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Analysis of self-generated PV energy consumption profiles in prosumers microgrid

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ABSTRACT

Self-harvesting and consumption of electrical energy from a small-scale photovoltaic (PV) system became quite a beneficial option for households who seek for an economical, independent and environment-friendly power alternative. However, in practice, prosumers without battery storage systems face some energy flow management issues, when only part of the generated energy is consumed instantly in place, while the rest is exported to the distribution grid or simply lost. The paper examines profiles of some preselected prosumers with small-scale PV installations with the purpose to evaluate losses caused by the inability to consume instantly all generated energy and thus resulting in redundant energy exchange between prosumer's microgrid and distribution grid. The analysis reveals certain anomalies, when local PV system produces enough power to cover all the electricity demand of the household, but energy is still imported from the DSO grid at the same time. These simultaneous flows of import and export active energy were calculated and showed quite significant numbers. The paper digs into this problem through a quantitative evaluation of energy flows within one preselected microgrid using one-second resolution experimental data. The results presented here help us distinguish the main factors leading to inefficient distribution of generated power in households.

1. Introduction

Climate change has become one of the greatest challenges of today's society. According to the International Energy Agency (IEA) report (Climate Change 2023), energy accounts for two-thirds of total greenhouse gas, which means the energy sector is the central player in efforts to reduce emissions and mitigate climate change. European Union (EU) countries set a goal to become climate-neutral by 2050, as stated in the European Green Deal ("Energy and the Green Deal" 2023). One of the EU Clean Energy Package (CEP) ("Clean Energy for All Europeans Package" 2019) directives, establishes an ambitious plan, according to which renewable electricity will constitute at least 32% of total electricity generation by 2030 (later EU Commission proposed a few revisions of the package to accelerate the take-up of renewables in the EU and to reach at least 45% by 2030) ("European Parliament" 2022). It also invites citizens to play an active role in the development of renewables by enabling renewable energy communities and self-consumption of renewable energy.

Self-generation and self-consumption of renewable electrical energy can provide financial, environmental and security benefits for households, grid operators and society at large (Strielkowski et al. 2021). However, rapid expansion of renewables within households brings some unexpected challenges both to the users and grid operators, since the conventional grid suffers resulting changes in energy flows. In this paper, we will focus on a situation of households with small solar plants in Lithuania who participate in the electricity trade market as prosumers (the energy-producing consumers). The paper examines profiles of some preselected prosumers with small (under 30 kW) photovoltaic (PV) installations and analyses some typical self-consumption efficiency-related issues and limitations.

2. Current situation of PV prosumers

In Lithuania, as in the rest of Europe, a rapid growth in the popularity of solar power plants among private sector households has been observed over the last few years. This was particularly encouraged by the drop in technology costs and the increase in the number of service providers as well as financial support from a country's government, which made PV installations the most cost-effective and widely available alternative for households (Bertsch, Geldermann, and Lühn 2017; Bórawski, Holden, and Bełdycka-Bórawska 2023; Fernández, Payán, and Santos 2021; Wicki, Pietrzykowski, and Kusz 2022). This tendency probably will remain in the future as the EU and member state governments actively support the solar energy development strategy ("EU Market Outlook" 2023; "EU Solar Energy Strategy" 2022).

Theoretically, the optimal utilisation of self-generated PV electrical energy would be if all this energy were immediately consumed in a local microgrid (a single household or community). Unfortunately, this goal is not easily achievable due to different generation and consumption patterns (Interreg Europe 2020). Therefore, self-consumption can cover only a part of the energy demand, while some excess generated energy is supplied to the Distribution System Operator's (DSO) grid (Fernández, Payán, and Santos 2021; McKenna, Pless, and Darby 2018). Higher rates of self-consumption can be achieved by other means (e.g. integrating of battery storage systems (Ciocia et al. 2021; Hassan et al. 2023; Luthander et al. 2015; Stephant et al. 2021), hot water heating appliances (Amabile et al. 2021; Pater 2023), smart energy management systems (Balakumar et al. 2022; Fustero et al. 2023), though with additional costs).

The problem on the larger scale stems from the limitations of conventional power grids, which have been focused on large, centralised power plants and one-way transmission and distribution. Distributed renewables make grid management more complicated because of their variability and intermittency, which generally makes matching supply and demand difficult. The growing number of prosumers in the grid only worsens the situation.

The disparity between self-generated PV electricity and household electricity consumption generally means that most of the electricity is generated during the day when people are (usually) not at home, and peak electricity consumption is in the morning and evening (Interreg Europe 2020). Storing the energy produced during the day and using it when it is most needed would be the right solution. A report from the European Commission reveals that with a locally installed energy storage system, the electricity self-consumption rate of an average Central European household with PV could increase up to 75% from 30% without it (Interreg Europe 2020; SWD 2015). However, batteries remain an expensive option for small users, and until their cost comes down and their capacity improves, high costs and long amortisation mean that they are unlikely to be widely adopted. Until these technologies mature, intermittency will remain a key issue.

One solution that does not require energy storage is the adjustment of individual energy consumption pattern and shifting most power-demanding consumption to midday hours (Afzalan and Jazizadeh 2019; Luthander et al. 2015; Öhrlunda et al. 2020). This can be achieved with smart devices that can be programmed to run at a given time. However, load shifting will require

not only technological innovations, but also behaviour change efforts, which might be challenging and even unacceptable for some users.

Yet another way to increase self-consumption is cooperation between neighbouring individual prosumers by forming closed communities of prosumers. Collaboration between them in terms of energy generation, sharing and accumulation, helps to minimise a total mismatch between generated and demanded power within community (Balakumar et al. 2022; González-Romera et al. 2019; Hassan et al. 2023; Stephant et al. 2021; Tercan et al. 2022). Despite having many advantages over the individual prosumer, communities are still a relatively new option whose prevalence will depend on legal, financial and social incentives in each country.

Lithuania promotes an alternative way of energy storage for small-scale prosumers (Ciocia et al. 2021). According to the Law on Energy from Renewable Sources (2011), excess electricity produced by a solar installation can be fed into the DSO grid and sent back to the self-generating prosumers when electricity is not produced (net-metering). For the self-generated and consumed amount of electricity prosumers are exempt from paying any taxes. However, they have to pay the fee for the use of the electricity grid (it was 0.04477 €/kWh in 2022) set by the National Commission for Energy Control and Prices (NCC). Despite the fact that the fee is relatively small today, it has a tendency to increase yearly along with the increase numbers of active prosumers in the grid.

Distribution and network costs are no less important aspects in the final electricity price estimation (Hennig et al. 2022). The retail price of electricity is comprised of three parts: the energy itself, transmission and distribution costs, and taxes/surcharges (Ciocia et al. 2021; CEER Paper on Electricity Distribution Tariffs Supporting the Energy Transition 2020). In practice, only those who consume electricity from the DSO grid pay the full price. Articles 15 and 16 of Directive (EU) 2019/944 of the European Parliament (Directive (EU) 2019) state that active consumers and citizen energy communities should be subject to network charges that account separately for the electricity fed into the grid and the electricity consumed from the grid. This applies to prosumers that use the grid metering service, which allows the grid to be used as a backup system for their excess power production and to partially avoid electricity transmission and distribution charges. If the current distribution network tariff system was reviewed, this would probably mean higher charges for all grid-connected prosumers. It should also encourage them to use behind-the-meter storage and use as much locally generated energy as possible, rather than choosing grid-scale storage solutions.

There is another important issue related to the exchange of energy between the DSO and the consumer microgrid, which arises in practice and is rarely discussed in the literature: a number of residential electricity consumers with photovoltaic systems connected to the local three-phase microgrid report about inefficient energy distribution between the local grid and the DSO grid. According to their solar inverter monitoring data, the energy produced by local PV systems during certain hours is sufficient to meet the local demand (excess energy is even transferred to the DSO grid), but at the same time, additional energy is consumed from the DSO grid. This means a double energy feed which results in additional costs for the household and unnecessary load on the grid. Although this problem is relevant to many users, there is no wider discussion on its causes and ways to solve it. Next, we will analyse the situation at prosumers end in detail.

