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# ANALYSIS OF THE EFFICIENCY OF POLYGENERATION IN A PRIVATE HOUSEHOLD MICROGRID

**Abstract.** *Modern challenges in the energy sector, particularly rising energy costs and declining reliability of electricity supply, are promoting the adoption of polygeneration microgrids. These systems integrate various energy sources, including photovoltaic modules, battery energy storage system, and backup diesel generators, providing energy autonomy and reducing dependence on utility grid. For Ukraine, which faces regular power outages due to damage to energy infrastructure, studying the efficiency of such microgrids is particularly relevant. The aim of this study is to analyse the efficiency of a private household microgrid equipped with 5 kW photovoltaic modules and a 10 kWh battery energy storage system. The focus is placed on analyzing self-consumption and self-sufficiency ratios. The analysis was conducted using daily, monthly, and annual data, taking into account seasonal variations in generation and consumption. The calculations showed a self-consumption ratio of 0.9997, indicating that the system is configured to effectively utilize locally generated energy. The annual self-sufficiency ratio reached 0.6262, covering 62.6 % of annual consumption. Seasonal data analysis demonstrated that self-sufficiency peaks during summer months due to high solar activity, while dependence on the utility grid increases in winter months. To improve self-sufficiency in winter, integrating alternative renewable energy sources to offset seasonal variations in solar activity is recommended. The results highlight the importance of implementing photovoltaic generation forecasting systems, demand-side management, and optimizing battery energy storage system operations to enhance microgrid efficiency. This study demonstrates the prospects of developing polygeneration systems in private households, particularly in the face of modern energy challenges.*

**Keywords:** polygeneration, microgrid, self-sufficiency, self-consumption, battery energy storage system, renewable energy sources, demand-side management.

## 1. Introduction

The modern challenges in Ukraine's energy sector, particularly the declining reliability of electricity supply due to damage to energy infrastructure [1, 2] and rising electricity costs, are driving the development of polygeneration systems in private households. These systems integrate various generation sources, such as photovoltaic (PV) modules and diesel generators. They also incorporate energy storage systems, for example battery energy storage systems (BESS), to ensure energy autonomy and optimal resource utilization.

Microgrids, as a key component of polygeneration systems, are designed to align energy generation with consumption, improve energy efficiency, and reduce dependence on the utility grid. Their ability to operate in islanded mode during power outages significantly enhances the resilience of microgrids [2] compared to utility grid, mitigating the effects of reliability declines [3, 4]. The integration of local generation and BESS introduces new challenges, such as system size optimization [4], BESS management [3], and demand regulation. Demand-side management in microgrids involves approaches like shifting consumption to periods of maximum local generation and reducing load amplitude without changing the total consumption volume [5, 6].

Figure 1 illustrates a simplified diagram of a household microgrid that integrates PV modules and a BESS. The BESS consists of a battery storage unit with a battery management system. A diesel generator serves as a backup power source, providing additional reliability. The inverter enables bidirectional exchange between the DC and AC buses, covering local load and exporting surplus electricity to the utility grid.

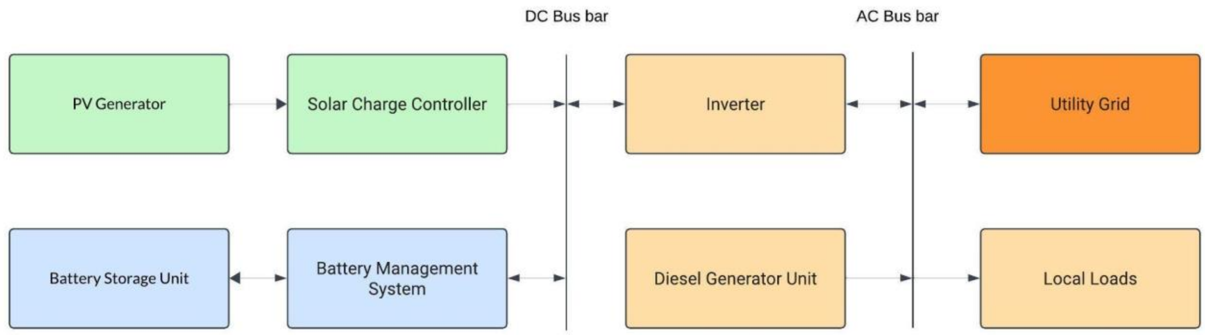


**Fig. 1.** Schematic diagram of the microgrid for the studied household

Papers [7–9] emphasize the importance of indicators such as the Self-Sufficiency Ratio (SSR) and the Self-Consumption Ratio (SCR) for evaluating the efficiency of microgrid operations. However, the optimal distribution of energy among various types of generation and BESS under different consumption conditions remains a challenging and complex issue [10].

