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Article

The New Model of Energy Cluster Management and Functioning

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Abstract: This article was aimed to answer the question of whether local energy communities have a sufficient energy surplus for storage purposes, including hydrogen production. The article presents an innovative approach to current research and a discussion of the concepts of the collective prosumer and virtual prosumer that have been implemented in the legal order and further amended in the law. From this perspective, it was of utmost importance to analyze the model of functioning of an energy cluster consisting of energy consumers, energy producers, and hydrogen storage, whose goal is to maximize the obtained benefits, assuming the coopetitive nature of the relationship. The announced and clear perspective of the planned benefits will provide the cluster members a measurable basis for participation in such an energy community. However, the catalogue of benefits will be conditioned by the fulfillment of several requirements related to both the scale of covering energy demand from own sources and the need to store surplus energy. As part of the article, the results of analyses together with a functional model based on real data of the local energy community are presented.

Keywords: energy community; energy cluster; energy storage; hydrogen; management

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1. Introduction

1.1. Energy Storage in Clusters—Legislative Conditions

The energy community is a concept without a unified definition. This term, however, appears in several community regulations and has the character of an open initiative operating in the field of renewable energy [1] and social space (Citizens Energy Community) [2]. The strong promotion of the civic character of the energy sector is reflected in legislative plans [3], as well as already established national implementations.

Energy clusters are the most advanced type of energy community. Polish law defines an energy cluster as a civil law agreement, that is, an agreement between cluster members to create energy-independent areas [4,5]. The lack of statutory benefits from the creation of such communities, in contrast to, for example, energy cooperatives [4,6,7] or prosumers [8,9] and virtual and collective prosumers [10], as well as the complex specifics of the relations between energy market participants and the operation of the power system, make it difficult to define the catalog of benefits for cluster members and the business nature of their functioning. Both the current definition of a cluster and its proposed redefinition do not provide clusters [11] legal personality, which significantly restricts the freedom of operating activities, including applying for subsidies and aid funds. Therefore, it has become necessary to find a legal formula for the functioning of an energy cluster that would allow for the obtainment of benefits expected under the proposed legislation and make clusters credible while looking for external sources of financing the investment. The proposed legislative solutions in the field of energy clusters introduce the following assumptions:

1. The new definition of a cluster provides for the obligatory participation of a local government unit in the agreement initiating the cluster, as well as the opening of the catalog of participants, including partnerships. The material scope will be extended to energy storage. The specific goal of such a cluster's operation is to provide economic, social or environmental benefits to the parties to the agreement or to increase the flexibility of the power system.
2. The entry into the register of energy clusters of the Energy Regulatory Office enables the use of a support system and the provision of a commercial service of peak load limitation.
3. The planned support system for energy clusters assumes the need to meet certain conditions related to the generation, storage and self-balancing of the energy cluster in two time horizons (stage I until 31 December 2026; stage II until 31 December 2029). The possible benefits are:
    a. Exemption from the RES fee (fee related to the operating costs of the auction system for renewable sources), cogeneration fee (fee related to the operating costs of the auction system for renewable sources), excise duty (excise tax, the value of which may change in the range of 0–20 PLN/MWh), and obligations related to certificates of origin (quasi-tax fee related to energy certification and support for renewable energy, biogas and energy efficiency).
    b. Lower distribution costs depending on the level of self-consumption of the cluster calculated according to measurement data, including hourly amounts of electricity taken from and transferred to the distribution network by members of the energy cluster. The proposed solution provides the following levels of reduced distribution fees:
        - i 5%—if energy generated in the cluster > 60% of consumption in the cluster.
        - ii 10%—if the energy produced in the cluster > 70% of consumption in the cluster.
        - iii 15%—if the energy produced in the cluster > 80% of consumption in the cluster.
        - iv 20%—if the energy produced in the cluster > 90% of consumption in the cluster.
        - v 25%—if the energy produced in the cluster > 100% of consumption in the cluster.

To obtain benefits, the following conditions must be met:

Until 31 December 2026:

- i At least 30% of the energy produced and introduced into the distribution network by the parties to the energy cluster agreement is generated from renewable energy sources.
- ii The total capacity of the installed generating installations belonging to the members of the energy cluster does not exceed 100 MW of electricity and allows for the coverage of no less than 40% of the total annual electricity demand of the members of the energy cluster during the year.
- iii The energy storage capacity of the members of an energy cluster is at least 2% of the total installed capacity of generating installations in this energy cluster.

Until 31 December 2029:

- i At least 50% of the energy produced and introduced to the distribution network by the members of this energy cluster is generated from renewable energy sources.
- ii The total capacity of the installed generating installations belonging to the members of this energy cluster does not exceed 100 MW and allows for the hourly coverage of no less than 50% of the total supplies to the members of the energy cluster in terms of electricity.
- iii The energy storage capacity of the members of an energy cluster is at least 5% of the total installed capacity of generating installations in this energy cluster.

1.2. Energy Storage in Clusters—Technical Conditions

Energy transformation and the need for decentralization will likely transform the current power system into a multi-microgrid network at the local energy community level. The problems that will remain in the case of the development of such a scenario will be the necessity of optimal control strategy considering energy storage and the use of renewable energy sources for off-grid operation [12], as well as the modernization of the receiving infrastructure in order to achieve measurable economic effects [13]. In the context of modern receiving infrastructure and its impact on the stability of the grid operation, the flexibility of consumers [14,15] aggregated within local energy communities is of additional importance.

Contemporary municipal energy aggregating the above-mentioned market participants often comprises microgrids located in the immediate vicinity that are part of a larger cluster structure. As indicated in [16], this helps to reduce the load on the power grid, but it requires the precise mapping of the load to implement adaptation measures and ongoing grid management. These activities are complicated and complex, as evidenced by the method of forecasting the load for power and electricity within the cluster microgrids described in [16]. An autonomous cluster microgrid is often built based on many distributed sources, which may cause system frequency instability. One way to stabilize the operation of a network is the use of energy storage in the form of super-capacitors [17]. However, this is a solution that only affects the quality of the system's work in the ultra-short-term dimension. At the level of energy clusters, the need to store energy in the short- and medium-term, i.e., on the level of hours and days and based on various technologies, becomes more important. An interesting example is a functioning energy cluster from North Texas consisting of 10 thousand houses, where hydrogen is the energy carrier used to meet the demands for both heat and electricity [18]. The use of hydrogen for energy storage is an implementation challenge from not only the technical perspective but also the algorithmic and tool perspective [19].

Regardless of solutions for physical energy storage, a number of concepts based on virtual substitutes [20] and energy tokenization [21,22] appear at the level of local energy communities, which are gradually gaining in importance and can be an interesting alternative. The issues of building optimal settlement models [22,23] and implementing peer-to-peer mechanisms [24] remain invariably problematic for local communities.

