Empowering Energy Communities and P2P Energy Sharing: A Novel End-to-End Ecosystem for Planning, Deployment, and Operation

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The widespread adoption of renewable energy sources has necessitated innovative solutions to address their inherent intermittency and facilitate energy democracy through Energy Communities (ECs). However, the successful planning, deployment, and operation of ECs face multifaceted socio-technical challenges. This publication presents a novel end-to-end ecosystem designed to foster the planning, deployment, and operation of ECs and peer-to-peer (P2P) energy relations. The ecosystem empowers stakeholders by addressing various challenges associated with the formation and management of ECs. A user-centric mobile application facilitates the identification and engagement of prospective EC members, evaluation of feasibility, and negotiation of operational, business, and financial models. The application also enables users to monitor the performance of their ECs or P2P energy-sharing relationships. An Energy Community Marketplace serves as a platform for interactions between feasible clusters and EC operators, acting as a broker to finalize the EC operator and establish connections with users' near real-time data access. The ecosystem inherently includes historical and real-time data integration based on user consent and GDPR best practices. The proposed ecosystem streamlines entire EC lifecycle, fostering active user participation, data-driven decision-making, and seamless integration of diverse stakeholders, ultimately supporting the energy transition and democratization goals.

CCS Concepts: • **Information systems → Data streaming**; **Process control systems**; *Online analytical processing*; • **Human-centered computing → Ubiquitous and mobile computing**; **Visualization**.

Additional Key Words and Phrases: Renewable Energy Communities, Citizen Energy Communities, Mobile Application, Energy data access, Energy community control, Energy Community Marketplace

1 INTRODUCTION

With the increased adoption of Renewable Energy Sources (RES) globally, the energy landscape is witnessing a paradigm shift to manage the intermittent nature of RES. A key development in this regard is the emergence of Energy Communities (ECs) and the accompanying concept of energy democracy. ECs are viewed as a promising avenue for enhancing self-sufficiency [Iazzolino et al. 2022], bolstering local economic circulation [Ruggieri et al. 2023], fostering social acceptance of renewable energy [Bauwens and Devine-Wright 2018; Biresselioglu et al. 2021], and optimising individual investments of RES [Manuel De Villena et al. 2022]. Furthermore, these communities can contribute to grid stability by providing grid flexibility services [Rocha et al. 2023] and facilitating demand response [Iazzolino et al. 2022].

The term *Energy Community* encompasses a wide range of meanings and configurations, given the varied types of actors, technologies, and complex network infrastructures involved. In a broad sense, an EC comprises a diverse array of stakeholders, including consumers, prosumers, social entrepreneurs, public authorities, and community organizations, as mentioned by [Iazzolino et al. 2022]. This multifaceted composition reflects the intricate nature of energy community structures and their adaptability to various contexts.

In response to the evolving energy landscape, various legislative bodies are incorporating the concept of Energy Communities into their respective jurisdictions. For example, European energy policies are shifting away from incentive-based programs, with the goal of attracting private financing. In this context, energy communities and collective self-consumption initiatives are gaining recognition as crucial elements in the transition. Their significance has been further underscored by directives issued such as the Renewable Energy Directive (RED II) (2018/2001/EU) [Union 2018] and the Internal Electricity Market Directive (IEMD) (2019/944/EU) [Union 2019]. The 2018 RED II marked a turning point by introducing the official definition of *renewable energy communities* (RECs) under Article 2(16) and proposing a regulatory framework specifically for them. Subsequently, the IEMD, which entered into force in 2019, built upon RED II by introducing a broader definition encompassing *citizens' energy communities* (CECs). This broader definition acknowledges the potential for communities to engage not only with renewable energy sources but also with other aspects of energy management. RED II furthermore defines peer-to-peer renewable energy trading as *"the sale of renewable energy between market participants by means of a contract with pre-determined conditions governing the automated execution and settlement of the transaction, either directly between market participants or indirectly through a certified third-party market participant, such as an aggregator."*

