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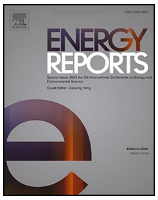

Research paper

Managing the development of decentralized energy systems with photovoltaic and biogas household prosumers

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ABSTRACT

The paper aims to reconsider the impact of developing decentralized energy systems with residential prosumers from the standpoint of energy security, first of all, the impact on supply security. Therefore, the paper complements and develops the methodology of the short- and medium-term energy security assessment in the condition of fast-acting threats. The evaluation of such an impact envisages the prosumers' system value in the power system, which contributes to strengthening energy security and supply reliability. We examined it from the standpoint of system security enhancement costs / avoiding losses caused by threats impact based on four system value components: the value of avoided lost load (VoLL) as the avoided losses and damages caused by disruptions and blackouts, the value of the decreased capacity needs: flexible load (VFD) and baseload demand decrease value (BDV) and the value of technological losses avoided (VL). Using the methods of energy security and system value assessment, the reconsideration of energy policy is suggested to stimulate the establishment of a vast share of decentralized locally balanced self-power-supplying systems under military and economic threats. The paper focuses on photovoltaic household prosumers and biogas small-scale prosumers, whose potential as self-sufficient demand has been underestimated.

1. Introduction

Establishing a vast share of decentralized locally balanced self-power-supplying systems is considered the main feature of mature power markets (Chygryn and Shevchenko, 2023); (Chygryn et al., 2023). Challenges of Russia's military aggression against Ukraine, associated with the destruction of energy infrastructure and threats to large-scale power generation and centralized power supply systems, have shown that decentralized energy supply systems with a high degree of autonomous energy supply are more stable and correspond to all three perspectives of energy security (sovereignty, robustness, resilience), defined by (Cherp and Jewell, 2011).

The power system of Ukraine faced some balancing challenges before 2022, and this situation worsened to a great extent after Russian attacks on hydro and thermal power plants, which maintained the semi-peak and peak areas of the daily power system load schedule. Approximately half of the country's power facilities were damaged. Also, because of shelling, renewable energy (solar, wind, bio-stations), which accounted for 7.9 % of electricity production in 2021, lost a significant part of generation (Tymchenko, for CNN, 2024). Despite this, certain developments in renewable energy sources in Ukraine have been observed over the past year. At the beginning of 2024, the installed capacity of RES facilities increased by 238 MW, compared to 2022, and totaled 8773 MW. About 157 MW of new wind power capacity, 56 MW

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of SPP, and 23 MW of biomass obtained a feed-in tariff. The total installed capacity of biogas complexes has not changed and equals 135 MW (Korol Danylo, 2024); (SAF Ukraine, n.d.).

In 2023, nearly 10 % of Ukraine's electricity was produced through wind and solar power plants (SAF Ukraine, n.d.). Although Ukraine has suffered losses caused by full-scale war, the continued support and development of renewable energy sources are important to ensure the stability and energy security of the country. Partial covering of the demand for energy by household prosumers should benefit the energy system.

Thus, this study aims to substantiate the priority of energy policy and its tools for establishing optimized self-sufficient energy systems with a high degree of decentralization with the participation of small and residential prosumers. The research examines the system impact by positive externalities of such power market participants along with the technical and economic parameters of their operation. The offered approach may provide reasons to affirm that such positive externalities in terms of value exceed the cost necessary for forming prosumers and consider it as direct costs of ensuring the state's energy security by strengthening the security of supply.

The remainder of this article is organized as follows: Section 2 presents a review of studies on the economic issues associated with prosumers, energy security and RES system value evaluation. Section 3 describes the research methodology and calculation stages. Section 4 presents the results of the PV and biogas prosumers system value calculation and outlines their role in the energy security perspectives. Section 5 provides the conclusions and further provisions for using the study results.

2. Material and methods

The economic efficiency and cost assessment of decentralized systems and the evaluation of the prosumers' share increase impact is usually based on the calculation of levelized cost of energy (LCOE) and payback indicators. However, it should take into account the system cost and overall system effect, which contribute to the strengthening of energy security and reliability due to a) autonomization, b) involvement of low-power sources for regulation, c) load optimization. Considering these impacts will provide a comprehensive assessment of energy policy and its implementation costs, which will allow for determining more precisely the volume of energy investments and their sources (sovereign institutions/state companies/private investors/households).

The review of prosumers' self-consumption (SCR) and self-sufficiency (SSR) rates under the different load patterns shows that the average SCR on non-working days is 42.2 % and 61.8 % on working days and depends in a great way on the technical performance while SSR depends on the battery capacity (Sudta and Singh, 2024). SSR varies from 30 % to 99 %, influencing the battery storage capacity and seasonal factors (Boell Foundation in Ukraine, 2020); according to Sudta, its highest value is 86.8 %.

According to the National Renewable Energy Development Plan by 2030 draft, the projected installed capacity of solar installations in households and energy cooperatives in Ukraine is 1150 MW, and by 2030, its value is forecasted at 2947 MW (Government portal, n.d.). At the same time, small "green" energy generation in Ukraine has a capacity of 185 MW, which is less than 2.5 % of the installed capacity of renewable energy in Ukraine and three times less than the installed capacity of generating units owned by households (615 MW) (Boell, 2019).