Microgrid management should ensure reliable and stable operation [2], leveraging the most efficient and economically viable use of renewable energy sources (RES) and BESS. Management strategies for microgrids should incorporate models for integrating RES and BESS, with the primary objective of storing surplus electricity generated by RES in the BESS and utilizing it during periods of local generation deficits [11, 12].

However, relying solely on this strategy is suboptimal, as it does not account for microgrid consumption patterns or the potential for exporting electricity to the grid. When connected to the utility grid, the microgrid should minimize electricity costs by storing energy during low-tariff periods and discharging it during high-tariff periods, taking into account differentiated tariff plans [13, 14].

In Ukraine, a two-tariff and three-tariff differentiated electricity pricing system is currently in place [15]. In paper [13], it was noted that by applying an advanced genetic algorithm, actively utilizing BESS throughout the day, and implementing demand-side management, a 14 % reduction in electricity costs was achieved under differentiated tariffs in Sri Lanka.

The primary hypothesis of this study is that optimizing the use of distributed energy resources enhances the efficiency of the polygeneration system and stabilizes the energy balance during peak loads. This hypothesis is examined through an analysis of local generation and consumption data collected from November 2023 to November 2024 in a private household.

The objective of this work is to evaluate the efficiency of a polygeneration system in a private household by analyzing self-sufficiency and self-consumption ratios. The study aims to identify patterns in system operation and provide recommendations for improving its efficiency.

## 2. Methods and Materials

The analysis of the efficiency of a polygeneration microgrid is based on evaluating its ability to meet local consumption needs through self-generation and energy storage. This includes covering consumption with local generation capacity, the ability to store surplus energy for use during local generation deficits, and evaluation the interaction between the microgrid and the utility grid.

The Self-Consumption Ratio (SCR) reflects the efficiency of using locally generated energy. It indicates the share of energy produced within the microgrid that is directly consumed locally, without being exported to the utility grid [7, 8]. This indicator is critical for evaluation the microgrid's ability to reduce grid dependence and maximize local energy utilization

$$SCR = 1 - \frac{W_{EXP}}{W_{PV}}, \quad (1)$$

where $W_{EXP}$ is the energy exported to the utility grid, kWh; and $W_{PV}$ is the energy produced by PV modules, kWh.

An SCR ranges from 0 to 1. At 0, all locally generated electricity is exported to the utility grid, while at 1, the entire volume of local generation is utilized within the microgrid. A high self-consumption ratio reflects low dependence on the utility grid, ensuring high autonomy and economic efficiency of the system.

The Self-Sufficiency Ratio (SSR) characterizes the microgrid's ability to meet its own consumption needs through local generation. This indicator determines the share of total consumption covered by energy generated within the microgrid, without involving imports from the grid [8, 9]. A high SSR is an indicator of the energy autonomy of the microgrid

$$SSR = 1 - \frac{W_{IMP}}{W_L}, \quad (2)$$

where $W_{IMP}$ is the energy imported from the utility grid, kWh; $W_L$ is the total electricity consumption, kWh.

The SSR values range from 0 to 1. A value of 0 corresponds to complete dependence on the utility grid and a mismatch between generation and consumption. A value of 1 reflects an ideal scenario where generation fully aligns with consumption, indicating high microgrid autonomy.

The Efficiency Coefficient quantifies the energy consumed by microgrid equipment for transformation and storage purposes and is calculated using the formula:

$$K_E = \frac{(W_{EXP} + W_L)}{(W_{IMP} + W_{PV})}. \quad (3)$$

The calculation of the SSR for each month requires determining the volume of electricity imported from the utility grid, which must account for the efficiency coefficient of the microgrid:

$$W_{IMP} = W_L - W_{PV} \times K_E, \quad (4)$$

The data on generation, consumption, and electricity imports for the period from November 2023 to November 2024 are presented in Table 1.

