DIGITAL TWINS IN BUILDING MANAGEMENT: BOOSTING EFFICIENCY IN RENEWABLE ENERGY COMMUNITIES

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Abstract

The study proposes a methodological approach for organizing, storing, and handling diverse data across disciplines using digital systems structured on the internet with a multi-level strategy. This workflow follows traditional knowledge process steps, storing and organizing outcomes in a unified web-based model using pre-existing ontologies. The goal is to distribute data among stakeholders and establish a decision support system for the energy community. The digital twin implementation integrates IoT technologies, Big Data analysis, and territorial modeling, enabling energy management solutions at both individual (residential) and larger (community) scales.

Introduction

The energy consumption of buildings is a pivotal factor in achieving sustainable development, encompassing economic, environmental, and social dimensions. This theme of sustainability is currently a high priority in global and European policies. In the European Union, buildings account for 40% of energy consumption and 36% of climate-altering emissions (Energy Efficiency in Buildings - European Commission.

In 2019, the European Community launched the European Green Deal, a comprehensive suite of strategic initiatives aimed at combating climate change and global warming. The primary objective of this plan is to achieve climate neutrality by 2050 (Fit for 55 - The EU's plan for a green transition - Consilium.

The European Green Deal highlights the need for a holistic and cross-sectoral approach to address climate challenges, where key sectors such as climate, environment, energy, transportation, industry, and agriculture work in synergy (EU 2019).

These initiatives are pivotal in reducing energy poverty, decreasing carbon emissions, and promoting energy independence(In focus: How can the EU help those touched by energy poverty?).

The emergence of new paradigms and innovative systems, such as Collective Self-Consumption models and Energy Communities, represents a significant shift in energy strategies. These community-focused energy models are transforming the landscape of renewable energy production, distribution, and consumption. Central to these models are the principles of localization and decentralization of energy generation.

Involving citizens, commercial entities, and local businesses, these models facilitate the creation, consumption, and exchange of energy with an emphasis on self-consumption and collaborative effort. Community energy systems and collective self-consumption facilities offer several advantages over traditional energy production models. These include the optimal combination of diverse consumption profiles, immediate utilization of generated energy, and a reduced load on existing grid infrastructures.

This approach not only contributes to environmental sustainability but also fosters a sense of community and collective responsibility towards energy consumption and climate action. Such initiatives, supported by policies like the European Green Deal, are essential steps towards a sustainable, energy-efficient future (Pisello et al. 2023).

Self-consumption of energy can take place at three different levels: individual, collective and community.

The concept of collective self-consumption is defined in the EU Directive 2018/2001(Directive EU - 2018/2001). The directive stipulates that the group of self-consumers (minimum two) who act collectively must be in the same building or condominium.

The text also stipulates that they can generate renewable electrical energy for their own consumption and can store or sell self-produced electrical energy. The main condition is that such activities do not constitute the main commercial or professional activity.

The consumer in the realm of renewable electricity is no longer merely a recipient of energy but has evolved into a 'prosumer.' The term 'prosumer' denotes a user who actively participates in all stages of energy production, as opposed to solely fulfilling the passive role of a consumer. A key advantage of this paradigm shift is the ability for individuals to act collectively, thereby sharing the costs and benefits of such systems, which may include joint maintenance and other pertinent practices.

Legally, participants in these systems share the energy they generate through the existing distribution network.

Each member is equipped with their own meter to measure individual consumption. However, to accurately assess the amount of energy shared for self-consumption purposes, the installation of a secondary metering system is necessary. This system is crucial for monitoring the distribution and sharing of generated energy among the participants.

Despite sharing the overarching goal of enhancing the management of renewable energy generation and usage, there are notable differences between Self-Consumption Units (SCUs) and Renewable Energy Communities (RECs). The primary distinction lies in their composition. An energy community, as defined by the EU Directives 2018/2001(Directive - 2018/2001) and 2019/944(Directive (EU) 2019/944 of the European Parliament and of the Council on common rules for the internal market for electricity and amending Directive 2012/27/EU, is typically comprised of associations of citizens, businesses, local administrations, and small enterprises. These entities collectively decide to produce, exchange, and consume energy derived from local renewable sources (Menegon et al. 2021). This collaborative approach not only fosters a sense of community but also aligns with broader objectives of sustainability and local empowerment in energy production and consumption (Notton et al. 2018).

