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Published in:
Applied Energy

DOI:
10.1016/j.apenergy.2024.123496

Published: 15/08/2024

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Sirviö, K., da Motta Pires, S., Rauma, K., & Evens, C. (2024). Multi-level functional analysis of developing prosumers and energy communities with value creation framework. *Applied Energy*, *368*, Article 123496. https://doi.org/10.1016/j.apenergy.2024.123496

Applied Energy 368 (2024) 123496

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Multi-level functional analysis of developing prosumers and energy communities with value creation framework

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HIGHLIGHTS

- Primary use cases bridge research and engineering, enhancing electricity system innovation.
- Energy communities' growth curve models operational maturity in evolving energy networks.
- Value-sharing framework fosters holistic understanding of energy transition.
- Prosumer and energy community roles are pivotal in socio-technical electricity network dynamics.
- Multidisciplinary approach is the key for defining active end-user energy roles.

ARTICLE INFO

Keywords:
Functional analysis
Power system management
Energy communities
Value creation
Value sharing

ABSTRACT

The evolution of decentralised energy systems, the rise of prosumers and the formation of energy communities (ECs) demand innovative approaches to assess and optimise value creation within these ecosystems. A significant gap exists regarding a unified approach and methods to identify, model, quantify and compare the multifaceted values in the social, economic, technical, and environmental context that ECs contribute to the broader energy system. This research bridges the gap in understanding the associations and value creation within ECs by developing a framework and methodology to understand and analyse the value creation within ECs and focusing on evolving end-user or prosumer involvement and interactions among diverse stakeholders. The research proposes a strategy to evaluate the various values produced by EC based on the action-oriented perspective of developing actors. By focusing on the evolving actions of end-users through different levels of use cases developed in this research, the stakeholders' motivations can be aligned with their activities. By doing so, the value formed within ECs can be explained, and a structured approach to quantifying these values can be established. This action-oriented approach and developed framework provide insights into holistic value creation and serve as a tool for identifying, quantifying, and comparing the values associated with ECs, which incorporate a range of key performance indicators (KPIs) to be developed to facilitate this analysis. The significance of the research extends beyond the theoretical realm, serving as a blueprint or guide for stakeholders to enhance value-creation strategies, guide policy development, and foster sustainable growth in ECs. By applying the developed framework and methodology, stakeholders can model and gain a holistic and deeper understanding of the multidisciplinary dimensions of the energy transition, identify synergies, and identify conflicts to boost collective

Acronyms: ADN, Active Distribution Network; ADNP, Active Distribution Network Planning; aFRR, Automatic Frequency Restoration Reserve; AS, Ancillary Service; BAS, Building Automation System; BSP, Balancing Service Provider; CEC, Citizen Energy Community; CHP, Combined Heat and Power; CM, Congestion Management; DER, Distributed Energy Resources; DR, Demand Response; DSM, Demand-side Management; DSO, Distribution System Operator; EC, Energy Community; EMS, Energy Management System; EV, Electric Vehicle; ES, Energy Storage; EU, European Union; FCR, Frequency Containment Reserve; FFR, Fast Frequency Reserves; FSP, Flexibility Service Provider; HEMS, Home Energy Management System; HL-UC, High-Level Use Case; IES, Integrated Energy System; KPI, Key Performance Indicator; LEC, Local Energy Community; MEAE, Ministry of Economic Affairs and Employment; MG, Microgrid; MGCC, Microgrid Central Controller; mFRR, Manual Frequency Restoration Reserve; PUC, Primary Use Case; PV, Photovoltaic; REC, Renewable Energy Community; RES, Renewable Energy Sources; RET, Renewable Energy Technologies; RR, Replacement Reserves; RTP, Real-time Pricing; SDN, Smart Digital Node; SUC, Secondary Use Case; TDNP, Traditional Distribution Network Planning; TOU, Time-of-use; TSO, Transmission System Operator; TUC, Test Use Case; UC, Use Case; UML, Unified Modelling Language; VPP, Virtual Power Plant.

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https://doi.org/10.1016/j.apenergy.2024.123496
Received 9 December 2023; Received in revised form 10 April 2024; Accepted 14 May 2024
Available online 25 May 2024

benefits. Through this approach, a deeper understanding of the energy transitions through ECs in a multidisciplinary context can be gained, and a roadmap can be created.

1. Introduction

This section presents a comprehensive overview of the evolving landscape of electricity distribution networks, focusing on the European Union (EU) and as a study case in the Finnish context. The importance of understanding the socio-technical dynamics and the role of active end-users, such as prosumers and energy communities (ECs), in this transformation is discovered and has become increasingly significant. This transformation, rooted in the socio-technical and other multidisciplinary dynamics of energy systems, invites a closer examination of how end users, often ordinary people with limited understanding of the intricacies of energy systems and billing, can become integral participants in this shift. The lack of consensus on stakeholders' definitions and value expectations and the need for multidisciplinary approaches to address these issues are highlighted. By addressing these concerns, we aim to create a common understanding among stakeholders, facilitating the development of energy communities that are accessible, transparent, and beneficial for all participants. This study outlines a value-sharing framework and models designed to evaluate future network operations, functionalities, and stakeholder value through actions-oriented end-user analysis. Its objective is to create a common understanding among stakeholders, facilitating the formulation and development of evolving operational scenarios and a multi-objective value-sharing framework. The outlined value-sharing framework (i) identifies the stakeholders interacting with evolving end-users and (ii) models the end-users' value-creation activities/actions. Further on, value-sharing mechanisms, other stakeholders' benefits and definitions of KPIs are left for future studies. The multi-objective perspective relates to the multi-level approach of studying evolving end-user actions and how this could be used for further development of the value-sharing framework, like defining KPIs. In addition, the value-sharing framework presented in this work enhances a holistic understanding of the energy transition.

1.1. Energy transition scenarios and stakeholder dynamics

The European Technology & Innovation Platform of Smart Networks for Energy Transition (ETIP-SNET) has published EU-level scenarios for the vision of an Integrated Energy System (IES) [1] in 2050 and the functionalities to be implemented by 2030 in critical research areas [2]. In line with those scenarios, the national-level Finnish energy visions [2–4] identify the key enablers being (i) IES, (ii) distributed energy resources (DER) implementation and utilisation for systems flexibility via enhanced markets, (iii) active customer in the central position, (iv) interconnection between different actors, and (v) the active distribution networks (ADNs) and microgrids. Many scientific publications present scenarios for future electricity distribution networks, but concrete pathways to reach the visions are yet to be shaped. For example, [5–7] presents a roadmap from today's distribution networks to reach the visions [2–4] in four phases.

The energy transition occurs in various systemic contexts: socio-ecological, socio-economic, socio-technical, and action-oriented [8]. So far, the most significant interest has been in the development of Smart Grids' technical definitions and concepts, and the regulation and business models are developing simultaneously. Feasibility studies of the novel active end-user concepts have been conducted primarily based on techno-economic considerations [9–11], lacking socio-technical perspective and actor interaction [5,7]. As the evolution of electricity end-users plays a central role in the development of distribution networks, it is vital to explore socio-technical dynamics, such as in [12], and agendas for transition assessing the value of ECs, such as in [13]. Furthermore, there is a need for improvement in the definitions and methodologies describing power system operations by various stakeholders. This is essential because the descriptions of concepts and objectives of operation vary depending on the stakeholders' interests and their level of operation. The significance of addressing this issue comprehensively, in a multidisciplinary manner over different domains, has been raised [14–16] for creating a holistic understanding and, thus, a value-sharing framework. Generally, the enhanced concepts should provide different stakeholders with economic, technical, societal, and environmental benefits.

1.2. Architectural evolution and methodological frameworks and developments in active distribution networks

The analysis of the architecture and functionalities for future active distribution networks (ADNs) have been outlined in [17–19]. Increasing flexibility in distribution network operation affects network planning, changing traditional distribution network planning towards active distribution network planning, as discussed in [7]. The planning criteria relate to the technical constraints (voltage levels, current limits, reliability, interconnection of components) and the techno-economic planning objectives (minimising the costs of capital investments, maintenance, power losses and the cost of undelivered energy). In active distribution network planning, investments and DER problems are considered together, bringing new sets of decision variables and constraints. Active distribution network planning integrates multi-energy and active management strategies into traditional distribution network planning due to the versatile use of DERs. DER control planning can achieve significant investment cost savings when compared to the passive "fit and forget" method. DER control operations can be active and reactive power control of the DG units, online network reconfiguration, demand response (DR), generation curtailment and energy storage control. Integrating active end-user behaviour in control operations palette entails a potential to enhance network flexibility. For this reason, considering multiple control actions and rules holds significant interest in active distribution network planning.

Different stakeholders will operate in the future electric distribution networks, such as prosumers, ECs, aggregators, distribution system operators (DSOs) and retailers. The stakeholders have different expectations of benefits, as presented, for example, in [20], so different value-sharing frameworks are to be developed concerning, for example,

- how benefits and costs are shared among the EC members,
- how the DSO concern the equitable allocation of costs and revenues associated with network maintenance and upgrades,
- how retailers involve strategies for fair pricing and services.

Moreover, value-sharing over an ecosystem can be understood as creating shared value for pursuing financial success in a way that yields societal or environmental benefits. Even though active end-users, prosumers, or ECs play a central role in energy transition, there is no consensus in the academic literature and public debate on their definitions, aims of operation or value expectations, and contributions [15,21–27] in a multidisciplinary context. ECs differ in their functions, business models, maturity level, geographical scope of operations, the number of members and their characteristics, governance, and the adopted legal form. Therefore, it isn't easy to provide a straightforward and entirely satisfactory definition of what they are [28]. Thus, depending on the context or purpose, some classifications are defined and can be more appropriate than others [29,30]. Definitions with a high level of abstraction make it challenging to identify the concrete implications of different ECs or vice versa; a pilot demonstrates and can define only a particular application and its case studies. Understanding the differentiation of various types of ECs, their evolution phases, functions, operating and business models [31] are crucial. This comprehension enables an insight into their interactions with the power and energy system [23], the implications of their development on existing organizational structures and regulation, and the influence they apply on policymakers and regulators. These aspects are critical elements within the field of EC research methodologies [32] and development.

Creating a comprehensive understanding of active end-users in the context of the socio-technical energy transition is vital. Studying the evolution of the end-users from consumers to prosumers or and potentially further, analysing their changing activities, and exploring the influence of policy on this evolution is central. Recognizing the importance of prosumers as innovators and collaborators in the energy ecosystem is key. Different disciplines approach the study of prosumers in different ways: technology research examines their technical and commercial impact on the electricity grid, while social sciences focus on their acceptance of renewable energy technologies. Innovation studies look at end-users' roles in adopting or co-creating renewable energy technologies. A holistic research approach, combining quantitative methods and integrating both large-scale and local perspectives, is essential to fully understand prosumerism in the energy transition. [33]

The socio-technical multilevel approach and framework are presented in [7,12,33,34] to describe the dynamics of prosumerism or EC development. Drivers for emerging and succeeding an EC include various factors such as socio-economic, energy policy, individual projects, and actors' characteristics [35]. The heterogeneity of EC shows apparent differences in the members' unique motivations and levels of engagement [36]. [37]

Based on the previous, a holistic behavioural or operational description of the developing distribution networks with the evolving end-users and with a value-sharing framework and models needs to take shape. Future network operations, functionalities, and incurred value for different stakeholders must be analysed in a multidisciplinary manner to create a shared understanding between the stakeholders. The definitions of actors, their use, and their relations need to be clarified. Frameworks and models should be developed to understand associations, interactions, and value sharing between the actors and shareholders and over the ecosystem. Consequently, this paper aims to demonstrate the development of evolving operational scenarios focusing on end-users, with the objectives being (i) define the related key actors and their operations, (ii) study different levels of operational scenarios, (iii) map relevant value drivers, and (iv) conduct an analysis. As a result, a synthesis, a multi-objective value-sharing framework, is introduced.