**Table 1.** Summary data of the polygeneration microgrid

| Export to Grid, kWh | Import from Grid, kWh | Total Consumption, kWh | Solar Generation, kWh |
|---|---|---|---|
| 1.1 | 1546 | 4136 | 3261 |

The monthly data on PV modules generation and household consumption for the period from November 2023 to November 2024 are presented in Table 2.

**Table 2.** Energy balance indicators of the polygeneration microgrid

| Month | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Generation, kWh | 111 | 60 | 70 | 117 | 225 | 253 | 342 | 437 | 570 | 467 | 346 | 208 | 55 |
| Consumption, kWh | 241 | 219 | 226 | 171 | 216 | 226 | 301 | 416 | 665 | 498 | 480 | 283 | 194 |

To analyze the dynamics of generation, consumption, and energy storage throughout the day, five daily profiles were selected. The first date, September 23, 2024, was chosen as the day with the highest peak solar generation during the observation period from September 23 to November 19, 2024. The second date, October 4, 2024, features similar ambient temperature parameters, enabling a comparative analysis of the influence of wind and solar radiation. The subsequent dates − November 9, 10, and 16, 2024 − were selected as examples of suboptimal BESS utilization strategies. The data are presented in Table 3.

**Table 3.** Daily energy performance indicators of the microgrid for selected dates

| Date | Export to grid, kWh | Import from grid, kWh | Total consumption, kWh | Solar generation, kWh | Peak consumption, kWh | Peak generation, kWh |
|---|---|---|---|---|---|---|
| 23.09.2024 | 0 | 0 | 11.3 | 13.7 | 0.82 | 3.38 |
| 04.10.2024 | 0 | 0 | 7.6 | 8.8 | 0.46 | 2.362 |
| 09.11.2024 | 0 | 11.3 | 11.1 | 1.2 | 0.601 | 0.422 |
| 10.11.2024 | 0.1 | 8 | 10 | 2 | 0.601 | 0.422 |
| 16.11.2024 | 0 | 8.8 | 9.3 | 2 | 0.64 | 0.37 |

The weather condition data for the selected dates in the area where the microgrid is located were obtained from the nearest meteorological station, "Dolyna − IKYIVO14", on the Weather Underground website (https://www.wunderground.com/) and are presented in Table 4.

**Table 4.** Weather conditions in the microgrid area

| Date | Average temperature, °C | Max wind speed, km/h | Average wind speed, km/h | Max solar radiation, W/m² |
|---|---|---|---|---|
| 23.09.2024 | 16.9 | 16.1 | 4.1 | 638 |
| 04.10.2024 | 16.9 | 30.6 | 11.3 | 534 |
| 09.11.2024 | 4.7 | 12.9 | 3.8 | 65 |
| 10.11.2024 | 3 | 11.3 | 4.8 | 109 |
| 16.11.2024 | 2.3 | 16.1 | 7.8 | 190 |

During periods of surplus local generation, excess energy can either be stored in the BESS for use during evening and nighttime hours or exported to the grid. The use of BESS reduces grid dependence, enhances household self-sufficiency, and minimizes energy losses. Additionally, BESS supports electricity supply in the event of grid outages [2]. Figures 2 and 3 present data on PV modules generation, local consumption, and the state of charge (SOC) of the battery for two typical days of surplus solar generation: September 23 and October 4, 2024.