The Digital Twin (DT) is revolutionising the energy sector by providing an innovative approach to management and monitoring. It enables the management of on-site energy exchanges, optimises the use of renewable resources, and allows users to monitor their own energy consumption (Xiong et al. 2021; Bortolini et al. 2022; Tahmasebinia et al. 2023; Testasecca et al. 2023). The future energy system finds a valuable support in the concept of the digital twin, as developed by Michael Grieves (Grieves and Vickers 2016).

According to Grieves, the Digital Twin (DT) system is based on three main elements: real-world physical products, their virtual counterparts, and the data connections between them. This setup allows the virtual model to mimic the real object's behavior, ensuring changes in the physical product are reflected in the digital one, often through IoT devices and sensors. (Barricelli et al. 2019). Digital twins in the construction sector facilitate the integration of the building's informational and physical models, thereby ensuring iterative optimization of both models. The DT leverages the geometric and parametric properties of Building Information Modeling (BIM) models, as well as streaming environmental data (e.g., temperature, humidity, consumption, etc.) collected from sensors (Brilakis et al. 2019). BIM serves as a common knowledge resource that can be employed as a singular source for data management and collection, facilitating the sharing, preservation, and provision of reliable guidance throughout the building's lifecycle. Data access is enabled through various mechanisms, including proprietary system manual interfaces, Application Programming Interfaces (APIs), and exporting via standard formats such as Industry Foundation Classes (IFC). To date, a unified standard in the IoT and BIM domain has yet to be established, yet numerous open standards are emerging. These are intended to provide a common language across different systems and devices, enabling interoperability and seamless communication among various entities. However, research on the integration between BIM and IoT remains in its nascent stages, where most studies primarily introduce conceptual theoretical propositions (Mengistu and Mahesh 2020; Tai et al. 2021). The importance of digital twins in the construction sector is underscored by the emerging demands for intelligent systems that are capable of representation, analysis, identification, and the enhancement of consumption patterns(Jradi and Bjornskov 2023). Efficient energy management necessitates a reliable data source through the transmission of data from an IoT infrastructure. Employing advanced methods such as machine learning, artificial intelligence, and deep learning, energy community managers can monitor, collect, and analyse data to produce reports, charts, and integrate informational models. Predictive analytics can be utilized to foresee potential issues and undertake preventative measures before they escalate into problems. With these tools, energy community managers make more informed decisions to the benefit of the RECs. Energy data analysis is a crucial aspect of understanding and managing consumption. By interpreting the collected data, RECs members can gain valuable insights into their energy consumption patterns and trends. This knowledge can assist them in making more informed decisions on how to best utilize their resources and reduce costs (Al-Ali et al. 2017; Adu-Kankam and Camarinha-Matos 2023). The digital twin is revolutionising the energy sector by amalgamating the prowess of IoT technology, Big Data analytics, and informational and spatial modelling. This facilitates the deployment of energy management solutions both at a granular level (individual residential units) and at a broader scale (energy communities). This endeavour seeks to delineate a methodological approach that affords RECs members facile access to data and to devise a system that aids them in making well-informed decisions. The methodology employs a variety of tools and techniques, such as statistical analysis and machine learning, to scrutinise data and generate reports.

The principal objective is to proffer an efficacious framework for the cataloguing, storage, and management of multidisciplinary data and information utilising web-based digital systems. This system ought to be scalable, secure, and user-friendly, enabling users to access and meticulously analyse data with alacrity. The chief aim of the methodology lies in the dissemination of reports among the diverse REC members, as well as in the development of a decision-support system.