Analysis of the benefits of prosumer flexibility and network operation optimization, presented by (Gough et al., 2020) shows that the total cost of a prosumer-only power system is reduced by 16.45 %, and its flexibility increases significantly due to the optimization of load and consumption. A 27.5 % reduction in energy losses due to local generation is also achieved. The transition to prosumerism is a pathway to increase the number of RES self-sufficient demand is based on the consideration that only 5–20 % of the companies need to use large-scale nonrenewable power, while 80–95 % of them can turn to self-supplied demand maintained by small-scale RES power generating capacities (up to 1 MW) (Sotnyk et al., 2021).

Prosumers equipped with battery energy storage systems (BESS) are capable of "shaving the peaks," i.e., shifting the generated electricity to the hours of peak load and enabling local generation-demand balancing within the various forms of market cooperation (participating in flexibility and demand response schemes established by energy utilities, aggregators for energy service companies) (Kotilainen, 2019). The incentives for the growing number of active market participants are known as the following: implication of dynamic market prices, a reduction in network charges, pricing mechanisms for new balancing groups, and direct trading (Grzanic et al., 2022; Mentel et al., 2018). Sufficient price incentives and diminishing barriers are the keys to participating in such sectors for aggregated prosumers (Zhou et al., 2023). Kotilainen (2019) stresses the importance of distributed energy storage as a significant flexibility resource of a grid because the cost-efficiently stored energy increases the relevance of distributed generation and prosumers' system value. Energy storage market role and particularly, simultaneous presence at the power and gas markets as well as at the different power market segments discussed by (Dimitriadis et al., 2022; Dimitriadis et al., 2023).

The researchers who performed RES system value evaluation focused on the peak shaving capability of prosumers with energy storage systems (ESS) and prosumers' self-sufficiency and on the electric vehicles as auxiliary services suppliers to the power system (Gudmunds et al., 2020; Sołtysik et al., 2021). The authors (Grzanic et al., 2022; Child et al., 2020; Couder, 2015); discussed the prosumer aggregation issues and, particularly, photovoltaics (Walch and Rüdisüli, 2023); household prosumers (Camargo et al., 2018; Colmenar-Santos et al., 2012); energy communities, microgrids (Hu and Chuang, 2023); market participation, decentralization and local models (Parra-Domínguez et al., 2023; Kästel and Gilroy-Scott, 2018); prosumers on biomass (Volpe et al., 2022). Cost-benefit issues of RES and prosumers-related energy technologies analysis (LCOE, profitability, investments) are performed by (Tran and Smith, 2018), who incorporated the sensitivity and uncertainty analysis into LCOE calculations, and (Kurbatova et al., 2023), who discovered the prosumers development trends based on LCOE dynamics. The role of prosumers as new actors in energy security and reliability of energy supply, which improve the decentralised energy ecosystem, is discussed by (Leal-Arcas et al., 2017; Saleh, 2018).

Biogas prosumers issues such as livestock farming and agro-industrial waste biogas generation are investigated by Cabello et al. (2022). Kurbatova (2018) envisages such prosumers as a part of energy cooperatives. (Plotnytska et al., 2019) consider them as a part of the agricultural cluster. Methodological issues of calculating the economics of biogas projects are covered in the papers by (Vu et al., 2015; Pryshlyak, 2021). Biogas energy policy issues, energy investment models, environmental taxes and pricing stimulation counties' case studies are performed in the research papers, e.g. future provisions (Scarlat et al., 2015; Theuerl et al., 2019); investments (Klimek et al., 2021); taxation (Bilan et al., 2022; Kuzior et al., 2023); biomass issues (Giwa et al., 2020; Biosantech et al., 2013).

Recent studies focus mainly on the cost-benefit analysis of prosumers but do not fully embrace the quantification of their impact and benefits to the grid operation, as well as achieving energy policy goals: energy security, system flexibility and power availability enhancement. Therefore, the research covers the existing gap by integrating the scientific and practical issues of efficiency of prosumers of different types and installed capacity size with system security and security of supply perspectives. Therefore, the further development of methodology and techniques for the system cost assessment of various energy generation technologies is necessary, taking into account the contribution of such technologies to energy security, or, in particular, security of supply.

2.1. Energy security approach

The International Energy Agency (IEA) defines energy security as "the uninterrupted availability of energy sources at an affordable price." (University of Aberdeen, n.d.). Energy security also means having access to sufficient energy to meet the power demand (Mentel et al., 2020). Energy independence is a state when a country has sufficient energy resources to meet its energy needs (Wołowiec et al., 2022). In contrast, energy security relates to having reliable and affordable energy within a country, regardless of energy source. The achievement of both of them enhances a country's national security and economic growth.

The established systems of energy security assessment comprehensively evaluate the degree of supply diversification, the availability of energy reserves, and the development of energy infrastructure. However, direct military aggression multiplies and, in a very short time, increases the risks that distort the calculation of a significant number of indicators due to the rapid change of input data, the unavailability of energy facilities and logistics routes in certain territories under hostilities / front-line territories. Energy security assessment systems such as Supply/Demand, Oil Vulnerability, Energy Security indices etc. are based on static data in the short term. (Jansen and Seebregts, 2010) stress that traditional approaches to long-term energy security, especially economic modelling approaches, tend to zoom in on the supply of one or more of the exhaustible (fossil) fuels (Jansen and Seebregts, 2010). However, IEA Model of Short-term Energy Security (MOSES) uses risk-and-resilience indicators, which makes it possible to assess the level of energy security more flexibly. Three perspectives of energy security: sovereignty, robustness and resilience Cherp and Jewell, (2011) are applicable for assessing energy security in the short term and are considered in this research.