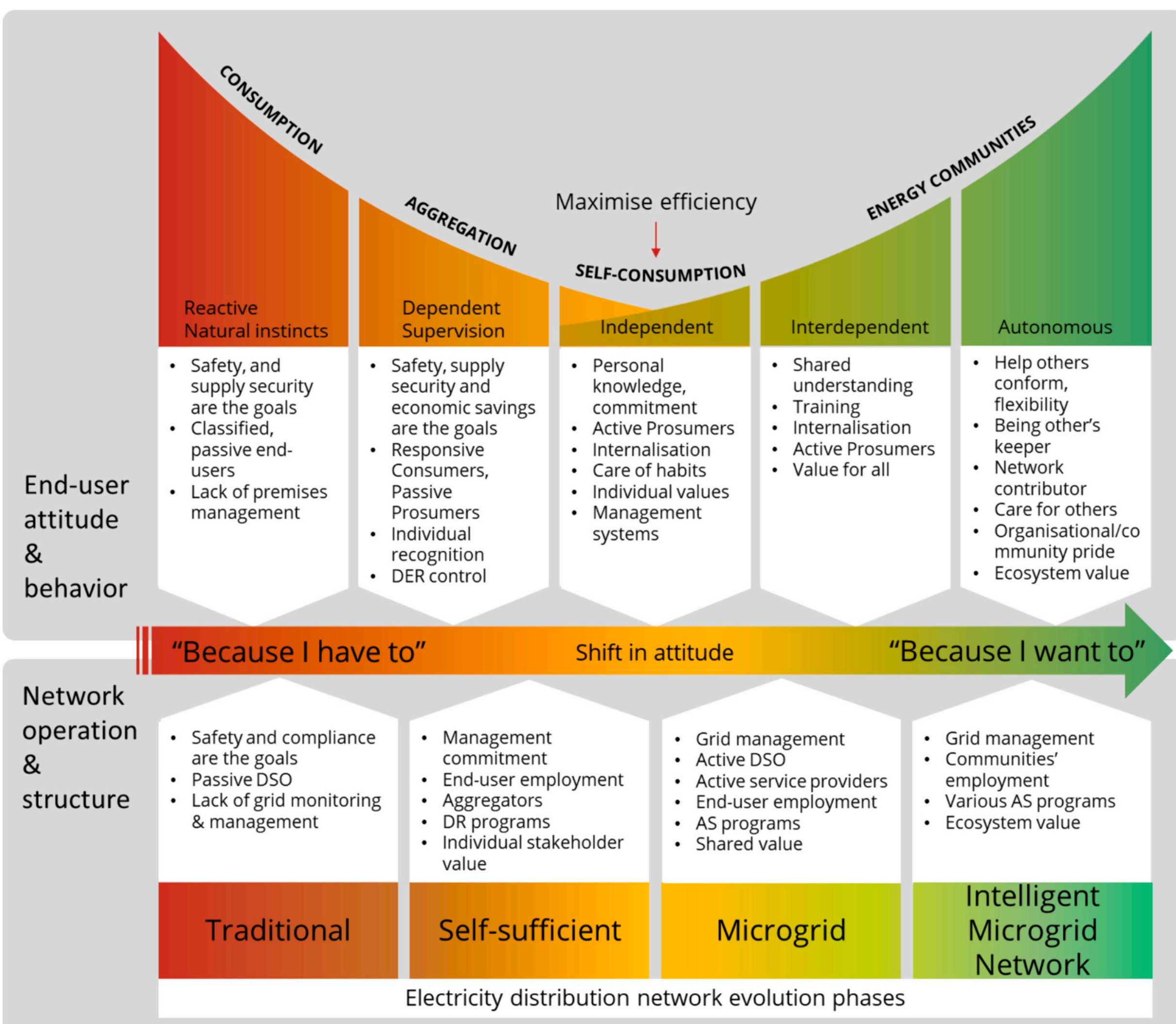

Fig. 1. Energy community growth curve – maturity of operation models and shift in values, beliefs and attitudes.

1.3. Methodology for functional analysis and organisation of the paper

In the evolving landscape of ECs, understanding their growth and impact within the energy ecosystem demands a comprehensive approach encompassing the multifaceted nature of grid structure, operation, behaviours, and value creation. This research endeavours to unravel the complex dynamics within ECs, proposing a novel examination of their development trajectory. Central to our inquiry is the elucidation of ECs' growth curve. This critical analysis integrates the core elements of grid infrastructure and operational practices with the behavioural patterns of its constituents and the resultant value creation. Fig. 1 serves as a pivotal methodological illustration of this growth curve, drawing together the components into a cohesive narrative. A recurring theme in our investigation is the challenge of reconciling perceived versus actual roles within ECs—where end-users may oscillate between states of independence and dependence, and identities may shift along the spectrum from consumers to prosumers. Such distinctions are crucial for conceptual clarity and practical implications in terms of generation and consumption volumes, as detailed in Chapter 2.3. This dichotomy underscores the necessity for developing multi-criteria Key Performance Indicators (KPIs) that effectively measure the current state and evolution of ECs within the broader energy ecosystem.

Laying this groundwork in the introduction sets the stage for a comprehensive exploration of ECs, emphasizing the need for nuanced metrics that reflect the complex realities of EC participation and contribution. This approach enriches the understanding of EC growth patterns. It informs the development of strategies and policies to foster robust, sustainable, equitable and just ECs, bringing significant value to all its involved stakeholders.

Further, this research conducts functional analysis through the use-case (UC) modelling and analysis method to describe and study this previously described multifaceted problem. UCs are commonly discussed in broad terms when describing a specific case study. However, UCs can be developed for several purposes and describe various levels of functionalities [38]. The exemplary usage of different levels of UCs is presented in [18]. Further, different levels of UCs can be mapped into the Smart Grid Architecture Model (SGAM) [38–40], as presented in [41]. Next, UC analysis is a common technique for identifying the requirements associated with software design, the primary goals of which are to design the system, communicate system behaviour, and define all externally observable behaviours. Another target for a UC analysis is to communicate clearly (i) system requirements, (ii) how the system is to be used, (iii) the roles the user plays in the system, (iv) what the system does in response to the user stimulus, (v) what the user receives from the system, and (vi) what value the customer or user will receive from the system. Now, this method is applied to a multidisciplinary scope in this paper. The method is based on the definitions in [38] and the method developed in [18] to analyse the relevant and selected levels of UCs found in the literature and the DisMa project [42]. This research uses the unified modelling language (UML) method and Enterprise Architect software to manage the UCs, the actors, and to create diagrams for analysing the UCs.

In the research, the UML method is utilised for analysing UCs primarily through its capability to visually represent the roles of different stakeholders and actors and their interactions within the EC ecosystem. The approach is methodical, starting with a description and analysis of actors, who may range from systems, devices, and individuals to entire organizations vested in the operation and benefits of the EC. These actors, including end-users, DSOs, Electricity Retailers (ERs), Service Providers, and Prosumers, are classified based on their roles and potential impact on the EC's operation and value creation.

The UML method enables the researchers to create detailed class diagrams that not only categorize actors by their attributes and operations but also depict their relationships, including inheritance and associations with other actors. This visualization helps understand how various actors interact within the EC, facilitating a shared understanding among stakeholders and highlighting the dynamics of these interactions.

The research further delves into the end-user categorisation, distinguishing between consumers, responsive consumers, and prosumers and articulating the evolving role of each in the context of energy consumption and production. These distinctions are crucial for developing multi-criteria KPIs that can accurately reflect the state and performance of ECs within the broader energy ecosystem.

Moreover, the study explores functional analyses of prosumers and ECs by developing High-Level Use Cases (HL-UCs) and Primary Use Cases (PUCs) that describe the operational functionalities and potential value contributions of different actor types to the EC. This includes detailed scenarios where ECs provide flexibility, support ancillary services (AS), and contribute to power balance and stability, showcasing the UML's utility in mapping complex operational concepts and interactions.

The UML-based analysis of UCs in the research thus serves multiple purposes:

- Clarification of roles and interactions: It provides a clear depiction of the roles of various actors within the EC, their attributes, operations, and how they interact with each other and the system at large.
- Identification of functionalities and value contributions: By mapping out UCs related to the operation of prosumers and ECs, the UML method helps understand the functionalities these actors can perform and the potential value they bring to the energy ecosystem.
- Development of multi-criteria KPIs: The detailed understanding gained from UML diagrams and UC analysis aids in creating KPIs that can measure the performance and impact of ECs from multiple dimensions, accommodating both quantitative and qualitative aspects.
- Facilitation of stakeholder communication: The visual and structured nature of UML diagrams can bridge understanding among diverse stakeholders, making the complex dynamics of ECs more accessible and facilitating collaborative efforts.

Overall, the UML method's application in this research provides a foundational framework for systematically analysing and optimising the operation and value creation of ECs, highlighting the importance of multi-stakeholder engagement and multi-criteria evaluation in the evolving energy landscape.

Section 2 explains the definitions used in this paper and the operating environment. Actors are described and analysed in Section 3, including regulatory, economic, and technical considerations. Section 4 presents the functionalities of prosumers and ECs. Finally, multi-objective considerations and a value-sharing framework are introduced in Section 5. Section 6 concludes and discusses the outputs of this research.

1.4. Contribution, novelty and scope

This research paper delves into the transition dynamics within electricity distribution networks in the EU region, with a particular focus on the Finnish context. It aims to elucidate the role of active end-users, ranging from individual prosumers to ECs, in the energy transition. This study addresses the multidisciplinary dynamics of energy systems, highlighting action-oriented perspective and its opportunities and challenges, in integrating end-users into these systems. Through a comprehensive overview, the paper introduces a value-sharing framework and models designed to evaluate future network operations, stakeholder values, and the functionalities required for a sustainable and participatory energy ecosystem.

This paper introduces several notable innovations in the study of ECs and electricity distribution networks:

- Value-sharing framework: A pioneering approach to conceptualising and evaluating the interaction between evolving end-users and other stakeholders within the energy system, facilitating the identification

and modelling of value-creation activities across multidisciplinary dynamics.
- Multi-objective evaluation models: Innovative models that integrate multidisciplinary perspectives for assessing future network operations and stakeholder values, advancing the understanding of energy transitions beyond techno-economic paradigms.
- Action-oriented end-user analysis: A novel methodological approach that emphasises the roles and activities of end-users in shaping the energy transition, offering insights into how ordinary individuals and communities can become active participants in energy systems.

By addressing these innovations, the paper aims to contribute significantly to the literature on energy transitions, providing a foundational framework for researchers, policymakers, and practitioners aiming to foster sustainable and inclusive energy ecosystems.

While the paper presents a robust framework for understanding and facilitating the development of ECs, it acknowledges several limitations:

- The focus is primarily on the Finnish context, which may limit the direct applicability of findings to other regulatory or cultural settings within the EU.
- The multi-objective perspective, while comprehensive, is preliminary and calls for further empirical validation and refinement through practical implementation and case studies.
- Value-sharing mechanisms, benefits to other stakeholders, and definitions of KPIs are identified as areas for future research, indicating that the current scope does not fully address these critical components of EC integration.

2. Definitions and Operating Environments of Energy Communities

ECs are an emerging actor type in energy systems that aims to promote small-scale renewable generation and empower citizens to become active end-users or prosumers. Active consumer-producer and EC types are defined in this paper based on EU and national legislation. General definitions are given in Regulation (EU) 2019/943 [43] and Regulation (EU) 2022/869 [44] and apply in this research. Electricity Directive (EU) 2019/944 [45] sets the framework for implementing citizen ECs (CECs) in member countries. Further, the Renewable Energy Directive (RED II), that is, Directive (EU) 2018/2001 [46], deals with renewable ECs (RECs). In 2018, based on the electricity market directive and the reports [3,4] issued by the Finnish Smart Grid working group, the Ministry of Economic Affairs and Employment (MEAE) of Finland prepared the necessary changes in regulations to implement the EC within buildings and put into effect by the Government Decree (767/2021) [47]. The MEAE appointed a working group in 2022 to determine the possible further development needs of the regulation to expand the definition of EC and the utilisation of separate lines [48].

2.1. Definitions according to EU legislation

EU legislation defines four concepts related to prosumption: renewable self-consumers and RECs [46], and CECs and active customers [45]. These definitions are not contradictory and overlap with the prosumer description [49], but four typical prosumer concepts can be formed within individual households, collective prosumers in one building, small and medium-sized enterprises and public institutions, ECs and cooperatives [50]. The following definitions related to the prosumer, or the system end-user apply to this research:

- *Grid user* [51]
- *System user* [45]
- *Customer* [45]
- *Final customer* [45]
- *Household customer* [45]
- *Non-household customer* [45]
- *Active customer* [45]
- *Citizen energy community* [45]
- *Renewables Self-consumer* [46]
- *Jointly Acting Renewables Self-consumers* [46]
- *Renewable Energy Community (REC)* [46]
- *Electricity Prosumers* [52]
- *RES Prosumer* [50]

This research understands the differences as follows:

A CEC is a community-driven initiative where citizens actively participate in energy production, consumption, and management. CECs are characterized by their focus on local energy production, often utilizing renewable energy sources (RES). The members of a CEC collaborate to develop and operate renewable energy projects, such as solar installations, within their community. The primary goal is to promote local energy self-sufficiency, sustainability, and community involvement in the energy transition. A REC is similar to a CEC but emphasises using RES. RECs can involve various stakeholders, including citizens, local businesses, institutions, and municipalities, who collaborate to develop and implement renewable energy projects within their community.

Renewables Self-consumers are individuals or entities that generate renewable energy for their consumption. They install renewable energy systems, such as solar panels or wind turbines, on their properties to meet their energy needs, reducing their reliance on the grid and often resulting in lower energy bills. Any excess energy produced can be fed back into the grid or stored. Jointly Acting Renewables self-consumers refers to a collective of self-consumers collaborating to generate and consume renewable energy. This collaboration allows them to pool resources, share installation and maintenance costs, and optimise the use of RES. It can involve neighbouring households, communities, or commercial associations. By working together, they can achieve greater energy self-sufficiency and promote the efficient utilisation of RES.

2.2. Definitions according to National Legislation

MEAE report [48] presents the concrete actions decentralised ECs can take in Finland to promote active participation in the electricity market. The CEC and the REC have been implemented regarding electricity by the Government Decree 767/2021 [47], in which 1 § 3 defines the local EC (LEC) covering the property's internal EC. Further on, the ECs' business models (socio- or regulatory-economic) can be classified into the property's internal EC, EC crossing property boundaries, closed distribution network (CDN), and virtual EC based on the following four elements:

1. public grid usage: grid-owning or virtual ECs,
2. locality: local or distributed virtual EC (EU directives define ECs as CECs and RECs, which the latter considers local),
3. boundaries: inside or crossing property boundaries (clarifies the differences within grid-owning ECs) and
4. the contract type: single or multiple contracts with DSO and retailers (refer to an EC formed behind or in front of the meter) [53].