Despite the legal endorsement for energy communities, technical obstacles persist [Roversi et al. 2022] that impede user adoption of such solutions. While ECs are fundamentally conceived as people-driven initiatives, a socio-technical gap emerges [Ryghaug et al. 2018] in identifying users who would be well-suited participants for an EC or P2P energy trading. In the planning phase of ECs, users currently face limited avenues to explore the potential of a prospective EC by discovering compatible energy consumers, prosumers, or producers. Access to energy data is of paramount importance for such investigations [Kashyap et al. 2021], and it must be obtained in compliance with the General Data Protection Regulation (GDPR). As a result, multiple challenges arise in finding a cluster of users well-suited for an EC. In the subsequent deployment phase, after potential users have been identified, bridging the gap between an EC operator and the participants presents another significant hurdle.

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The ensuing operational phase heavily relies on near real-time data access from the users, contingent upon their data-sharing consent.

To address these challenges, we propose a novel IT-based infrastructure ecosystem for energy communities that encompasses the planning, deployment, and operational phases of an EC and P2P energy-sharing relationship. This infrastructure adopts GDPR-compliant best practices to facilitate active user participation.

2 ENERGY COMMUNITIES LANDSCAPE

The establishment and operation of an EC is a multi-faceted process that requires a systematic approach spanning from initial planning to long-term maintenance. To ensure successful implementation and sustainable functioning, a comprehensive set of steps must be undertaken as delineated below:

(1) *Identifying and Engaging Prospective EC Members:*
The first crucial step involves identifying users who are willing to form an EC. These could be individuals, organizations, or businesses with synergistic value propositions and a shared sense of collective responsibility towards renewable energy. It is vital to comprehend their individual goals [Gjorgievski et al. 2021] for community participation and the means of interaction they can have with other EC users. Similar structures of user participation, such as those in community renewable energy projects, face challenges in identifying stakeholders due to diverse motives and engagement levels, as discussed in [Bauwens 2016].

(2) *Establishing the Collective Goals and Value Propositions:*
As a people-led initiative, the goals of each EC may vary based on the users' value propositions and aims [Hoffman and High-Pippert 2010]. Collective goals can range from reducing energy bills and increasing the share of renewable energy to lowering carbon emissions, combating energy poverty, fostering community engagement, increasing energy independence, and improving the local economy.

(3) *Conducting Socio-Technical Feasibility Assessments for Prospective Energy Communities:*
In the planning phase, it is crucial to understand the current energy consumption and production patterns of prospective EC users. Often, complementarity (for example, [Lowitzsch et al. 2020]) is evaluated between users' energy profiles and installed RES that can bring a symbiotic relationship within the EC. Conducting such studies aids in resource planning, grid connectivity, exploring the potential for providing grid services, and identifying opportunities for optimized renewable energy integration. Furthermore, the EC topology should also be determined at this stage based on user types and energy consumption profiles, ranging from centralized to distributed or decentralized, as denoted in [Gui and MacGill 2018]. This exercise of conducting socio-technical studies leads to the identification of feasible clusters for prospective EC deployment. This step heavily relies on the availability of the metering data of energy consumption and production, also known as Historical Validated Data (HVD), of the users. While the Clean Energy Package [European Commission 2019] establishes customer rights to access energy data and share it with chosen eligible parties, fostering new data-driven services, the lack of standardized procedures across countries poses a significant obstacle to implementation, as observed in [Karagiannis et al. 2023].

(4) *Identifying Relevant Stakeholders Based on User Clusters and Community Goals:*
Once feasible clusters are identified through empirical studies, a mechanism is needed to identify other stakeholders most relevant to the identified users from Step 1, the collective goals of the EC from Step 2, and the feasibility test results from Step 3. The aim of this step is to identify prospective EC operator(s).