Sovereignty. The sovereignty perspective envisages maintaining military, political and/or economic control over the energy system. To minimize risk, it envisages switching to trusted suppliers and avoiding the domination of a single supplier's role through diversification, substituting imported resources with domestic ones, and casting. The Ukrainian power system went into isolated mode on the eve of a full-scale invasion and was synchronized with ENTSO-E soon after. This ensured sovereignty from the power systems of Russia and Belarus, with parallel work being implemented until then. In addition, it diversified the sources of emergency services and imported power due to commercial imports. The lack of a full nuclear fuel cycle in Ukraine makes it impossible to maintain complete self-sufficiency and sovereignty with regard to nuclear fuel. However, its timely diversification increased the energy security level significantly. In the gas sector, since 2015, there has been a switch from the Russian monopoly model of gas supply in favor of European import sources diversification, including reverse supply, in the background of own production enhancement. Such a strategy made it possible to reach almost complete self-sufficiency in natural gas in 2024 (Ukrinform, 2024), taking into account the significant reduction in natural gas consumption in the country in the background of industrial production shortage and the temporary occupation of certain territories. Objectively, the increase in the number of industrial and household consumers with a high share of self-sufficiency in electric and thermal energy also contributed to sovereignty.

Robustness. This perspective aims to build energy supply systems resistant to external influences, such as resource shortages, equipment failures, and natural disasters. In peacetime, the resilience of power systems to sharp fluctuations in consumption depends on the generation reserve availability and its maneuverability, as well as the sufficiency of inter-system and intra-system transmission connections. The experience of the Ukrainian power system operation in long-term military aggression targeted at the energy infrastructure is unprecedented since WWII. It shows that the robustness of electricity supply lies in the extensiveness of intra-system connections and the possibility of alternative energy supply schemes. In peacetime, it is also relevant for the resistance to forced interruptions in energy supply due to natural disasters. A diversified energy mix makes it possible to partially or completely replace one type of capacity with another if lost. Decentralized energy supply systems are the least susceptible to the targeted destructive influence and have the greater robustness, the greater the share of their self-sufficiency.

So, if, in a general sense, a high level of robustness is ensured by minimizing risks by energy infrastructure modernizing and demand growth managing, in the situation with the current challenges for Ukraine, it is the branching of intra-system connections and alternative energy supply schemes use, diversified energy mix and high degree of electric grids decentralization.

Resilience. According to (Cherp and Jewell, 2011), "the resilience perspective searches for more generic characteristics of energy systems (flexibility, adaptability, diversity) that ensure protection against any threats by spreading risks." In the conditions of an unprecedented loss of generating capacities, the sufficient level of resilience of the power system of Ukraine may be in reaching the rate of capacity withdrawal at the rate of restoration, the high level – in exceeding it. The pace of restoration depends on the type and complexity of energy equipment. The unified and less technologically complex objects can be restored faster as small-capacity power objects take less renewal time than large-capacity units.

It is also about reformatting the scale of energy facilities in favor of medium and small-scale power stations (gas peakers, ESS), as well as reformatting the energy mix towards the geographically distributed power generation on renewable fuel (conditionally "200 projects instead of 20", literally: "Biomass thermal power plants – 55 projects, highly maneuverable power plants – 70 projects, energy storage installations – 55 projects" (RFI, 2024).

Power reliability assessment methods based on system adequacy and system security involve calculating the level of power supply operational and balance security, taking into account the sufficiency of capacities in a power system ready to cover the peak load. Therefore, the gross capacity margin is the level by which the available generation capacity exceeds the maximum demand, and the reserve margin of generation capacity is its variation. The most adapted method for the evaluation of short-term system security is the reserve margin of generation capacity, which embraces the total de-rated capacity of all plants and the loss of plant capacity due to the shutdown of the largest plant, loss of a transmission line and considering the impact of other extreme events on supply, as well as the additional de-rating due to primary fuel shortage.

3. Theory and calculation

3.1. Prosumer system value estimation method

The need to assess the system value (SV) has been realized during the implementation and operation of various energy technologies, evolutioned from niche innovations to techno-economic transitions of energy mix. Most often, SV is used for a comprehensive assessment of the peak shaving effect of ESS separately or together with solar photovoltaics and wind turbines, RES grid limitations, electric vehicle chargers, pumped storage hydroelectric power stations, SMART grid and DSM systems. It consists of the assessment of power costs that are optimized due to new technology use. The value is estimated based on CAPEX of replaced capacities if we consider avoiding the construction of new power units or the LCOE or spot prices for electricity if we consider replacing existing capacities in the power system.

The distribution of prosumers requires a broader consideration of the impact on SV from the cost standpoint for strengthening system security / avoiding losses caused by threats. For a power system, such costs can be: the value of avoided lost load (VoLL) as the avoided losses and damages caused by disruptions and blackouts, the value of the decreased capacity needs: flexible load (VFD) and baseload demand decrease value (BDV), and also the value of technological losses avoided (VL), which could be included into the previous value, as well as be evaluated separately (Fig. 1).