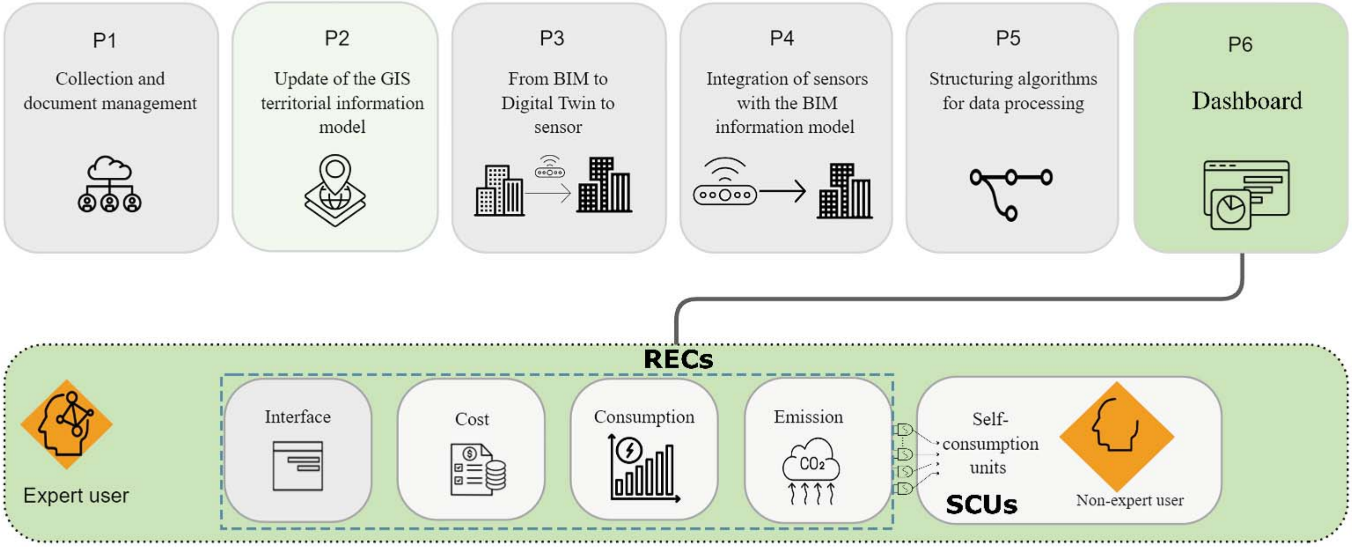

Figure 1 Methodological Framework

Methodology

A comprehensive framework designed to bolster self-consumption units and complex systems like Energy Communities. This research work provides an analysis of current tools, their features, and the best practices for their application to develop an effective management and monitoring infrastructure. The system facilitates the creation of geographical interfaces for community energy operators through the integration of digital twin technologies. Digital Twins (DTs) lack sufficient autonomy to optimise consumption based on information received from Building Information Modelling (BIM) and Internet of Things (IoT) systems, as the unpredictable behaviour of occupants plays a pivotal role. Energy consumption is significantly influenced by user intentions and goals, as well as their expectations in terms of energy savings. With the support system, all stakeholders can better manage the community's economic framework and energy efficiency programmes. REC members have access to the latest updates on the energy system and benefit from reliable recommendations to make informed decisions.

The framework designed to support the management and monitoring processes of the energy community is based on a portal (Web-GIS) containing specific interfaces for sharing information about the energy community and collective self-consumption units. The digital techniques underpinning the methodological framework include Geographic Information Systems (GIS-based), useful for georeferencing different energy communities, primary and secondary substations, followed by architectural entities. The digital techniques underpinning the methodological framework include Geographic Information Systems (GIS-based), useful for georeferencing different energy communities, primary and secondary substations, followed by architectural entities.

i. BIM digital models of buildings structured according to the proprietary guidelines of the energy community. BIM models are implemented on the platform using web-based graphic libraries.

ii. Relational databases structured for the systematisation and querying of data.

iii. Machine Learning algorithms for energy profiling divided into clusters and future predictions of consumption and costs.

iv. Web-based systems for report provision.

The proposed methodology is divided into document collection and management; updating the GIS territorial information model; from BIM to Digital Twin; integration of sensors with the BIM information model; structuring algorithms for data processing and conceptualisation of the dashboard.

P1: Collection and Document Management

This part is dedicated to the cataloguing and administration of documents within the energy community, as well as the pivotal elements that must be incorporated into the process. Entities such as local authorities, citizens, associations, and businesses are required to upload data pertinent to the RECs or collective SCUs. The assemblage and management of documents entail the structuring of a pre-established repository. The subsequent step involves their cataloguing to facilitate ease of search and retrieval. This includes the employment of metadata tags and other forms of categorisation to ensure that data are readily accessible. Once organised and catalogued, the data must be stored in a secure and reliable manner. The most critical phase of the process is data management, which entails ensuring regular updates and protection of the data, and that all

Figure 2 Illustration of a GIS spatial model applied to RECs

participants in the REC have access to the necessary information. The documents must provide clear instructions and information on different aspects of the energy community. Technical reports, safety verifications, regulatory documents, and statutes must all be included in this list. The collection of this information is essential to support the community. To ensure secure and reliable storage, the system must be hosted on the cloud or another reliable storage infrastructure. The collection and management of documents are fundamental tools to facilitate the efficient functioning of the REC.