3. Analysis of prosumers profiles

In order to assess the nature and extent of the problem, the historical data of grid users' electricity consumption profiles throughout the year 2020 in Lithuania were collected and studied. Then the daily graphs of electricity exchange between the DSO grid and 32 different prosumers' household grids (microgrids) with solar PV installations located across different Lithuania regions were selected and used for analysis. During that period, the selected prosumers did not use any power accumulators (battery systems, hot water tanks, etc.). The data were obtained from standard three-phase smart meters with remote data transfer function. Each set of recorded data included

numerical values of accumulated hourly imported energy E_c (taken from the DSO grid and consumed locally) and exported energy E_g (excess of the generated in PV system, which was transferred to the DSO grid) covering the period from 1 January 2020 to 31 December 2020.

A standard bidirectional smart meter measures the average of import and export active power P_{ci} and P_{gi} values over the ith time interval Δt. The import and export energy values E_c and E_g are calculated by integrating power values:

$$
\begin{aligned}
E_c &= \sum_{i=1}^{N} (P_{ci} \cdot \Delta t) = \sum_{i=1}^{N} E_{ci}, \\
E_g &= \sum_{i=1}^{N} (P_{gi} \cdot \Delta t) = \sum_{i=1}^{N} E_{gi},
\end{aligned}
\tag{1}
$$

where E_{ci} and E_{gi} are the import and export energy over ith time interval, respectively, and N is the number of time intervals.

In the case of the three-phase household microgrid, the values of E_{ci} and E_{gi} are found as follows:

$$
\begin{aligned}
E_{ci} &= E_{cL1i} + E_{cL2i} + E_{cL3i}, \\
E_{gi} &= E_{gL1i} + E_{gL2i} + E_{gL3i},
\end{aligned}
\tag{2}
$$

where E_{cL1i}, E_{cL2i}, E_{cL3i} are import energies from DSO grid and E_{gL1i}, E_{gL2i}, E_{gL3i} are export energies through three-phase lines $L1$, $L2$ and $L3$ over ith time interval.

Analogously, the values of P_{ci} and P_{gi} are found as follows:

$$
\begin{aligned}
P_{ci} &= P_{cL1i} + P_{cL2i} + P_{cL3i}, \\
P_{gi} &= P_{gL1i} + P_{gL2i} + P_{gL3i},
\end{aligned}
\tag{3}
$$

where P_{cL1i}, P_{cL2i}, P_{cL3i} are imported and P_{gL1i}, P_{gL2i}, P_{gL3i} are exported power values over ith time interval in three-phase lines $L1$, $L2$ and $L3$.

Smart meters used in households have a time interval Δt equal to 1 h, so they record the energy in kilowatt-hours (kWh). Each data set of P_{ci} and P_{gi} had an array of $365 \times 24 = 8760$ lines. For better clarity, we introduced an additional index j, which denotes the number of the day in the year ($P_{ci} \rightarrow P_{cij}$, $P_{gi} \rightarrow P_{gij}$). Since both the imported power P_{cij} and exported power P_{gij} were accumulated during 1-h period ($\Delta t = 1\ h$), the numerical values of energies correspond to kWh. Figures 1–3 illustrate a full year data of P_{cij} and P_{gij} from the three typical households with different installed
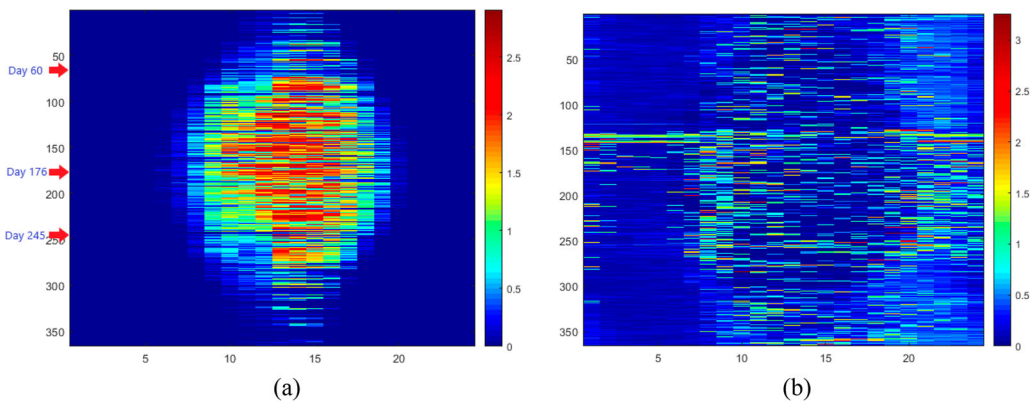
Figure 1. Yearly distribution of exported power P_{gij} (a) and imported power P_{cij} (b) in kW of the household No. 1. Total installed power – 4 kW.
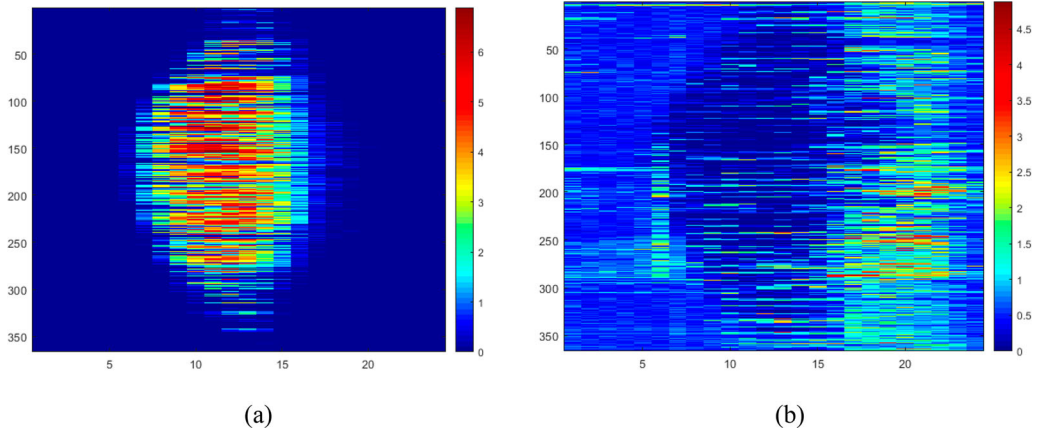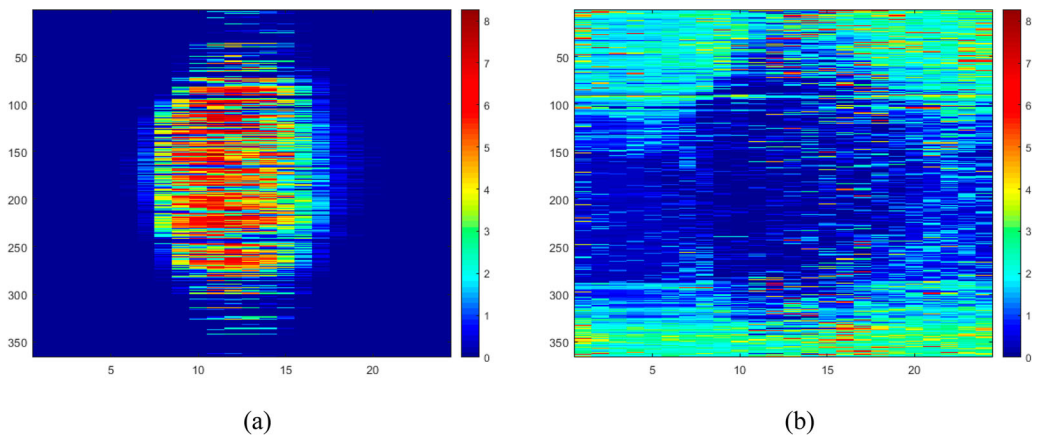
Figure 2. Yearly distribution of exported power P_{gij} (a) and imported power P_{cij} (b) in kW of the household No. 5. Total installed power – 15 kW.

power ratings. The *X*-axis represents the hours of the day, and the *Y*-axis represents the days of the year. Exported and imported power is shown in colour, which value in kW is denoted in a vertical colour bar on the right.

It is easy to track overlaps of import and export power within given datasets during daytime, when the PV system excess energy is exported yet another energy is imported from the DSO grid at the same time. To see this situation in more detail, Figure 4 gives three examples of hourly distribution of the imported power P_{cij} (blue columns) and exported power P_{gij} (red columns) over the *j*th day ($\Delta t = 1\ h, i = 1 \ldots 24$) for the household, which yearly data are presented in Figure 1 (certain days are marked with the red arrows in Figure 1).