VoLL is the value expression of electricity supply disruptions caused by production, transmission or distribution failures (Couder, 2015). It can be estimated in the money units per kWh as the total damage caused by undelivered electricity divided by the volume of undelivered electricity (Tol, 2007). At an efficient market, this parameter shall be equal to the wholesale peak price of electricity, and this value is the average willingness of consumers to pay to avoid an additional period without a power supply (Tol and Leahy, 2011). It also equals the supply security value and is estimated using the production function approach. We can compare it as well to the difference between the retail electricity price level of electricity offered with the non-limitation of supply guarantee (which offsets the import price disparity) and the average retail electricity price level (in Ukraine) or with the cost of power system emergency assistance, provided by ENTSO-E neighbouring power systems. (Reichl et al., 2013) evaluate the impact of power outages in the number of severely/very severely affected individual households or non-households (in one thousand entities).

In the event of capacity lack in a system, the following mechanisms are activated in sequence: use of self-sufficiency opportunities (autonomous generation), commercial import, power system emergency assistance and, lastly, supply limitations (scheduled and emergency shutdowns). In case the limitations cannot be avoided, the consequences related to damage or threat to life are difficult to evaluate, so VoLL estimated the willingness to pay for the disruption avoidance, which is in a great way underestimated. Herewith, there are difficulties in the lost load value estimation because of the hidden costs of low power reliability: impacts on life-support systems, heating and cooling, refrigerating, security systems and traffic lights operation, water supply and sanitation (Reichl et al., 2013).

The decentralized power systems are capable of avoiding technological losses, i.e. the total amount of electricity losses in the elements of electrical networks that occur during the transmission of electricity, electricity consumption for the substations' own needs, electricity consumption for ice melting and corona discharges, as well as significantly reduce losses caused by imperfection of electricity metering by technical means. With the implementation of smart metering, the least costs are entirely leveled. Therefore, ***VL*** for the power system as a whole during the operation of decentralized power supply systems is almost completely equal to the cost of electricity produced and lost as technological costs.

Moreover, the other role of prosumers is "peak shaving" due to their self-sufficiency in peak consumption. This gives the prerequisites for flexible capacity demand decrease, which value (**VFD**) is another component of prosumers' SV. Together with that, the prosumers' own generation partially or fully covers their baseload demand (daily minimal consumed load). Its value is the value of avoided baseload supply from the grid, which forms the fourth SV component, which is the baseload demand decrease value (**BDV**).

The formulation of these components using the self-sufficiency rate, the widely used prosumers' indicator, is given below. The self-sufficiency rate is usually defined as the volume of generated and consumed electricity (E_{gc}, Fig. 2, striped area) divided by the total volume of consumed electricity (E_{load}):

$$SSR = \frac{E_{gc}}{E_{load}} \tag{1}$$

where

$$E_{gc} = E_{gen} - E_{to\ grid} \tag{2}$$

We can detail the SSR indicator for baseload demand and flexible demand of a prosumer to be able to estimate what part of basic and what part of variable (peak) consumption is provided by self-production, using two sub-indicators SSR_b *and* SSR_p:

$$\text{Baseload self} - \text{sufficiency rate of a prosumer} SSR_b = \frac{E_{gc\ b}}{E_{load\ b}} \tag{3}$$

$$\text{Flexible load self} - \text{sufficiency rate of a prosumer} SSR_p = \frac{E_{gc\ p}}{E_{load\ p}} \tag{4}$$

To define the prosumer's daily load profile zones, we apply the coefficients used to describe the configuration of the daily load curve of the power system: the minimum load coefficient $\alpha_{\min}$, which is the minimal and maximal load ratio:

$$\alpha_{\text{minc}} = \frac{P_{\text{minc}}}{P_{\text{maxc}}} \tag{5}$$

Approximating the $E_{gc\ b}$ area to a trapezoid, let us express it formulaically using the consumption heterogeneity coefficient K:

$$E_{gcb} = [a(1-K) + b(1+K)]\frac{P_{\text{minc}}}{2} \tag{6}$$

where $K = 1 - \frac{P_{\text{minc}}}{P_{\text{maxc}}} = 1 - \alpha_{\text{minc}}$;

Based on Eq. (3), we can define the sub-indicator SSR_b by the following formula:

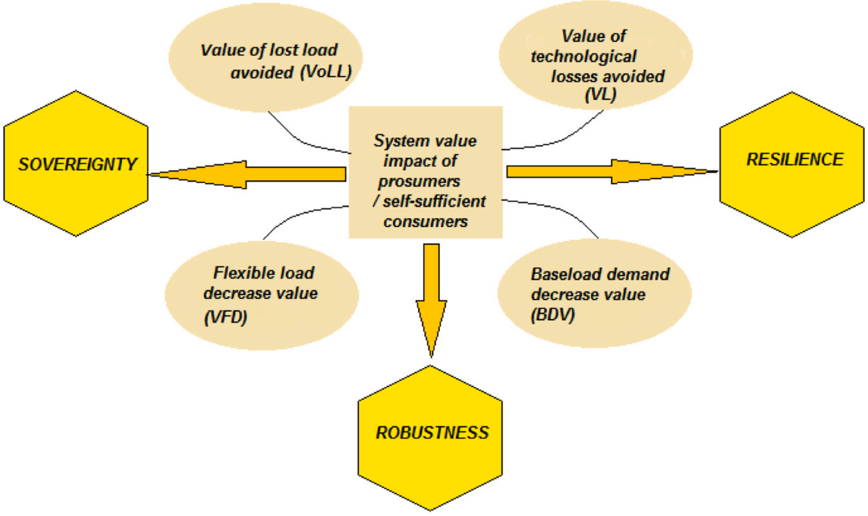

Fig. 1. Energy security perspectives and prosumers' SV components.
Source: the authors