(5) *Negotiating and Finalizing Operational, Business, and Financial Models:*
With all prospective stakeholders and goals identified, this phase involves negotiating the operational model and business relations between EC users. Financial models should be based on the potential gauged from preliminary studies and the estimated costs, including technological installations, infrastructure development, grid connections, and operational maintenance. Based on the value proposition and goals, as mentioned in [F.G. Reis et al. 2021], various business model archetypes are possible, such as energy cooperatives, community prosumerism, local energy markets, community collective generation, third-party-sponsored communities, community flexibility aggregation, community energy service companies (ESCOs), and e-mobility cooperatives. Prospective EC operators can negotiate with EC users the technological, administrative, and financial models and explain their approach for optimizing parameters aligned with individual user goals. There should be flexibility to adopt the EC operator and optimization algorithm, fostering innovation and adoption of new mechanisms, such as the one mentioned in [Manuel De Villena et al. 2022]. The outcome of this step includes selecting the appropriate EC operator, negotiating and finalizing the terms of operations, and adopting the modus operandi and relevant business model.

(6) *Establishing Contractual Agreements and Regulatory Compliance:*
This step involves establishing contracts between the EC operator and users, as well as the EC and the national permitting authority. Relations within the group of users and their collective relation with the EC operator should be clearly defined. Users (consumers, prosumers, producers) should be at the center of the community, with the contract specifying the scope and length of the power purchasing agreement (PPA). For formalities with regulatory authorities, procedures differ by country. The broad scope includes signing installation and operation agreements, registering the EC, reaching agreements with system operators and participants, connecting to the grid, and integrating with designated national infrastructure. Furthermore, this step includes the decision on whether the EC should adopt static or dynamic distribution. Static distribution means each participant is always allocated the agreed share generated, with surplus fed into the grid. Dynamic distribution relates to the

case when energy generated by facilities is allocated among participants based on demand to increase self-sufficiency, with individual surpluses going back into the "community surplus system." In case of Dynamic distribution, the energy allocation share can change based on the individual demands of the users within the EC.

(7) *Deployment and Operationalization of the Energy Community:*
Once the community receives the desired permits and has fully installed the technological and RES assets, it can legally commence operations. Community prosumers can begin producing and consuming energy generated at their properties and share excess energy with community consumers. The setup of the EC in the deployment phase requires steps such as recording master data of generation facilities and participants, transmitting metering points from participants to system operators, and transmitting the allocation mode of generation facilities to system operators.

(8) *Continuous Monitoring, Optimization, and Billing Operations:*
Regular monitoring and optimization are essential to ensure the performance of an EC. This requires near real-time metering data access from users, which can be extracted by establishing a consent-based, GDPR-compliant platform for accessing data from the standardized interface of smart meters. Additionally, this step encapsulates billing and operations that require transmitting energy data from all generating facilities and participants, processing and preparing data for participant billing, and informing users about Service Level Agreements (SLAs). Furthermore, users should also be empowered to monitor their own participation in the EC and P2P relationships they are part of.

(9) *Long-term Maintenance and Asset Management:*
Finally, ECs require continuous controls and maintenance to ensure installed assets last for the community's full duration. The terms of maintenance are committed to in Steps 5 and 6.

The establishment and operation of an EC is a multi-faceted process that requires a systematic approach spanning from initial planning to long-term maintenance. To address the intricate socio-technical aspects inherent in the development of energy communities, we propose a novel end-to-end one-stop solution for fostering the planning, deployment, and operation of ECs. This solution empowers EC stakeholders by methodically addressing each of the requisite aforementioned steps. The proposed solution adopts an ecosystem approach, following a modular architecture by incorporating various building blocks. The following section provides a detailed description of these building blocks and their functionalities within the proposed ecosystem.

3 PROPOSED SOLUTION

The proposed ecosystem is meticulously designed to facilitate all the necessary steps required for establishing an Energy Community (EC). To implement the proposed solution, we developed a robust system comprising several building blocks, each with specific functions. These blocks are exhibited in Figure 1 and are briefly explained in subsequent subsections. The building blocks are categorized into four categories based on their functions. Additionally, this section describes how each block positively impacts the prerequisite steps for forming and operating an EC or P2P energy-sharing relationship.