Fig. 2 illustrates different EC categories along with the physical grid structure. The categories are described in more detail in the following paragraphs.

2.2.1. The Property's internal energy community

The property's internal EC resources are limited to the property or a corresponding group of properties. It could be, for example, an apartment building with solar panels installed and the electricity they produce is shared among the residents. The ECs within the property include the LECs realised with credit calculation (in-front-of-the-meter ECs) and the back-metered (behind-the-meter ECs). An LEC within the property is located behind one connection, a legal entity whose metering has been carried out by credit calculation, according to [47]. [48]

In-front-of-the-meter EC refers to a model that allows *collective self-consumption* (jointly acting renewables self-consumers) [54] in a single property, such as an apartment complex, campus, shopping centre, or office building, to use and share their renewable energy generation and storage collectively. The model involves informing the DSO about how

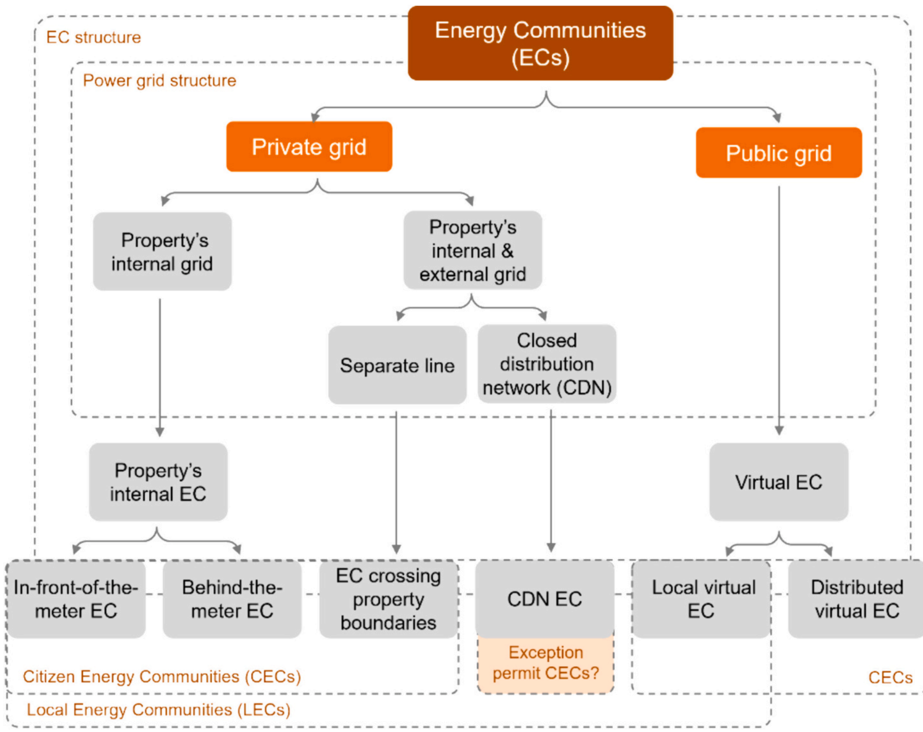

Fig. 2. Classification of energy communities. Adapted from [48].

the energy production and storage outputs are divided among the collective members. The DSO and the retailer(s) handle the billing, while the DSO plays a crucial role in managing the data. Customers can participate in the collective while maintaining their existing DSO contracts and retain the right to switch retailers. [48,53]

The main benefit of self-consumption is often cost savings on electricity taxes and network tariffs. The DSO is responsible for measuring energy usage across the property in a credit accounting system. With an amendment to the Metering Decree (1133/2020) MEAE [55], electricity produced within the collective can be subtracted from the overall energy usage of the property based on distribution shares, thereby eliminating the need to pay distribution network fees or taxes for self-produced energy that is consumed within the property. The specific refund calculation principles are defined in regulations and carried out by Finland's balance responsible party, Fingrid, and available in Fingrid's Datahub [56], ready to establish EC per the Government Decree [57]. [48]

Behind-the-meter EC is a property's internal EC that is responsible for its members' electricity metering and invoicing of production and storage. The property has one DSO-metered connection to the distribution network. The EC has one network service contract with the network company and an electricity contract with the retailer. Back-metered ECs are regulated in the Electricity Market Act (588/2013) [58]. [48]

Since the end-users in a Behind-the-meter EC must not have DSO's smart meters, they can have sub-meters provided by a service company. The EC organises customers' billing according to a chosen allocation method. As end-users give up their retail contracts, this model contradicts the customers' freedom of choice. Yet, it is a used model in rental agreements, for example. On the other hand, an EC (like a housing company) can benefit when negotiating their shared electricity contract with a retailer. [53]

2.2.2. *Energy community crossing property boundaries*

The business models of this EC are similar to previous EC models, and the only difference is that the generation units exist on another property, in which case possible security issues have to be managed [48,53]. This scenario could involve solar panels installed on a separate plot of land, with electricity generated for consumption in a different property. For example, in a situation where the solar panels are connected via a separate line to the point of use in an apartment building located on one property, and the electricity in the apartment building is then distributed using a credit calculation (LEC) among the residents of the apartment building, i.e., different places of electricity use. The difference is whether a separate production unit is connected via a separate line to a separate electricity use point, which is a single point of consumption (e.g., a single-family house does not form an EC) or whether a separate production unit is connected to a separate electricity use point, from which it is further distributed among the EC using a credit calculation (like a local EC in an apartment building). The separate line should not create a ring connection with the power grid or between power grids that connect electricity usage locations. [48]

2.2.3. *Closed distribution network*

Grid owing ECs or CDN-ECs are communities that do not use public grid. Residential ECs with their own distribution networks are rare. Islands and other remote locations have such systems, as well as some municipalities [53]. For example, in Switzerland (a non-EU member), a neighbourhood (houses next to each other with no public land between them, behind one point of common coupling) can form a consortium that can operate behind one DSO meter [54].

In EU Directive 2019/944, member states have been allowed to use CDN in ECs, which means that CDNs can be CECs if they meet both criteria of CDN and CECs. The construction of CDNs requires a permit in Finland, which the Energy Agency issues. According to current Finnish legislation, permits for CDNs can only be granted to geographically limited industrial or business areas involved in electricity network operations or providers of shared services. Applicants whose electricity network supplies electricity to consumers are generally not eligible for such permits, except in cases where consumers have specific connections with the applicant, such as employment-based or similar relationships. The regulation of CDNs will be incorporated into the national regulations based on the electricity market directive. For example, the

LEMENE project [59] has applied for a license for a CDN. [48]

2.2.4. Virtual energy community

Virtual ECs are not restricted to a single property or group of properties and can be categorized into local virtual ECs and distributed virtual ECs. Under current Finnish legislation, the members of virtual ECs are treated as regular consumption or production customers by network companies and other participants in the electricity market. They are accounted for in the balance sheet accordingly. It's important to note that the members of virtual ECs do not own the distribution network, and electricity distribution occurs through the public distribution network. The network company is responsible for metering. [48]

A local virtual EC, or a locally distributed EC, is a community not located in the area of one property but in the area of one distribution network. The local virtual EC uses the local distribution network behind a point in the distribution network, such as a distribution transformer where all EC members are located. [48]

The members of the *distributed or decentralised virtual EC* can be located anywhere in the electricity market's offer area, in Finland's case, anywhere in Finland using the public electricity network for electricity distribution [48]. In this kind of EC, distribution fees and taxes are paid even if the production is small-scale [48]. Yet, it is possible to create trading between entities via a digital platform provided by an energy retailer. Finland plans a model enabling energy consumption netting from a distant production plant [54]. This kind of EC can also be a virtual power plant (VPP) aggregating production and demand-side resources and participating in different energy and flexibility markets. Distributed virtual EC cannot offer local grid services because it comprises distributed customers. [53]

2.3. Prosumerism

Factors like legal status, size, energy sources, and grid connection categorize prosumers. They span residential, commercial, and industrial sectors, forming public and private communities. Legal concerns and diverse roles prompt varying management across the EU. Prosumers engage with various energy vectors, on/off-grid, technology-driven (like electric vehicles (EVs), energy storage (ES), renewable energy technologies, smart technologies, energy management, or smart buildings) or socially focused (energy sharing/trading) solutions. They are valued as ecosystem co-creators, participating in innovation through feedback, testing, and joint development, including piloting and living labs. Prosumers can form communities that can also be called prosumers [33]. [60]

The research [61] introduces energy presumptions in decentralised energy systems from a socio-economic stance, addressing the ambiguity in distinguishing energy consumers, prosumers, and electricity/thermal energy producers. Prosumerism components include time horizon, balancing energy demand and production, and organizational ownership. Economic dimensions yield Consumer, Self-consumer, Producer, and Prosumer categories. Prosumers are individual ($>$ 50% ownership) or collective ($\leq$ 50% ownership), e.g., Individual Self-consumers control entities with predominant energy production, while remaining shareholders are collective self-consumers. A shareholder consuming up to 50% of a collective entity's energy is a Collective Self-consumer.

Creating ECs brings challenges like (i) community engagement and participation due to diverse needs, interests, and knowledge levels about energy systems, (ii) financing and economic viability due to investments in infrastructure, (iii) regulatory and legal barriers due to regulatory and legal frameworks designed for centralised energy systems, (iv) technical complexity in integrating DER, (v) grid integration and energy market interactions in coordinating energy flows and value creation mechanisms, (vi) scalability and replication due to locality, (vii) data management and privacy due to vast energy consumption, production, and distribution data. Addressing these challenges requires a collaborative effort involving policymakers, regulators, community members, energy industry stakeholders, and technological innovators. It is crucial to have supportive policies, adequate financial mechanisms, technological advancements, and community engagement strategies to foster the successful creation of ECs.

Although these previously presented definitions and classifications of ECs and prosumers, or prosumerism, and their operating environment and challenges in EC development describe the phenomenon and its diversity, more understanding of how these shareholders, actors, or entities evolve in the economic, societal, and technical dynamics is needed. Additionally, the evolution of other key actors, such as energy utilities, significantly impacts prosumerism development, particularly in the growing importance of energy equity. [62]. Behavioural and evolutionary descriptions at different levels of a system's operation can describe the socio-technical dynamics of the entire system. Typically, UC studies describing a system's operation and dynamics between different actors have been considered by technical or techno-economic aspects. This research combines social (regulatory), economic and technological elements focusing on the end-user functionalities to illustrate the dynamics in which an EC evolves. As a result, possible mixes and pathways for prosumerism can be identified.

2.4. Market services reference framework and operating environment

The electricity market consists of day-ahead, intraday, and real-time, i.e., balancing marketplaces, which can be considered time windows of physical electricity trading. The basis of the power exchange, the primary marketplace, is the day-ahead spot market. Next, the intraday aftermarket or correction market of spot trading aims to trade as close as possible to an hour before the actual electricity delivery. Further, automatic and manual reserves are traded in balancing markets to maintain the power balance during operating hours. Both up-regulation (increase in generation, decrease in consumption) and down-regulation (decrease in generation, increase in consumption) are possible for the balancing energy markets. Fig. 3 presents the time association of frequency regulation and operating reserves [7]. [5]

Ancillary services (ASs) supporting power system operation are presented in Table 1 by market domains tied to the purpose of service provision and remarked if included in this research considerations.

3. Description and analysis of actors

Actors can be systems, devices, programs, persons operating the system, or stakeholders expecting benefits. Actors' operations can change the system state. In this research, the key actors are selected as the stakeholders considered in the developed value-sharing framework. To illustrate the different types of system users, a diagram of the classified actors was developed, presented in Appendix 1, and described in the following paragraphs. The class diagram presents the actors' attributes and the operations that they provide. Moreover, the diagram illustrates how the different actors inherit and how they are associated with other actors. Though actors are typically classified, for example, based on business models or technical implementation, the actors' roles are interesting in the context of functional analysis in this research. Further, a shared understanding can be created among stakeholders by making the actor's interactions visible.

3.1. End-user

The end-user, often defined as the end-customer, plays a vital role in the power system transition. Visions of the future power system put the "active customer" in the centre, which can be from household, commercial, or industrial sectors. This research focuses on household or small commercial end-users.