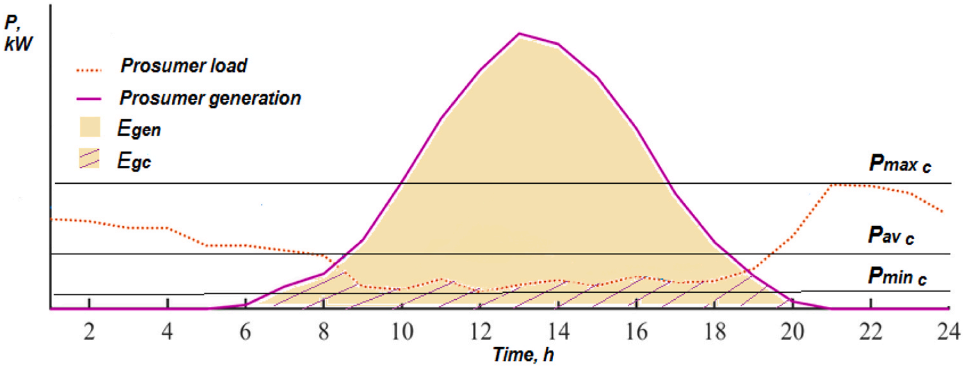

Fig. 2. Typical generation and load profiles of a consumer.
Source: the authors

$$SSR_b = \frac{E_{gcb}}{E_{loadb}} = \frac{[a(1-K)+b(1+K)]\ \frac{P_{\text{minc}}}{2}}{24P_{\text{minc}}} = \frac{[a(1-K)+b(1+K)]}{48} \quad (7)$$

The flexible part of the electricity volume generated and consumed by a prosumer can be defined as $E_{gc\,p} = E_{gc} - E_{gc\,b}$, or, if applying the coefficient K to $E_{gc\,p}$, as an approximated trapezoid area:

$$E_{gcp} = [a(2-K)+bK]\ \frac{P_{\text{maxc}} - P_{\text{minc}}}{2} \quad (8)$$

Based on Eq. (4), we can define the sub-indicator SSR_p by the following formula:

$$SSR_p = \frac{E_{gcp}}{E_{loadp}} = \frac{[a(2-K)+bK]\ \frac{P_{\text{maxc}} - P_{\text{minc}}}{2}}{E_{load} - 24P_{\text{minc}}}. \quad (9)$$

Thereby, by means of SSR_b and SSR_p, the system value components *BDV* and *VFS* (annual values) can be evaluated as follows:

$$BDV = SSR_b \bullet SSD \bullet LCOE_b \bullet 8760 \quad , \quad (10)$$

$$VFS = SSR_p \bullet SSD \bullet LCOE_p \bullet H_f \quad . \quad (11)$$

where H_f, annual duration of semi-peak (flexible) power system load, for the power system, it can be applied 3850 h as average.

3.2. Potential and role of biogas small-scale and household prosumers

When considering the development of possibilities for prosumers' growth, preference is usually given to those who use solar power generation. Less attention is paid to the prosumers operating individual biogas reactors. However, biogas is today's cheapest and most scalable form of renewable gas. It is a dispatchable energy carrier and can be deployed to balance intermittent renewable energy generation. Moreover, biomethane (upgraded biogas) can directly substitute natural gas and be stored and deployed across the whole energy system using the existing gas infrastructure and end-use technologies. Additionally, biogas is well placed to deliver significant, long-term socio-economic benefits, thereby supporting the transition to a sustainable and circular economy (European Biogas Association, n.d.).

The increase in the production of plant growing and stockbreeding to meet the needs of the consumers leads to an increase in the volume of household waste and in the burden on the environment (Ziabina et al., 2023; Chygryn and Shevchenko, 2023). Plant growing waste of organic origin, stockbreeding and poultry waste of organic origin and human waste negatively impact the soil, air and water basins. Among organic and plant waste utilization approaches, bioconversion in an oxygen-free environment, or biogas fermentation, is distinguished. This is an ecologically safe way of biowaste processing to obtain an ecologically clean fuel that is biogas. Solving the problem of waste disposal through bioconversion will contribute to the enhancement of the environment's quality and energy security. Biogas enables the integration of rural areas and industry to strengthen energy independence.

In recent decades, the interest in biogas has grown in developed countries and worldwide. Many bio-installations are deployed in European countries, India, China, and North and South America. There are currently almost 20,000 biogas plants and almost 1400 biomethane plants in Europe (Bioenergy International, 2023). The total volume of biogas production in Europe has gradually increased; as of 2022, it was 179 TW (Fig. 3).

Germany has the largest number of biogas plants among European countries – 9 527 installations. Of these, 950 are small biogas plants with a capacity of up to 150 kW. Other top producers are France, the UK, the Netherlands, Italy and Denmark (Djatkov et al., 2021). Low-capacity biogas plants are considered to influence the development of the biogas production sector in a great way in the vast majority of EU countries due to the energy policy promoting the expansion of decentralized and rural bioenergy and the stimulating and supporting of small farms and enterprises that dispose of organic waste, depending on their volumes.