3.1 Access to Historical Validated Data

As the name suggests, the building blocks categorized under this module serve the crucial and important function of providing access to metering and consumption data i.e. Historical Validated Data (HVD). As one can relate to the prerequisite steps required for ECs, HVD plays a pivotal role. The components marked with an asterisk (*) in Figure 1 are parts of the HVD supply chain.

Typically, smart meters transfer energy data to the Meter Data Administrator (MDA), which in many cases is the Distribution Network Operator (DNO). This collected data is validated by the MDA and made available for sharing based on customer requests. The European Union's Clean Energy for All Europeans Package [European Commission 2019] empowers consumers by granting them the right to access their own energy-related data, including metering, production, and consumption information. The legal landscape allows users to share their energy data with third-party Eligible Parties. These third parties act as parties requesting or processing data shared by the customer and can leverage this data to provide valuable services such as identifying prospective EC clusters and finding synergies between users.

Data can be requested from country-specific existing Data Infrastructure that consists of national energy data management environments and online data hubs where historical metering and consumption data is collected, validated, and stored. This data must then be made available to established actors or eligible parties as required. However, data sharing is currently carried out in various ways across different countries, involving diverse players, processes, formats, and schemas. To address this challenge, the EDDIE (European Distributed Data Infrastructure for Energy) framework interfaces with these data-sharing infrastructures, offering a streamlined consent management user flow. By doing so, it simplifies the process of obtaining user consent for data sharing and ensures that data is accessed and shared securely and transparently. Additionally, the EDDIE Framework provides a transformation towards a common pivotal format, enabling seamless integration and compatibility of data across different Member States and diverse data-sharing infrastructures. Therefore, by leveraging EDDIE framework, our proposed solution facilitates the HVD, based on user consent, which in turn is stored in the cloud.

3.2 Access to in-house data sources

The building blocks associated with near real-time data access are indicated with a circumflex (ˆ) symbol in Figure 1. In-house data sources pertain to near real-time data obtained from the standardized interface on smart meters in most Member States of EU, given that the smart meter has been ordered and installed after July 4th, 2019. Accessing and processing this data can be challenging for customers due to its in-house availability and the need for transformation into a common format for further use. To address this challenge, the Administrative Interface for In-house Data Access