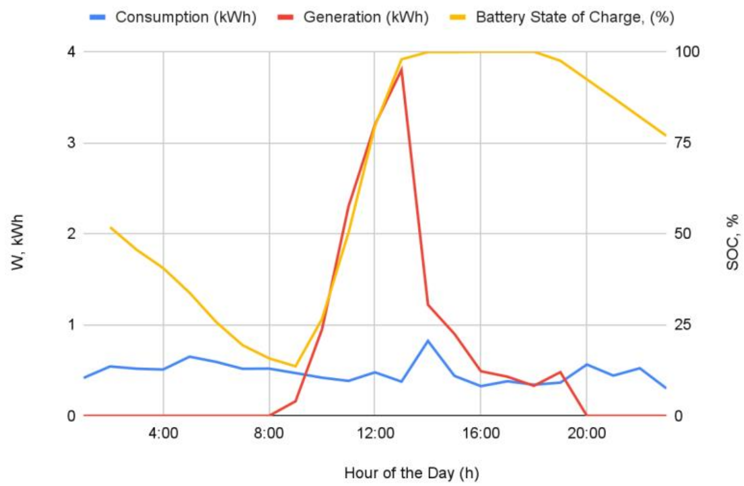


**Fig. 2.** Daily consumption and solar generation data for September 23, 2024

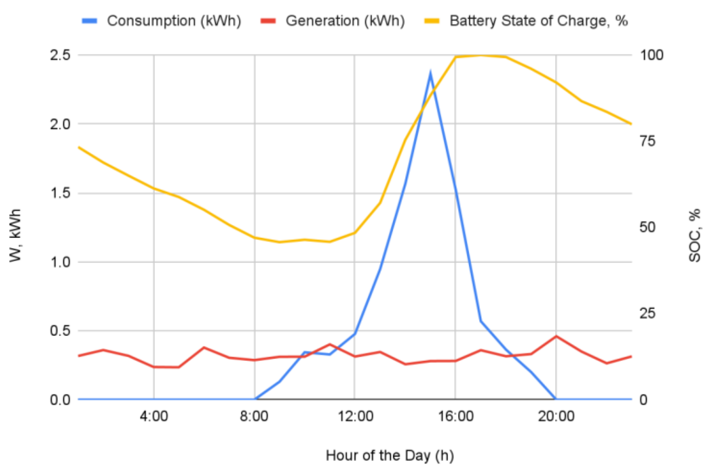


**Fig. 3.** Daily consumption and solar generation data for October 4, 2024

The following data reflect suboptimal use of the BESS in the context of differentiated tariffs and low PV modules generation. Figure 4 shows a consistently high SOC of the battery throughout the day on November 9, 2024, highlights the inefficient utilization of the BESS.

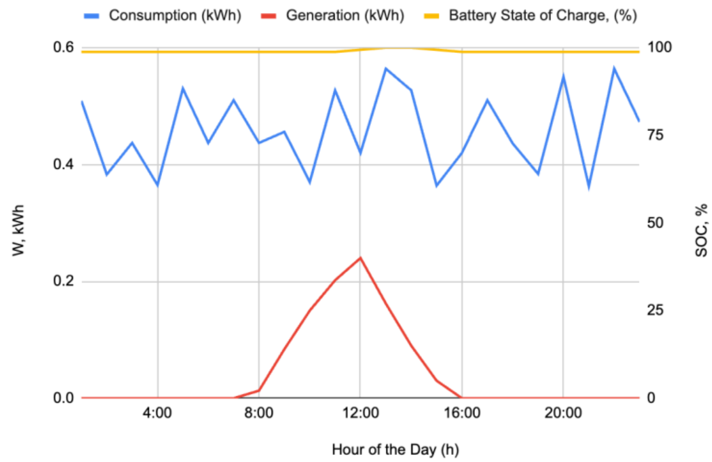


**Fig. 4.** Daily consumption and solar generation data for November 9, 2024

One way to solve this issue is by optimizing the BESS settings. Specifically, it is necessary to adapt charge and discharge management algorithms to ensure active use of the BESS during peak load periods or times of higher tariffs. It is also worth considering consumption and generation forecasts to avoid excess energy storage.

The data for November 10, 2024 (Figure 5) indicate suboptimal energy storage timing, with the BESS charging from the utility grid during the morning peak. This led to the export of surplus solar generation to the utility grid during the day (Table 3).