The power generation sector in Poland is undergoing transformation. Power units based on hard coal and lignite are increasingly being replaced by dispersed renewable sources, the development pace of which has exceeded the expectations of the legislators and representatives of the power sector. From this perspective, there have been more and more emerging technical problems relating to the ability to connect generation sources to the distribution network [25], as well as secure network management and development [26,27]. One of the more frequently appearing arguments and recommended investment scenarios is the construction of distributed renewable energy sources in tandem with energy storage [28]. These activities are promoted both at the level of the smallest sources, such as micro-installations [29–32], and at the system level, which is reflected in, e.g., capacity auctions [33,34].

Currently, there are several technologies that enable energy storage via pumped storage plants using biomethane, batteries, the use of compressed air technology in hydrogen technologies. The high cost of this type of installation still severely limits its use on a large scale. Still, more and more often, they are becoming elements of pilot installations with research and commercial applications. It is worth emphasizing that, in the opinion of the International Renewable Energy Agency (IRENA), energy storage technologies have a large potential for cost reduction due to the current stage of their development. Though significant steps have been made in recent years towards the commercialization of energy storage technologies (e.g., there was a significant 73% decrease in costs of batteries used for electric vehicles in 2010–2016), IRENA estimates still indicate the possibility of further reduction costs of 50–60% in this area by 2030. This reduction in costs will contribute to increases in the capacity of energy storage, and according to Wood Mackenzie, the cumulative annual growth rate will be 31% and the cumulative capacity will be 741 GWh by 2030 [35]. At this point, a question arises: which storage technology will be optimal from the point of view of costs, security, and geopolitical independence?

From the perspective of the global energy industry, battery technologies, in particular lithium-ion technologies, are currently the fastest growing storage technologies. This is due to, inter alia, high maturity and huge investments in this technology related to electric vehicles, which naturally entail the development of accumulators for the commercial power industry and a decrease in costs. Lithium-ion technologies are primarily used in short-term storage. In Poland, several investments have been implemented in recent years using this technology, including:

- By Polska Grupa Energetyczna: Rzepeć; 2.1 MW and 4.2 MWh; Góra Żar: 0.5 MW and 0.75 MWh [36].
- By PKP Energetyka: Garbce; 5.5 MW and 1.2 MWh [37].
- Via Energa: Puck 0.75 MW and 1.5 MWh [38].
- By Tauron: Cieszanowice 3 MW and 0.7 kWh [39].

Hydrogen storage is an alternative to lithium-ion technologies [40]. On 8 July 2020, the European Commission published the Hydrogen Strategy for a Climate-Neutral Europe (hereinafter referred to as the European Hydrogen Strategy) [41]. In this strategy, green hydrogen is mentioned as one of the key energy carriers that can contribute to achieving the objectives of the European Green Deal. The main goal of the strategy is to stimulate the development of the renewable sector, i.e., "green" hydrogen, so that it is a fully zero-emission, freely available source of energy in the EU by 2050. The diffusion of the production and use of hydrogen is to be one of the ways to connect sectors and contribute to decarbonization where electrification is impossible or difficult (e.g., steel or chemical industries and transport or energy generation). Through energy storage, hydrogen can also make it possible to balance systems that are increasingly based on renewable energy. The strategy identifies hydrogen as a promising option in the transport sectors where electrification is difficult. In the first phase, the early adoption of hydrogen solutions may be for internal use (e.g., in local city buses), in commercial fleets (e.g., taxis), or in certain parts of the rail network where electrification is not feasible. It has been pointed out that hydrogen refueling stations can easily be supplied by regional or local electrolyzers. However, their locations will need to be chosen based on a transparent analysis of the fleet's demand and the different requirements for light and heavy vehicles. A comprehensive inventory of investments will be established under the European Clean Hydrogen Alliance. The European Commission's Next Generation EU recovery plan and funding instruments, including the European Strategic Investments segment under the InvestEU program and the EU Emissions Trading System Innovation Fund, will increase financial support. They will help reduce the renewable energy investment gap created by the COVID-19 crisis. The European hydrogen strategy defines the types of hydrogen depending on where they originate. Hydrogen production pathways have different emissions due to technology and energy sources, and they also have different cost implications and material requirements.

The hydrogen economy can be described as the value chain of collectively generating this fuel via technologies for the production, storage, and distribution of hydrogen, including centralized and distributed systems that use the transmission and distribution grid (as well as other forms of transport), followed by the use of it as a final product (transport, industry, heating and professional, industrial, and dispersed energy generation systems) and as a substrate in industrial processes (including hydrogen energy storage) for the production of synthetic fuels and energy carriers. Given hydrogen's relatively low importance in the economy at present but its great potential importance in the future, the sustainable and ultimately economically justified development of individual components of the value chain will provide opportunities for continuous increases in the use of this fuel [42].

Thus, energy storage has become a necessity that will determine the development of local structures of energy communities [43], and evolving systems make the use of battery and hydrogen technologies for use at the molecular level and for use in the storage and production of electricity (the most desirable and promoted direction). In this context, it was justified to question whether local energy communities will have a sufficient surplus of power and energy to be able to use them for storage purposes, including the production, storage, and use of hydrogen. We accordingly formulated a research hypothesis confirming the existence of such potential.

Firstly, this paper fills a research gap, as there has not been much previous study of the discussed solutions, and our interest in the use of hydrogen fuel in this context also indicates an innovative approach to the issues under consideration.

Since the relationship among energy community members, i.e., simultaneous cooperation and competition [44], involves more than two market players, we studied network coopetition as community actions would be impossible to individually achieve by involved actors. Moreover, from the perspective of smart cities [45], local communities can be used to enact actions aimed at increasing the effectiveness of activities and building local energy self-sufficiency. Our analysis focuses on the effects of competitors' cooperation, which constitutes an added value and would not be individually achievable [46].

2. Materials and Methods

Solving the posed research problem and testing the research hypothesis were preceded by a literature study. The implementation of such required the application of an appropriate methodological approach shown in the diagram in Figure 1.

