Key defining features of establishing and operating industrial and citizen energy communities

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Abstract. The aggregation of end-users who produce, consume, and exchange surplus energy within the borders of a shared geographical area manifests a new way of using renewable energy as represented by Energy Communities (EC). At that, both industrial and "residential" community microgrids can be such consumers, which act as a single controlled object in relation to the external power grid. The reasons and objectives of prosumers joining their forces to form an EC differ depending on their predominant type and nature (industrial enterprises, residential buildings, farms, etc.). These include consumers' need for energy autonomy, lowering of otherwise high electricity tariffs, improvement of energy supply resilience and reliability, minimization of urban pollutant emissions, more efficient use of renewable energy sources, etc. This study relies on a general methodology developed by the authors to assess key defining features of the establishing and operating ECs of industrial and community microgrids serving residential loads. We demonstrate how methods of multi-criteria decision-making and artificial intelligence can take into account these features in an efficient way so as to maximize the local and system-wide effects of different types of ECs.

1 Introduction

Industrial and citizen ECs are two types of energy communities that have emerged as a result of the growing interest in sustainable and decentralized energy systems [1]. Industrial ECs are primarily groups of core industrial facilities that usually work together to optimize energy use and reduce environmental impacts. Secondarily, they may additionally (but not necessarily) include residential loads of households and small enterprises of other categories, for example, those involved in agricultural activities. In most cases, such communities consist of facilities from the same or different industrial and/or commercial sectors and can share energy resources and infrastructure to improve efficiency and reduce costs. For example, a group of plants may share a CHP plant to generate electricity and heat, or they may share renewable energy sources (RES). The features shared by ECs include the tendencies of the transition from conventional energy technologies to more environmentally friendly and safe ones (including renewables). Another common feature is the mandatory use of energy storage

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systems in order to offset the intermittency of energy generation by renewables and to comply with stricter requirements (compared to citizen ECs) for the reliability of power supply systems.

The transition from fossil fuel-based energy to RES-based electricity (which includes, among others, gasification-based power plants, or GPPs) requires large-scale upfront investments, given the much higher needs and baseloads in the industrial sector than in other sectors (e.g., the built-up area). This inhibits the development of such projects on the part of industrial companies. One way to address the investment challenge is collective investment in RES systems and the creation of "community energy" shared by companies of the industrial cluster. The joint investment can help to reduce costs by almost 30% [2], as well as significantly reduce power losses in the entire network.

Another type of ECs, which is an aggregation of community microgrids, usually includes core components such as groups of households and/or farms, and may additionally include catering, entertainment, and residential facilities that work together to produce and consume energy in a more sustainable and efficient manner. These communities can be organized around shared renewable energy resources (including GPPs) as well as energy storage systems that allow households to "store" and optimally manage surplus energy, such as that generated by rooftop solar photovoltaic cells (PVCs). These facilities, when operating together, can save on their energy bills, increase their energy security, and reduce their carbon footprint. Important principles for the design and operation of such ECs are, among others, the principles of social justice and maximum availability of services to all segments of the population.

It is clear that the distinction between the two types of ECs is, to some extent, arbitrary, since historically the first ECs were "mixed" in that they included elements of citizen and industrial communities. These were mainly ECs of remote areas (e.g., the Far North) with no connection to external power systems, where the total generation and loads were made up of a limited number of components available.

In many countries around the world, governments have introduced various mechanisms to incentivize electricity generation from renewables mainly targeting citizen ECs, in which almost all shareholders are households and small businesses [3]. On the contrary, Russia has established a regulatory framework for the development of ECs of the predominantly industrial type. And the first step in this direction was the emergence of the concept of active energy complexes (AEC) in on-premises systems of power supply of industrial enterprises [4]. AECs in this case are understood as commercial microgrids connected to the UES that include generation facilities (up to 25 MW) that do not participate in the wholesale market and do not include residential loads of the population.