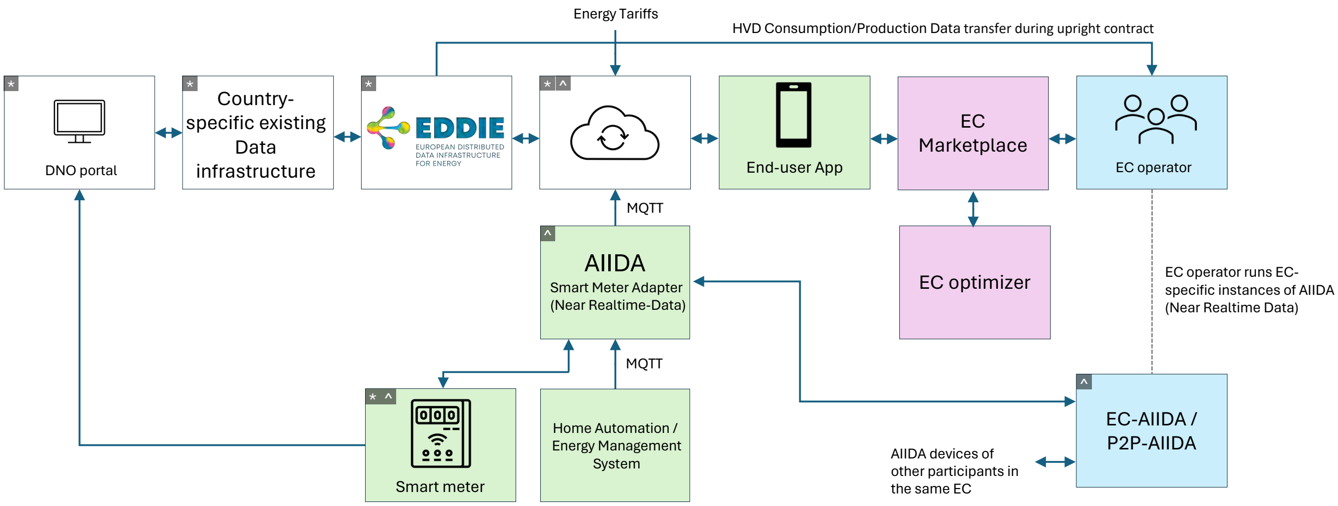

Fig. 1. Architecture of the proposed novel ecosystem solution depicting interactions between various developed building blocks. The building blocks shaded green are executed in the end-user environment, while the pink ones reside in the EC marketplace environment. The blue shaded blocks are hosted by the EC operator. Building blocks marked with an asterisk (*) correspond to the historical metering data supply chain, and those with a circumflex (ˆ) symbol correspond to the near real-time data supply chain.

(AIIDA) is designed to read data from various meter models, standards, and configurations, making it available through an online, consent-based mechanism.

The AIIDA component interacts with the cloud using MQTT protocol to send the requested data. To ensure user privacy and security, data can only be sent once users give explicit permission to share their data. EC operators execute an AIIDA instance in their environment, which communicates with the AIIDA instances of the users participating in the same EC. Based on user consent, the AIIDA instances of the users share their near real-time data with the EC operator's AIIDA instance and receive external signals simultaneously. This bidirectional real-time communication capability of AIIDA between users and EC operators additionally empowers all stakeholders to make informed decisions. Moreover, AIIDA can connect to other energy assets, such as Energy Management Systems and Home Automation devices, to control and inform these in-home assets about external signals like energy tariffs or signals from the EC operator once the user is part of an active EC. Therefore, AIIDA acts not only as the broker for near real-time data access but also as the means of communication between the external signals and the in-house assets for operational control and maintenance. Consequently, the AIIDA component plays a crucial role during the operational phase of an EC.

3.3 End-user App

We have developed an innovative, user-centric mobile application designed to empower end-users to initiate, deploy, operate, and monitor various ECs or P2P energy relations. This app enables users to identify a beneficial EC or P2P candidate to establish an energy-sharing relationship. It also helps in estimating the potential of establishing an EC or P2P with their preferred group of users. The application offers an intuitive interface where users can generate their QR codes and share with other user(s) they would like to share energy with or make an EC with, as shown in Figure 2(a). By scanning the QR codes, a reference to other users of the app is established. The QR code serves as an anonymous reference for the energy profiles used in the EC-Marketplace or EC-Optimizer to identify suitable partners.

To evaluate the feasibility of a potential EC or P2P relationship, a user can select other users and click on the 'Evaluate' button. When a user selects potential collaborators (individuals they are interested in forming an EC or engaging in P2P trading with), they initiate the data exchange process. When multiple potential participants in an energy community or P2P trading have been captured through the scanning of QR codes in the app, the list of anonymized IDs of potential candidates is transferred to the EC Marketplace. The unique identifier embedded within the QR code facilitates the linkage of datasets from these users at the EC marketplace. Subsequently, each end-user app instance (corresponding to a specific user) transfers relevant data, including energy consumption and generation profiles, to the EC marketplace. EC marketplace, using EC optimizer, evaluates various scenarios to help users determine the (i) optimal configurations in P2P scenarios and (ii) whether participation in an energy community would be more efficient.