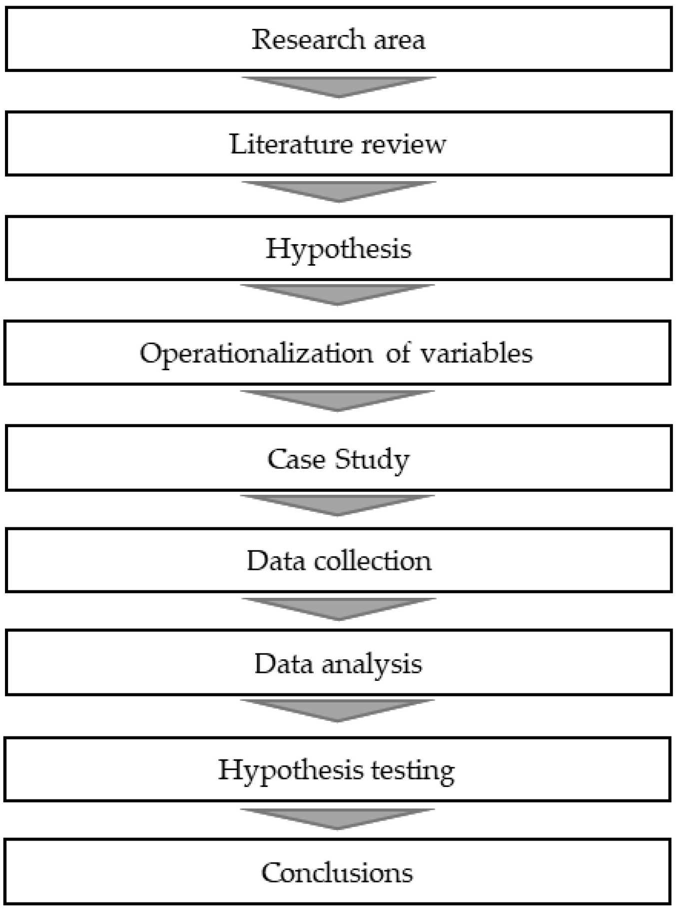


Figure 1. Research procedure scheme. Own elaboration.

The key elements indicated in the diagram are: case selection, data collection, data analysis, and inference preceded by a hypothesis test. Due to the small number of active energy communities in Poland, one that integrated the necessary elements (i.e., production, storage and recipients), expressed openness to cooperation, and provided the necessary data and information was selected.

An example of an energy community with the potential to generate energy from renewable sources and then store it is the Tychy Energy Cluster established in October 2020. It operates in the cities of Tychy and Bieruń (Poland, Metropolis GZM), and, apart from local governments, it also merges several dozen municipal and private companies. Currently, the dominant production technology in the cluster is biogas, with a total capacity of approximately 3.25 MW, 2.3 MW of which is at the disposal of the Regional Center for Water and Sewage Management (RCGW) (Concession number: WEE/4898/13571/W/OKA/2016/M Mi1) [47] at the sewage treatment plant, which is the leader of the cluster. The remaining generation technologies in the cluster are natural gas cogeneration (598 kW) and photovoltaic sources (701 kW). The demand side is dominated by medium voltage customers from the B tariff group—18 energy consumption points with a total contracted capacity of 14.15 MW. The contracted power in the entire cluster is more than three times higher than the total power of the generation sources operating within it, as shown in Figure 2.

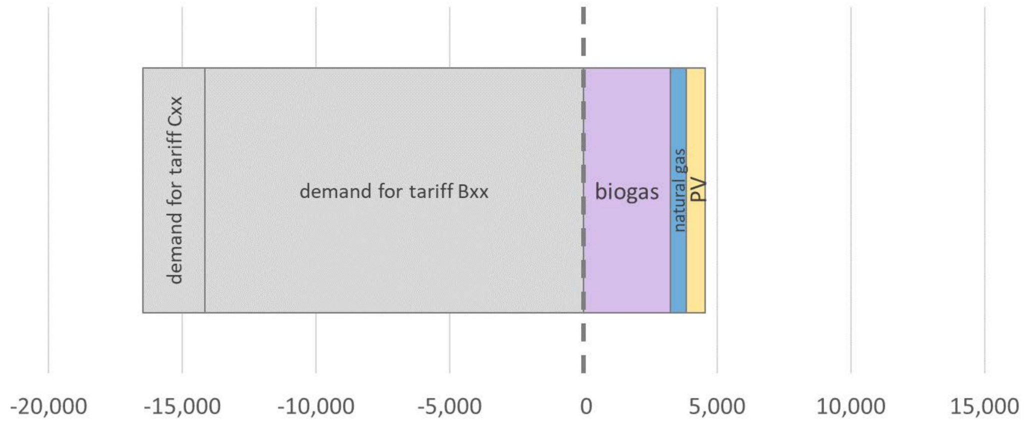


Figure 2. The power balance of the Tychy Energy Cluster (MWh) as of 31 December 2021. Own elaboration.

Data on the generation of electricity produced within the cluster and its total consumption by the group of members included in the analysis indicated approximately 21 GWh of imbalance. Of the approximately 20 GWh generated by the generating units, approximately 14.3 GWh was used internally. Thus, the self-consumption coefficient of energy produced in the cluster amounted to approximately 70%, as shown in Figure 3.

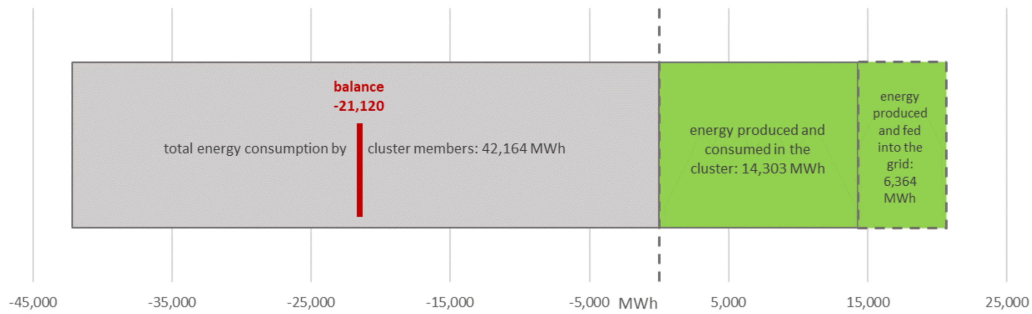


Figure 3. Energy balance of the Tychy Energy Cluster in 2021. Own elaboration.

Based on the balance data for 2021, it was concluded that the Tychy Energy Cluster does not meet the conditions necessary for it to use the legally designed benefits for energy clusters. The resulting surpluses were also found to be insufficient for the effective storage required to secure energy needs in periods of increased energy and power consumption. However, an analysis considering the cluster's ability to achieve the status of a self-balancing area could be carried out based on data and assumptions from the long-term development plans of the Tychy Energy Cluster. The verification of the research goal required the following steps:

- The preparation of a power and energy balance with estimates of the surplus and shortage of electricity for two-time perspectives, i.e., 2023 and 2026.
- The inclusion of all ongoing investments in generation capacity, the completion of which will take place by 31 December 2023, along with the initiated investments that will be implemented in the period of 2023–2026, as shown in Table 1.
- The invariability of the demand structure in the period until 2026, as adopted under the strategy of the Tychy Energy Cluster.
- The establishment of an energy balance based on daily–hourly data on electricity consumption and generation. If necessary, when mapping production sources that are under construction or planned for implementation, it was assumed that actual profiles corresponding to a given production technology with a scaled and adjusted power level will be used.
- The selection of a battery store with the power and capacity levels that meet three key criteria. The first one is to obtain the minimum levels required from the perspective of the planned, statutory catalog of benefits for the cluster authorized to take advantage of them. The second is the establishment of a storage capacity level that could improve energy security and support the operational activities of the distribution system operator (DSO). The last criterion is the possibility of providing commercial services, including the readiness to participate in auctions on the capacity market to provide flexibility services, as well as the sale of stored surplus energy on the wholesale market at the prices of the current market to generate additional revenue for the cluster.
- Due to the confidential nature of the received data and information, we did were not able to extend the description of the model and indicate which data were used, how they were used in the energy balance analyses, and the depth and scale of the approximation.

Table 1. List of commenced and planned investments.

Year	Number	Technology	Installed Capacity [kW]	Built or Planned Capacity [kW]
2021	1	Biogas	1200	
	2	Biogas	1090	
	3	Natural gas	598	
	4	PV	207	
	5	Biogas	964	
	6	PV	494	
2023	7	PV		50
	8	PV		50
	9	PV		145
	10	Biogas		499
	11	PV		101
	12	PV		200
	13	Biogas		255
	14	PV		2000
	15	PV		2000
2026	16	PV		145
	17	PV		3000
	18	Biogas		1300
	19	PV		300
	20	RDF		1500

3. Results

Cluster members have been implementing several investments in new generation capacities, the completion of which will result in a significant change in the energy balance, as shown in Figure 4.

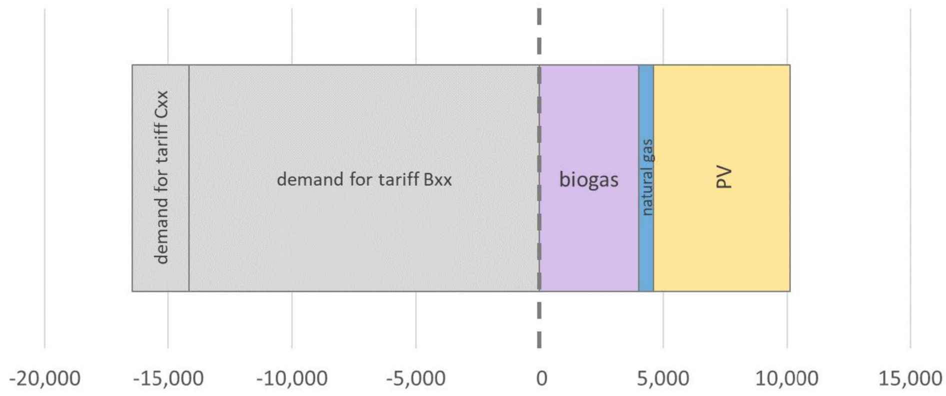


Figure 4. Balance of the power of the Tychy Energy Cluster forecast as of 31 December 2023. Own elaboration.

The increase in power by 2023, compared to the present state, will mostly be due to the construction of photovoltaic installations, the total installed capacity of which will increase by approximately 4.5 MW. Over the next two years, a 0.5 MW biogas aggregate is also planned for one of the cluster members and the replacement of the existing aggregate in the RCGW, which will translate into a power surplus of 0.255 MW compared with the currently operated source. When implementing these plans, the ratio of the installed capacity in the sources to the contracted capacity of the recipients should amount to approximately 2/3. The changing power structure will increase the generation profile. The balance was described considering both the existing and planned generation sources. The projection of generations from non-existent generation sources was performed similarly to that in the cases of recipients from whom no measurement data were obtained. For individual investments into generation sources, a generation course was assumed in line with the historical reference profile for a given source type (e.g., PV and biogas/RDF) after it was properly scaled to the installed capacity expected for each source. The daily and monthly balances are presented in Figures 5 and 6, respectively.

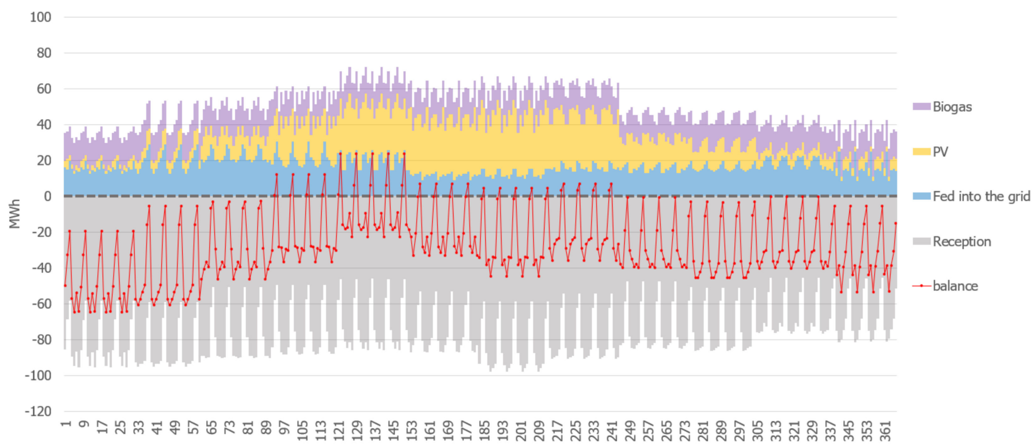


Figure 5. The projected imbalance of the Tychy Energy Cluster in 2023—daily. Own elaboration.

The cluster's annual imbalance will be reduced to approximately 10 GWh in 2023, with a simultaneous increase in generation from new sources by 11.7 GWh. This means that approximately 85% of energy from newly created sources will be used inside the cluster. With the dominant share of PV sources in planned investments, the seasonality of the cluster imbalance will deepen, indicating much greater self-sufficiency in the summer.

In the years of 2024–2026, assuming the implementation of further planned investments, the total installed capacity of the sources should approximately equal the contracted capacity of the recipients, assuming no increase in the future. In the optimistic scenario of the maximum considered capacities under the planned investments, there will be another

3.5 MW in photovoltaics and 1.3 MW in biogas cogeneration by 2026. Moreover, the plans of the cluster members include the construction of a 1.5 MWe cogeneration unit using RDF waste fuel. Such a development perspective and the initiated investment activities will translate into the power balance of the cluster, the forecast of which is presented in Figure 7.

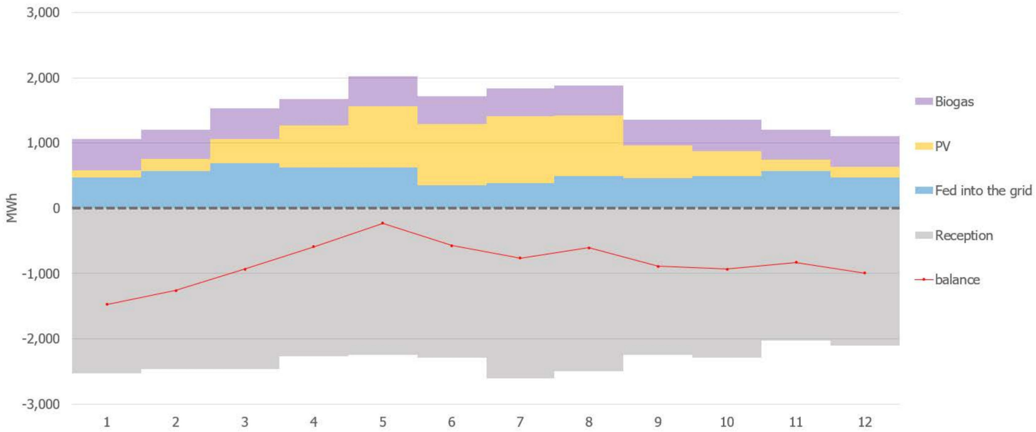


Figure 6. The projected imbalance of the Tychy Energy Cluster in 2023—monthly. Own elaboration.

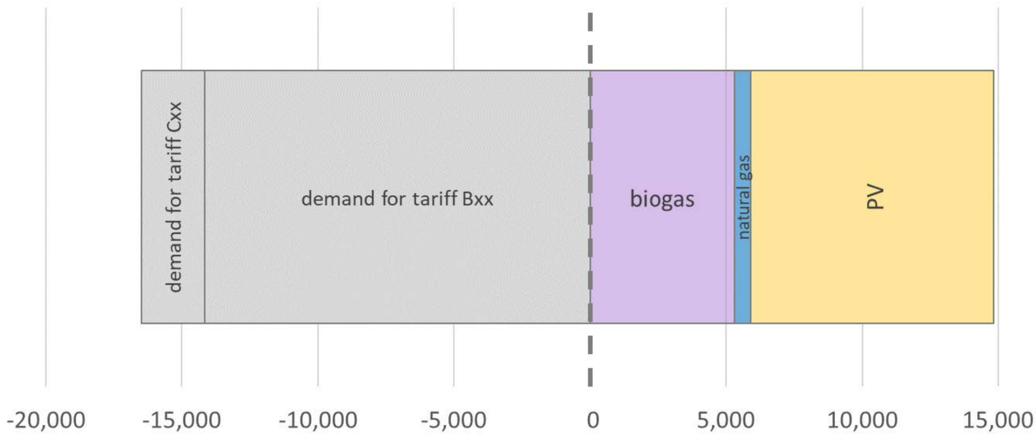


Figure 7. Balance of the power of the Tychy Energy Cluster forecasted as of 31 December 2026. Own elaboration.

In the years of 2024–2026, the total installed capacity at the disposal of its members will increase by approximately another 6 MW, which will significantly reduce the dependence on the electricity consumption from the grid. Considering the specificity and profile of generation, the energy balance was forecasted as the shape presented in Figures 8 and 9.

About 45% of the increase in power will be 2023–2026 is due to the construction or modernization of existing sources in the cluster. Among them, we can distinguish an approximately 1.3 MW power increase in biogas aggregates at RCGW and the construction of 1.5 MW of power in a trigeneration installation of RDF. The regular nature of the work of these sources will allow for a significant reduction in imbalance, which will present the highest values in the winter season. The forecasted energy balance after adding the abovementioned capacities and another 3.5 MW in PV will allow for an annual generation surplus over the demand of approximately 14 GWh. The simulation results indicated the possibility of a cluster imbalance of up to 6 MWh at the daily level in January. The marginal scale of imbalance at the daily level in 2026 will create space for the use of storage technologies, the construction of which is also envisaged in investment plans.

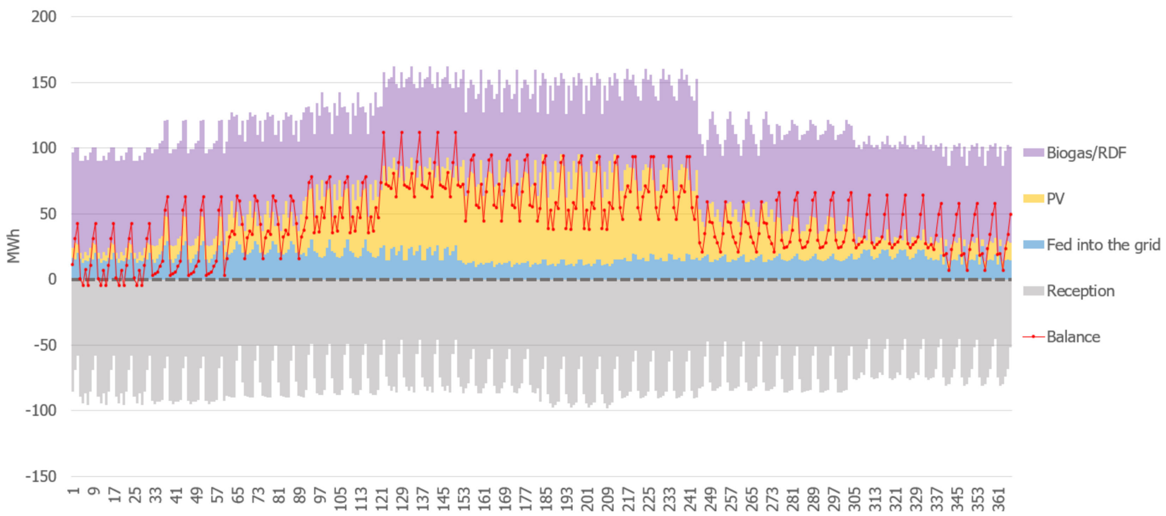


Figure 8. The projected imbalance of the Tychy Energy Cluster in 2026—daily. Own elaboration.

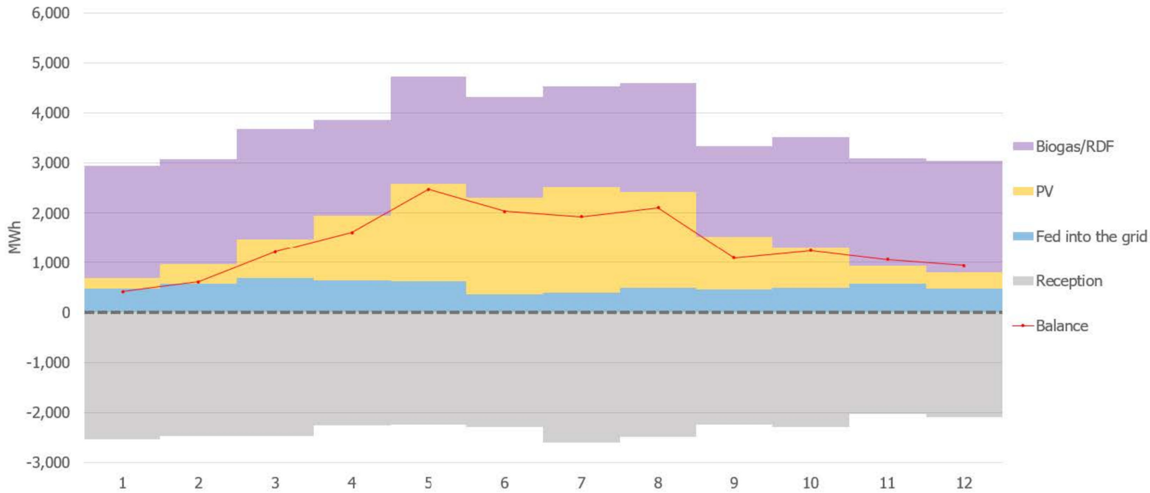


Figure 9. The projected imbalance of the Tychy Energy Cluster in 2026—monthly. Own elaboration.

The results for the energy balance obtained for 2023 and 2026 indicated the presence of significant surplus energy that can be stored and used in later periods in the short-term horizon. Based on the adopted assumptions, the operation of the TPS-FLEX lithium-ion warehouse was simulated at 360 kW/1440 kWh. Its presence will be used for the purposes of improving the operating conditions of the network infrastructure and minimizing the consumption of electricity from outside the cluster structures. Moreover, it was assumed that commercial flexibility services will be provided to an external DSO. Graphs of the possible commercial sale of stored electricity and the degree of charge of warehouses are presented in Figures 10 and 11, respectively.

An alternative to battery technologies is the conversion of surplus energy into hydrogen, followed by its storage and recycling into electricity. Due to the energy potential of the Tychy Energy Cluster, including the persistence of energy surpluses after 2026, it was reasonable to consider solutions of this type that enable energy storage in the medium-term. For this purpose, the installation of an electrolyzer capable of hydrogen being produced and commercially used was contemplated.

Figure 10. Structure of the forecasted sales potential of the stored energy of Tychy Energy Cluster in 2026—monthly. Own elaboration.

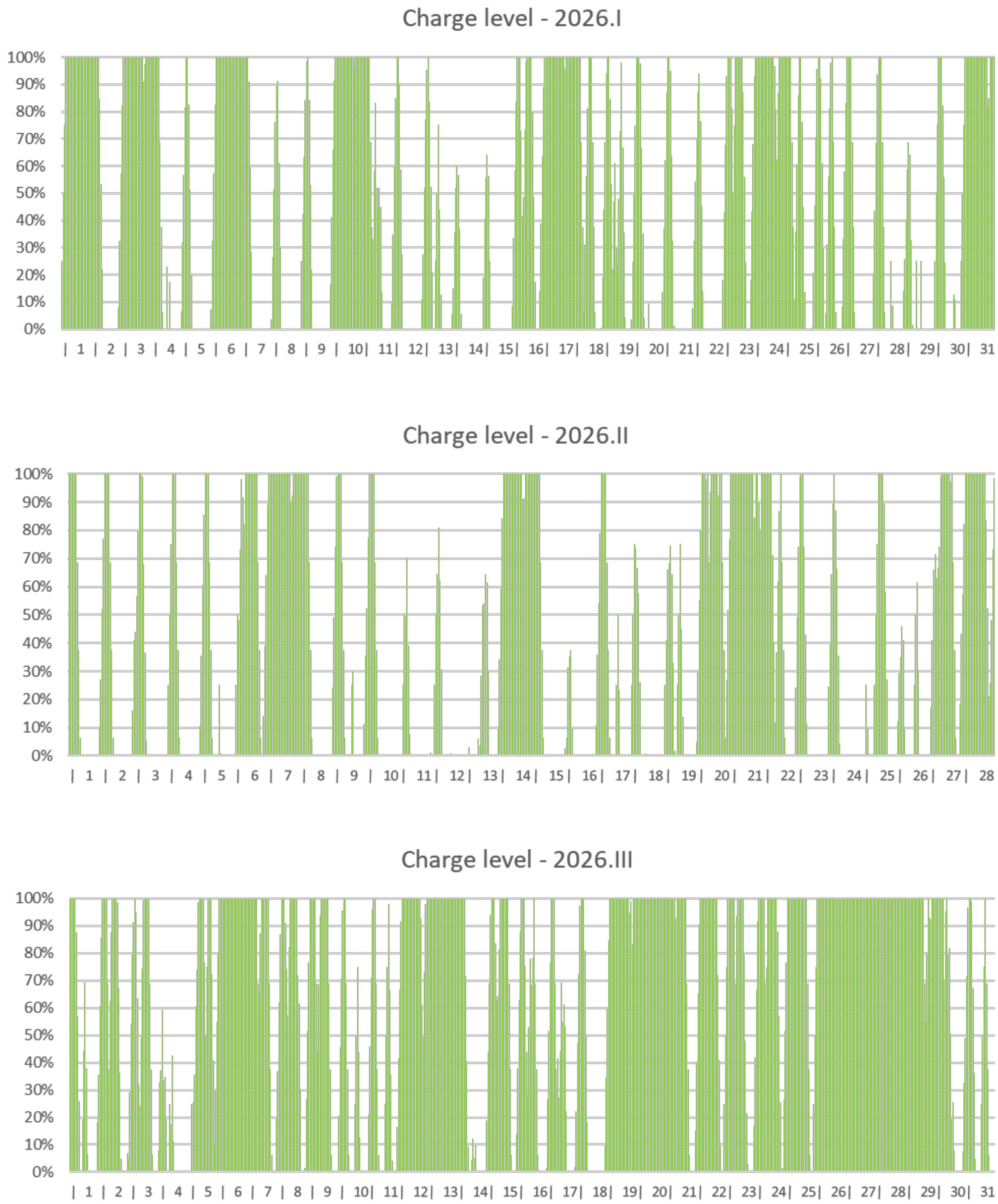
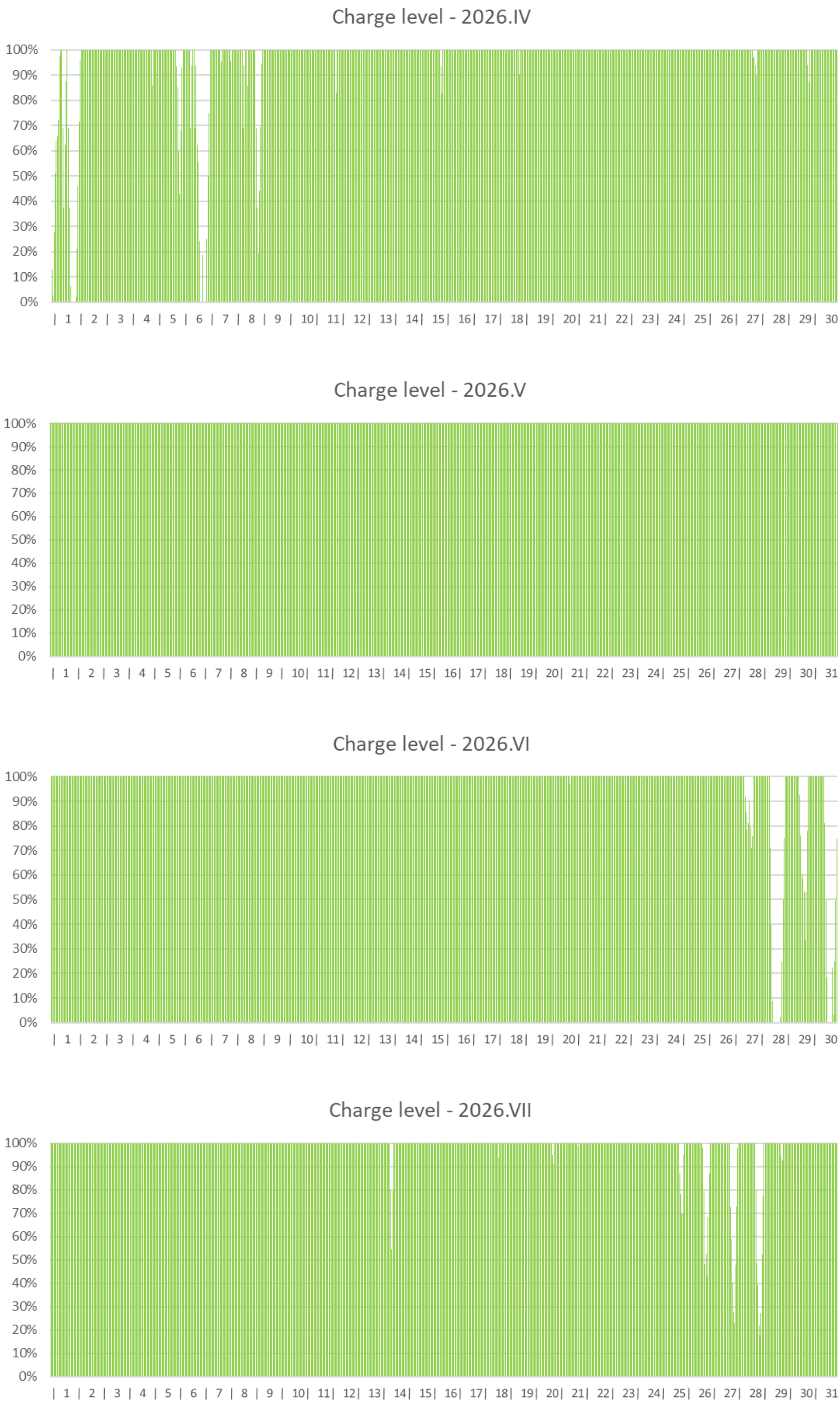


Figure 11. *Cont.*



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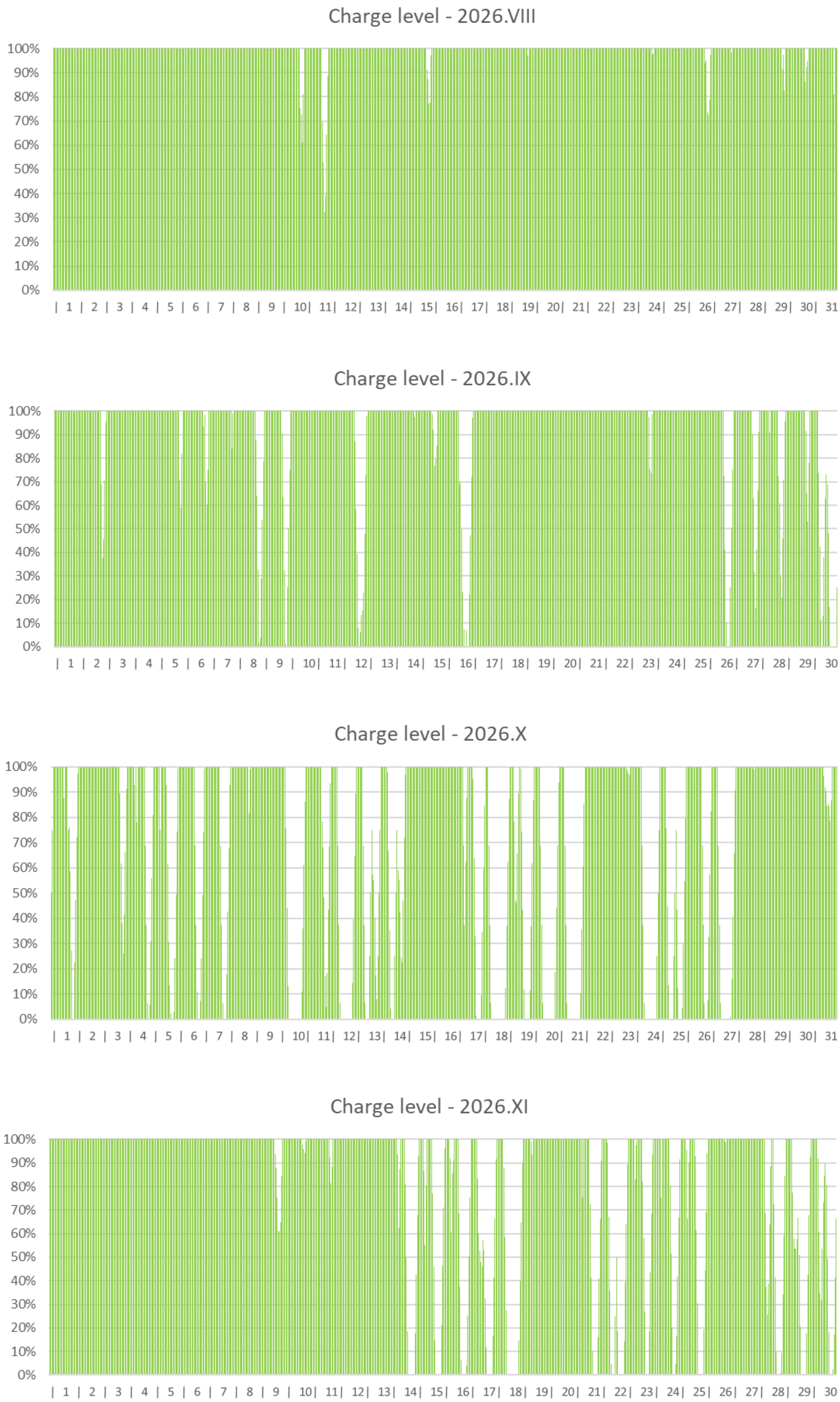

Figure 11. *Cont.*

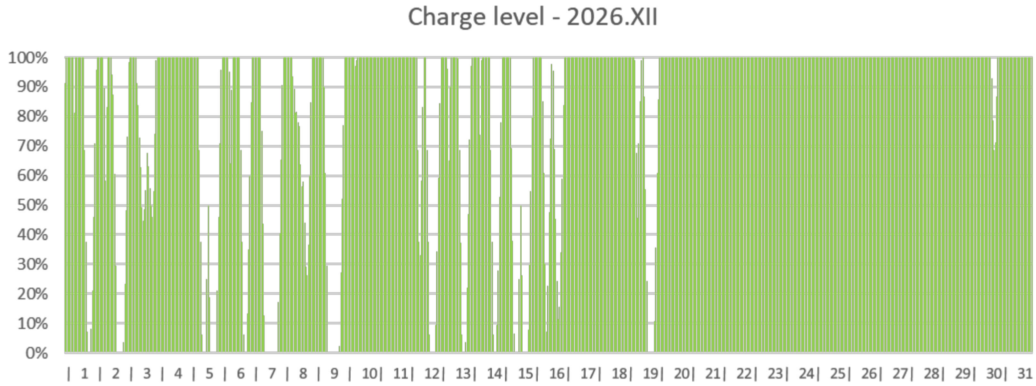

Figure 11. The forecasted loading level of warehouses—monthly. Own elaboration.

However, these activities must be preceded by ongoing research and development works on the production and storage of biohydrogen produced in the dark fermentation process. The biological production of hydrogen using microorganisms is becoming an increasingly promising new technology. One potential application is the dark fermentation process, which produces (in addition to biohydrogen) carbon dioxide and a mixture of reduced, more easily degradable organic compounds. Considering the available raw materials and the bioenergy potential of the wastewater treatment plant, Regionalne Centrum Gospodarki Wodno-Ściekowej S.A. began the implementation of the research project "Production of Biohydrogen in the Dark Fermentation Process". The main research concept of this project is the possibility of combining the dark fermentation and methane fermentation processes in a two-stage system, which could allow for greater energy recovery, hydrogen production in the first stage of the system, and an increase in methane production in the second stage. The scope of the project covers the production of biohydrogen by microorganisms in the activated sludge of the sewage treatment plant in Tychy-Urbanowice with the use of sewage, sludge, and organic fractions of waste. Over the course of project implementation, methods of obtaining appropriate microorganisms for hydrogen production from microorganisms in the activated sludge have already been developed and optimized. The parameters of the dark fermentation process carried out on a laboratory scale were selected to intensify the amount of hydrogen produced from the tested sludge and waste. Liquid products, such as alcohols and volatile fatty acids, that (in addition to carbon dioxide and hydrogen) are formed in the dark fermentation process can be used as raw materials in further research stages, during which their methane potential is measured. In addition to the possibility of additional energy recovery from liquid dark fermentation products, solutions worth considering in the future include the enrichment of biogas production and biomethanation using the gases obtained in the dark fermentation process (hydrogen and carbon dioxide), as well as the further industrial use of the liquid products of dark fermentation, such as organic acids and alcohols.

4. Discussion and Conclusions

The transformation of the energy sector in the face of current geopolitical conditions requires decisive acceleration and a focus on constructing local energy-independent areas based on dispersed, renewable energy sources equipped with energy storage. The existing and planned legislative mechanisms supporting this direction of transformation provide for the strengthening of local energy structures via a statutorily defined catalog of benefits and the creation of tangible incentives. Local energy communities, including energy clusters, will become beneficiaries of these solutions after meeting certain criteria.

Our analysis shows that the implementation of energy communities in clusters, where it is legally possible, may bring substantial benefits. The results of our study have far-reaching practical implications. It should be highlighted that our simulations were based on real data, tariffs, and regulations, which we used to conduct pioneering calculations of the energy balance of a real functioning cluster along with an assessment of the impact of the proposed regulation on the functional model. Energy market members can establish coopetitive energy clusters to ensure their energy self-sufficiency. It is worth pointing out that the ongoing construction of generating units in the cluster and further confirmed plans for their expansion will enable the analyzed cluster to achieve an energy surplus of 14 GWh per year by 2026. At the same time, thanks to the storage infrastructure, it will be possible to balance the cluster members at the hourly level while gaining the sales potential of the energy stored in warehouses at a level of 12.7 GWh per year. In this study, we focused on the volumetric assessment of the energy balance in the cluster, intentionally not dimensioning the income–cost structure. From the perspective of the ongoing and developing energy and fuel crisis, dimensioning these benefits is an area for further research exploration. Moreover, it seems valuable to extend the conducted research through volumetric sensitivity analysis considering the changing costs of production and storage technologies due to the crisis, as well as economic sensitivity analysis considering the already established energy price trends on the wholesale and retail markets.

Therefore, we encourage policymakers to incorporate energy communities and coopetition platforms into the institutional arrangements supported under sustainability policies. Finally, a policy implication of our study is that municipalities should be encouraged to collaborate in various arenas. While legal frameworks help establish such collaboration, managerial capabilities and experience are needed to successfully embrace coopetition among energy market members [48].

Our analyses show that the skillful planning and selection of members for energy clusters, including coopetitors, guarantees the full energy self-sufficiency of these structures, even at the hourly level. A necessary condition that goes hand in hand with the appropriate number and power of generation sources is the availability of storage capacity that can support the balance of the energy cluster in the short- and medium-term.

Based on our analyses of an actual cluster structure, it can be concluded that building up civic energy capacity within communities has a real chance of becoming an important element in supporting and ultimately creating local energy security, especially in the context of ongoing armed conflicts. The analyzed example shows that the initiated investments in generation and storage capacity will enable energy clusters to temporarily store energy in addition to balancing energy needs in the short-term. It should be emphasized that the currently most popular lithium-ion energy storage technology has created an opportunity to provide flexible services and commercial energy resale to interested market participants. The proper parameterization of warehouses, adapted to the profile of surplus energy, can effectively secure this type of activity at the hourly level, thus additionally guaranteeing the availability of electricity to be used for resale in all months of the year.

It remains a challenge to improve technologies that allow for long-term energy storage while reducing the cost of storage. From the perspective of energy communities, the desired horizon is not just hours but days or even weeks, which will become possible in the long-term when using hydrogen technologies. From this perspective, reducing the cost of producing hydrogen will play a key role in making all its applications more competitive. External analyses have indicated that the cost of producing low-carbon hydrogen could fall by 60–70% in the coming decade, with a strong correlation between the cost of production and the region of origin. However, there is currently no profitability in the supply chain. The use of hydrogen at present—in any industry—is unprofitable. Only a coherent and consistent EU energy and industrial policy to disseminate hydrogen technology will reduce the costs of production, transport, and end-use of this fuel. The EU aims to promote and achieve the economic viability of renewable or low-carbon hydrogen. The current immature phase of the hydrogen market and the huge funds spent by the EU mean that the cost of building individual elements of the supply chain is and will remain opaque, so end-users will need relatively detailed knowledge of the financing options for the supply chain and the costs associated with building it to ensure that the fuel cost is kept to a minimum.

Maximizing control of the emerging supply chain's critical elements (such as charging stations) will be essential.

In our opinion, the statutory redefinition of energy clusters providing measurable benefits from energy storage will significantly affect the functioning of this type of energy community, supporting the processes of system energy decentralization and permanently changing the market paradigm. The limitations of this study can be attributed to its particular case study presentation. As these issues are state-of-the-art solutions, the study was not designed under exhaustive ambition. Therefore, we strongly encourage the further scrutiny of the use of hydrogen and other technologies in achieving energy self-sufficiency in light of coopetitive clusters and energy communes.

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