At the same time, it is important to note that there is no specific concept of design of different types of microgrids and ECc in the RF yet [10]. However, the involvement of private investors in the development of distributed energy forms the sector of small energy businesses in the Russian Federation. The sector already competes with the traditional sector of large businesses, and also promotes the development of competition and increases the efficiency of the energy industry [11]. For example, intelligent power systems of industrial and agricultural enterprises as well as those of public utilities have been created in the Russian Federation on the basis of distributed generation facilities: they are industrial local power systems (PJSC "Surgutneftegaz", Nizhniy Tagil Iron and Steel Works, AEC in Tikhvin, etc.), local power systems of public utilities (10 MW micro-CHPP "Berezovaya", Novosibirsk; 7.2 MW micro-CHP "Sfera", Yuzhno-Sakhalinsk) [12].

2 Analysis of the key defining features of formation and operation of energy communities

In general, ECs as an engineering structure are a group of microgrids or facilities within well-defined electrical boundaries that act as a single controllable entity with respect to the external power grid. An EC can be connected to an external grid or operate in the islanded mode [1]. Such a community is usually based on open and voluntary membership. It is controlled by shareholders or members in a more or less autonomous and effective way, with such shareholders and members located in close proximity to the location of RES projects that are owned and developed by the same entities. Shareholders or members are understood here as ordinary individuals, small businesses, local authorities (in the case of citizen ECs) or mostly legal entities (in the case of industrial ECs).

It should be noted that to date there are no clearly defined concepts and distinctions between citizen and industrial ECs. Review of the published research on the topic shows that the name and purpose of communities in most cases is determined by the type of the main, or "core", consumers, who are also co-owners of RES, co-managers of ECs, and their founders. Therefore, a group of industrial facilities joining their forces usually constitutes an industrial EC, whereas a group of facilities related to the population and general public form a citizen EC. ECs in isolated and remote areas are often a hybrid (mixed) option.

2.1 Industrial energy communities serving residential loads

In the case of industrial ECs, it is economically and conceptually advantageous for enterprises to make joint investments in RES-based generation and infrastructure, which allows sharing costs between participants, as well as sharing administrative efforts (e.g., obtaining permits for the construction of a RES-based power plant).

2.2 Citizen energy communities

For citizen ECs, the most suitable option is collective investment in RES projects and infrastructure by residents themselves. The most advanced and unconventional practices of their design emerged at the sites located in the Great Britain, the Netherlands, the USA and Australia. A case in point is the demand-side response project launched in an EC of Bethesda, UK. The project implements an arrangement of collective investment of residents in the construction of a small HPP. It also employs formal incentives for residents to consume electricity primarily from this HPP in the hours when the output is at its maximum and the price of electricity is at its minimum [5]. The urban ECs of the Netherlands, which are part of the architecture of cities and settlements, also have their own unique features. They do not have energy storage but seek to flatten generation and load profiles through the high level of synergy of the widest variety of load components and alternative generation facilities (e.g., cafes and electric vehicle charging stations). The efficient operation of such ECs is organized with the help of intelligent control systems developed by Spectral and Metabolic energy companies [6,7]. On the contrary, the main challenge for the EC market in the USA is to ensure reliability of power supply in the event of natural disasters, as well as to provide an environmentally friendly alternative for backup DPPs used during outages of the main power supply. For this purpose, microgridshave been created in the cities of Goleta, Calistoga and in the Montecito neighborhood of Santa Barbara with the co-investment of residents [8].

Based on the above, we can highlight several key defining features of industrial and citizen ECs:

1. Scale: Industrial ECs tend to be larger (operating at a larger scale) than public ECs because they include several industrial facilities working together to optimize their

energy use. Citizen ECs are usually smaller and include households or farms working together to produce and consume energy.

2. Energy sources: industrial ECs often rely on conventional energy sources such as natural gas, coal, or oil, as well as large-scale renewables such as WTs and solar PVC. Public ECs rely primarily on the power plants that use gasification of the associated gas obtained by recycling the products of forestry and agriculture that are part of these ECs. Secondarily, ECs make use of small-scale rooftop solar PVCs. And only large and "rich" citizen ECs will prefer to invest money in the construction of WTs on shared property terms.

3. Ownership and management: Industrial ECs may be owned and professionally managed by a single legal entity, such as a public utilities company or a group of industrial facilities. Citizen ECs are often owned and collectively managed by households themselves, which can pose challenges with respect to governance and decision-making.