As a particular example, we can take hours 8:00, 11:00 and 12:00 in Figure 4(b), when power is consumed from the DSO grid (blue columns), although the power exported to the DSO grid at that time (red columns) is higher and would be enough to cover all demand. Even if generation was not enough to meet the full demand like during hours 9:00 and 10:00, it would still be possible to substantially reduce power import by utilising locally generated energy. The data from the last day of February and the first day of September are shown in Figure 4(a,c). It can be observed here that even
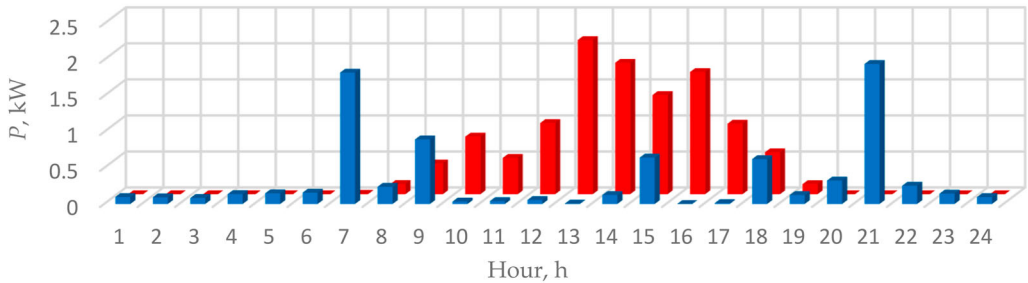

Figure 3. Yearly distribution of exported power P_{gij} (a) and imported power P_{cij} (b) in kW of the household No. 8. Total installed power – 20 kW.
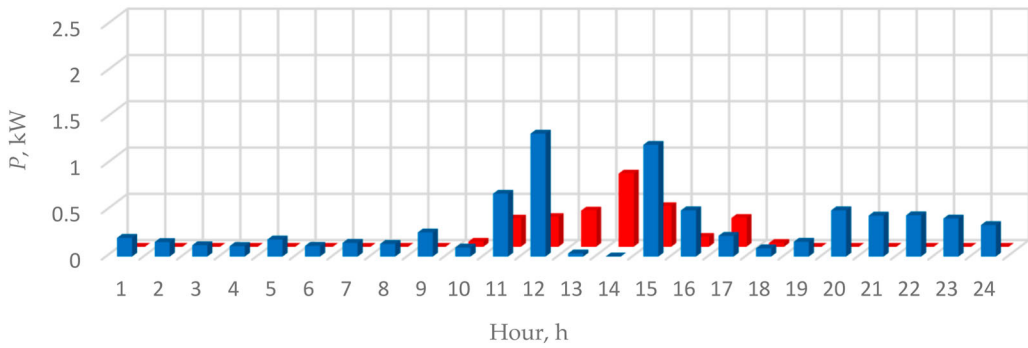
(a)
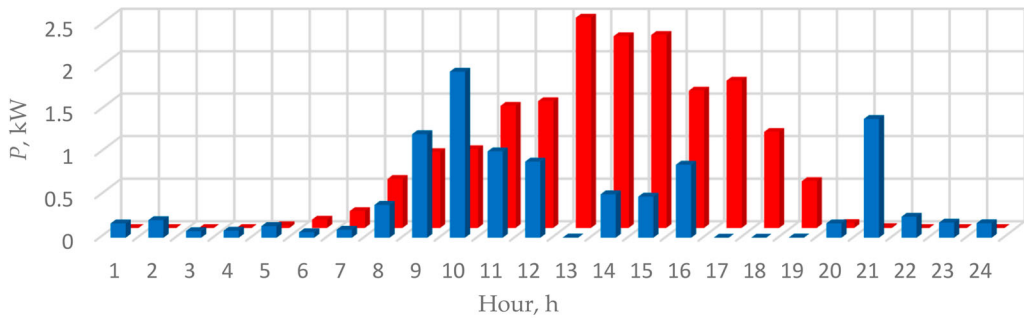
(b)

(c)

Figure 4. A detailed view of imported power P_{cij} (blue columns) and exported power P_{cij} (red columns) distribution during certain days: 60th (a), 176th (b) and 245th (c).

with lower PV generation and different consumption pattern, the above-mentioned problem remains relevant.

In order to quantify the amount of energy transferred inefficiently in this way, the calculations were made using the original measurement data. As it was shown above, during each 1-h time interval Δt, both import and export power can flow through a smart meter.

The difference of these two powers during ith hour:

$$\Delta P_{ij} = P_{gij} - P_{cij}. \tag{4}$$

A positive ΔP_{ij} value indicates that the PV system generates enough power (energy) and part of this power can be used to fully compensate import. This condition is valid for all periods where the generation is not equal to zero. When ΔP_{ij} is negative, all power generated by PV system could be used to partially compensate import, since generation is not enough to cover all local demand. To use the full potential of the local PV system and obtain maximum benefits from it, the priority must always be the maximum utilisation of locally generated energy instead of imported. In this case the total amount of reduced export power P'_{gij} could be

$$P'_{gij} = \begin{cases} \Delta P_{ij}, & \text{if } \Delta P_{ij} > 0 \\ 0, & \text{otherwise} \end{cases}, \tag{5}$$

and the deficient amount of power P'_{cij}, that must be imported anyway

$$P'_{cij} = \begin{cases} |\Delta P_{ij}|, & \text{if } \Delta P_{ij} < 0 \\ 0, & \text{otherwise} \end{cases}, \tag{6}$$

Equations (5) and (6) define the condition of energy flows optimisation we aim for. A comparison between the original imported power P_{cij} and the potentially reduced imported power P'_{cij} during one year for the object shown in Figure 1 is given in Figure 5.

Figure 6 shows more detailed pictures of both measured and calculated imported power during the three preselected days mentioned above ($j = 60, 176, 254$). Here we can notice that even with a small PV generation (Figure 6(c)), such a system can be used more efficiently and a certain amount of energy import still can be reduced. However, this effect depends on PV generation: during long sunny summer days, the decrease in power import is more significant than during spring or autumn periods. In the winter period generation is very low, so the improvement is negligible.
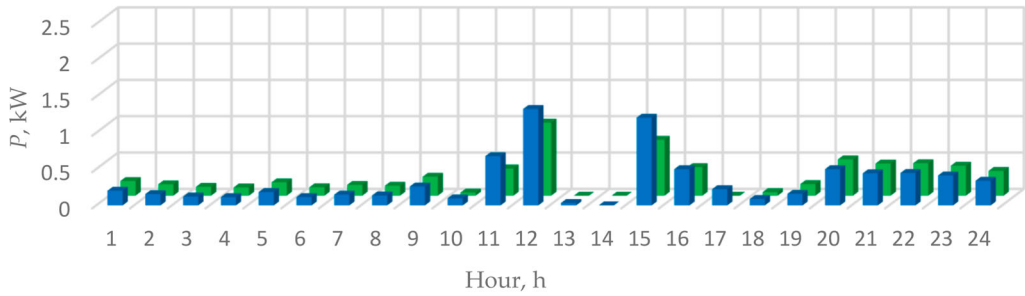
A total decrease of the imported power over the jth day can by expressed as

$$\Delta P_{cDj} = \sum_{i=1}^{M} (P_{cij} - P'_{cij}), \tag{7}$$
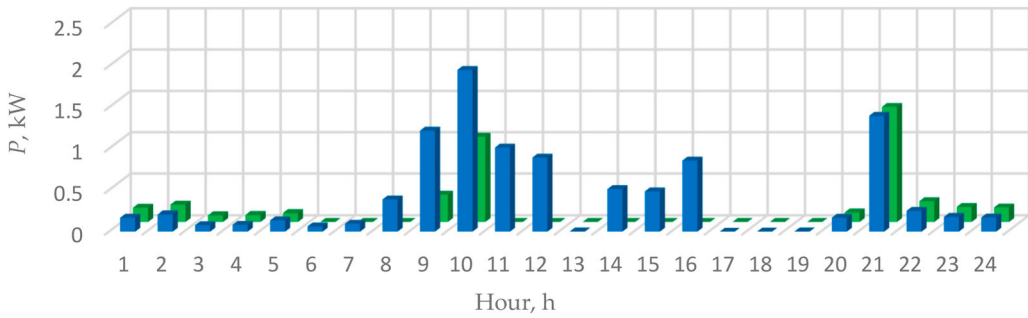