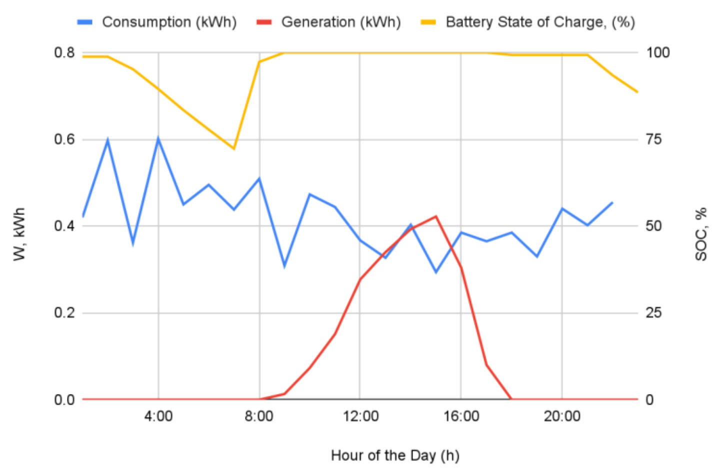


**Fig. 5.** Daily consumption and solar generation data for November 10, 2024

In these conditions, exporting energy is suboptimal behavior since the surplus of renewable energy generation during the day is minimal. Additionally, using the BESS as an energy source after 11:00 PM, when electricity prices are at their lowest [15], is also inefficient.

The data for November 16, 2024, illustrate another type of suboptimal microgrid behavior, where minimal solar generation surplus is followed by BESS charging from the utility grid during periods of higher electricity prices compared to nighttime.

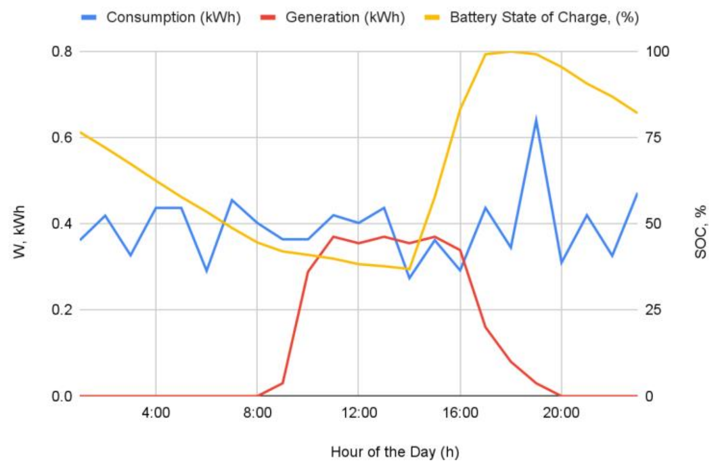


**Fig. 6.** Daily consumption and solar generation data for November 16, 2024

### 3. Results

The annual analysis of the microgrid provides an evaluation of its key performance indicators. The annual SCR is 0.9997, indicating nearly complete utilization of local generation. This means that the microgrid minimizes energy losses through exports and effectively utilizes all locally generated resources.

The SSR is 0.6262, showing that 62.6 % of the microgrid's energy consumption was covered by its own generation. This result highlights the significant contribution of local generation sources, though part of the consumption still relies on imports from the grid.

The annual efficiency coefficient of the microgrid is 0.86, which highlights the high performance of the energy transformation and storage systems. These metrics reflect the seamless operation of all system components, ensuring stable and efficient energy supply for the household throughout the year.

Figure 7 illustrates data on PV modules generation, local consumption, electricity imports, and the calculated SSR for each month from November 2023 to November 2024:

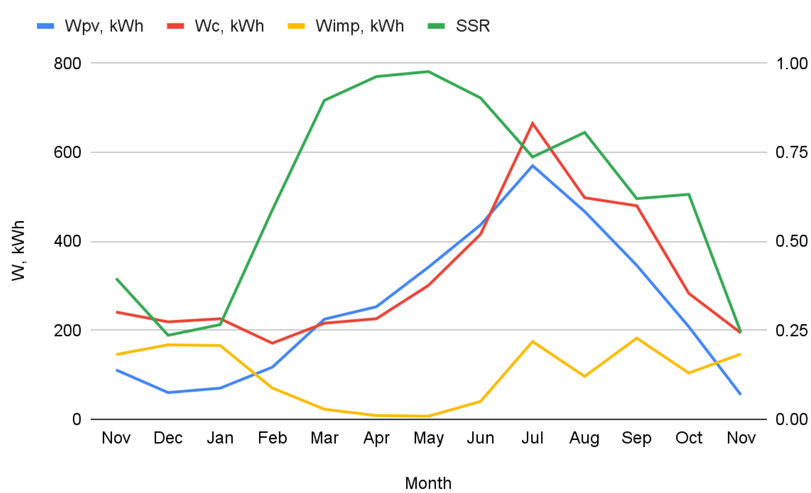


**Fig. 7.** Self-Sufficiency Ratio

The calculation of the SCR for each month was not performed because the share of electricity exported to the grid is less than 0.05 % of the generated electricity, and variations in the ratio fall within the margin of error.