P2: Update of the GIS Territorial Information Model

The second section is dedicated on sharing a geographical representation of the current state of the energy community. A colour-coding system identifies the various communities with individual self-consumption units. Regarding buildings, there are three distinct types of input data essential for defining the territorial information model. The first type is derived from national statistical institutes' censuses across Europe which furnish essential details regarding the age of buildings. The second type of data emanates from regional topographical databases, which include, among other details, information on the buildings' intended use. The final categorisation originates from Building Information Modeling (BIM) systems, incorporating both geometric data and consumption metrics.

The confluence of these databases facilitates the determination of specific characteristics for each building, such as its age class, surface-to-volume (S/V) ratio, number of storeys, and occupant count. Utilizing the GIS system, in conjunction with previously prepared BIM models, smart meters' analyses are conducted to glean precise consumption data. Following the delineation and consumption allocation to building clusters, the data are aggregated into summary tables. Grasping the behavioural dynamics of a community of buildings throughout the year is paramount, as it harbours significant practical ramifications for the management of RECs.

P3: From BIM to Digital Twin

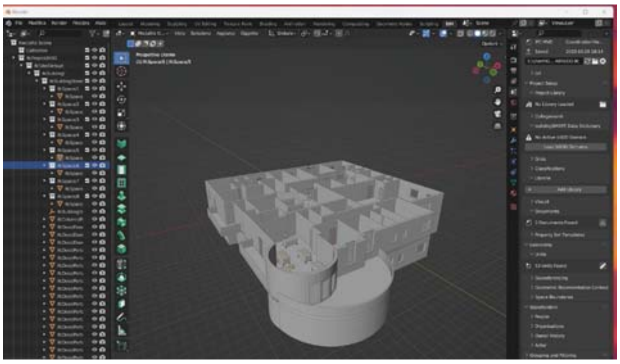

Figure 3 Building Information Model (Simplified Representation), Blender with BIM Add-on

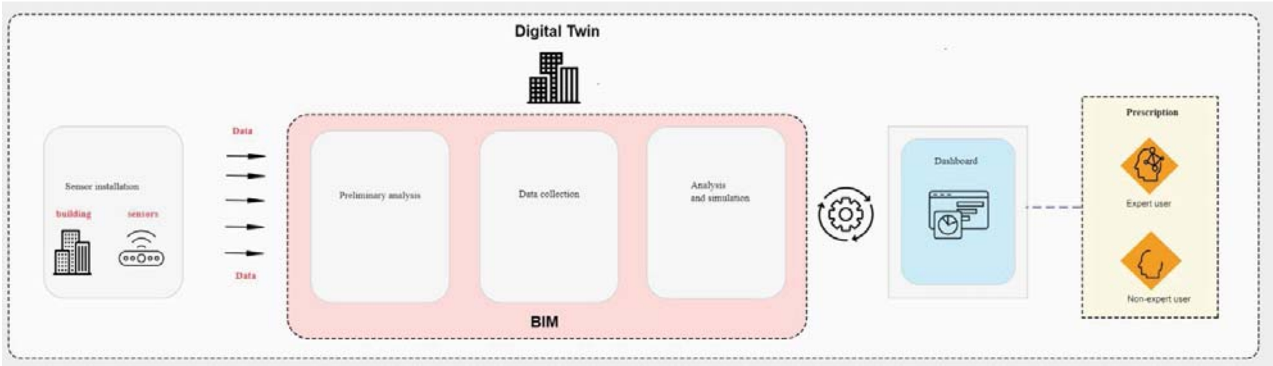

Figure 4 Flowcharts: from BIM to Digital Twin

A digital twin can be conceived in several stages, yet it is most efficacious when established in the initial design phase of self-consumption units; hence, the data amassed can serve as a foundation for managing subsequent stages.

Building Information Modelling (BIM) is the most apt approach for creating the building's digital twin, as it is integrated with parameters functional to the monitoring phase. Furthermore, it is employed as a source for the collection and management of data which is conveyed to the GIS-based territorial system. Although BIM encompasses information about the building and space, it cannot solely provide comprehensive insights into the building's behaviour upon which to base decisions for the community or individual users. To this end, this endeavour integrates the model with information gathered in the initial phase (P1), such as the building's typology, residential units, and the occupancy level of the users. To ensure the correct implementation of the digital twin, it is crucial to associate all necessary documents for the selection and installation of the sensor network with the BIM. Supported by the informative model, we are capable of precisely determining the optimal placement for each individual sensor, thereby enabling the REC to maximise the network's performance and minimise the costs associated with installation.