In cases where no potential participants are transferred to the EC Marketplace, such as when a user does not scan any other QR code from other users, an independent evaluation is conducted to identify feasible EC or P2P relations and to determine the conditions under which participation in an energy community would be possible. The marketplace may present multiple unique energy communities for selection in this scenario. Consequently, the end-user app provides an innovative way to address the first step *'Identifying and Engaging Prospective EC Members'*. Furthermore, by facilitating the evaluation studies by providing the required HVD through EDDIE framework,

Fig. 2. Screenshots of the end-user mobile application for facilitating EC and P2P energy trading. (a) Interface for generating and scanning QR codes to form an energy community. (b) Results of the feasibility studies for P2P. (c) Details of an offer from functional EC for the user. (d) Identification of a planned EC. (e) Visual overview of personal demands vis-a-vis EC demands. (f) Historical EC performance of a week. (g) Monitoring of EC performance based on near real-time data. (h) Performance of P2P energy sharing based on near real-time data. (i) Interface for predicting demand and surplus energy by end-users and monitoring the accuracy of their predictions. (j) Example of the relation of the user with another EC where the symbiotic relation is more prominent.

it supports the third step *'Conducting Socio-Technical Feasibility Assessments for Prospective Energy Communities'*.

The results of these feasibility studies are shown to the users, as demonstrated in Figure 2(b), including whether the user would benefit from performing a P2P energy trade with the intended user and the reasoning behind the recommendation, which can pertain to societal, economic, regulatory, or technical constraints. Based on the data from users, EC marketplace gauges which offerings from existing ECs might be beneficial for them, as depicted in Figure 2(c). EC optimizer is responsible for identifying optimal configurations of participants in an energy community or in a P2P scenario.

Moreover, users can evaluate the scope of opportunities for an EC. For example, as shown in Figure 2(d), the energy community 'YZ' is inactive, and an asset for energy storage could benefit the EC. It refers to the scenario that the EC is planned and will be operational once enough suitable participants with desired assets have been identified and motivated to participate in the particular EC. Therefore, a user can upfront gauge benefits and consider installing a home storage solution accordingly.

The offers from prospective EC operators, based on the interactions on the EC marketplace, are communicated to the users through their app. In conjunction with the EC marketplace, the app provides an innovative method to fulfil the fifth step, *Negotiating and Finalizing Operational, Business, and Financial Models*. The user app offers functionalities to accept the negotiated terms of operation and grant permission for near real-time data access to the selected eligible party by the user. Furthermore, the app interacts with the regulatory authority to transmit the required information about the EC through the already-established link via the EDDIE. Therefore, the same app facilitates the prerequisite steps, *'Establishing Contractual Agreements and Regulatory Compliance'* (Step 6) and *'Deployment and Operationalization of the Energy Community* (Step 7)',.

Once the user is part of an EC or in a P2P energy-sharing relationship, they can monitor the performance of these interactions based on the real-time data received from the AIIDA and historical data fetched from EDDIE interfaces. One such user-friendly element is the donut chart across a time scale, as showcased in Figure 2(e), which conveys the user's energy needs (inner ring) performance vis-à-vis the energy demands of the EC (outer ring) over a period of 24 hours. Similarly, another EC with a relatively more prominent symbiotic relation with the user can be observed in Figure 2(j). This provides visual feedback to the users about the symbiotic relationship existing between the user and the community as a whole. Users can also visualize the overall energy demand overview of the preceding week as depicted in Figure 2(f).

Additionally, users can monitor the performance of their ECs based on near real-time data fetched through AIIDA. One can visualize the energy demand and generation in the EC or the P2P setup, as exhibited in Figure 2(g). This helps users to apprehend the available surplus energy in the community and the amount of energy they consumed at the same time. Similarly, they can visualize the performance of the P2P energy trade with other user(s), as shown in Figure 2(h). The sliding bar allows users to choose the granularity of data with respect to the time domain.

