities. In larger communities, while improvements are minimal with size increase, PV penetration still plays a crucial role.

From a power metric perspective, Italian communities benefit from extended feedback hours without corresponding surges in peak feedback, likely due to the flatter, longer PV production curves. These conditions mitigate the mismatch between production and demand, central to the net-zero energy goal.

5 CONCLUSIONS

Integrating renewable energy sources, specifically photovoltaic generators is a core challenge of the present energy infrastructure. A key issue is the mismatch of the production and consumption periods, which is most often examined with load-matching indicators. While there are several studies for separate countries, this study compares the challenge and its effects across five European countries. The study used the same residential consumption profiles across country-specific PV distributions and generation profiles to better understand the challenge. The key takeaway from the evaluated load matching indicators and power metrics is that when targeting a specific PV penetration, as in the case of forming net zero energy buildings and communities, countries with more PV production potential are also more appealing for load matching. In terms of metrics, Italy exhibited much better LMIs and power metrics than the other countries. This underlies the importance of PV system sizing based on the specific county. For achieving the same yield, in the Italian case, PV systems could be sized smaller, ending in improved load-matching characteristics.

An important limitation of the present study is the usage of the same consumption profiles across different countries. Future work will address the assessment of country-specific load data that may impact the results. However, such data is believed to widen the gaps among the countries, especially in the case of weather-dependent power-to-heat appliances like heat pumps.

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