P4: Integration of Sensors with the BIM

The objective of this phase is to identify the most suitable type of sensors for the construction of a monitoring system, taking into account the requirements and spatial properties of the structures identified in the previous analysis (P3). As part of this step, the techniques for sampling and transmitting data from the control devices are outlined and implemented. The application of smart meters for monitoring energy consumption, along with sensors, facilitates the analysis of usage habits within individual residential units. Utilising data from both external and internal temperatures can enhance the prediction of energy consumption. It is essential to determine the type of monitoring device that best suits the specific needs of the building. This task involves a thorough analysis of performance, application limits, and costs of available technologies. Given that the expenditure required for hardware is one of the most significant concerns for households, this study leans towards a non-intrusive monitoring system with economical sensors that are easily programmable to minimise the cost of the entire system. BIM can provide significant assistance in this phase to define various sensor configurations and compare them as an additional source of information in the building.

In addition to the technical and economic considerations, the security of the data collected and transmitted by these sensors warrants careful attention. The integrity and confidentiality of data within the monitoring system are paramount, necessitating the implementation of robust encryption protocols to safeguard data in transit and at rest. User authentication and access controls are crucial to ensure that only authorized individuals can access sensitive information, thereby preserving the privacy of the residential units involved. The proposed system will also explore the adoption of blockchain technology to provide an immutable ledger for data transactions, enhancing trust and transparency within the community. By incorporating these security measures, the monitoring system not only optimizes energy consumption and operational efficiency but also ensures the protection of sensitive data, aligning with global standards for data privacy and security.

P5: Data Processing Algorithms

In the context of refining the BIM information model, it is essential to elaborate on the development of sophisticated algorithms tailored for the efficient management of data captured by monitoring sensors. The integration of sensor-generated data with BIM-centric applications is achieved through Python scripting. These scripts are not merely facilitative but are at the core of the data processing mechanism, enabling a dynamic and seamless exchange of data between the sensor array and the BIM ecosystem. Such integration is pivotal for real-time data analysis and automated responses within the BIM framework.

Further enhancing the functionality of these scripts, machine learning algorithms are deployed to scrutinize patterns in energy consumption meticulously. These algorithms are adept at sifting through vast datasets to identify anomalies and inefficiencies that may not be immediately apparent. By learning from historical data, they can predict future trends, enabling preemptive actions to optimize energy use and reduce waste. This is particularly beneficial in managing complex systems such as HVAC and in the predictive maintenance of various devices and machinery, where early detection of potential issues can prevent costly downtimes and repairs.

The strategic use of machine learning in this domain not only enhances operational efficiency but also contributes significantly to energy conservation efforts. By analyzing consumption patterns and identifying areas of excessive use, these algorithms can provide actionable insights for energy savings. This leads to the development of targeted recommendations that are both pragmatic and feasible, ensuring sustainable energy utilization across different applications. Moreover, the predictive capabilities of machine learning algorithms extend to forecasting maintenance needs, thereby alerting facility managers and consumers well before potential system failures occur, ensuring reliability and continuous operation.

P6: Dashboard Conceptualization

The dashboard is conceptualized as an interactive tool for the visualization and interpretation of data originating from a centralized storage system. It employs an analytics engine to convert raw data into intelligible reports, charts, and diagrams. The dashboard is customized to cater to diverse user groups, each with varying levels of expertise and access rights.

For novice users, the dashboard is made accessible through a cross-platform mobile application, enabling them to view summary charts that provide an overview of pertinent data related to their self-consumption units, along with a straightforward depiction of REC. Conversely, community managers are provided with a more comprehensive desktop interface for conducting detailed analyses, thereby facilitating informed decision-making processes.

The dashboard architecture is predicated on user privilege levels, thereby dictating the granularity of the presented data. Expert users are afforded extensive visibility, ranging from a holistic view of the energy community to detailed information on self-consumptions units. Novice users, on the other hand, are presented with data relevant to their specific dwelling units, complemented by summary reports that encapsulate key information about their own energy community.

The dashboard is segmented into four main sections, each designed to highlight different aspects of the energy community's data:

General Data: This section employs geographical visualization to outline the energy community's layout, identifying communities and associated substations through a color-coding scheme. An integrated alert mechanism proactively notifies expert users of necessary actions within the RECs framework. Additionally, this section provides direct access to essential REC documentation, such as community statutes and incentive management guidelines.