3.1.1. Consumer

Most end-users in the present electricity distribution system can be

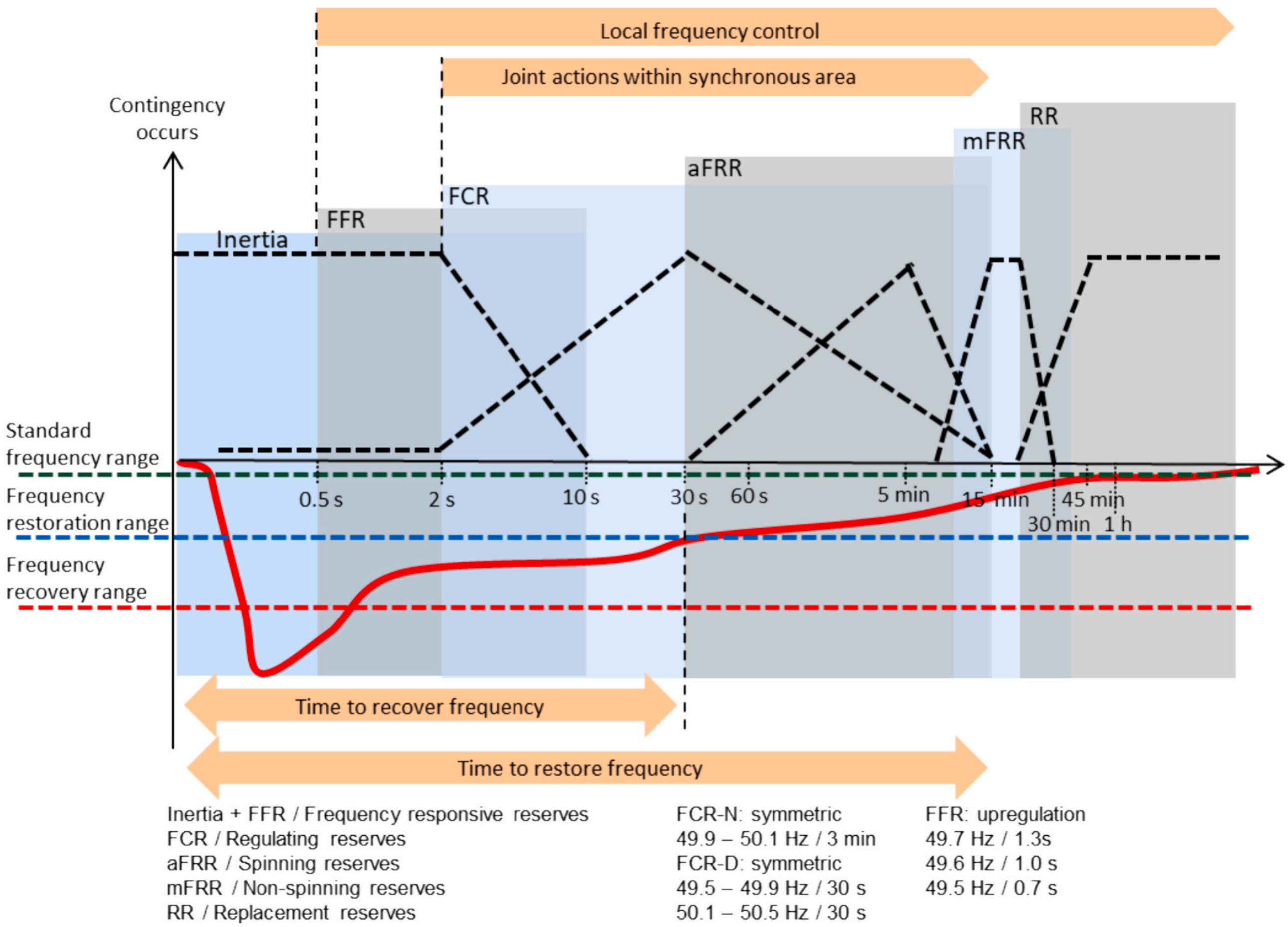

Fig. 3. Time association of frequency regulation and operating reserves. [7].

classified as Consumers. *Consumers* have their value of the connection capacity, tariff type, demand profile and the number of passive loads. A consumer can consume electricity for lighting, heating, cooling, powering electronic devices, operating machinery, etc. The main actors a consumer interacts with are a DSO, an energy retailer, and the property grid. As the distributed generation boom emerges, consumers start to evolve. Exchange value becomes essential, as well as social and ethical issues. [12]

3.1.2. *Responsive consumer*

When a consumer has assigned some controllable but passive loads to DR markets and started using a building automation system (BAS) and home energy management system (HEMS), we can define the consumer's new role as a responsible consumer. *Responsive Consumers* can offer flexibility to join the DR markets through an aggregator. Responsive Consumers make individual choices regarding price, product attributes, services and values. Aggregated loads from Responsive Consumers can comprise, e.g., a VPP.

3.1.3. *Prosumer*

Prosumer differs from the Responsive Consumer profile by producing electricity with their generation units and storage and the possibility of selling the excess electricity to the markets. A prosumer can be either passive or active type concerning the electricity network. In this context, *Passive Prosumers* can be described as Renewables Self-consumers as well as Jointly Acting Renewables Self-consumers, presenting a community of passive prosumers. On the contrary, *Active Prosumers* are interested in interacting with other actors or stakeholders to benefit, for example, their energy economy, which shows up in various controls and contracts. It can be concluded that a prosumer [52] can represent a renewables self-consumer [46], a jointly acting renewable self-consumer [46], a CEC [64], a LEC [47] or a REC [46].

In this research, private house prosumers are considered to be included in Property's Internal EC or Renewables Self-consumers. Housing company prosumers are considered the Property's Internal Energy Community, CECs and Jointly Acting Renewables Self-consumers. Microgrid prosumers are considered CDN-ECs and RECs. A virtual EC and a LEC can comprise an individual prosumer, collective prosumers or self-consumers. EC prosumers can also buy services from an aggregator or other business.

3.2. *Distribution system operator*

The *DSO* plays a crucial role in EC development, so the dynamics in end-user and DSO development in the socio-technical dynamics and complementary business models [65] are vital to comprehend. The evolution of DSOs with ECs reflects a shift towards more decentralised, sustainable, and participatory energy generation and consumption models. For example, a new actor role, Microgrid operator, is emerging. The evolution proceeds in RES and ES solutions integration, smart grid technologies adoption, DR programs implementation, microgrids, digitalisation and data-analytics, regulatory changes, end-user engagement and carbon-neutral goals.

3.3. *Electricity retailer*

The *electricity retailer's (ER's)* core business is to sell electricity to its customers and make a profit, and it is essential in developing the DR system. There are different types of electricity contracts for electricity customers, for example, a fixed price or an agreement based on hourly

Table 1
Services implemented in the different European Power Systems. Adapted from [63].

Market Domain	Market Sub-domain	Service	This Research Apply
Balancing markets	Standard frequency response services	Frequency Containment Reserve (FCR)	x
		Automatic Frequency Restoration Reserve (aFRR)	
		Manual Frequency Restoration Reserve (mFRR)	
		Replacement Reserves (RR)	
		Fast Frequency Reserves (FFR)	
	New/emerging frequency response services	Ramp control	
		Smoothed production	
		Balance responsible party's portfolio balancing	
Congestion management	Intra-zonal	Operational	x
		Short-term planning	x
		Long term planning	x
	Cross-border	Redispatch, and Counter trading	
Non-frequency ancillary services	Reactive power/ voltage control	Obligatory reactive power service (ORPS)	
		Enhanced reactive power service (ERPS)	x
		Fault-ride through (FRT) capability	
		Local Grid Balancing	
	System restoration	Black Start	
		Islanding Operation	
		Damping of power system oscillations	
Adequacy	Capacity remuneration mechanism	Strategic reserve	

pricing. Household customers can have variable electricity prices based directly on the day-ahead market price, enabling them to participate in DR by shifting consumption to cheaper hours. An ER has to estimate the hourly consumption of its customers to purchase the right amount of energy from the power exchange. When the estimate is too low (or too high) compared to the realised consumption, the ER must buy the difference (or sell the surplus) from the balancing energy market. In both cases, the ER may suffer financially. If an ER has price-sensitive customers and can forecast how consumers react to different prices, the ER can consider this in bidding. For a retailer with balance responsibility, contract implications to all types of DR are essential. [66]

3.4. Service provider

A balancing service provider *(BSP)* is a market participant providing balancing services, either or both balancing energy and balancing capacity to its connecting TSO [43]. A TSO is responsible for procuring balancing services from BSPs to ensure the operational security of the power system [67]. Balancing responsible parties need to be able to trade via forward markets and at the day-ahead stage and fine-tune their position on the same trading day (e.g., when wind forecasts or market positions change).

A *flexibility service provider (FSP)* is either an aggregator providing flexibility services or the owner or representative of large-scale or small-scale assets connected to the electricity network, which can provide energy services for TSOs or DSOs. The FSPs can be industries, energy storages, buildings, aggregators, or renewable power producers with assets located within a market area. An FSP can be an active prosumer or an aggregator. Further, an *Independent aggregator* is "a market participant engaged in aggregation who is not affiliated to the customer's supplier" [45]. The FSP is an enabler between customers and the flexibility market. The market may be anything from local to ones that cross national borders. Since most electricity consumers are neither savvy nor interested in setting up an EC or operating it from a technical viewpoint (installing devices and taking care of their correct functioning), new business opportunities will likely arise for companies that would like to carry out this work. FSPs operate close to the final customer anyway, so it could be natural for such companies to operate ECs.

3.5. Control and Management Systems of Active Prosumer

The active prosumer's *energy management system (EMS)* is a central automation and control system providing enhanced functionalities in an EC. This paper does not study the EMS functions in detail since the focus is on the end-user functionalities and use cases. However, the EMS functions can be divided into energy management and AS in the grid-connected ECs. In addition, in the case of a microgrid, there are frequency and Volt/VAr control, intentional and unintentional islanding, transition, protection, and black-start functions [18]. In the microgrid, the EMS is a core functionality of the microgrid central controller (MGCC) [18].

In a centralised EMS for ECs, data from generation and controllable assets, loads (such as end-user appliances) and infrastructure is received, predictions are made (e.g., weather, prices), and overall EC operation is optimised. In decentralised ECs, members pursue individual gains, which may not align with overall EC benefits. The EC-individual benefit relationship relies on the value-sharing mechanism. When this comprehensive mechanism aligns with its objectives, members optimise personal benefits while simultaneously enhancing overall EC benefits.

4. Functionalities of prosumers and energy communities

The functionalities of the prosumers and ECs are considered from among the general-level descriptions and the UCs developed in national research projects (DisMa, ProCemPlus, and ProCem) aiming to find connections between different UC levels. Typically, UCs are developed from a technical concept point of view, and value is assessed from the techno-economic angle for benefitting stakeholders' businesses. Now, the perspective is action-oriented, focusing on the end-user operations in a multidisciplinary framework.

The presentation of a generic operation or concept of a system can be described by a high-level use case (HL-UC). An HL-UC describes the functionality of interest with classified actors and their functions. *Functionality* is the sum of functions or any aspect of what an actor (e.g., prosumer or an EC) can perform in the system or towards another user or stakeholder (e.g., DSO). Functionalities can be presented from the operations and management point of view, and they identify a concept description or features of a system. *Functions* describe dedicated "tasks or operations" by which a desired functionality is achieved.

On a practical level, a primary use case (PUC) implements a UC on a specific system using the defined boundary conditions and characteristics. Hence, a PUC can be mapped on a defined system architecture, breaking down the UC into one or more implementation possibilities, namely specialisations. Further, test UCs (TUCs) could be developed to analyse the quantitative value of different stakeholders. In addition to these, secondary UCs (SUCs) could be used to describe the critical functionalities (for example, dispatch or transition functions) used by multiple PUCs [68]. [18]

4.1. Use cases related prosumers and energy communities evolution in the flexible power system operation

In this research, the studied application is a prosumer or EC of residential, household, and small commercial customers. The operation of a prosumer or EC (prosumerism) aims to gain benefits by offering flexibility functionalities mainly from the economic perspective in the distribution network's earlier evolution phases. However, alternative aspects, such as social or environmental, can provide value. The flexibility functionalities or HL-UCs are energy management, power balancing and flexibility offering. Fig. 4 illustrates prosumers, associated actors, and functions in the flexibility operation. The functions for power balancing include EC energy management. The functions for flexibility include energy balancing, congestion management (CM) and non-frequency AS. The functional or operational goals depend on the end-user type and can be for maximising self-sufficiency and energy efficiency (economic), autonomy (social), and environmental benefits, for example.

Table 4 in Appendix 2 presents UCs developed in the DisMa project. This study selected the relevant UCs from where the main actors are Prosumer and EC, providing flexibility functions in the distribution network's normal situation. Therefore, UCs regarding grid monitoring, protection, hardware management, security and maintenance are excluded. UCs regarding microgrid operations for offering services in the grid-connected mode (main grid normal situations) are included. Consequently, both intended and unintentional islanding (main grid disturbance situations), i.e., microgrid transition modes, are excluded. The relevant UCs of the scope of this research are represented by UC1–3 in Table 4. In addition, UCs having prosumers and ECs as key participants are considered UC4–8, though the main actors are the service providers and the microgrid operator.

4.2. Developing high-level use cases of the energy communities

The UCs developed in the DisMa project, presented in Table 4, Appendix 2, are described by technical focus, and only some identify value expectations for ECs. Table 2 develops these UCs further towards *actor-oriented HL-UC* names and shows the related end-user coalition types by the distribution network evolution phases.

More HL-UCs should be developed considering EU and national-level regulations, for example, for different AS concepts with great potential for generating shared value through various ECs. Further, regarding the distribution grid development and the possibility of its sub-area operating as a microgrid, a vast number of flexible services can be addressed to gain value for an LEC. HL-UCs generally apply to various ECs but must be divided into virtual/distributed and local cases. VPPs and virtual ECs can benefit if aggregated for base power markets and balancing markets. LECs offer a broader scope for AS than virtual, including services for the DSO's CM and the TSO balancing markets. In addition, the CDN-EC can provide flexibility as a controllable resource to the upstream grid services both in the grid-tied and islanded operation modes, which require a microgrid market/pool. Combining various CDN-ECs by interconnecting them, e.g., locally by secondary-substation-wide or regionally by primary-substation-wide, can provide the most extensive possibilities of flexibility. In this kind of intelligent microgrid network, the challenge for all stakeholders is which markets the prosumers offer their resources, posing challenges for grid control. Besides, the fundamental idea of ECs includes other energy vectors than electricity. Having, for example, local CHP or heat storage makes this task more challenging.