(a)

(b)
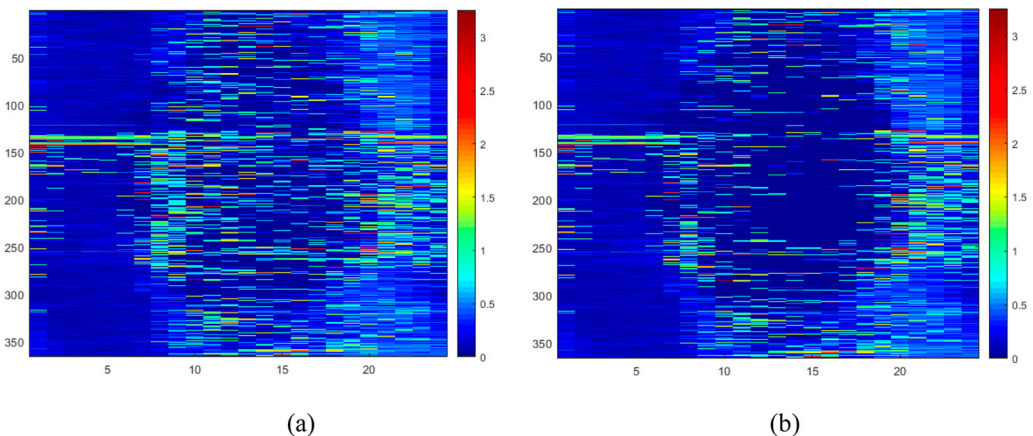
Figure 5. Comparison between the measured imported power P_{cij} (a) and the optimised imported power P'_{cij} (b) in kW over the year.

(a)

(b)
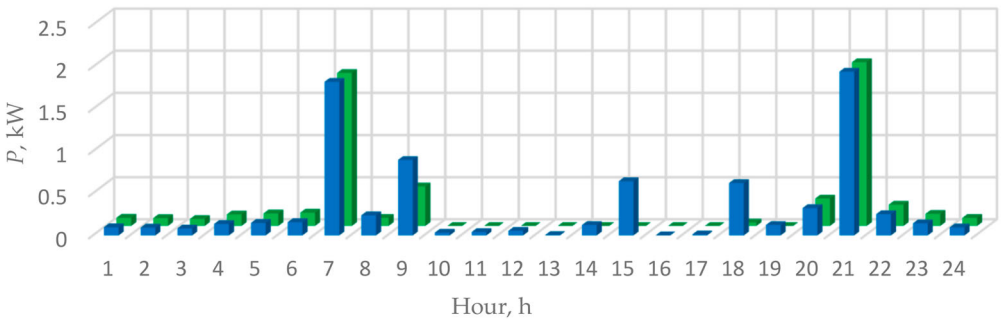
(c)

Figure 6. A detailed view of measured imported power P_{cij} (blue columns) and optimised imported power P'_{cij} (green columns) during the three aforementioned days: 60th (a), 176th (b) and 245th (c).

and over the year

$$\Delta P_{cY} = \sum_{j=1}^{N} \sum_{i=1}^{M} (P_{cij} - P'_{cij}) = \sum_{j=1}^{N} \Delta P_{cDj}, \tag{8}$$

where M is the number of hours in a day and N is the number of days in a year.

Figure 7 shows the calculated values of imported power P'_{cij} and exported power P'_{gij} of the potentially optimised microgrid for the same household during the same three days of the year.
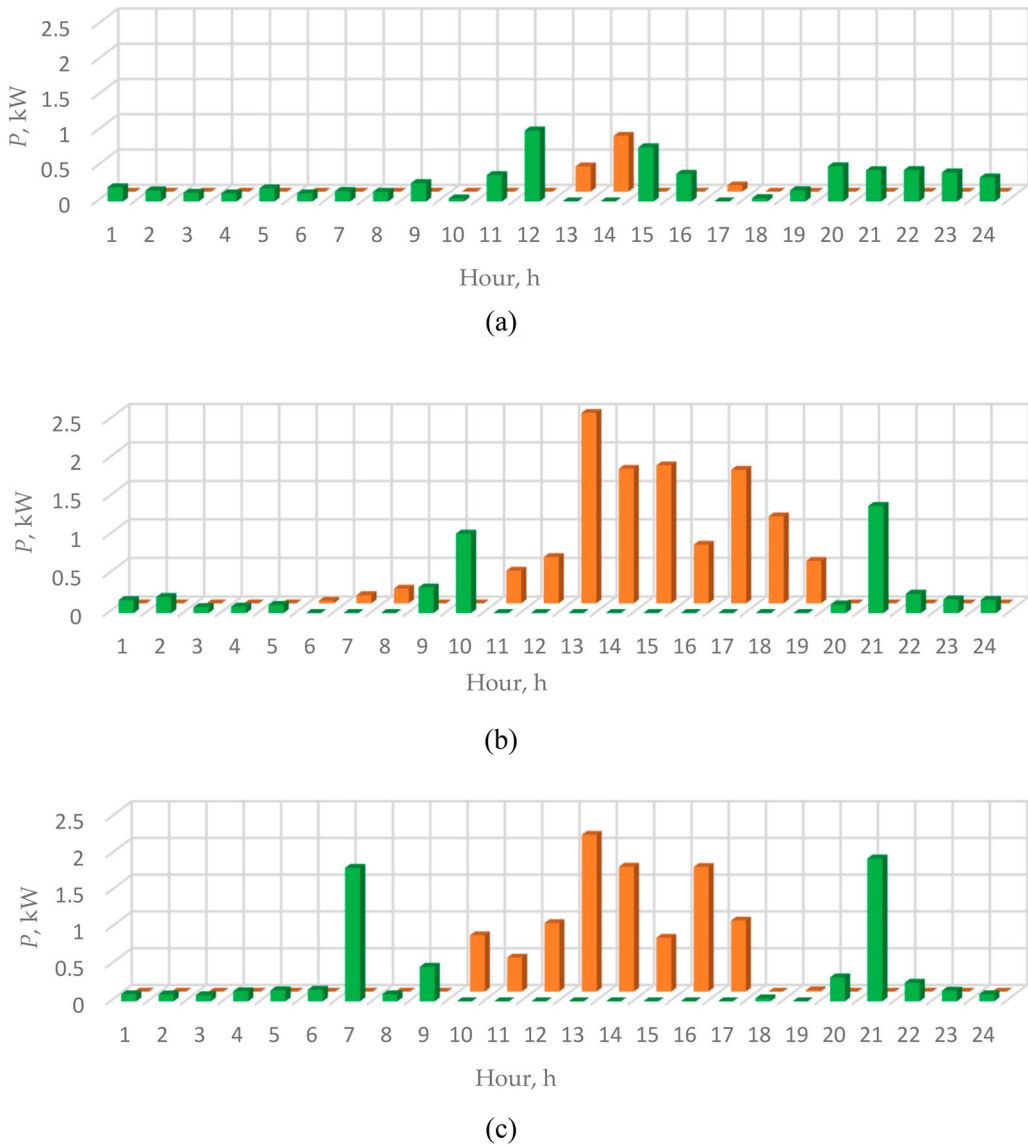
Figure 7. Calculated optimised imported power P'_{cij} (green columns) and optimised exported power P'_{gij} (orange columns) over the three days of the year: 60th (a), 176th (b) and 245th (c).

Comparing these data with the measured data presented in Figure 4, we see a decrease in both imported and exported power flows between the DSO grid and the household microgrid. Besides, no overlaps of imported and exported power are present in those examples. In order to quantify the power flows over the jth day for each household, total imported power P_{cDj}, total exported power P_{gDj} and a ratio r_{Dj} of these quantities were calculated:

$$r_{Dj} = \frac{P_{gDj}}{P_{cDj}} = \frac{\sum_{i=1}^{M} P_{gij}}{\sum_{i=1}^{M} P_{cij}}. \tag{9}$$

This ratio shows what part of the power is exported to the DSO grid during the jth day of the year, comparing it with the total power imported from the grid on the same day.

Table 1. Analytical data for the three days of the household from Figure 1.