In EU countries, low-capacity biogas plants are classified into capacity groups, each of which, in turn, has a separate incentive tariff rate: the lower the facility's capacity, the higher the tariff. Obviously, the capital investment return is multifactorial in each individual case. Still, biogas production with a capacity of 50 kW, 75 kW or 150 kW has payback, and its construction may be of interest to small and medium enterprises.

The construction of a biogas plant is particularly appropriate for small livestock and plant farms since they have a guaranteed raw material base in relatively large volumes, and therefore, they receive an extra profit. In such a case, an ecological solution to the issue of animal waste products and plant remains disposal, as well as the self-supply by energy resources and fossil fuels substitution, the production of biofertilizers to form a high-quality fodder base of a farm, or for organic farming (Agrobiogas, n.d.).

Installing small biogas power plants in farms makes them energy-independent, increases production volumes, and solves the waste disposal problem. Using biogas in a decentralized energy supply helps reduce the import of energy carriers and increase the reliability of energy supply, particularly in rural areas. More and more European farms are commissioning biogas plants in the vicinity to provide themselves and nearby villages with electricity and heat. In addition, fermentation residues from the reactor can be used as a high-quality fertilizer in agriculture. Due to the constant availability of raw materials, electricity and heat can be produced throughout the year, thus creating additional economic support for many farms, contributing to domestic agriculture's stability and development. Processed biogas can be used flexibly and independently of the place of production due to the possibility of

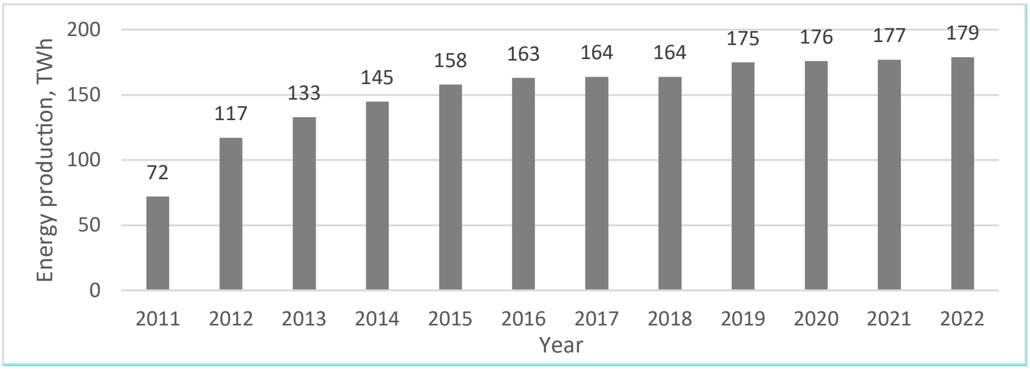

Fig. 3. Development of biogas production in Europe.
Source: (Bioenergy International, 2023)

feeding it to the gas transport system and storage, which helps to level the imbalance of other renewable energies such as wind and solar.

The efficiency of biogas plant project implementation for household prosumers and small entrepreneurs (farmers) is based on the potential of biogas production. The calculation of the excrement output use can be based on (Polyovyi et al., 2011) and determined by the formula:

$$\mathrm{Be} = N – H_e \tag{12}$$

Calculation of biogas yield based on (Polyovyi et al., 2011) is determined by the formula:

$$B_b = B_e – H_b \tag{13}$$

The amount of electricity obtained from the household with one cow per day is determined by the formula [53]:

$$V_e = \frac{(V_b \times \mathrm{T})}{3600} \times \eta \tag{14}$$

In the research, V_e is assumed 2.81 kWh/cow per day.

Biogas can be continuously produced on demand among all renewable energies based on available local raw materials. The smallest biogas prosumers are the households that own at least one or two cows, and while the number of such households is significant, they usually fall out of the prosumers' capacity assessment. Assessing the potential of the smallest prosumer equipped with a biogas processing unit can avoid underestimating its role in the energy mix and security of supply.

4. Results and discussion

In order to calculate the efficiency of biogas plant project implementation for household prosumers and small entrepreneurs (farmers), it is necessary to determine the potential of biogas production (Table 1). Data on the number of farm animals take into account only households (State Statistics Committee of Ukraine, n.d.).

According to the most recently published data, the pre-martial (as of 2020) average monthly electricity consumption by the population of Ukraine was 165 kWh/month (Energymap, n.d.). Using the data from Table 1, we can evaluate the electricity volume that can be obtained from 1 cow. The daily output of excrement from a cow is 55 kg (Priekulis and Aboltins, 2015). The standard rate of thermal energy output from 1 m^3 of biogas is 21 MJ (Polyovyi, 2011). The efficiency of the biogas generator can be assumed at the level of 35 % (Biogasworld, n.d.). So, the total volume of electricity output per month, calculated using the formula (14), is 84.3 kWh. If a household keeps ten cows, it can produce 843 kWh per month, which is 411 % more than the average monthly electricity consumption.

SV evaluation of household PV and biogas prosumers

A typical profile of a prosumer, e.g., in (Karalus et al., 2023), operating a photovoltaic power generation unit involves a yearly average duration of the prosumer's generation mode of 8–12 hours. At the same time, depending on the load profile of the prosumer, which can be unoptimized or optimized according to the generation profile, the time of release of the excess generated electricity to the external network can vary significantly (the change of seasons further increases this variability), but the most appropriate range is 3–8 hours.