4. The ways to flatten load and generation profilesare mainly determined by the requirements for the reliability of power supply to consumers. The requirements are stricter for industrial enterprises that are part of industrial ECs than for other categories of consumers. Therefore, industrial ECs, as well as all ECs of isolated areas, use different types of storage units to offset the irregular nature of generation and load profiles. Citizen ECs often solve the problem by "piling" additional generation and load components, while simultaneously addressing the issues of job creation, social development of territories, and availability of services to the population.

3 Experimental case study

We examined and compared the two types of ECs through an experimental case study shown in Fig. 1. We considered an isolated EC consisting of three settlements located in close proximity to each other while being very remote from the centralized power system. The settlements have their own distributed energy sources: DPP, GPP, PVC, and wind turbines (WT), as well as battery storage (BS). The case study is derived from the real-world situation observed in the Primorye Territory [14].

We investigated several scenarios for combining microgrids of individual settlements into an EC to assess the benefits of forming an industrial and citizen ECs:

1. The Industrial community scenario assumed that Settlements 1 and 3 had industrial loads only: three-shift and single-shift enterprises, respectively; Settlement 2 had only residential domestic loads.
2. The Citizen community scenario assumed that Settlements 1 and 3 already had "mixed" loads, i.e., domestic and industrial loads, with a small percentage of the latter.

We assumed that the considered EC is optimally controlled with the aid of the proprietary software package "Autonomous Operator", the model of which was reported in [14]. The program calculated the maximum profit of each microgrid $J_{u,opt}^{SU}$, which it could have obtained without joining the EC, and the profit of each microgrid operating as part of the EC $J_{u,opt}$. Then these profits were compared as per the expression (1).

$$J_{u,opt} \geq J_{u,opt}^{SU} + \alpha \tag{1}$$

where $J_{u,opt} = J_{u,opt}^{energy} + J_{u}^{peak}$ $-$ is the total profit of the microgrid u within the EC; $J_{u,opt}^{SU}$ is the maximum profit of the microgrid u that it could have made without joining the EC; $\alpha \geq 0$ is the slack variable to be maximized. The results of simulating the operation of microgrids of settlements under the considered scenarios are presented in Table 1. We assessed the efficiency of microgrid load flow control both for their stand-alone operation (i.e., independent from each other) and as part of the EC.

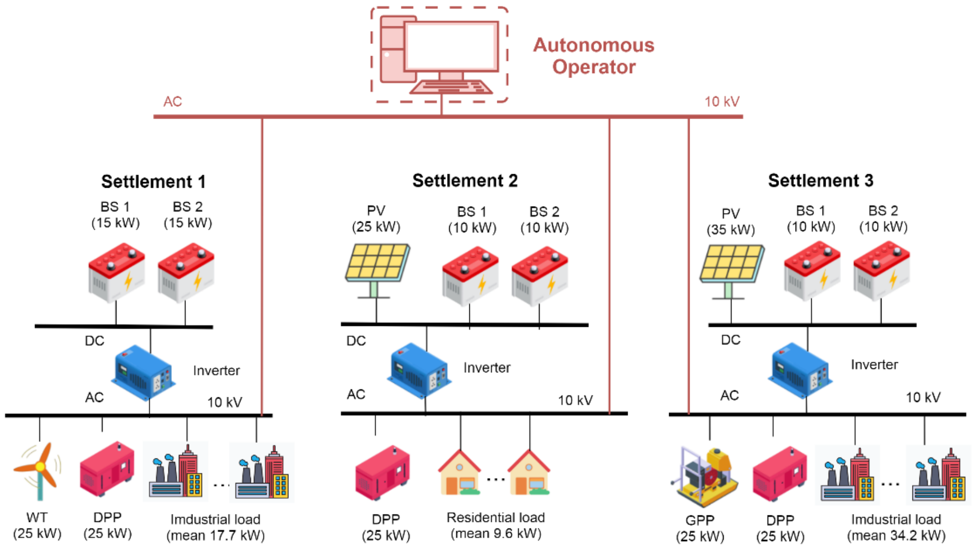


Fig. 1. General layout of the EC that includes three microgrids of settlements for the initial industrial community scenario.

Table 1. Comparison of total weekly profits of settlement microgrids operating both on their own and as part of the EC.