Day of the year	P_{cDj}, kWh	P_{gDj}, kWh	r_{Dj}, %	ΔP_{cDj}, kWh	r_{0Dj}, %
60	7.89	2.77	35.1	1.53	19.4
176	10.32	17.75	172.0	6.22	60.3
245	8.09	11.61	143.5	2.19	27.1

Another important parameter r_{0Dj}, which represents the ratio of the decrease of imported power ΔP_{cDj} after microgrid optimisation and the original imported power P_{cDj}, was calculated:

$$r_{0Dj} = \frac{\Delta P_{cDj}}{P_{cDj}}. \tag{10}$$

This parameter shows the theoretical relative reduction of import power on the jth day after microgrid optimisation, when energy flow overlaps during each hour are eliminated. Both parameters r_{Dj} and r_{0Dj} were calculated for all 32 households for each day of the year. Table 1 shows the results for the three preselected days of the household mentioned in Figure 1.

It can be seen from the table that when the power generated by the PV system is high (176th day), the total amount of decrease of the imported power per day after optimisation is up to 60.3% of the total power import before optimisation. In the case of a lower PV generation, this percentage value is lower as well, but also significant: 19.4% on the 60th day, and 27.1% on the 245th. The transfer of this energy to the DSO grid puts an additional load on it, which requires additional investments in increasing the power of the DSO grid and developing its infrastructure. The table also shows a certain correlation between r_{Dj} and r_{0Dj}, which is not coincidental, since both of them depend on PV generation and power export.

In a similar way, the above-mentioned accumulated parameters over the year were calculated for all 32 households. The preliminary results were published in our previous work (Šiupša et al. 2022). Total decrease of the imported power ΔP_{cY} over the year

$$\Delta P_{cY} = \sum_{j=1}^{N} \sum_{i=1}^{M} (P_{cij} - P'_{cij}) = \sum_{j=1}^{N} \Delta P_{cDj}, \tag{11}$$

and the ratios r_Y and r_{0Y}:

$$r_Y = \frac{P_{gY}}{P_{cY}} = \frac{\sum_{j=1}^{N} \sum_{i=1}^{M} P_{gij}}{\sum_{j=1}^{N} \sum_{i=1}^{M} P_{cij}}, \tag{12}$$

$$r_{0Y} = \frac{\Delta P_{cY}}{P_{cY}}, \tag{13}$$

where M is the number of hours in a day and N is the number of days in a year.

Both these ratios represent some mean values over the year; however, the range of their dispersion might be much larger, since they are an outcome of coincidental interaction between fluctuating PV generation and erratic electricity consumption. Therefore the additional parameter – the standard deviation of daily parameter r_{oDj} – was used to describe the dispersion of power import decrease over one year:

$$\sigma_{r0Y} = \sqrt{\frac{\sum_{j=1}^{N} (r_{0Dj} - \overline{r_{0D}})^2}{N-1}}, \tag{14}$$

where $\overline{r_{0D}} = \sum_j r_{0Dj}/N$ is the average of r_{oDj} over the year.

Table 2. Analytical data of household power import/export during the year of 2020.

Household No.	Installed power, kW	P_{cY}, kWh	P_{gY}, kWh	r_Y, %	r_{0Y}, %	σ_{r0Y}, %
1	4	2667	2719	102.0	18.4	15.3
2	8	2842	3818	134.4	17.2	16.3
3	10	6264	3650	58.3	8.4	12.0
4	12	5918	3434	58.0	10.9	11.5
5	15	5621	5482	97.5	10.3	10.9
6	15	12,116	5009	41.3	8.1	10.1
7	20	10,555	7296	69.1	6.9	9.9
8	20	11,765	7110	60.4	6.1	10.6

All 32 households were arranged in ascendant order according to installed power, and parameters r_Y, r_{0Y}, σ_{r0Y} were calculated for each of them. Table 2 summarises the calculated results with 8 typical households' data.

The results apparently demonstrate dependence between installed power and ratio r_{0Y}: the highest ratio is observed at the lowest installed power and it decreases as this power increases. This means the prosumers with the lower power installations (naturally, lower annual energy consumption as well) can expect greater benefits from microgrid power flows optimisation.
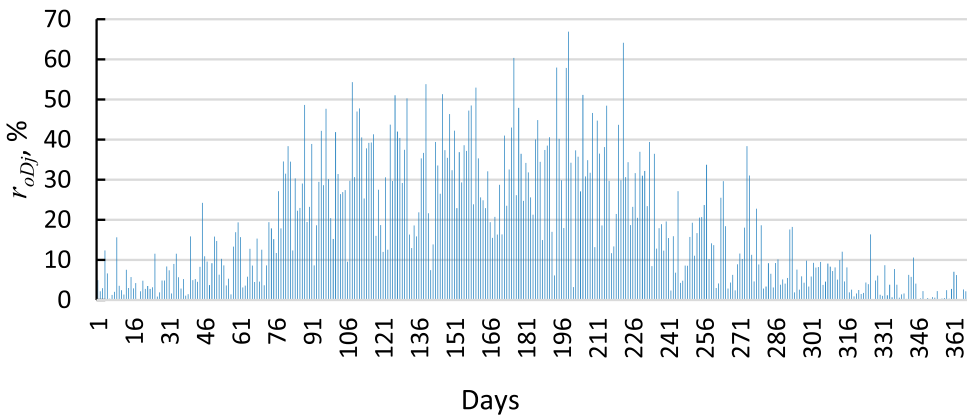

(a)
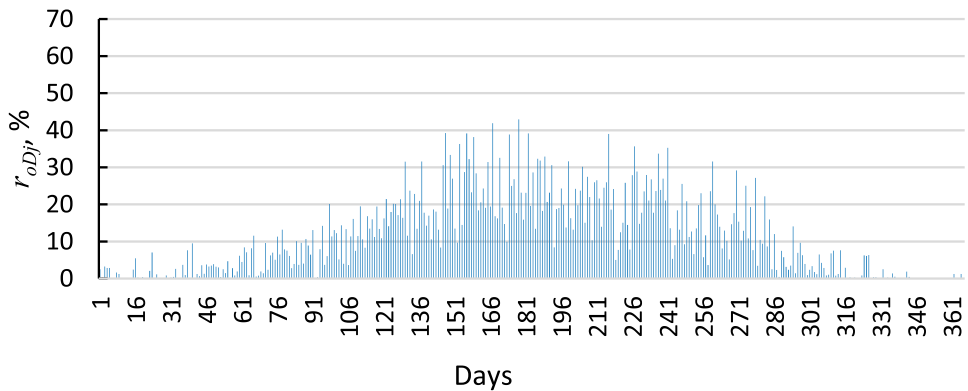
(b)

Figure 8. The distribution of parameter r_{0Dj} during the year for household No. 1 (a) and household No. 8 (b).

Household No.1 has the highest r_{0Y} value among all 32 households. Also households with lower power installation have a slightly higher dissipation of parameter r_{oDj}. In order to better understand the distribution law of the parameter r_{0Dj} and its origin, it was graphically depicted in Figure 8 for each day of the year for two households: household No. 1, which has the lowest installed power and household No. 8 with the highest installed power. It can be seen from the figure that the maximum values of the parameter coincide with the periods of maximum generation, i.e. during the summer months. In the winter period, the parameter values drop down close to zero. Other factors, like total installed power, individual consumption pattern, have little effect on the nature of the parameter variation.

Parameter r_Y describes how installed PV system power corresponds to household yearly power demand. As we can see from Table 2, the best situation is in households No.1 and No.5, where ratio r_Y is close to 100%. However, ratio r_Y has no significant influence on r_{0Y}, which is obvious from households No.5 and No.6 situation: both of them have the same installed power and very different power demand but still similar r_{0Y} values.