Costs and Consumption: Acknowledging the significance of financial and consumption metrics in energy resource management, this section provides insights into energy costs, consumption patterns, and future projections. It includes a comprehensive report detailing the energy costs of community-level and individual self-consumption units, breakdowns by energy source, incentive allocations, comparative analyses with similar communities, and future cost and consumption forecasts. Graphical alerts are utilized to signal anomalies, encouraging users to modify their consumption behaviors.

Emissions: This segment enables community members to monitor and assess the REC's contribution to CO2 emission reduction, providing a tangible measure of the community's sustainability efforts.

Self-Consumption Units (Novice User): Tailored for novice users, this section offers an interface that allows users to access summary information from the previous sections specific to them own self-consumption unit, thereby facilitating an intuitive and streamlined user experience.

The dashboard is designed not merely to present data but also to enhance user engagement and awareness of specific aspects of the energy community, thereby enabling users to make informed decisions based on the presented data.

Discussion

The deployment of this dashboard heralds a substantial advancement in the domain of renewable energy management, pertinent to both SCUs and RECs. Its primary objective is to streamline the engagement with sustainable energy practices, rendering them more accessible and intuitive to the end-users.

Within the confines of SCUs, which serve as the nucleus of individual energy production and consumption dynamics, the dashboard emerges as an instrumental tool. It leverages real-time monitoring capabilities to discern patterns of peak energy production, often coinciding with troughs in energy consumption. This synchronicity allows the dashboard to advocate for the scheduling of energy-intensive tasks during periods of abundant renewable energy generation, thereby optimizing the utility of renewable resources.

Expanding its utility to the broader ambit of RECs, the dashboard plays a pivotal role in the nuanced orchestration of energy flows among a consortium of interconnected entities. It aids in the strategic allocation of surplus energy, ensuring its efficacious distribution within the community. This strategic approach to energy management engenders a harmonious balance within the REC, mitigating the challenges posed by the inherent variability of renewable energy sources.

Furthermore, the dashboard transcends its operational utility by incorporating a predictive maintenance feature, crucial for the proactive upkeep of renewable energy systems. By continuously monitoring the health and efficiency of these systems, it preemptively identifies potential issues, thereby safeguarding the continuous optimal performance of energy assets.

In its essence, the dashboard also serves as a decision-support system, facilitating strategic planning for the expansion or augmentation of renewable energy infrastructures within RECs. By amalgamating diverse data streams, including historical energy consumption patterns, current trends, and predictive analytics, it furnishes a holistic view of the energy landscape. This empowers stakeholders with the necessary insights for informed decision-making regarding future investments in renewable energy technologies, thus reinforcing the community's trajectory towards sustainable energy practices.

Conclusions

This work outlines a comprehensive methodological framework designed to bolster the efficacy and operational efficiency of Energy Communities (RECs).

The primary objective of this initiative is to devise an advanced, user-friendly dashboard that offers real-time insights into the performance metrics of RECs, alongside granular data on each individual self-consumption unit. This is particularly focused on providing detailed information regarding costs and consumption patterns. The significance of this contribution lies in its ability to facilitate industry experts in their endeavors to effectively manage and monitor RECs by leveraging sophisticated digital models, cutting-edge geographic information systems, and robust web-based relational databases.

Addressing the pervasive issue of data fragmentation and cognitive heterogeneity in the building sector is paramount. This sector is characterized by the disparate structuring of data across numerous repositories, which inevitably leads to critical information gaps. This fragmentation hinders the seamless management and interpretation of data within energy communities or collective self-consumption systems. Therefore, it is of utmost importance to equip energy community managers with a streamlined, intuitive platform that presents essential information in a clear, accessible manner. This approach is vital for bridging the information divide and enhancing the decision-making process.

In parallel, the promotion of a smart energy system is instrumental in motivating individuals to alter their energy consumption behaviours towards more sustainable and environmentally friendly practices. This necessitates a robust support framework that not only facilitates the digital transformation of services and the automation of processes but also emphasizes the empowerment of REC members. The analysis conducted by the International Energy Agency underscores the critical role of citizen involvement in the successful adoption and optimal utilization of future technologies within the energy sector.

Looking forward, the potential for engaging members and fostering a sense of credibility and trust within local communities cannot be overstated. Hence, future research endeavors will be directed towards exploring the realms of training, knowledge dissemination, and strategic communication activities. These areas are identified as pivotal for the sustained growth and impactful operation of RECs. Such initiatives will aim to enhance the collective understanding of energy management practices, promote widespread adoption of sustainable energy solutions, and ultimately contribute to the overarching goals of energy efficiency and environmental stewardship.

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