Putting BESS into operation by a prosumer can significantly increase the value of E_{gc} and reduce the amount of electricity delivered to the network. In this way, it is capable of increasing the self-sufficiency rate of a prosumer: overall SSR as well as sub-indicators SSR_b *and* SSR_p to varying degrees depending on the consumption profile and its optimization.

For a biogas prosumer (option 3), a parameter is assumed as 4 h, and b parameter – as 16 h.

The evaluation of household PV (options 1–2) and biogas (option 3) prosumer self-sufficiency rates and system value components BDV and VFS is presented in Table 2.

VoLL estimation is a complex assessment of all losses and monetized damages from power outages, and it is complicated because of hidden

Table 1
The potential of the main livestock waste for the production of biogas by household prosumers in Ukraine (as of 2022).

Kind of animals and poultry	Livestock and poultry, thousand heads	Value	Daily output of excrement from a head, kg	Manure exit, tons/day	Output of biogas, Nm^3 /t of substrate	Output of biogas, Nm^3/day
Cattle	1 641	Min	40.0	65 624	25.0	1 640 600
		Max	55.0	90 233		2 255 825
Pigs	2 032	Min	15.0	30 479	28.0	853 398
		Max	22.0	44 702		1 251 650
Sheep and goats	926	Min	2.1	1 944	30.0	58 325
		Max	3.5	3 240		97 209
Horses	171	Min	19.0	3 257	63.0	205 166
		Max	26.0	4 456		280 753
Poultry of all species	88 764	Min	0.3	22 191	1.4	31 068
		Max	0.6	53 259		74 562

Source: built based on (Plotnitska et al#, 2019); (State Statistics Committee of Ukraine, n.d.); (Priekulis and Aboltins, 2015).

Table 2
The inputs and results of BDV and VFS evaluation for every 100 MW of SSD.

Parameter	Option 1 (PV)	Option 2 (PV)	Option 3 (biogas)
a, hours	3	8	4
b, hours	12	12	16
Pmin c, MW	0.001	0.001	0.001
Pmax c, MW	0.005	0.005	0.005
K	0.8	0.8	0.8
E load, MWh	0.1	0.1	0.1
SSD, MWh	100	100	100
LCOE b, USD/MWh	150	150	150
LCOE p, USD/MWh	50	50	50
SSR_b	**0.46**	**0.48**	**0.62**
SSR_p	**0.24**	**0.36**	**0.33**
BDV, mln USD	**61**	**64**	**81**
VFS, mln USD	**5**	**7**	**6**

Source: own calculations

costs. When the consequences related to damage or threat to life are difficult to evaluate, in cases of large-scale blackouts and long-term electricity shortages, in particular, related to emergencies and martial law, it is possible to apply the willingness-to-pay for the disruption avoidance method for VoLL estimation.

In the Ukrainian power system, in situations of capacity shortage, the volume of imported electricity into the system increases. The price disparity between the DAM markets of EU countries and Ukraine is favorable for imports due to high price caps on the Ukrainian market. However, the cost of imported electricity for end users doubles or more due to high competition at the auction for access to cross-border transmission capacity. The marginal crossing price for import reached 100–150 EUR/MWh. Thus, the price of imported electricity for the final consumer can reach more than 300 EUR/MWh, and some industrial consumers are ready to pay such a price for which the risk of interruption of electricity supply is high enough (productions with electric arc furnaces, continuous casting technology, electrolytic processes, etc.) This price can be taken as the price that consumers are willing to pay for continuity of electricity supply, which can be applied to estimate VoLL.

As stated above, as a result of the decentralized power supply systems operation, VL avoids the cost of electricity produced and lost as technological costs. Taking into account the technical conditions and technological level of transmission networks, the actual level of transmission losses together with commercial ones (which is unmetered consumption due to theft of electricity or non-payment) can be evaluated as 20 % of the electricity output needed to supply electricity to the autonomized consumers (Bohonko, 2016). Thereby we can suppose that approximately 20 MW for every 100 MW of self-supplied demand (SSD) is avoided which equals USD 9 mln a year, based on the average electricity production cost of 50 USD/MWh. Moreover, decentralized power supply systems could be treated as an efficient instrument to improve institutional and interpersonal social trust on the way to sustainable development (Kostenko et al., 2022) and phase the transformation within III and IV industrial revolutions (Melnyk, 2021).

The estimation of annual SV for every 100 MW of prosumers' self-sufficient demand is presented in the Table 3.

The estimated system value of prosumers with SSD equal to 100 MW can be 1.7–2 times greater than the appropriate investment cost (CAPEX). In our analysis, three LCOE values are used: for basic energy-generating capacities, for flexible capacities that provide semi-peak and peak zones of the power system daily load, as well as the LCOE of prosumers themselves for comparison. Prosumers using solar photovoltaics are the most widespread, so we rely on them in our analysis, as well as on the small bioenergy-based prosumers, which are also emphasized in our study. Obviously, the prosumers equipped with BESS and/or DSM have higher LCOE values, SSR and system value effects.

Table 3
Annual SV estimation for 100 MW of SSD of prosumers, mln USD.

