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Emergence and prospects of digital mediation in energy communities: ecosystem actors' perspective

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Abstract

Background Energy communities (ECs) hold out the promise of cleaner and more flexible energy systems through self-generation, demand response, and storage. Digital mediation plays a pivotal role within the EC ecosystem, which is a set of autonomous organizations coordinating and engaging in joint value creation activities by facilitating energy generation and consumption, coordination, and information and knowledge sharing. Although the extant literature has stressed the potential role of digitalization in empowering ECs and citizens, there remains a lack of comprehensive empirical studies and theorization on how ECs can benefit from digital mediation and develop a digitally mediated EC ecosystem. Thus, this research explores the current benefits of digitalization for ECs, and how the ecology of actors envisions the role of digital mediation in scaling and strengthening the EC ecosystem.

Results Based on 22 interviews with EC representatives and the ecology of actors (i.e., stakeholders in the ecosystem) in Finland, our results underscore that digital mediation supports ECs in monitoring and controlling their operations and in addressing demand response and trading through data retrieval, exchange, and optimization, so contributing to better decision-making. The existing ecology of actors envisions a developed digitally mediated EC ecosystem that can enable the sharing of experiences, peer-to-peer support in planning phases, and the operations of communities.

Conclusions This study contributes to the prior research by identifying the benefits of digital mediation within the ecology of actors. The findings of the study demonstrate that the early stages of EC ecosystems are characterized by a loosely connected ecology of actors, rather than a fully developed EC ecosystem. In doing so, this research highlights the crucial role of platformization in the EC context. EC managers should explore and develop mechanisms to observe the emergence of EC ecosystems, lead the responsibilities for coordination, and determine their community's objectives and business model, utilizing digital platforms to evaluate prospects. Governments should consider providing incentives and implementing a favorable regulatory framework to encourage new actors. They can be at the forefront in developing digital platforms and collectively defining a shared vision of digital transformation for ECs.

Keywords Energy communities, Ecosystem, Digitalization, Collaboration

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Background

Historically, the energy system has been designed in a more centralized fashion and predominantly run by central governments and big players such as state-owned mono- or oligopolies [1], thus excluding ordinary citizens and any role they might play in the governance of the energy sector [2]. However, a shift toward sustainable and fair energy systems requires a greater degree of citizen participation and empowerment. Therefore, a prominent role on the part of citizens in energy transition becomes essential, as they form energy communities that are interconnected with various entities such as other energy initiatives within the community, utilities, social entrepreneurs, public and private institutions, and community organizations. These entities deal with investing in, producing, selling, and distributing renewable energy [3, 4], exhibiting a high level of ownership and control [5].

Although ECs offer decentralization and potential democratization through the development of flexible energy systems, it is difficult for these communities to operate in a vacuum as they are individually fragile. Thus, ECs require pooled resources and coordinated efforts to collectively strengthen their resilience [4]. In order to evolve and grow, an EC needs to engage with an ecology of external interconnected actors [6], such as prosumers, service providers and distribution system operators, intermediary organizations, research institutes, and communities within the ecosystem [4, 7]. The ecosystem notion elucidates how autonomous yet interrelated organizations coordinate and co-create joint value in terms of products, services, or technologies. Through such mutual interdependence, organizations develop complementary assets, ranging from obtaining their reach to distribution channels and knowledge and expertise, inducing sectorial change and coordinating successful co-evolution [8, 46, 49]. Furthermore, mobilizing digital technologies and digitalization processes appears to play an important role in enabling ECs to thrive in the energy transition, facilitating energy generation and consumption, coordination, and information and knowledge sharing [9]. Several scholars have stressed the need to unpack the role of technologies in the transition [9, 10] by enabling new collaborative practices provided by digitalization. This becomes even more important when exploring how ECs benefit from digitalization, and how different ecosystem actors perceive the role of digitalization in the emergence of ECs, as energy transition is subject to change in the incumbent energy system.

However, the literature has revealed specific barriers (e.g., economic, financial, organizational, legal), due to which the role of ECs in sustainable energy transition has been marginal and they have failed to realize their potential [4, 11]. Although prior research has stressed the potential role of digitalization in empowering ECs and citizens [9], there remains a lack of comprehensive empirical evidence and developed theorization on how emerging ECs can benefit from these novel digital technologies. These benefits involve better coordination with other ecosystem actors to manage the operations of communities and strengthen collaboration, and share relevant and timely knowledge and information. Most of the related studies have focused on designing and implementing digital technologies and support platforms in the energy system, in terms of the integration of the Internet of Things (IoT) for power distribution, storage, grid monitoring, and smart metering [9, 12], and in creating communication channels between communities [13]. However, an ecosystem actor perspective that explores the importance and prospects of digital mediation in ECs and how ecosystem actors envision the role of digitalization in scaling and strengthening the EC ecosystem has remained predominantly unexplored. Several scholars have also called for further research to explore how best to manage the relations with other ecosystem actors, such as incumbents [4], and the mobilization of digitalization to impact energy communities and the ecology of interconnected actors [9]. