Digital Transformation for Local Energy Communities: Challenges and Opportunities

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***Abstract*—Local Energy Communities (LECs) are a key element of the transition to a low-carbon economy, as they enable citizens, businesses, and public entities to produce, consume, and share renewable energy. To operate and integrate effectively into the energy system, LECs need to digitalize and semantically interoperate their data. However, LECs encounter several obstacles to achieving full digitalization, such as the lack of common standards and vocabularies, the diversity of data sources and formats, the privacy and security issues, and the need for user-friendly and scalable solutions. Moreover, LECs face challenges in collecting and analysing the data necessary to model the behaviour of building occupants, energy flexible resources, distributed generation, and grid conditions, which are essential for improving the design and operation of LECs in a variety of real-world settings and increase community engagement. In this paper, these challenges have been analysed and recommendations have been provided, based on the experience gained through OMEGA-X project. By developing a multi vector energy data space and innovative data-driven services, OMEGA-X enables local energy communities to maximize renewable energy use, reduce costs, contribute to decarbonization and achieve collective self-consumption. Two project's pilot sites, a residential energy community in Portugal and a commercial energy community in Serbia, have been presented to demonstrate the potential of data-driven platforms to optimize energy operations, engage citizens, and foster sustainable energy markets.**

Keywords—energy community, energy data space, data exchange, challenges, sustainability

I. Introduction

The global community faces the urgent challenge of reducing greenhouse gas emissions to combat climate change. The European Union (EU), aiming to be climate-neutral by 2050, has set ambitious goals for 2030, such as the 'Fit-for-55' package, which mandates a 40% share of Renewable Energy Sources (RES) in final energy consumption, later increased to 45% with the REPowerEU plan, see EU Green Deal. To support this transition, the energy sector requires significant digitalization, spanning from smart homes and buildings to multi-energy grids, alongside the development of innovative services and business models. Hence, in 2018, in the EU Directive 2018/2001 on the Promotion of Energy from Renewable Sources[1], the Local Energy Communities (LECs) concept was introduced as a collaborative network that produces, consume, and manages energy within a localized area. It was expected that LECs would decentralize the generation of renewable energy, encourage local consumption, and facilitate energy sharing among members. This localized approach shall enhance energy security and reliability but also shall support the broader adoption of renewable energy sources, contributing to sustainability and resilience in energy systems. As part of the Clean Energy for all Europeans Package adopted in 2019 the recast of the revised Renewable Energy Directive (REDII) came into force in November 2023 [2], followed by the Union's Electricity Market Design, which was launched in June 2024 [3]. Both directives establish a strategy to enhance energy sharing within distributed energy systems (DESs) and significantly increase the use of renewable energy sources (RESs). Moreover, they place a significant emphasis on the role of citizens. They encourage the formation and operation of energy communities, where citizens can collectively produce, manage, and consume renewable energy. Nowadays, five years after the adoption of the EU Directive 2018/2001, there are thousands of local energy communities across Europe, with numbers continually growing due to increasing interest in renewable energy and community-led initiatives. These communities help mobilize private capital investment and diversify energy sources, thereby increasing the resilience of the energy market and reducing dependency on fossil fuels. Citizens are encouraged to engage in collective self-consumption and to participate in peer-to-peer energy trading, further democratizing the energy system. However, the process of establishing these LECs is not simple and analyses have shown that it differs from country to country [4] .

This paper discusses the benefits and challenges of LEC digitalization through the experience gained in two different case studies (CS): CS-1 the city of Evora (Portugal) and CS-2 the R&D Campus in Belgrade (Serbia) [5]. The digitalization process, underscored by the recent European Strategy for Data, highlights the essential role of data spaces in fostering secure and interoperable environments [6]. These data spaces are pivotal for enhancing collaboration, innovation, and scalability across sectors, thereby supporting the broader objectives of efficient energy management and sustainable urban development. Hence, in Section 2, the opportunities for LECs are presented based on advanced data-driven services offered by technology providers. Based on the comparative analysis of the pilot sites in Section 3, Section 4 concludes with a summary of findings and suggests future directions for research and development, underscoring the potential impact of well-digitalized LECs on the energy transition.

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II. INTEGRATION SOLUTIONS FOR LECS

A. *About OMEGA-X initiative*

The high-level objective of the EU funded OMEGA-X project (Orchestrating an interoperable sovereign federated Multi-vector Energy Data Space (EDS) built on open standards and ready for GAia-X, 2022-2025) is to implement a data space (based on European common standards), including federated infrastructure, data marketplace and service marketplace, involving data sharing between different stakeholders and demonstrating its value for real and concrete energy use cases and needs, while guaranteeing scalability and interoperability with other EDS initiatives, not just for energy but also cross-sector. The OMEGA-X EDS is built upon the design principles proposed by the Big Data Value Association (BDVA),and presented in [7]. The open standards and the common semantic data model allow secured and enhanced data sharing and collaboration opportunities for different actors. The main benefit of this configuration lies in the possibility of integrating multiple vectors (electricity, heating and cooling, etc.) and different domains (e.g., mobility). In Figure 1, the ecosystem of stakeholders is visualized around a central marketplace of OMEGA-X datasets and services. The red circle illustrates a data connector deployed at the stakeholders' side to exchange data and services in a trusted and secured manner. There are several open-source projects based related to the development of data connectors (see Table 3) in [8], while in OMEGA-X this component is provided by Sovity [9].

With the goal to demonstrate that the approach is applicable also for LECs, several case studies have been conducted including the case study of Évora, Portugal and the Institute Mihajlo Pupin (PUPIN) R&D Campus in Belgrade, Serbia. EDP - Energias de Portugal, as a facilitator for LEC, monitors the production and injection system, consumption and self-consumption per client in the small parish of Valverde in Évora, Portugal. The primary objective of this pilot is to explore various strategic options for optimizing energy management, maximizing self-consumption, and fostering stronger community engagement. The PUPIN R&D Campus comprises a set of buildings, while the PUPIN proprietary software (View4 SCADA) is used for monitoring the RES production, building consumption and the exchange with the grid. In the PUPIN case, the EDS approach applied in the project shall prove that collaborative environments where data is shared among trusted partners could improve the quality of services needed for accurate forecasting and optimal setting of assets. Table I summarizes the requirements defined by the managers of each LEC, divided into five groups, highlighting the differing priorities of each community established at the project's outset.

B. *LEC Digital Transformation Requirements*

Digitalization is pivotal for the efficient operation of LECs because advanced metering infrastructure and data-driven solutions are essential for modeling the behavior of energy resources, real-time monitoring, optimization of energy flows and data/energy exchange with the electricity grid. Digitalization enhances real-time control and makes energy systems more connected, intelligent, and sustainable. Together, these technologies support the energy transition and empower communities to actively shape their energy future. To fully leverage the potential of these digital advancements, however, it is crucial to have robust frameworks for managing and interpreting the vast amount of data generated.

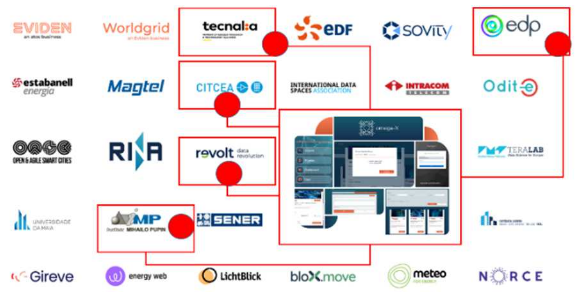

Fig. 1. OMEGA-X Data ecosystem. (*peer-to-peer data exchange between two partners*)

This is where semantic models come into play. These are critical tools in structuring, organizing, and interpreting data by capturing relationships between different entities within a domain. Utilizing modular ontologies, in the context of data integration and exchange, semantic models ensure that datasets from diverse sources can be understood and utilized cohesively. For more information, see https://w3id.org/omega-x/.

C. *Innovative Data-Driven Services for LECs*

The ongoing digital transformation within LECs is driving the development of innovative, data analytic services aimed at improving operational efficiency and consumer engagement. By leveraging advanced analytics, and artificial intelligence, service providers are creating solutions that enhance energy efficiency, help integrating renewable energy, and provide greater observability. These services also introduce gamification elements, equipping LEC managers with powerful tools to improve the user experience and foster the growth of these community-driven energy models [10]. The effectiveness of data-driven services depends on both the availability and quality of data. Factors such as privacy concerns, as well as technical and economic considerations, significantly influence the data accessible within each LEC, thereby affecting the range of potential services. The OMEGA-X marketplace provides a variety of services tailored for LECs. The nature and data availability of each community play a key role in determining which services are most relevant and valuable, as shown in Table II. For example, not all the four LECs participating in the project have metering systems for thermal or water systems, and every LEC manager has different data availability due to their role.

TABLE I. LEC REQUIREMENTS (1= HIGHEST PRIORITY, 5= LOWEST)

#	Prioritization of LEC Requirements		
	General description	***CS-1***	***CS-2***
1.	**Interoperability:** Diversity of Data Sources and Formats & Lack of Common Standards and Vocabularies	5	3
2.	**Smart Services:** Modeling of energy resources (distributed generation, consumption and grid conditions), as well as building conditions (static and dynamic parameters)	3	2
3	**Automation:** Data Collection and Analysis, Platform Deployment	4	1
4	**Privacy and Security Issues**	2	4
5	**Awareness Raising and Engagement Tools**	1	5

TABLE II. OMEGA-X LEC DATA-ANALYTIC SERVICES

Service Name	*Number of pilots*
Detection and Correction of Measurement Errors Local Energy Communities Designer	3

Service Name	*Number of pilots*
Electrical Losses Detection and Benchmarking Gamification for electrical energy savings Optimizing sharing coefficients in collective self-consumption Planning Services for Renewable Integration	2
Thermal Losses Detection and Benchmarking Water Losses Detection and Benchmarking	1

D. *Example of a service in the OMEGA-X Data Space*

UPC serves as a service provider in the OMEGA-X EDS. The UPC *Detection and Correction of Measurement Errors* service can be applied to different time series data, hence being interesting for any LEC regardless of their data offer. This service seeks to detect, identify, and solve data anomalies, such as outliers or missing values from data sources, to ensure the optimum data quality and usability for any application or service [11]. Figure 2 shows the methodology followed by the service. By using data analytics techniques, the algorithm detects missing data and anomalies. To impute corrected values, the model chooses between statistic methods such as univariate or interpolation, or multivariate machine learning models. Figure 3 represents the output of this service when applied in a time series data stream from a PV system, testing three different strategies for data imputation. In this example, the mice random forest (micerf) clearly performs better than imputing the mean or the most frequent value.

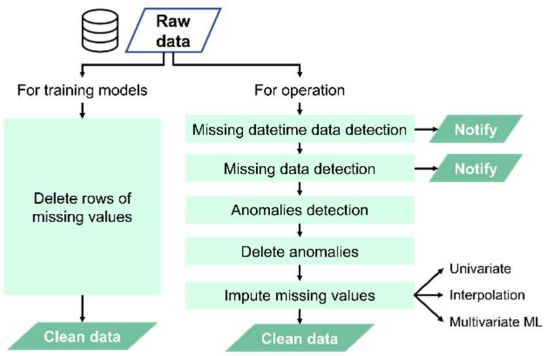

Fig. 2. Detection and Correction of Measurement Errors flowchart

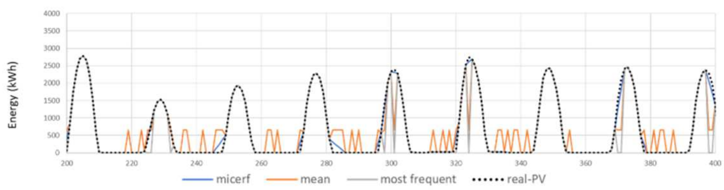

Fig. 3. Correction of Measurement Errors in PV time series data

III. LEC Implementation Challenges

A. *CS 1: Residential Energy Community in Portugal*

The Valverde LEC in Évora, Portugal, serves as a significant case study for a residential energy community, involving 10 domestic consumers equipped with PV panels (with a minimum capacity of 1.5 kWp per installation) and second-life batteries rated at 4.0/4.4 kW/kWh. Consumers aim to self-consume as much locally produced energy as possible, while any surplus is shared with other members of the community. EDP, acting as the *LEC Operator*, plays a pivotal role in facilitating the energy operations of the LEC. Within the OMEGA-X project, Valverde leverages this data to investigate and develop strategic services aimed at enhancing LEC operations, benefitting from shared, real-time data, making the community more adaptive and responsive to both individual and collective energy needs. These include *Local Energy Communities Designer*, *Detection and Correction of Measurement Errors*, and *Planning Services for Renewable Integration*. The shared data infrastructure provided by OMEGA-X enables real-time decision-making and continuous improvements, transforming raw data into actionable insights that optimize both energy consumption and distribution. This not only improves energy efficiency but also enhances community engagement, paving the way for more sustainable and scalable LEC models in the future. Indeed, awareness raising is one of the major challenges, by encouraging active participation and engagement from end-users, stakeholders, and communities. On one side, the proposed *Gamification Service* can be a useful tool to engage users and raise awareness. By creating challenges and rewards for reducing energy consumption, participants may become more invested in the overall goals of the LEC. On the other side ensuring that consumers understand how their data is protected and used is crucial, since it provides a sense of data ownership to the community members. In this sense, the OMEGA-X project emphasizes data sovereignty, and the use of tools that provide transparent and secure data-sharing mechanisms through the use of the Sovity connector, built on International Data Spaces (IDS) standards, data flows only through secure channels and is only shared with authenticated and authorized partners. To comply with this data privacy and security needs, some data policies were specified in order to limit the accessibility of data only to the authorized people.

B. *CS 2: Commercial Energy Community in Serbia*

Having the ambition to introduce collective self-consumption and to serve as a showcase for flexibility for satisfying the specific energy demand with multiple alternatives (electricity from grid and PV, heat from thermal plant, electric boiler or A/C), PUPIN has many challenges related to the integration of energy services such as services for energy dispatch optimization, demand and production forecasting algorithms. In the process of deployment of the integrated solution, the *LEC operator* (in our case PUPIN) depends on service providers that have the required solutions. Hence, a middleware and orchestration solutions are required to connect the *service consumer* (the PUPIN department responsible for maintaining the LEC infrastructure with the photo-voltaic (PV plant) as RES and the SCADA system) with the *service providers*. The *service consumer* transfers the real data in timely manner (e.g. 1 min). The data received is send to the *service provider* (either PUPIN services or services from the OMEGA-X EDS, e.g. Tecnalia for providing *planning services and decarbonization scenarios*, the UPC *Detection and Correction of Measurement Errors* for improving the data quality) for processing the data and calculating the optimal setting points for the infrastructure. To that aim, PUPIN established a platform, (see Figure 4) on one side to ensure the connection with the SCADA system that monitors and controls the infrastructure, and on the other side to host the necessary software components (data models, services and data connectors) for data exchange with service providers in the OMEGA-X EDS.

C. *Recommendations And Best Practices*

Interoperability aspects are at the core of the EDS's vision[12]. The actors, either in the role of data/service provider or data consumer shall uniformly exchange data. Hence in case a LEC operator contracts a technology provider to process the LEC data, the LEC operator shall provide a semantic description of the datasets according to the agreed semantic schema. OMEGA-X Semantic models provide a bases for creation of a knowledge graph (KGs) [[13] where different type of datasets (measurements as dynamic and description of the assets as static data) are integrated for analysis and decision-support purposes, see the Knowledge

Graphs APIs box in Information layer in Figure 4. In PUPIN case, the KGs enhance the transparency of the available datasets and harmonize the description of data within the LEC and towards the OMEGA-X EDS.

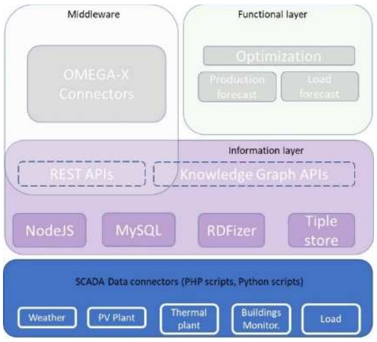

Fig. 4. The OMEGA-X Platform deployed at the PUPIN Institute

For the specific case of Evora, the users are private building owners, so the privacy and security of their data is of the outmost importance. To be complaint with the GDPR and security standards, the Sovity's connector allows the definition of policy rules, where it can be specified who can access data, but it should also allow to change and remove data from the Marketplace whenever requested. Additionally, the developed services for this pilot should not allow the explicit identification of individual LEC buildings. As for raising user awareness and engagement, the Gamification for electrical energy savings service should provide a clear and user-friendly interface with challenges (e.g., daily, or monthly challenges) and incentivize the users by displaying their savings and their rankings inside the community, and possibly give rewards to the top rankings. Finally, in some cases, such as the example of the Portuguese pilot, some services need to be adapted according to the legislation of the country (e.g., Portuguese legislation defines that members can enter or leave the community whenever they want). Services like LEC Designer should be adapted for the Portuguese pilot so this change in the community structure can be done seamlessly, without affecting the members and their energy transaction process. The Optimizing sharing coefficients in collective self-consumption service should also be flexible enough to adapt whenever there is a change in the community structure.

IV. CONCLUSION

As demonstrated by the OMEGA-X project, advanced data-driven services services are crucial for optimizing energy management, enhancing community participation, and promoting the development of sustainable energy markets. Several key recommendations emerge from these findings. First, the establishment of robust frameworks for effective data management and interpretation is essential. Second, ensuring interoperability and adherence to common standards is critical for seamless integration across different systems. Additionally, innovative services, such as gamification, have proven valuable for increasing awareness and community engagement. Safeguarding data privacy and security, particularly in accordance with regulations like the General Data Protection Regulation (GDPR), remains a priority. Case studies from Portugal and Serbia underscore the potential of data-driven platforms to improve energy efficiency, maximize the use of renewable energy, and facilitate the wider RES adoption. Future research and development should focus on further enhancing the digital capabilities of LECs, exploring new data-driven services, and adapting solutions to meet the specific needs and legislative requirements of different regions. Continued innovation and collaboration will enable LECs to play a central role in driving the transition to a low-carbon economy and supporting the achievement of climate objectives.

ACKNOWLEDGMENT

This work is funded by the European Union's Horizon Europe innovation action program under grant agreement no [101069287] (OMEGA-X). https://omega-x.eu/.

REFERENCES

[1] *European Parliament, Directive (EU) 2018/2001 of the European Parliament and of the Council, of December 11, 2018, on the Promotion of Energy from Renewable Sources. PE/48/2018/REV/1, OJ L 328, 21.12.2018, p. 82–209.*

[2] "European Parliament, Revised Renewable Energy Directive (REDII, PE/36/2023/REV/2), OJ L, 2023/2413, 31.10.2023, ELI: http://data.europa.eu/eli/dir/2023/2413/oj."

[3] European Union, *Directive (EU) 2024/1711 of the European Parliament and of the Council of 13 June 2024 amending Directives (EU) 2018/2001 and (EU) 2019/944 as regards improving the Union's electricity market design*.

[4] G. Yiasoumas *et al.*, "Key Aspects and Challenges in the Implementation of Energy Communities," Jun. 01, 2023, *MDPI*. doi: 10.3390/en16124703.

[5] "OMEGA-X project, https://omega-x.eu/ ."

[6] "Regulation (EU) 2023/2854 of the European Parliament and of the Council of 13 December 2023 on harmonised rules on fair access to and use of data and amending Regulation (EU) 2017/2394 and Directive (EU) 2020/1828 (Data Act) (Text with EEA relevance)."

[7] A. Dognini, A. Monti, and C. Joglekar, "Blueprint of the Common European Energy Data Space-Version 1.0," 2024, doi: 10.5281/zenodo.10964387.

[8] M. Bacco, A. Kocian, S. Chessa, A. Crivello, and P. Barsocchi, "What are Data Spaces? Systematic Survey and Future Outlook," *Data Brief*, p. 110969, Oct. 2024, doi: 10.1016/j.dib.2024.110969.

[9] "Sovity: Sovereign data exchange with your partners in Data Spaces, https://sovity.de/en/sovity-en/."

[10] A. Hernandez-Matheus *et al.*, "A systematic review of machine learning techniques related to local energy communities," Dec. 01, 2022, *Elsevier Ltd*. doi: 10.1016/j.rser.2022.112651.

[11] S. Barja-Martinez, M. Aragüés-Peñalba, Í. Munné-Collado, P. Lloret-Gallego, E. Bullich-Massagué, and R. Villafafila-Robles, "Artificial intelligence techniques for enabling Big Data services in distribution networks: A review," Oct. 01, 2021, *Elsevier Ltd*. doi: 10.1016/j.rser.2021.111459.

[12] V. Janev *et al.*, "Responsible Knowledge Management in Energy Data Ecosystems," *Energies (Basel)*, vol. 15, no. 11, Jun. 2022, doi: 10.3390/en15113973.

[13] D. Popadić, "Towards a Solution for an Energy Knowledge Graph." [Online]. Available: https://lov.linkeddata.es