In the Finnish context, [5] describes flexibility possibilities through energy management HL-UCs for the electricity distribution network in its self-sufficient, microgrid, and intelligent microgrid network phases. The STRATA [69] project conducts UC definitions and analysis for the smart digital node functionalities as an alternative to the traditional MV/LV transformer with the Finnish DSO Caruna. The project defines a Smart Digital Node whose functionalities include basic grid management, resiliency, local optimisation, local hosting capacity, and the services for the local grid, markets and ECs. These functionalities are parallel to the figure of a MGCC. Again, the UCs relate to prosumers and ECs.

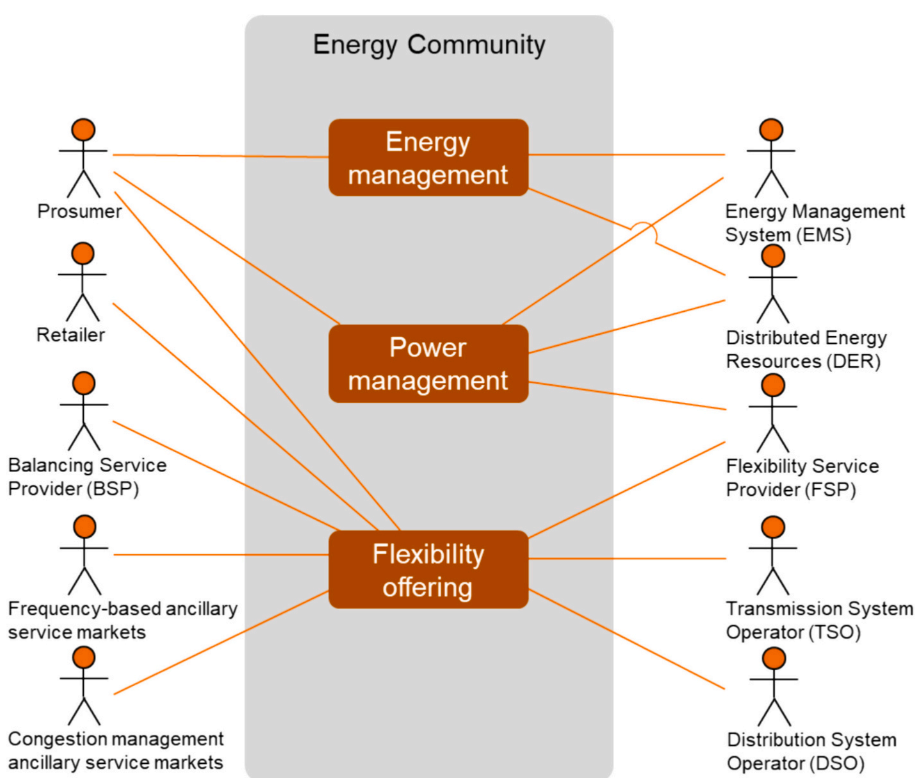

Fig. 4. Diagram for high-level use cases of flexibility.

Table 2
High-level Use Cases of the Energy Communities.

HL-UC (DisMa UC)	High-Level Use Cases of Energy Communities (ECs) (Actor-oriented use cases)	Community type					Distribution grid evolution phase
		Virtual	Local	Jointly Acting Renewables Self Consumers	CEC	REC	
1 (1)	Prosumer energy cost minimisation in an EC by surplus energy sharing	x	x	x*	X	x	Traditional, Self-sufficient
2 (2)	Prosumer energy cost minimisation in a LEC through EC or microgrid (MG) operator's RTP control		x	x*	X	x	Self-sufficient
3 (3)	LEC's power peak shaping		x	x*	X	x	Self-sufficient
4 (4–6)	EC providing flexibility for balancing markets (frequency-based ancillary services (AS))	x	x	x*	X	x	Self-sufficient
5 (4)	LEC providing flexibility for congestion management (CM) (zonal/local AS)		x	x*	X	x	Self-sufficient
6 (2,4)	CDN-EC providing flexibility for CM in grid-tied operations (zonal/local AS)		x	x*	X	x	Microgrid
7 (4,7)	CDN-EC providing flexibility for CM through MG islanded operation (zonal/local AS)		x	x*	X	x	Microgrid
8 (8)	CDN-EC providing flexibility CM through networking MGs (zonal/local AS)		x	x*	X	x	Microgrid Network

* if considered in the same building complex.

4.3. Developing primary use cases of prosumers

PUCs are developed to describe functionalities in a more real context and thus aid in identifying value creation. Since no PUC descriptions are publicly available, and no national projects are yet covering this topic, this paper develops fictive but very realistic PUCs. Based on the *Active Prosumer or EC class* Fig. 6 (Appendix 1), the PUCs are developed based on the HL-UCs presented in Table 2.

The main actors' characteristics of the developed PUCs are presented in Table 5 (Appendix 3), considering residential and small commercial prosumers. The PUCs include a variety of end-users, which can be regarded as being in different phases of evolution, as presented in Section 3. A responsive consumer describes a traditional or passive consumer becoming more active through load control based on the Spot price or by DR programs. Passive prosumers include renewables self-consumers and jointly acting renewables self-consumers. Further, an active prosumer explains a passive prosumer who becomes willing to provide flexibility in interacting with other actors or stakeholders to benefit, for example, their energy economy, in various controls and contracts.

4.3.1. Primary use cases of distributed energy management – Consumers and passive prosumers

A non-commercial and passive type of EC is formed between prosumers. The prosumer(s) own photovoltaic (PV) units and controllable loads that an EV-ES unit. *Distributed energy management in energy communities* UC (Table 4) or *Prosumer energy cost minimisation in an EC by surplus energy sharing* HL-UC (Table 2) describes the operation. The PUCs describe DR options, where DR mechanisms are tools for end-user demand-side management (DSM). The demand curve can be manipulated fundamentally by peak shaving, valley filling, load shifting, strategic conservation, strategic load growth, and flexible load shape. This research considers PUCs using peak shaving and load shifting methods. Still, fundamentally, any of those could be utilised in the ECs' energy management.

This kind of case could also be considered an EC of one prosumer, but in that case, value sharing between the prosumers is not applicable. The value creation is purely economic and based on load control. The passive type of EC consists of types 1 and 2 of end-users. The responsive consumers have an independent load control system that follows Spot price. Following PUCs can be developed.

PUC1. *DR for the load shifting of passive consumers* via *time-of-use (TOU).*

Traditional load shifting by TOU of consumers' heating loads. Different transmission and energy fees for daytime and night (e.g., 7–22 and 22–7). Also, a boiler is typically connected to TOU control.

PUC2. *DR for the load shifting of active consumers* via *RTP.*

Load shifting by RTP-based control of active consumers' heating loads. Consumers have an independent heating load control system that follows the Spot price variation and decides the most inexpensive hours to switch on the load. Also, a boiler can be connected.

PUC3. *DR for the load shifting of responsive consumers* via *AS markets,* i.e., *VPP of responsive consumers.*

Load shifting by a control agreed with an aggregator. Consumers have a service provider's control system that controls heating loads. Also, a boiler can be connected. A VPP can be built upon an aggregator that provides aggregated loads to the balancing markets, providing power balance support services.

4.3.2. Primary use cases of flexibility control in energy communities – Active prosumers

Active ECs can play a vital role in providing tertiary, secondary, and primary reserves for the operation of power systems. Regarding tertiary reserves, active ECs can contribute by participating in flexible DR programs by adjusting their electricity consumption patterns according to system needs. By reducing or shifting their electricity usage during peak periods or when generation capacity is limited, ECs help alleviate strain on the grid. Additionally, ECs can support secondary reserves by integrating DERs such as PV, wind, and ES systems into the power system. Through aggregation and coordination, ECs can offer a collective capacity from these DERs that can be dispatched as secondary reserves. When there is a sudden surge in electricity demand or a generator failure, ECs can swiftly adjust the operation of their DERs to provide extra power to the grid within minutes. While it is less common for ECs to provide primary reserves directly, there are emerging models that allow their participation in this domain. For instance, if an EC operates a microgrid equipped with a combined heat and power (CHP) system, the CHP unit can serve as a primary reserve. The CHP system, capable of generating both electricity and heat, can promptly respond to changes in demand or supply disruptions by adjusting its output. In such cases, ECs can collaborate with grid operators to offer their CHP units as primary reserves, thereby contributing to grid stability.

Considering the availability of flexible resources across different voltage levels, flexibility control PUC can encompass responsive demand and generation control, accommodating the needs of a dynamic power system. The flexibility control could be a concept-level building block for the EMS [5]. In this research, PUCs are developed for active ECs as follows:

PUC4. *Passive Energy Communities.*

This PUC considers a non-commercial and passive type of EC consisting of passive prosumers. Passive prosumers have PV systems, controllable loads and can have BESS. In this case, the passive prosumers' DERs are utilised to aim for self-sufficiency in an LEC (Fig. 1), and surplus energy can be sold back to the energy retailer. The LEC is the property's internal or local virtual EC type and thus operates in a dedicated DSO grid. A passive EC could also be formed from a separate line or CDN, but they are left out of this PUC study since their transmission fees differ.

PUC5. *Passive Energy Communities Providing Power Balance Support Ancillary Services.*

This PUC considers a non-commercial and passive type of EC consisting of passive prosumers, as in the previous PUC, but load control and energy management of a virtual EC are based on the agreement with an aggregator. The aggregator provides bids to the base power day-ahead (Elspot) and balancing intraday (Elbas) markets. This PUC is similar to PUC3. (VPP of responsive consumers), the difference is between the consumers and the passive EC that is aggregated. In this UC, internal value sharing of an EC must be agreed upon. The aim of the operation is cost reduction and self-sufficiency.

PUC6. *Active Energy Communities Providing Power Balance Support Ancillary Services.*

A non-commercial and active type of EC is formed between active prosumers. The prosumers own PV units and controllable loads and hold separate fixed and mobile ES units (in EV) to offer full-range DER flexibility through an aggregator in the Elspot and Elbas markets. This PUC omits CECs.

PUC7. *Active Energy Communities Providing Frequency Stability Support Ancillary Services.*

A non-commercial and active type of EC is formed as previously. An aggregator controls the active prosumers' DER for offering flexibility as a reserve in FFR, FCR or FRR marketplaces presented in [5]. This PUC omits CECs.

PUC8. *Active Energy Communities Providing Local Ancillary Services*

A non-commercial and active type of EC is formed as previously. The active EC offers flexibility for DSO's CM and voltage control. This PUC omits CECs.

4.4. Uniformity and coherence of the use cases

Uniformity and coherence of the UCs are analysed regarding how previously presented different levels of UCs are aligned. Table 3 collects the different UCs, end-user classes and types and operating environments aiming to harmonise and make consistent PUCs for value creation evaluation. This table can be utilised for developing TUCs. Thus, more detailed UCs should be developed to evaluate these different UCs against each other based on multiple and multidisciplinary criteria. Also, the TUCs could aid in finding a clear path for developing functionality for the ADN operation.

5. Multi-objective value considerations and value-sharing framework

The varying levels of UCs developed within this paper aim to enhance comprehension of the value creation indicated by prosumers within both the ecosystem and community contexts. Value creation is about increasing the overall worth and effectiveness of the energy ecosystem. It is important to identify the elements of value creation, boundaries, and challenges, such as stakeholders' contradictory expectations and legislation. Value sharing is about the equitable distribution of the benefits and costs among different stakeholders in the electric energy ecosystem. This section concludes the UCs related to end-users actions in evolving ECs with value creation and sharing perspectives of the electric energy ecosystem's value. A multidisciplinary framework, presented in Fig. 5, is discussed and developed.

5.1. Prosumer as a central actor in the energy ecosystem

An outlined energy ecosystem framework, as presented in this research, provides a structured approach to identify and model the relationships between different stakeholders (e.g., end-users, DSOs, energy retailers, service providers, and prosumers) and their value-creation activities within the EC. It sets the stage for analysing how these stakeholders interact within the evolving landscape of electricity distribution networks and how their actions can influence the development and operation of ECs. This framework aims to enhance understanding of the energy transition by identifying key actors, modelling their interactions, and mapping their value-creation activities. However, it does not delve deeply, for example, into the socio-technical dynamics that underline these interactions, nor fully explore the complex interdependencies between social behaviours, technical developments, and regulatory frameworks.