## 4. Conclusions

This study analyzed the key performance indicators of a polygeneration microgrid, including the calculation of self-consumption and self-sufficiency ratios based on annual data for 2023–2024, as well as daily performance data for the period from September to November 2024.

The minimal volume of electricity exported to the grid over the year indicates that the BESS effectively compensates for daily fluctuations in solar generation. By accumulating surplus local generation and utilizing it to optimize the timing of generation and consumption within the microgrid, a balanced energy profile is achieved.

An analysis of the monthly SSR and SCR confirms the positive impact of the BESS, which enables energy storage and subsequent discharge. The SSR varies from 0.236 in the winter months to 0.997 in the spring and summer seasons, reflecting the uneven distribution of solar radiation. The high SSR indicates that increasing PV modules capacity is inefficient for improving the SSR in winter. Increasing PV modules capacity in summer would negatively affect the SCR due to the BESS's limited ability to store excess energy, as well as the need for exporting energy or reducing energy generation in islanded mode. To enhance SSR during the winter season, integrating wind turbines to compensate for seasonal fluctuations in PV module generation is recommended.

A critical step in improving efficiency involves using predictive models for renewable energy generation, accounting for differentiated electricity tariffs and battery degradation [16] to actively utilize the BESS during the autumn and winter seasons. It is important to note that the BESS in microgrids plays a critical role as an uninterruptible power source, and the system must consider the required autonomy time in islanded mode.

To further enhance system efficiency, it is advisable to implement demand-side management strategies to optimize the daily consumption structure, particularly by shifting consumption to periods with a positive energy balance. Such measures will reduce losses caused by the mismatch between generation and consumption and will also improve the overall SCR of electricity.

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# АНАЛІЗ ЕФЕКТИВНОСТІ ПОЛІГЕНЕРАЦІЇ В МІКРОМЕРЕЖІ НА ПРИКЛАДІ ПРИВАТНОГО ДОМОГОСПОДАРСТВА

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**Анотація.** *Сучасні виклики в енергетичному секторі, зокрема зростання вартості енергії та зниження надійності електропостачання, стимулюють впровадження полігенераційних мікромереж. Такі системи інтегрують різні джерела енергії, зокрема фотоелектричні модулі, системи зберігання енергії та резервні дизель-генератори, що забезпечує енергетичну автономність і зменшує залежність від централізованих мереж. Для України, яка стикається з регулярними перебоями електропостачання через пошкодження енергетичної інфраструктури, дослідження ефективності таких мікромереж є особливо актуальним. Метою роботи є оцінка ефективності мікромережі приватного домогосподарства, обладнаного фотоелектричними модулями потужністю 5 кВт і акумуляторною системою зберігання енергії ємністю 10 кВт·год. Основна увага приділена аналізу коефіцієнтів самоспоживання та самозабезпечення. Аналіз виконано на основі щоденних, місячних і річних даних з урахуванням сезонних змін генерації та споживання. Розрахунки показали, що коефіцієнт самоспоживання становить 0.9997. Система налаштована таким чином, щоб ефективно використовувати локально згенеровану енергію. Річний коефіцієнт самозабезпечення досягнув значення 0,6262, покриваючи 62,6 % річного споживання. Аналіз сезонних даних продемонстрував, що в літні місяці самозабезпечення досягає максимальних значень завдяки високому рівню сонячної активності, тоді як у зимовий період залежність від централізованої мережі зростає. Отримані результати підкреслюють важливість впровадження систем прогнозування генерації фотоелектричних модулів, керування попитом та оптимізації роботи системи зберігання енергії для підвищення ефективності мікромереж. Це дослідження демонструє перспективність розвитку полігенераційних систем у приватних домогосподарствах, особливо в умовах сучасних енергетичних викликів.*

**Ключові слова:** полігенерація, мікромережа, самозабезпечення, самоспоживання, система зберігання енергії, відновлювані джерела енергії, керування попитом.

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