The user-centric approach of the proposed ecosystem is further emphasized by an additional functionality in the app that allows users to indicate their anticipated demand and generation. This feature enables users to actively participate in demand-side management by directly indicating their energy needs or surplus in the app. For instance, if a user anticipates an additional demand of 14 kWh from 03:00 to 04:00, they can indicate the availability of energy in the app, as shown in Figure 2(i). The EC operator can approve the additional demand or quote the actual amount of energy it can provide, here 13 kWh. This enables users to improve their forecasting accuracy over time. This feature enhances the overall user experience and promotes active engagement in ECs and P2P energy relations. The predicted changes that are approved by the EC operator are depicted with green color. Conversely, if a user expects to require less energy (e.g., 6 kWh at 5:00), they can indicate the upcoming demand in the end-user app. This bid for surplus or deficit energy is communicated to the AIIDA instance of the EC operator where the operator aggregates all bids from users. Through their respective AIIDA instances, users receive real-time information about feedback from EC operators. This transparency empowers all stakeholders of EC to make informed decisions. By directly participating in the bidding process, users actively shape the demand side management within the EC, fostering a more flexible and efficient system.

Therefore, the app further supports effective monitoring at the user level contributing towards the eighth step concerning continuous monitoring. By providing EC operators an interface for required data, it facilitates *'Continuous Monitoring, Optimization, and Billing Operations'*. This user-centric mobile application streamlines the process of forming and managing ECs, providing users with a convenient and accessible tool to engage in energy communities and contribute to the energy transition. By facilitating data sharing, cluster identification, and communication with EC operators, the app plays a crucial role in empowering end-users and promoting the growth of Energy Communities and P2P energy sharing.

3.4 Energy Community Marketplace

The end-user app and the EC marketplace work together in close coordination to streamline the formation and management of ECs. The EC marketplace functions as a platform to facilitate interactions between different feasible clusters and EC operators as service providers. The potential of prospective ECs can be calculated, and the identified clusters can be published on the EC Marketplace. EC operators participating in the EC marketplace can present their EC models and terms to the users of the identified cluster. The EC marketplace then acts as a broker between the users of the prospective EC cluster and willing EC operators, helping to negotiate offer terms, the business model of the EC, and the mode of operation, among other aspects. Once all stakeholders are finalized, the EC marketplace further facilitates the connection between the EC operator and the users' near real-time data access through AIIDA.

By providing a unified platform for interactions between users, clusters, and operators, the EC marketplace plays a vital role in promoting the growth and development of Energy Communities. Specifically, it heavily contributes to facilitating *'Identifying Relevant Stakeholders Based on User Clusters and Community Goals'* (Step 4), and *'Negotiating and Finalizing Operational, Business, and Financial Models'*. It simplifies the process of establishing and managing ECs, ensuring that users can easily find suitable operators. As the optimization approaches are very dynamic with the advancement of AI, the platform should be able to accommodate the multiple optimization models. Therefore, we have designed it such that there lies an opportunity to involve any third-party EC optimizers fostering innovation and efficiency in the complete ecosystem.

4 CONCLUSION

This publication presents a novel end-to-end ecosystem for facilitating the planning, deployment, and operation of energy communities (ECs) and peer-to-peer (P2P) energy relations. The typical prerequisite steps, outlined in Section 2, are systematically addressed by the diligently designed building blocks of the proposed solution, detailed in Section 3. The end-user mobile application developed serves as the cornerstone for the entire framework, enabling seamless communication between users and other stakeholders within the ecosystem. The EC marketplace acts as a pivotal platform, bridging the gap between prospective user clusters and EC operators. The ecosystem's modular architecture, comprising robust building blocks, ensures seamless interaction between all stakeholders. The integration of secure and GDPR-compliant data access components facilitates data-driven decision-making, while the user-centric design empowers end-users to actively initiate, negotiate, and monitor their involvement in energy communities. The ecosystem's modular architecture ensures streamlined interaction between the end-user, EC marketplace, and EC operator environments, fostering a more sustainable, democratized, and decentralized energy future.

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