4. Experimental research of microgrid power flows

The results presented in the previous section showed a significant portion of energy transfer in both directions between prosumers microgrid and DSO grid during each hour of a day. The data of exported and imported power used in our research were obtained from the standard DSO smart meter, where power is averaged over the course of each hour and summed over all three-phase lines data. In our previous work (Šiupša et al. 2022) we raised a hypothesis that situations with bidirectional power flows arise due to the asymmetric and time-varying phase load distribution of the three-phase household grid, when one heavily loaded microgrid line consumes both PV-generated
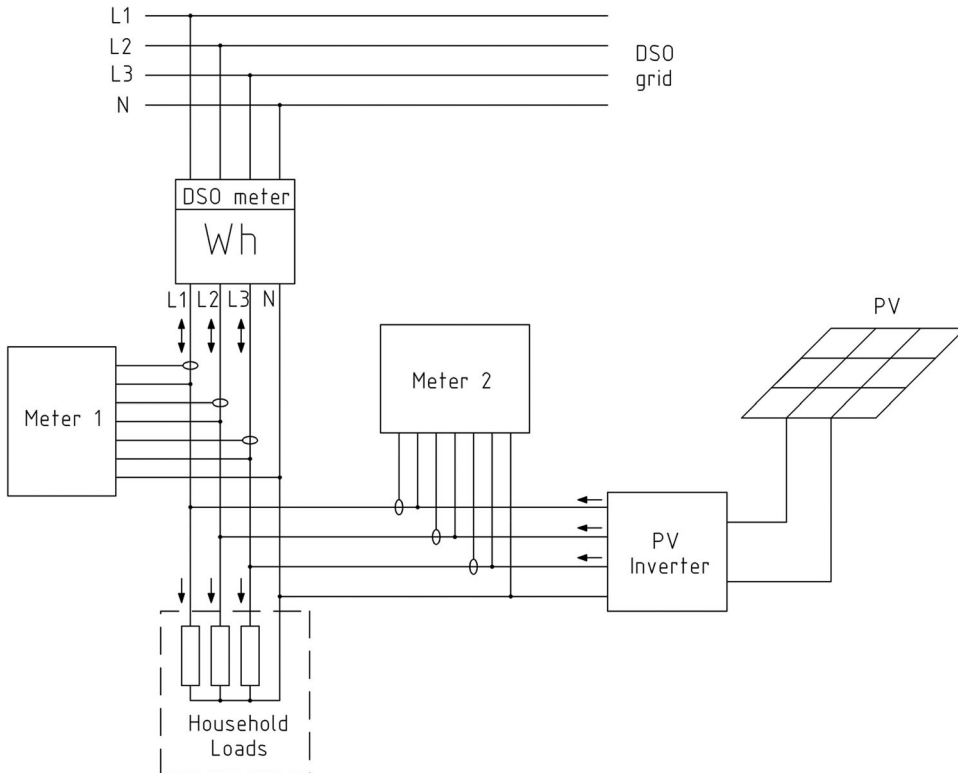

Figure 9. Scheme of experiment equipment arrangement.

and DSO grid power, while others two consume and export only PV generated excess power at the same time. However, there might be other reasons for this phenomenon, like variation in solar irradiation intensity or high power load switching during 1-h period. In order to investigate the power consumption and generation processes in a household microgrid with a PV power plant in more detail, an additional experiment was carried out. The experiment took place in one selected household, with three-phase microgrid of 20 kW total power installed and PV system with no backup. The scheme of the experiment equipment is shown in Figure 9. Measurements were made with two smart bidirectional electricity meters – Meter 1 and Meter 2 – which measure power flow on each of three-phase lines. These two meters were connected to the measuring lines via current transformers, which are factory calibrated with each meter to ensure accuracy. The measuring accuracy of the meters is 1% and the maximum time resolution is 1 s. Meter 1 measures the imported and exported power, while Meter 2 measures the power generated by the PV plant. Meter 2 can measure the power flow from household microgrid to the PV plant, however in practice it was small, used for PV inverter's own use only, and therefore was neglected. The meters have been configured to continuously send every second measured data to the SQL server. All data accumulated on the server were further processed according to the methodology described in Section 4, taking into account the fact that in this case the period Δt is equal to 1 s. The hourly data from the standard DSO smart meter were collected as well. The period of data collection covered the months of February–May 2023. Such a structure allowed not only to assess the dynamism of ongoing processes more accurately but also to estimate the impact of the power generated by the PV plant on both household consumption and export. In addition, this made it possible to evaluate the ongoing processes in each phase line of a three-phase microgrid.

As an example, Figure 10 shows the data obtained from the Meter 2 on 9 April 2023. These data reflect the fluctuations of solar radiation during the day. As mentioned above, Meter 2 measures generated power values over i-th one-second time interval on three-phase lines $L1$, $L2$ and $L3$. Let us denote these power values as P_{GL1i}, P_{GL2i} and P_{GL3i}. These values with one-second time resolution are shown in red, blue and green, respectively, and time is expressed in hours on the X-axis. As we see, power generation begins approximately from 7:00 and lasts till 20:00 and all three curves practically coincide, which indicates, that the inverter of PV system is symmetrical, i.e. it distributes generated power evenly across all phase lines.

Power consumed by the household in each power line Lx, $(x = 1, 2, 3)$ during nth one-second time interval can be calculated as follows:

$$P_{VLxi} = \begin{cases} P_{GLxi} - P_{gLxi}, & \text{if } P_{gLxi} > 0 \\ P_{GLxi} + P_{cLxi}, & \text{if } P_{cLxi} > 0 \end{cases}$$
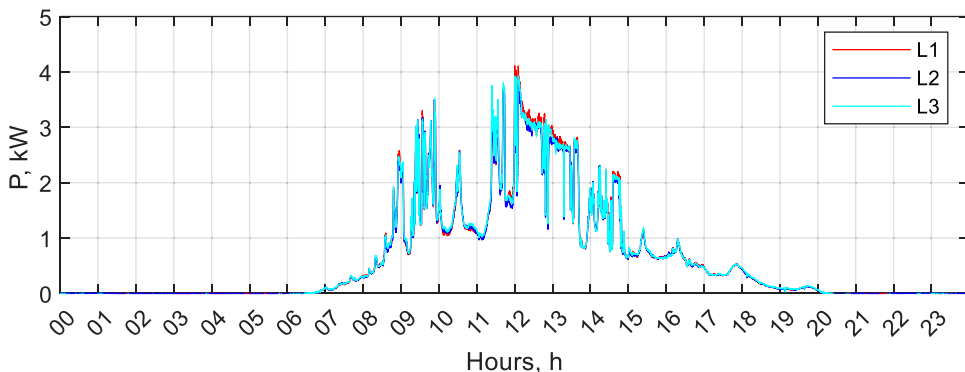

Figure 10. Generated power in each power line during one day.
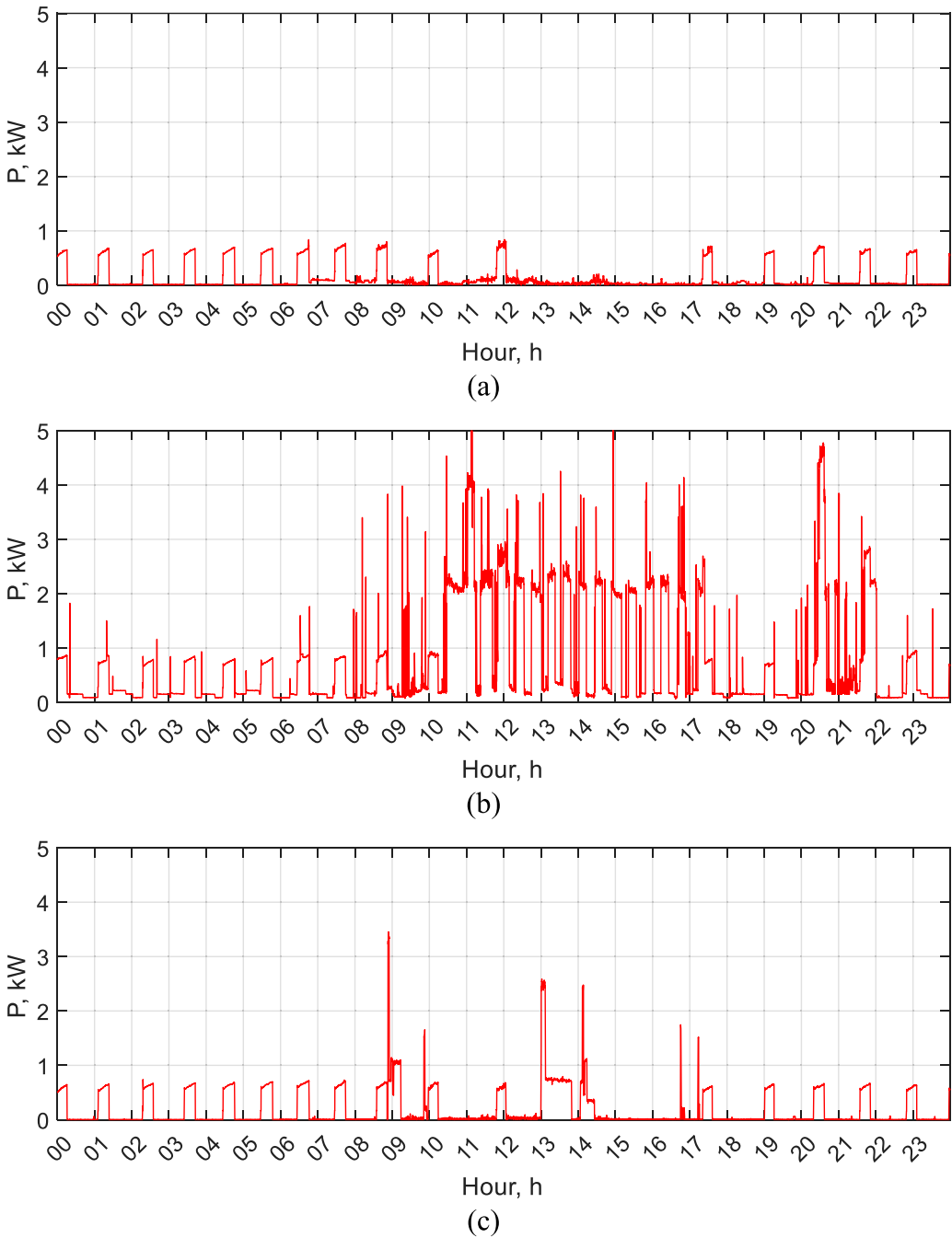
Figure 11. Consumed power in three power lines: *L1* (a), *L2* (b) and *L3* (c).