Ecosystem innovations are greatly dependent on other stakeholders' inputs [78]. Since an ecosystem's value is the sum of stakeholders' contributions [79], actor roles are synthesised in ecosystem value creation. The ecosystem actor relationships need to be mapped where actors, resources, activities, value contributions, and ecosystem value propositions are identified since actors can access the resources that enable activities to contribute to ecosystem value [79]. According to this idea, Fig. 5 illustrates the roles of prosumers and ECs in a multi-stakeholder electric energy ecosystem. Prosumer values related to this research UC analysis are defined in Table 3. In the larger context, prosumers can bring various benefits to the energy ecosystem in a multidisciplinary perspective (outer sector of Fig. 5), including, for example:

- environmental friendliness by renewables adoption lowering carbon emissions,
- cost savings by pooling resources to invest in renewable energy systems,
- energy independence or self-sufficiency by generating own energy,
- resiliency of the power system,
- community engagement by promoting a sense of community involvement and collaboration,
- innovation and technological advancement by embracing new Smart Grid technologies,
- support for the legislation by testing regulatory and policy offer incentives, subsidies, or regulatory frameworks that encourage EC formation, providing additional benefits to participants,
- education and awareness by raising awareness about energy consumption patterns, efficiency, and the importance of transitioning to RES, and
- local economic development by developing energy infrastructure can create jobs and stimulate economic growth.

The proposed framework indicates quantitative and qualitative measures to evaluate the value-creation for different stakeholders within

Table 3
Actor-oriented primary use cases, end-user characteristics and operating environment mapping.

PUC N:o	PUC name	End-user class (Fig. 6, Appendix 1)	End-user type (Table 5, Appendix 3)	Nord Pool		TSO's AS					DSO's AS		MG internal services	Value for prosumer Fig. 4
				Day-ahead Elspot	Elbas Intra-day	FFR 1 MW Up in 0.7–1.3 s [70,71]	FCR-D 1 MW Up in 30 s [72,73]	FCR-N 0.1 MW Up and Down in 3 min [72,73]	aFRR 1 MW Up and Down in 5 min [74,75]	mFRR 10 or 5 MW in 15 min [76,77]	CM	Volt/ VAr		
1	DR for the load shifting of passive consumers	Consumer	1											Cost reduction
2	DR for the load shifting of active consumers	Responsive consumer	2.1	x (indirect)										Cost reduction
3	DR for the Load Shifting of Responsive Consumers – VPP of Responsive Consumers	Responsive consumer	2.2	x (indirect)	x									Cost reduction, Self-sufficiency
4	Passive Energy Communities (ECs)	Passive prosumer	3.1, 3.2	x (indirect)										Self-sufficiency
5	Passive ECs Providing Power Balance Support Ancillary Services (AS)	Passive prosumer	3.1, 3.2	x	x									Cost reduction, Self-sufficiency
6	Active ECs Providing Power Balance Support AS	Active prosumer 2.2.1–2.2.3	3.1, 3.2, 4.1 – 4.5	x	x									Returns, Self-sufficiency, Collectivity
7	Active ECs Providing Frequency Stability Support AS	Active prosumer 2.2.1–2.2.3	3.1, 3.2, 4.1 – 4.5	o	o	(x)	(x)	x	x					Returns, Self-sufficiency, Collectivity
8	Active ECs Providing Local AS	Active prosumer 2.2.1 2.2.3 2.2.4.1	3.1, 3.2, 4.1 – 4.5	o	o	o	O	o	o		x	x	o (2.2.3)	Returns, Self-sufficiency, Collectivity, Influence

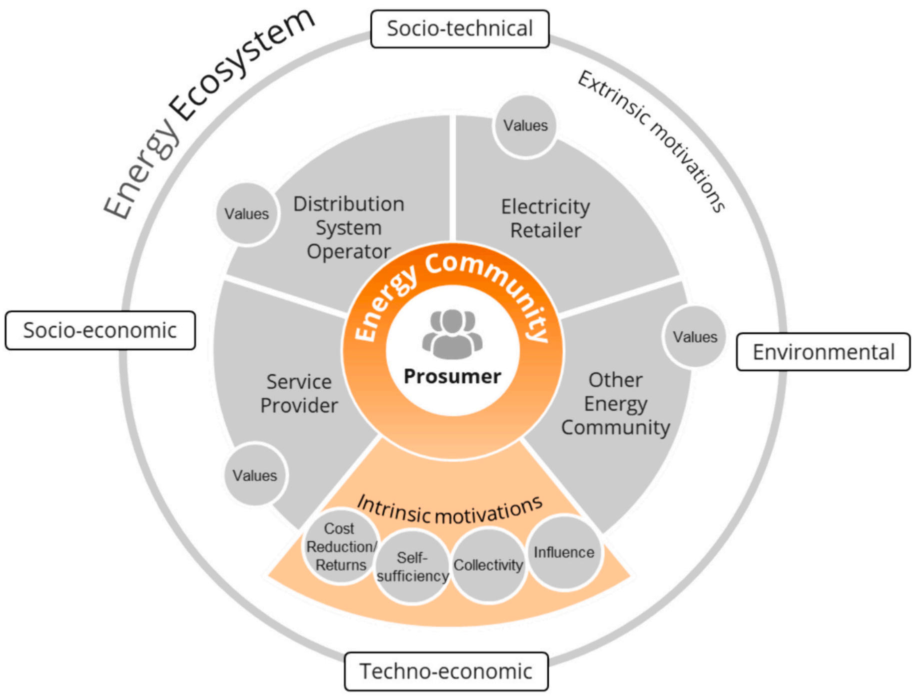

Fig. 5. Prosumer and energy community in electric energy ecosystem value creation.

an EC. For instance, a grid operator prioritizes local grid stability (Value 1), measurable through the System Average Interruption Duration Index (SAIDI) and power quality metrics. An aggregator aims to maximise profits by selling locally produced energy and flexibility services (Value 2), quantifiable in monetary terms. Meanwhile, one end-user seeks to enhance their sense of community belonging (Value 3), a qualitative value, whereas another could aim for energy savings (Value 4), quantifiable in kilowatt-hours (kWh). Different perceptions of value complicate an EC's holistic assessment when considering multiple stakeholder perspectives. Firstly, because these values are measured and weighted differently for various stakeholders, even for ones that belong to the same stakeholder group; secondly, because the nature of the benefits is often not measurable in a traditional sense, making them difficult to compare against each other.

As Fig. 4 and Fig. 5 illustrates, prosumers play a central role in developing and implementing ECs, directly or indirectly interacting with all stakeholders. Therefore, prosumers are critical for creating value for the different stakeholders in ECs. In some contexts, however, the value perception between stakeholders may be conflicting, with actions that create value for one member of the EC yielding a decreased benefit to another. Appropriately identifying the relevant benefits for each stakeholder group and a manner to quantify and compare them is crucial for optimising the value-creation strategies in an EC, ensuring that sufficient social, operational (i.e., technical), and economic benefit is yielded to the stakeholders that most value them. Therefore, a framework that supports these definitions is highly beneficial in the context of an EC.

The presented framework is outlined to enable the consideration and comparison of value in the context of an EC. The following steps are natural for further development of the framework utilizing a particular application or use case: 1. Assessment of potential stakeholders in the EC, 2. Assessment of potential value creation for each stakeholder, 3. Definition of KPIs to measure each value, 4. Establishment quantification techniques to compare and grade value creation, and 5. Prioritisation and optimisation of value according to KPIs and EC constraints.

By adopting such approach, it is possible to effectively establish a comparison basis and quantify different values (even ones that are easily measurable against ones that are not so tangible) and set the constraints for the value creation optimisation problem – the tremendous output and contribution from the creation of this framework.

5.2. Value of energy communities

Economic and social benefits are central motives in participating in EC as presented in [80]: economic benefits, autonomy, self-sufficiency, environmental benefits, community spirit, regionality, convenience and the simplicity of participation. Motivations can be intrinsic (satisfaction) or extrinsic (desired outcomes). Co-creation relies on intrinsic motivations (curiosity, skill development) and extrinsic incentives (reputation, compensation). Prosumerism and co-creation incentives encompass altruism, social ties, technology interest, and financial rewards. Clear benefits sustain co-creation, often via monetary/non-monetary incentives. Involvement empowers participants, and intrinsic rewards often surpass extrinsic ones. [81]

This paper identifies value-creation elements and approaches for an EC from socio-technical, techno-economic, environmental, and socio-economic perspectives. ECs can offer significant value to their members in various ways, including:

1. Socio-technical

- *policy and advocacy influence:* having a stronger voice in advocating for supportive policies and regulations that promote renewables adoption, which can benefit both the community and the broader region (legislation affects the business models that a prosumer may use and also their attractiveness; a positive business case will be a prerequisite for most stakeholders to engage in a project) [22,82]
- *personal empowerment:* belonging to an EC empowers individuals to take an active role in their energy choices, fostering a sense of personal responsibility and environmental stewardship [83,84],
- *technological learning and innovation:* learning and adopting cutting-edge energy technologies,
- *community engagement:* making collective decisions that create stronger social bonds and a sense of community [22,85]

2. Techno-economic

- *cost savings:* the prosumer business model defines not only the allocation of costs, risks, decision-making, and monetary savings but also establishes the intricate roles and dynamics among the stakeholders [22,49,82,83,85–87]
- *increased value in properties*: renewable energy systems can increase the resale value,
- *independence and security of supply in energy:* through the integration of DERs, especially during supply disruptions or price fluctuations [22,82,86,88]
- *resilience and reliability of power:* having DER can be especially valuable in rural or remote areas (in autarchy, like CDN-EC) [82],

3. Environmental

- *reduced environmental impact:* with the integration of renewable DER, according to individual values (a desire to contribute to the energy transition) [22,85]

4. Socio-economic

- *educational opportunities:* workshops, training sessions, and information about energy efficiency, conservation practices, and sustainable living, help members make informed choices [22],
- *economic benefits:* stimulate local economies by creating jobs related to the design, installation, maintenance, and operation of renewable energy systems [22].

The specific value of an EC can vary based on factors such as the community's goals, size, geographic location, available resources, and the level of engagement and collaboration among its members. The success of LEC projects is significantly influenced by cultural factors, which consist of national institutional and political norms, cultures of social enterprise, and local cultural context surrounding community energy groups [89]. From the societal perspective, the EC value forms from proactively encouraging participation in a more ecological lifestyle and providing a sense of community and security through energy self-sufficiency. End-users' interest in co-creation is critical in developing the communities. From a technological perspective, the EC value builds on the RES technologies, the electricity distribution system, and the control and management systems of different actors.

Value sharing in ECs is one of the critical issues that need to be addressed for ECs to be adopted at a large scale. The value of household ECs can be considered from an economic perspective, decreasing energy costs through flexibility services, grid tariff savings, and possible tax exemptions. A value-sharing mechanism typically describes how the economic value is distributed to EC members, which is produced by its activities. The EC value, or the financial benefit, is generally evaluated as a difference between the total bill of the EC and the sum of independent households if they had not joined the EC. The economic evaluation of the Finnish case studies [90] based on energy fees, tax and tariff considerations showed that value creation is driven mainly by tax and tariff reduction. The increasing power and energy management complexity in the high penetration DER systems attracts local control scheme development for ECs and microgrids and schemes for global coordination. Development of local control schemes for ECs includes scheme development for value-sharing mechanisms. For example, based on financial value sharing, there are several mechanisms developed: even share [90,91], production capacity share [90,91], consumption-based allocation [90,91], marginal contribution (MC) [90,91], shapely [90,91], fixed share of production/storage [91], supply-demand ratio (SDR) [91], worst-case excess [91,92], and coalitional game theory [93]. Further, authors in [91] evaluate techno-economic value-sharing mechanisms for end-users by fairness, stability, understandability, incentives for smart control, and computational requirements. Stability describes the ability to retain all EC members and is achieved if no member can benefit from leaving the EC. The stability of an EC has been studied in [94]. This kind of evaluation should be extended over socio-technical, socio-economic, and environmental perspectives. The developed value-sharing mechanisms should incentivise EC members to act in a way that satisfies the whole EC.

The war in Ukraine showed that the green transition is a goal related not only to climate change but also to geopolitics and energy self-sufficiency. Therefore, in Finland, where the electric energy price has been typically low in Northern countries and average in Europe [95], the economic value creation of ECs should be re-evaluated. The Ukrainian war also caused an energy crisis, an energy shortage that raised discussions about energy poverty and power limitation. These new aspects are affecting the value creation framework and model development. Addressing energy equity and affordability is crucial to achieving the nation's climate, economic, and societal goals; hence, the utilities' operations must incorporate new EC engagement practices [62].

6. Discussion

In the literature and research project documentation, mainly HL-UC and TUC are developed, which implies either research or engineering. Developing PUCs in place bridges the gap between research and engineering, which is essential for innovation. For example, it was noticed that the UCs in the studied (DisMa) project were developed from different primary user functionalities. Also, there was inconsistency in whether the main actor was defined based on the behavioural perspective, technical functionalities, expected benefit or a management system perspective. Hence, a holistic understanding is challenging to gain. Therefore, the developed PUCs are essential for research and creating a shared understanding among stakeholders. Functional analysis of this nature fosters a comprehensive understanding at a system level. The developed UCs are based on EU and Finnish legislation. However, the developed methodology can be utilised regardless of geographical area.

In the future, the development of multidisciplinary PUCs is vital, and the different UCs are necessary to synchronise and map to align under the correct level of theme. Even though different levels of UCs were introduced in 2012 [38], the methodology is merely used for designing a system architecture development, rarely applied to generate a common understanding as in [18]. However, [17] can be considered to demonstrate this methodology at the very top level – the whole power system. Further, for example, research [96] evaluating DSOs' CM coordination concepts for interactions between ECs, markets, and distribution grids can be understood as the concept-level descriptions, i.e. HL-UCs, which could be developed further for developing more concrete KPIs. Also, analysing interactions of the multiple actors' functionalities/controls is necessary [18]. For example, results [97] call for a broader set of UC related to interactions and coordination mechanisms of various ECs and other electricity market participants and analysis of the value creation for ECs' functionalities. The research found several classifying criteria for EC elements. Classifications can be based on legislation, technical functionalities, business cases (like in [28]), end-user characteristics (like in [98]), and value expectations, among others—however, a comprehensive understanding requests holistic classification and a multi-level perspective.