SV component	Option 1 (PV)	Option 2 (PV)	Option 3 (biogas)
BDV	61	64	81
VFS	5	7	6
VL	5	5	7
VoLL	7	7	7
SV	**78**	**82**	**101**
CAPEX	44	44	59

Source: own calculations

5. Conclusion and policy recommendations

Objective short- and medium-term assessment of energy security in conditions of rapid threat manifestation needs the analysis of security of supply from three perspectives of energy security: sovereignty, robustness and resilience. System value assessment of prosumers expansion evaluates prosumers' systemic impact and goes beyond the economic effects of individual consumers self-sufficient demand projects.

The *sovereignty* perspective suggests the autonomization of energy supply and maintaining the self-sufficient demand due to the spread of all forms of prosumers (industrial, housing and communal enterprises, energy cooperatives, small entrepreneurs, households). The formalization and assessment of their self-sufficiency in the basic and variable parts of electricity consumption in a power system carried out in the paper show the release of generating capacities and their possible direction for the energy supply needs of other scarce consumers. In the long term, it reveals a shift in the energy mix with savings in capital costs for constructing the replaced capacity. Such system value component as grid loss avoidance also contributes to sovereignty.

The extensiveness of intra-system connections and the possibility of using alternative energy supply schemes form the resistance to forced interruptions in energy supply and its *robustness* as a whole. A diversified energy mix allows for replacing lost capacity with another one. Decentralized energy supply systems are the least susceptible to purposeful destructive influence. The greater the degree of robustness, the larger the share of their self-sufficiency. Lost load avoidance, which is another system value component, also contributes to robustness: secured energy supply is socially relative.

The prosumers' contribution to the *resilience* of power supply is their flexibility and adaptability due to the short terms for the restoration and maintenance of low capacity units and microgrids, flexibility in their distributed placement and relatively low specific capital costs as well as the easier technology and fuel switch and the combined operation of two or more power generation technologies.

The assessment of household prosumers system value gives the reason to affirm that for a power system can be one and a half to two times greater than the initial cost of its incipience. Costs of disconnections, blackouts, transmission and distribution losses, which are avoided due to a prosumer's self-sufficiency, the value of baseload and flexible power generating capacities release and providing them to other electricity consumers – these are the SV components. Self-sufficient demand, based on the different prosumer technologies (PV, wind, biogas, heat pump etc.), makes it possible to integrate small-scale municipal and rural residential consumers into the energy independence enhancement, especially in wartime, and it needs special support from the state energy policy.

Therefore, current regulatory policies should focus on facilitating the participation of new entrants in the decentralized power supply at the local and centralized flexibility segments of prosumer markets as the system value of such entrants is much higher than their incipience cost. This synergetic effect is capable of reducing the overall need for investments and expenses in the security of supply in several directions (new baseload and flexible capacity construction, transmission and distribution grid expansion and service, overload managing and "bottlenecks" elimination and reserve capacity maintaining, operational and balance power system reliability).

Further research will help the deeper understanding of the prosumers role in security of supply as their share grows to more than 50 % in emerging energy markets. It is also important to assess the systemic value of the different energy technologies used by consumers in order to obtain tools to promote the most effective and rapidly deployed of them.

Abbreviations

Acronym	Definition
DSM	Demand-side management
SV	System value
ESS	Energy storage systems
BESS	Battery energy storage systems
IEA	International Energy Agency
LCOE	Levelized cost of energy
SCR	Self-consumption rate
SSR	Self-sufficiency rate
VFD	Value of flexible demand avoided
BDV	Baseload demand avoided value
VL	Value of losses avoided
VoLL	Value of lost load avoided
PV	Photovoltaics
SPP	Solar power plants
ENTSO-E	European Network of Transmission System Operators for Electricity
MOSES	Model of Short-term Energy Security
Symbol	**Description**
Be	excrement output, kg
N	number of cattle, ths heads
H_e	excrement output normative, tons per day
B_b	biogas output, m^3 per day
H_b	yield of biogas from 1 ton of organic fertilizers
V_e	electricity volume from biogas unit, kWh
Vb	biogas volume, l
T	calorific value, MJ/m^3
η	biogas unit efficiency, %
H_f	annual duration of flexible load in power system, h
α_{minc}	minimum load coefficient
β_{dc}	load density coefficient
a	number of hours of prosumer's off-take to the grid, h
b	duration of prosumer's generation mode, h
P_{minc}	minimal load of a prosumer
P_{maxc}	maximal load of a prosumer
P_{avc}	average load of a prosumer
E_{gc}	volume of generated and consumed electricity
K	consumption heterogeneity coefficient
$E_{gc\ b}$	volume of generated and consumed baseload electricity
$E_{gc\ p}$	volume of generated and consumed flexible load electricity
E_{gen}	volume of generated electricity
E_{load}	volume of consumed electricity
$E_{load\ b}$	volume of consumed baseload electricity
$E_{load\ p}$	volume of consumed flexible electricity
$E_{to\ grid}$	volume of electricity taken-off to grid

Author Agreement Statement

We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We understand that the Corresponding Author is the sole contact for the Editorial process.

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Uliana Pysmenna: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Meng Li:** Resources, Investigation, Conceptualization. **Iryna Sotnyk:** Supervision, Project administration, Funding acquisition, Conceptualization. **Sviatoslav Petrovets:** Writing – original draft, Methodology, Data curation. **Tetiana Kurbatova:** Writing – review & editing, Formal analysis.

Declaration of Competing Interest

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.egyr.2024.10.011.

Data Availability

Data will be made available on request.

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