where $x = 1, 2, 3$ is number of power line; P_{gLxi} and P_{cLxi} are exported and imported powers, measured by Meter 1 on the Lx line.

Figure 11 shows an example of power P_{VLxi} calculated with one-second time resolution during the same day as in Figure 10(a) shows consumed power P_{VL1i} in line $L1$, Figure 10(b,c) shows consumed power P_{VL2i} and P_{VL3i} in lines $L2$ and $L3$, respectively. Similarly, the imported P_{cLxi} power
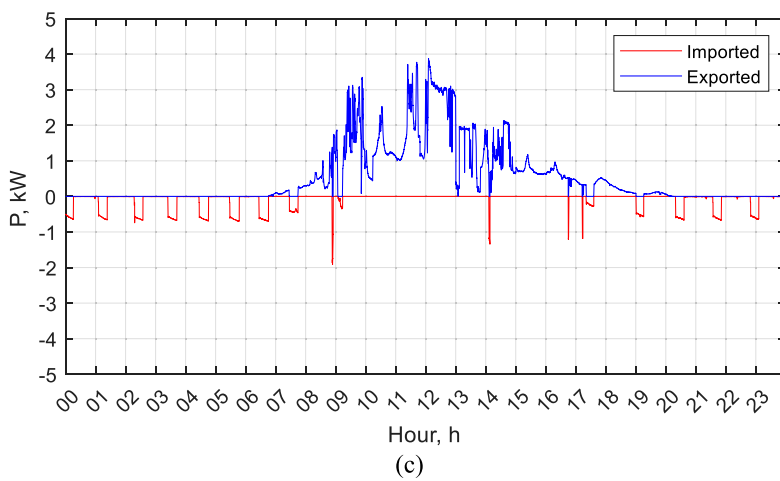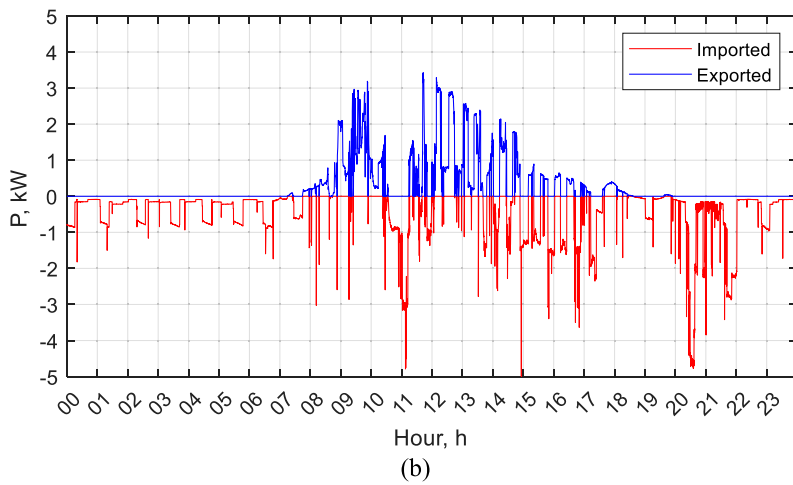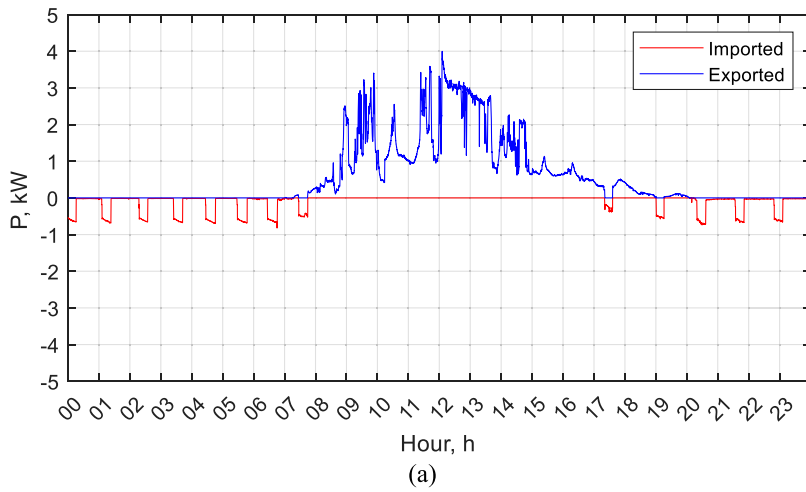
Figure 12. Daily imported (red line) and exported (blue line) power in power lines *L1* (a), *L2* (b) and *L3* (c).

and exported power P_{gLxi} from Meter 1 during the same day are presented in Figure 12. Here the values of imported power are shown as negative quantities.

It is obvious from the consumption graphs (Figure 11) that the lines in household are loaded asymmetrically. The asymmetry is especially evident between 8:00 and 18:00 and between 20:00 and 23:00, when energy consumption in the line $L2$ increases prominently.

Since the load on lines $L1$ and $L3$ is low, when the PV system generates power (approx. between 8:00 and 20:00, Figure 10), almost all of this power is exported (Figure 11(a,c)). However, the line $L2$, which had a high load at that time, do not always have enough solar power and then the power needed to be imported (Figure 11(b)). Thus, there are certain time intervals when at the same moment line $L2$ is importing power and lines $L1$ and $L3$ are exporting excess of power, i.e. instantaneous bidirectional power flows occur between the household microgrid and the DSO grid.

Obviously, the problem of bidirectional power flows arises, when the PV plant generates a power. This problem becomes particularly noticeable when the generation of the PV system exceeds the demand of the household grid in at least one of the three-phase lines, and in at least one of other lines, this generated power is insufficient due to the heavy load there. The power generated by the household PV system depends on solar radiation and is a slow process compared to the process of load variation. This is well illustrated in Figure 13, where an example of data observed in a household for an incomplete minute time interval is provided. These are data obtained in one afternoon of February 2023. The X-axis represents the time of day (one-second time resolution), while the Y-axis represents the power generated by the PV system (data acquired from Meter 2, blue shade columns) and imported and exported power (data acquired from Meter 1, brown shade columns) every second in each of the three-phase lines. Imported power data are depicted as columns of negative values.