As the studied functionalities set requirements for the grid infrastructures, planning and design processes, markets, regulatory and customer processes, and other functionalities, the next step involves developing detailed UCs for cross-evaluation using diverse criteria. Additionally, these UCs offer insights into shaping ADN functionalities. PUCs are poorly publicly available, which is a shortcoming for research. In future, multidisciplinary research could benefit if UCs are developed in a more standardised manner in analysis, for example, by defining value creation in multi-objective case studies, i.e., parallel UCs. Further, the TUCs could be developed to provide quantitative results.

Before ECs can become a reality on a large scale, end customers must be interested in adopting new technologies, businesses, and operation models in addition to existing ones. However, a large part of the research and development carried out in ECs intrinsically expects end customers to have interest and time to engage in these activities, which may not be true in real life. When developing new EC -services, end-user engagement should be one of the main concerns. More focus should be placed on the question: How can end-users enjoy the benefits of an EC? In addition to the end users, it is also important how essential it is for actual market players, such as ERs and generation companies, to find new business models in ECs. Suppose ECs conflict with the business models of traditional ERs. In that case, convincing end users to join ECs might be challenging.

Comprehensive financial estimations on EC-related services are challenging to carry out due to their level of maturity and regulation, which is likely to undergo significant changes in the coming years. Naturally, setting up services to enable services such as ECs or DR is very expensive, and the revenues come from various sources. That is why the services must be built as modularly as possible to adapt to the changes and include as many revenue streams as possible.

The path towards fully realising the benefits of ECs involves more than technological innovation, regulatory support, and economic benefits. It demands a concerted effort to bring end-users along on the journey, addressing their concerns, misconceptions, and the inherent complexity of the energy sector. Additionally, acknowledging the need for time and patience in facilitating this transition is crucial. Our work aims to contribute to this ongoing dialogue, advocating for a user-centric approach in the evolution of ECs in a multidisciplinary context.

7. Conclusion and future work

In this work, a common framework for value creation in the context of electricity distribution networks is presented. The methodology is universal even if the use cases are based in Finland and the EU.

This research sharpens the definitions of different types of end-users in the evolution of the electricity distribution network and describes their operating environment according to the EU and national-level definitions. As a result, different energy communities are categorized, and other vital actors associated with the developing end-users are described. Different levels of use cases are studied to analyse the functionalities where the end-user is the primary actor. Based on these use cases, eight actor-oriented primary uses cases are derived for understanding value creation framework of ECs in energy ecosystem.

The research points out the need for multi-criteria value identification based on the stakeholders' functionalities and analysis of them. The developed value creation framework for different stages of distribution system evolution paves the way for understanding systemic roadmaps. A classification that differentiates the various forms of energy communities by their functions and maturity level creates a framework for gaining a shared understanding and facilitating discussion, which aids in the development of tools, sandboxes and regulations. The most flexibility potential would seem to be in the local EC. The key performance indicators of different value elements must be defined and developed using socio-technical, environmental, techno-economic, and socio-economic principles.

Furthermore, the framework presented in this work offers a methodology to quantify value creation from different perspectives (social, economic, technical) under a common analytical structure. It provides a means to compare concrete/extrinsic (kWh delivered, Euro saved) and abstract/intrinsic (feeling of energy safety, satisfaction from participating in an EC) values. Furthermore, the framework helps determine the critical values and the KPIs used to assess them in different situations for ECs, depending on the specific context and goals of the analysis. As far as the authors know, a similar framework hasn't been introduced in the context of ECs in any scientific publications.

For future research, a multi-objective value-sharing model regarding the studied UCs could be developed to analyse value creation in EC. A high-level multidisciplinary functional analysis could be conducted for the future power system, like [17], defining the functionalities and different levels of use cases and their evaluation criteria. For example, it is imperative that current electricity retailers actively explore and engage in new business models involving ECs. The large-scale realisation of ECs depends on participating and integrating these existing electricity providers (retailers and system operators). For ECs to establish themselves and thrive, it is essential that all parties, particularly electricity retailers, acknowledge and leverage the mutual benefits inherent in such collaborations.

Authors in [99] present the Power System Sustainability Index (PSS index), assessing power system development across social, economic, and environmental aspects using eight local indicators: per capita household electricity consumption, commercial electricity consumption relative to GDP, power system external dependency, generation energy efficiency, capacity utilisation, organic fossil fuel share, renewable energy share, and greenhouse gas emissions per primary energy unit. Regression analysis data can drive multi-objective optimisation using local indicators, guiding changes for power system sustainability. This kind of method could be extended to the technical aspects and adapted for comprehensive value creation, sharing and assessment model development.

Our findings highlight the potential of ECs in transforming electricity distribution networks by integrating active end-users. However, successfully implementing such models requires addressing the gap between current user understanding and energy management and billing complexities. Future research should focus on developing tools and platforms that simplify energy concepts alongside policies that support users' understanding, engagement and trust-building. Moreover, a gradual transition strategy, allowing users to adapt at their own pace, will be key to fostering a more inclusive and equitable EC ecosystem.

CRediT authorship contribution statement

Katja Sirviö: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sergio Motta:** Writing – review & editing. **Kalle Rauma:** Writing – review & editing. **Corentin Evens:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. While preparing this work, the authors used ChatGPT/OpenAI to aid in identifying and completing possible general-level value-creation elements of energy communities. After using this tool/service, the authors reviewed and edited the content as needed and took full responsibility for the publication's content.

Data availability

No data was used for the research described in the article.

Acknowledgements

This work was supported by the Academy of Finland through the project Distributed Management of Electricity System (DisMa, grant number 323696) and Business Finland through the project Energy Community as a Driver of Electrified City (ECADEC, grant number 8852/31/2022).

Appendix A. Appendix 1

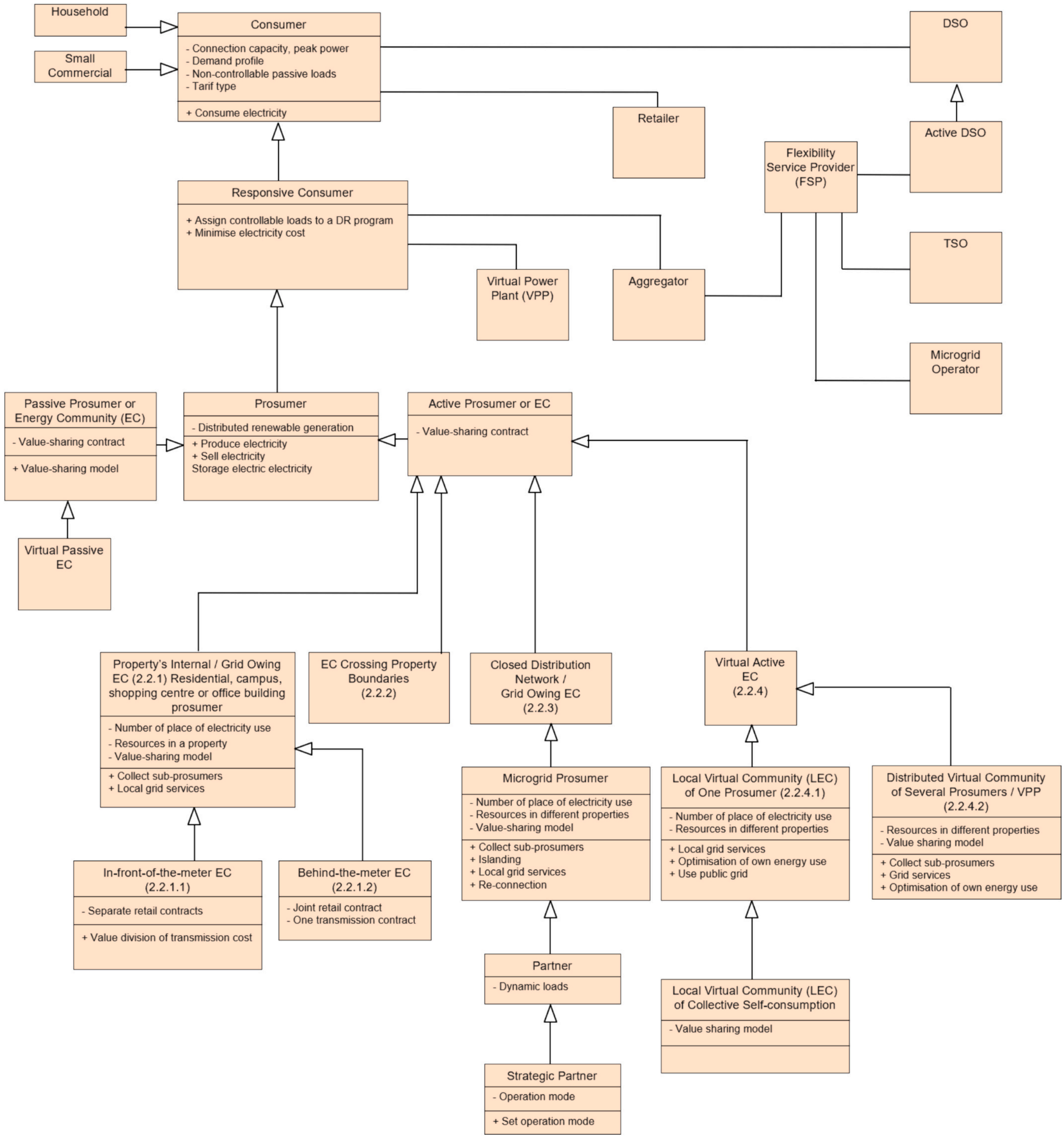

Fig. 6. Class diagram of end-users.

Appendix B. Appendix 2

Table 4
High-level Use Cases of the DisMa Project.

No.	Main Actor	Associated actors/ Participants	Use Case Name and Description	Main actor's goal of the operation	Value expectation
1 (7)	Energy Community (EC)	An EC operator provides prosumers (publishes data) information on selling and buying prices and the value-sharing mechanism enabling their distributed decision-making. The main grid operator sells electricity to the EC and purchases its excess generation, setting prices for both transactions through the EC operator.	**Distributed Energy Management in ECs (2.2.1)** Passive prosumers form the energy management of an EC. The EC is noncommercial and has no operation cost. Prosumers may change their electricity consumption behaviour according to the share they receive based on the value-sharing mechanism. So, some prosumers' electricity profiles can be adjusted according to the value-sharing mechanism (agent), selling and buying prices, and other prosumers' electricity consumption profiles. This UC can be modelled as a two-level optimization problem where the EC's added value is maximised while the prosumers' cost is minimised at the lower level. Formation of this bi-level problem is a centralised approach where data of all prosumers appliances and their preferences must be gathered and analysed in a central control. Hence, this UC aims to solve the problem in a distributed manner where each prosumer optimises their electricity consumption profile based on local information. A central approach achieves the solution for the EC. **Main operational scenario:** 1. The main grid operator publishes buying and selling prices to the EC operator. 2. The EC operator publishes the prices to prosumers. 3. The prosumers optimise their electricity consumption according to the prices. 4. The prosumers share their electricity consumption profiles with neighbours. 5. The prosumers estimate the total EC consumption profile based on the shared individual profiles. 6. The prosumers optimise their electricity consumption according to the prices, estimated total EC load profile, and the value-sharing mechanism. 7. The workflow iterates between 4 and 6 to converge. 8. The prosumers consume electricity based on their optimised profiles and receive their share from the added value created by the EC formation.	Because buying electricity from the network is higher than selling it to the network, forming an EC and consuming potential extra generation inside the EC is beneficial.	A prosumer wants to minimise its electricity cost, while the EC aims at maximising the added value achieved by sharing the surplus local generation. The added value the EC gains equals the surplus generation times and the difference between buying and selling prices. The added value is divided between prosumers. An economic value-sharing mechanism is necessary for sharing the added value.
2 (11)	EC	The microgrid (EC) operator monitors the microgrid, communicates with members, runs the local market, metering	**Energy Management of Microgrid in Normal Mode (2.2.3, 2.2.4.1)** In normal mode, the microgrid	Minimise the net operating cost of the microgrid. In a grid-connected microgrid, any power imbalance can be	The EC's operator indirectly controls all members by changing RTP to maximise community benefit. In

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Table 4 (*continued*)

No.	Main Actor	Associated actors/ Participants	Use Case Name and Description	Main actor's goal of the operation	Value expectation
		and billing, follows DSO tariff for import or export energy, and follows retailer price for import or export energy. EC members/prosumers schedule resources according to real-time pricing (RTP).	connects to and exchanges energy with the main grid, so it can be considered a LEC. **Main operational scenario:** 1. The microgrid or EC operator gathers information about prosumers connected to the grid (forecast of consumption in future intervals) 2. The operator runs an imperfect competition market model (e.g., Cournot model) to calculate RTP by repeating the following steps until convergence. • The operator sends the initial RTP. • Members optimise/schedule their consumption and production and send the power information to the operator. • The operator updates the RTP using the amount of production and consumption of all members, the energy price of retailers, and the network tariff. • If the updated RTP differs from the old one, the operator sends the RTP to all members and returns to the optimisation stage.	effectively compensated by the main grid, meaning there will be no surplus or shortage of power. Self-sufficiency.	contrast, each member optimises their behaviour according to RTP to minimise cost.
3 (22)	EC	The other Prosumers in the same EC have the same objective as the EC; hence all prosumers share the same goal.	**Power Peak Shaping in Energy Communities (2.2.1, 2.2.3, 2.2.4.1)** **Main operational scenario:** 1. Prosumers schedule to use their facilities and operate loads as usual. 2. Prosumers share their net load profile. 3. The total EC load profile is determined or approximated based on released load profiles. 4. Prosumers reschedule the operation of their facilities to minimise EC peak power. 5. The process iterates Steps 3 and 4 until no further reduction is observed in peak power within a predefined number of iterations. 6. Prosumers publish their final schedule and operate their resources accordingly. Simplifying assumptions: 1. Operation of the responsive loads can be adjusted over a predefined period, only flexible in their operation time and within a predefined period. 2. EC's storage units can be EVs (mobile) or independent batteries (fixed). EVs are not considered in this UC to avoid unnecessary complexities. (If they would be considered, then ECs would behave as Strategic Partners [12]).	The EC aims to minimise power-peak during the next day.	Prosumers want to minimise the EC's daily peak power, which is a bit unrealistic. EC members may care about the annual but not necessarily the daily peak power. A more realistic objective function could be daily cost minimisation.