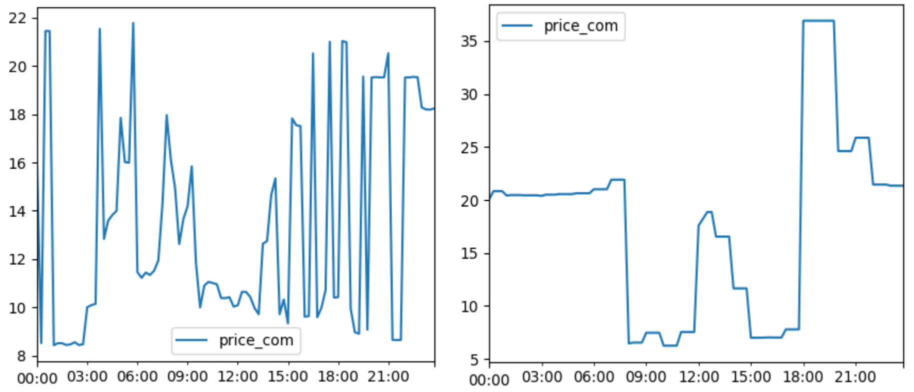
Microgrids	Total profits of microgrids, RUB			
	Citizen community scenario		Industrial community scenario	
	Stand-alone $J_{u,opt}^{SU}$	EC, $J_{u,opt}$	Stand-alone $J_{u,opt}^{SU}$	EC, $J_{u,opt}$
Settlement 1	341.96	669.16	-5,663.35	-4,595.49
Settlement 2	220.00	446.56	-769.22	-676.51
Settlement 3	-6,298.45	-5,161.29	793.88	1,302.33

It is clear that in all cases the operation of settlement microgrids as part of the EC proved more profitable than when they operate on their own, which contributes to the long-term aggregation of EC participants. As we expected, the industrial community scenario of EC formation and operation entails higher costs for Settlements 1 and 2, compared to the citizen community scenario. Moreover, Settlement 3 enjoyed significantly better conditions in terms of profit maximization. This can be explained by the fact that increased industrial loads entailed high operating costs to serve them.

Furthermore, more significant reductions in the levelized cost of electricity [LCOE] (i.e., the electricity tariff) may be achievable under the industrial community scenario in the EC - see Fig. 2.

It is clear that under the industrial community scenario, the price of electricity in Settlement 1 in the local EC market fell steadily during the day from the set value of 22 RUB/kWh to about 6 RUB/kWh due to the active exchange of electricity between microgrids. At the same time, the maximum reduction in the EC was only 9 RUB/kWh under the public scenario. It is important to note that a reduced price for an industrial enterprise with its higher loads seems to be a more significant economic fact than that for the household sector.

We also assessed the environmental impact for the considered EC scenarios. The Autonomous Operator model also aims to minimize the amount of CO_2 emissions generated when the DPP is on (the emission cost was assumed to be 0.1 EUR/kWh, or 8 RUB/kWh). Table 2 shows the cumulative CO_2 penalties during the one-week test simulation for the scenarios considered. It is clear that the industrial community scenario did not lead to a significant increase in CO_2 emissions when using DPPs. In the case of Settlement 1, it even caused lower costs for this item.



a) Citizen community scenario b) Industrial community scenario

Fig. 2. Graphs of daily changes in electricity price (RUB/kWh) in the EC for Settlement 1 under different scenarios.

Table 2. Cumulative penalties for CO_2 emissions during the one-week test simulation

Microgrids	Cumulative penalty for CO_2 emissions, rubles.	
	Citizen community	Industrial community
Settlement 1	4,400	2,640
Settlement 2	2,560	2,720
Settlement 3	5,440	6,000

4 Conclusion

Our analysis of key features of ECs highlighted in this article can prove instrumental in identifying opportunities and challenges that come with industrial and citizen ECs and making informed decisions regarding their design, implementation, and operation. It should also be noted that to date there is no clear-cut distinction between the notions of industrial and citizen ECs. In most cases, ECs are of a mixed type, or symbiosis, which is most characteristic of potential ECs of remote and isolated areas of the Russian Federation (for example, the Far North and Yakutia), where other options are unavailable. We compared the benefits from the operation of consumers as part of microgrids of a certain type and as part of a microgrid community. As a result of the comparison, we have revealed the undoubted advantage of mixed-type ECs due to the high synergy of a wide range of generation and load components, as well as energy storage units of different types.

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