From the power histogram in Figure 13, it can be seen that the power generated by the PV system (blue shade columns) over the considered period of time from 13:14:11 to 13:14:48 practically does not change and is approximately the same in all three-phase lines. It also means that during this period the solar radiation is constant and the PV inverter generates symmetrical power in all three-phase lines. Examining the power histogram of Meter 1, we can distinguish three operating modes in the microgrid with PV plant:
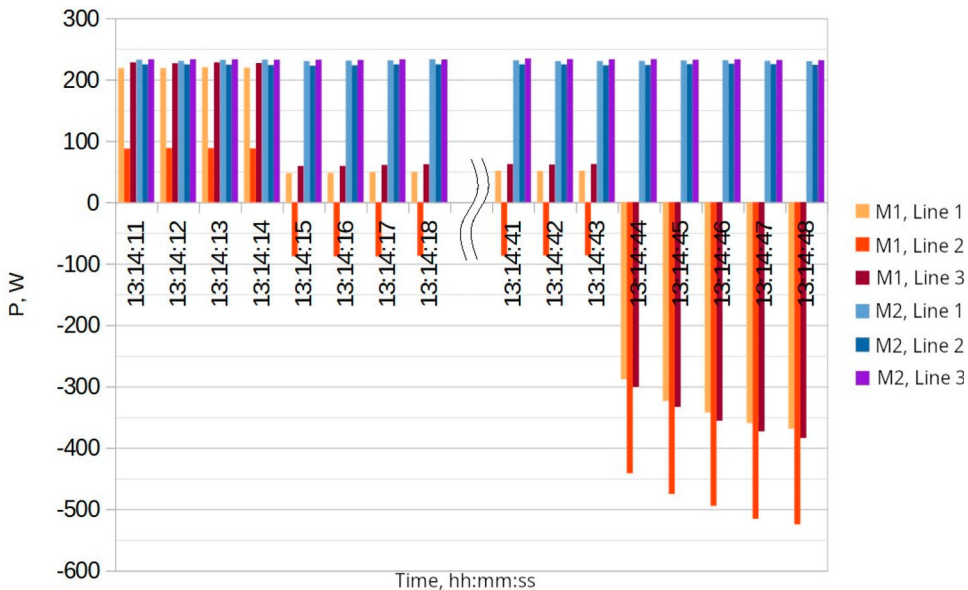
Figure 13. Example of power flows switching in three-phase microgrid during 1-min time interval.

(I)   In the time interval 13:14:11–13:14:14, the electricity consumption in lines $L1$ and $L3$ is very low and almost all the power produced by the PV system in these lines is exported. There is a little bit higher household consumption in the line $L2$, but the power generated by the PV system is sufficient to cover this consumption, so the rest of the power is also exported. Thus, the household microgrid generates exportable power in all lines.

(II) In the interval 13:14:15–13:14:43, a mid-power three-phase energy-consuming equipment is switched on in the microgrid, the power consumption of which is still covered by the PV plant in lines $L1$ and $L3$. An additional load is connected to the line $L2$ and the PV generation is no longer sufficient to meet this demand, so the deficient amount of power is imported. Thus, the household microgrid exports power through lines $L1$ and $L3$, and imports power through line $L2$.

(III) In the time interval 13:14:44–13:14:48, a powerful three-phase equipment is switched on in the microgrid and the energy generated by the PV system is no longer enough, so the household microgrid imports energy through all three lines $L1$, $L2$, and $L3$.

This shows that the operating modes of the household three-phase microgrid can change very fast: depending on the variation of microgrid load, the ratio of imported and exported power in three-phase lines may change several times per minute. Therefore, evaluating these processes with 1-h power flow measurement resolution, as used in standard meters, is not accurate.

To compare the effect of resolution, the parameter r_{0Dj} was calculated using one-second and one-hour resolution data acquired over the same time period. Data from 84 days obtained from February to April 2023 were used to calculate this parameter. The one-hour resolution data of the exported power $P_{g(h)}$ and imported power $P_{c(h)}$ were recalculated from the one-second (s) resolution data by accumulating the data per hour in each three-phase power line and summing the data of all lines:

$$
\begin{aligned}
P_{gLx} &= \sum_{i=1}^{H} P_{giLx}, \\
P_{g(h)} &= P_{gL1} + P_{gL2} + P_{gL3}, \\
P_{cLx} &= \sum_{i=1}^{H} P_{ciLx}, \\
P_{c(h)} &= P_{cL1} + P_{cL2} + P_{cL3},
\end{aligned}
\tag{16}
$$

where H is a number of seconds per hour ($H = 3600$) and $x = 1, 2, 3$ is the number of power line.

The daily parameter r_{0Dj} was calculated according to the methodology presented in Chapter 3, using both one-second (s) resolution and one-hour (h) resolution data:

$$
\begin{aligned}
r_{0Dj(h)} &= \frac{\Delta P_{cDj(h)}}{P_{cDj(h)}}, \\
r_{0Dj(s)} &= \frac{\Delta P_{cDj(s)}}{P_{cDj(s)}}.
\end{aligned}
\tag{17}
$$

A total reduction of the imported power $\Delta P_{cDj(h)}$ and $\Delta P_{cDj(s)}$ over the jth day was calculated according to (6) and (7) formulas, keeping in mind, that $M = 24$ at (h) resolution and $M = 86,400$ at (s) resolution.

Total imported power $P_{cDj(h)}$ over the jth day by one-hour data resolution:

$$
P_{cDj(h)} = \sum_{i=1}^{M} P_{cij(h)},
\tag{18}
$$

where M is the number of hours in a day ($M = 24$).
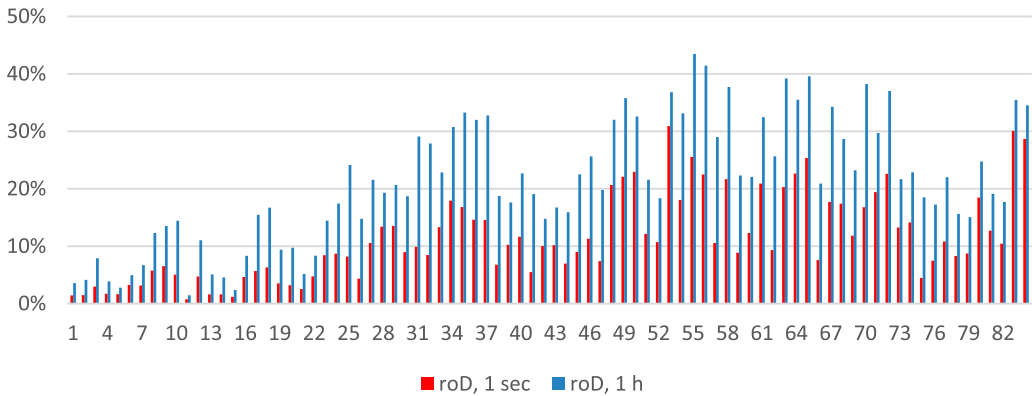
Figure 14. Distribution of calculated parameter r_{0Dj} using 1-h time resolution data (blue columns) and one-second time resolution data (red columns) during 82-day period.

The results of calculations are presented in Figure 14. Parameter percentage values $r_{0Dj(h)}$ calculated with one-hour resolution data are shown in blue, and values $r_{0Dj(s)}$ using one-second resolution data are shown in red.

From the obtained results, it can be seen that using more accurate one-second resolution data, values of the parameter $r_{0Dj(s)}$ are approximately two times smaller than values of parameter $r_{0Dj(h)}$. The average of $r_{0Dj(s)}$ over certain 84-day period is 11%, and the average of $r_{0Dj(h)}$ is 21%. We can reasonably state that one-second resolution allows to eliminate the influence of factors that change slowly in time, such as the variation of the intensity of the sun or load switching. In this way, the main factor causing double power flows remains the asymmetric phase load distribution of the three-phase grid.

5. Conclusions

The rapid growth of small-scale PV system installations within households brings some unexpected challenges regarding the effective management of PV-generated power flows in three-phase microgrid.

An analysis of data from DSO smart meters in 32 prosumer households has revealed that, despite sufficient PV generation, these households continue to import energy from the grid at the same time. It was calculated that the yearly overlap of imported and exported energy r_{0Y} was approximately from 6% to 18% and varies between different households. On specific days this ratio reaches 60% and more. The highest r_{0Y} values are observed at the lowest installed power and it decreases at higher power. This means the prosumers with the lower power installations and lower consumption can expect greater benefits from microgrid power flows optimisation.

Another benefit is for grid operator, since the power flows optimisation reduces load on the DSO grid and saves resources of its infrastructure.

To determine factors of power flow overlaps during a 1-h period, the experimental data from one household were collected, using one-second time resolution smart meters. Analysis of one-second resolution data showed that approximately half of bidirectional power flows arise due to the asymmetric and time-varying phase load distribution of the three-phase household grid. Another half is due to other reasons like variation in solar irradiation intensity or high power load switching during a 1-h period. An experimental study involving more households is needed to achieve a more accurate estimate of this distribution.

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