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Table 4 (*continued*)

No.	Main Actor	Associated actors/ Participants	Use Case Name and Description	Main actor's goal of the operation	Value expectation
			3. Only undispatchable power generation units are considered, so the user cannot decide how much power a unit generates. For example, PV has intrinsic characteristics like intermittency (power generation changes over time) and uncertainty (the user cannot predict power generation precisely). The generating power is forecasted.		
4 (14)	Flexibility Service Provider (FSP)	Customers own the controllable equipment. Markets (yearly, day-ahead, short-term congestion management (CM))	**Flexibility Offering** The FSP is an enabler between customers and the flexibility market. The market may be anything from local to ones crossing national borders. There are different flexibility UCs for 1. TSO – frequency AS (e.g., frequency containment), 2. DSO – non-frequency AS (e.g., CM, grid restoration), 3. BRP – portfolio optimisation (e.g., reduce cost for electricity purchase, increase revenue from generation, avoid imbalance charges), and 4. EC – self-balancing (increase self-consumption), peak load control, TOU optimisation, emergency power supply, aggregator (offer EC flexibility out). **Main operational scenario:** 1. Market gate opening 2. FSP determines flexibility offer with the Customer 3. FSP offers flexibility to the Market before gate closure 4. Market informs FSP that it received the flexibility offer		
5 (5)	Balancing Service Provider (BSP)	DERs will be allowed to participate independently or through aggregators or retailers. Battery operator/owners AMR connected DERs FFR/FCR-D market collects the support bids from DERs in yearly and monthly markets.	**DERs Providing Ancillary Services for FCR-D and FFR Markets** The inverter-based generation decreases power system inertia, necessitating fast-responding reserves to limit the rate-of-frequency-change (ROCOF) during a disturbance event in the transmission grid. Battery operators, owners, and DERs will be allowed to participate independently or through aggregators or retailers. **Main operational scenario:** 1. Reservation • Reserve bids (e.g., hourly or yearly) specify the time, date and hour, volume in MW, price, type of reserve (consumption or production or aggregated), and regulation method. 2. Procurement 3. Activation • A nuclear unit or a dimensioning fault occurs in	Provide reserve units or groups as balance services (FCR-D/FFR) to TSO.	

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Table 4 (*continued*)

No.	Main Actor	Associated actors/ Participants	Use Case Name and Description	Main actor's goal of the operation	Value expectation
			the network, causing frequency deviation. • The FCR-D and FFR reserves sense the frequency signal and decide on activation. After a frequency change of −0.5 Hz, FCR-D activates 50% in 5 s and 100% in 30 s. At 49.7–49.5 Hz, FFR activates within 0.7 to 1.3 s. Reserve units provide support (upward/downward) to arrest ROCOF. 4. Verification • Frequency and event data are recorded at the reserve plant and sent to connecting TSO upon request. • TSO assess reserve performance in the specified support window and record window data. 5. Settlement • TSO calculates each event window's gross and net profits and penalties. • The reserve provider receives net payment for each window.		
6	Aggregator; balancing service provider (BSP)	TSO BSP Balance Resource Operator (BRO) (a power plant, reserve, single customer, DER owner contracting with an aggregator or BSP) Sub-Aggregator (access to control multiple resources, can offer the controllability to Aggregator operating on the market level, has monitoring and control connections to its resources not for aggregator needs but for remote maintenance and control) Forecasting tools/Service provider	**DERs Providing Ancillary Services for FCR-N Markets** FCR-N is both an energy and power product so the operator offering FCR-N will get paid for both the power that is available as well as the energy used to regulate the grid up- and downwards. **The main operational scenario:** 1. The aggregator obtains weather, load and market forecasts from the service provider and available reserves/operational plans from DERs/sub-aggregators. 2. Aggregator estimates and submits price bids of FCR-N (for TSO) to the AS market. 3. Aggregator receives a notification when TSO accepts the price offer on the market platform. 4. Aggregator sends a request to sub-aggregator/DERs to activate/schedule the delivery of reserves. 5. DER/Sub-aggregator reports/ sends verification to Aggregator about activated reserves and the delivery of FCR-N reserves. The Aggregator/Sub-aggregator receives measurements from DER IEDs. 6. Aggregator reports to TSO about the activated amount of resources and delivery of FCR—N. 7. The aggregator bills the TSO and pays participated DERs.	The aggregator gathers reserve capacities and sells them to TSO or other market participants. Aggregator optimises, and group offers in the market to maximise net profit for reserve providers.	
7	Microgrid Operator (MGO)	Consumers Producers	**Island Operation of Microgrid - Energy Management** The power management schemes cover the microgrid inertia,	The microgrid operator aims to minimise microgrid operation costs while	Consumers aim to reduce their electricity bills. Producers aim to maximise

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Table 4 (*continued*)

No.	Main Actor	Associated actors/ Participants	Use Case Name and Description	Main actor's goal of the operation	Value expectation
		Prosumers	frequency, and voltage. This UC considers distributed management paradigms and a microgrid market where all stakeholders buy/sell electricity. Energy management of a microgrid in islanded mode would need bi-level optimisation. The local market is not a perfect competition market. The market is small, and the decision of one actor may affect the price. Therefore, the local market needs an imperfect competition (oligopoly) model. **The main operational scenario:** 1. Consumers, producers, and prosumers provide the microgrid operator with relevant information about their generation and consumption. 2. The operator evaluates the state of the microgrid, schedule generation, and load of all the stakeholders to minimise operation costs while meeting operational constraints. 3. The stakeholders receive the schedules and operate their facilities accordingly.	meeting operational constraints.	their profit from selling their energy production. Prosumers aim to minimise costs.
8	Microgrid operator (MGO)	DSO coordinates power transfer between microgrids (if the connection is via the public distribution network). Microgrid-hosted Prosumers deploy resources for self-demand, sharing surplus energy and requesting additional energy as needed. Adjacent Microgrid operators meet their interconnected demands and exchange energy for mutual benefit. Such exchange is advantageous when one microgrid has excess energy while the other faces a deficit. Establishing a multi-microgrid network often proves beneficial, enhancing network inertia for frequency control and boosting voltage support and fault current capabilities.	Energy Management in Multi-Micro Grid Network in Island Mode	Serve its hosting load with the least cost and help the neighbouring microgrids (disconnected from the main grid) to serve their load.	An MGO operates the microgrid aiming to serve the hosting load with the lowest price and helping the neighbouring microgrids to
9	Distribution System Operator (DSO)	DSO External consultants DataHub	Distribution Grid Development Plan - Utilisation of Flexibility **The main operational scenario:** 1. DSO gathers information on consumers and the area being designed 2. DSO acknowledges the boundary conditions for strategic planning: • Consumption predictions for planning horizon (external consultants) • Flexibility potential of customer mass (external consultants)	Create a long-term strategic development plan.	

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Table 4 (*continued*)

No.	Main Actor	Associated actors/ Participants	Use Case Name and Description	Main actor's goal of the operation	Value expectation
			• Current and upcoming legislation and regulation • Emerging/existing market(s) for flexibility • Emerging technologies • Branding and "trends." 3. DSO formulates a cost-benefit analysis for flexibility usage 4. DSO decides the level of flexibility solutions to be included in strategic planning		
10	MGO	(17)	Island operation of microgrid - power management		
11	Microgrid central controller (MGCC); EMS	(4)	Creation of island microgrid (scheduled islanding)		
12	MGCC; EMS	(3)	Creation of island microgrid (black start)		
13	Microgrid Controller	(28)	Smooth Islanding (Without Outage)		
14	MGCC	(19)	Microgrid synchronisation with outage		
15	MGCC	(20)	Microgrid synchronisation without an outage		
16	Centralised Protection Controller	(18)	Microgrid protection during the island and the changes when creating an island		
17	DER owner	(26)	Secure Integration of DER to Microgrid		
18	DER owner	(6)	DER Registration		
19	Remote Controlling Entity (25)	DER, DER Controller (control from DSO level), MGO, Security Gateway	Secure control of remote DER	Assure remote DER control in the microgrid.	
20	DSO	DSO, Microgrid controller	Service restoration for DSO	Boosting supply security for external feeder-connected customers.	
21	DSO	Network planner (e.g., DSO), Contractor, AS provider(s), Consumer(s)	Network component replacement/ addition	Addition or replacement of network components and updating the information system.	
22	DSO (system)	Grid operator, Consumers, Prosumers, Producers	Distribution grid monitoring	Supervise/monitor distribution grid status	
23	Automation Engineering Company	Communication engineering company, Configuration management repository	Remote hardware management	Remote hardware configuration management	
24	Black starting agent	Isolation actor, Grid-forming resource, Grid-following resource, Load	The distributed approach of creating an island microgrid (black-start)	Stable formation of microgrid and feeding load as much as possible	
25	TSO's inertia monitoring tool	Inertia forecasting tool, Reserve sufficiency tool, Unit commitment and economic dispatch tools, Production units	Inertia monitoring	Ensure real-time inertia for power system stability, and publish daily trajectory. Calculate total inertia from online synchronous generators using unit parameters and status. Use a unit commitment model with inertia constraints to address low inertia. Set inertia floors based on diverse energy resources and capacities, considering FFRs, load reserves, virtual inertia, and batteries.	
26	Client Software)	Computation service (a web service)	Computation as a service (publish-subscribe)	Subscribe to computed output from an external entity (instead of on request).	
27	Client Software	Computation service (a web service)	Computation as a service (request-response)	Request an external entity to compute something	

Appendix C. Appendix 3

Table 5
End-user exemplary characteristics in the primary use cases.

End-user type	Consumption [kWh/a]	PV unit, panels [pcs]	PV unit [kWp; m^2]	Controllable heating loads [kWp]	Controllable loads [kW] (boiler, cooling, ventilation, heat pump)	BESS [kWh]
1.1 Passive consumer (TOU); household 250 m2	35,000			37,5	3 (boiler)	
2.1 Responsive consumer (Spot); household 250 m2	35,000			37,5	3 (boiler)	

(*continued on next page*)

Table 5 (*continued*)

End-user type	Consumption [kWh/a]	PV unit, panels [pcs]	PV unit [kWp; m^2]	Controllable heating loads [kWp]	Controllable loads [kW] (boiler, cooling, ventilation, heat pump)	BESS [kWh]
2.2 Responsive consumer (DR); household 250 m2	35,000			37,5	3 (boiler)	
3.1 Passive prosumer; household 250 m2	35,000	25	10; 49	37,5	3 (boiler)	
3.2 Passive prosumer; household 120 m2	18,000	12	5; 24	10	3 (boiler)	
3.4 Passive prosumer; housing company: 10 apartments, 800 m2, 2400 m3	40,000	60	24; 118	0	20/80 (heat pump+boiler)	
3.5 Passive prosumer; commercial 5000 m2, 15,000 m3	300,000	75	30; 147	0 (district heating)	100 (ventilation)	
4.1 Active prosumer; household 250 m2	35,000	25	10; 49	37,5	3 (boiler)	10
4.2 Active prosumer; household 120 m2	20,000	12	5; 24	10	3 (boiler)	5
4.3 Active prosumer; household, 120 m2	7300	12	5; 24	0	3/12 (heat pump+boiler)	5
4.4 Active prosumer; housing company: 10 apartments, 800 m2, 2400 m3	40,000	60	24; 118	0	20/80 (heat pump+boiler)	10
4.5 Active prosumer; commercial 5000 m2, 15,000 m3	300,000	75	30; 147	0 (district heating)	100 (ventilation)	60

The thermal coefficient (COP) of the heat pump is 4.5, i.e., the device produces 4.5 kW of heating energy per one input kilowatt. The design power of electric heating is 25 W/m^3 or floor 150 W/m^2. A 1730 × 1133 (1,96 m2) panel gives 400 Wp. Specific electricity consumption is 20 kWh/m^3.

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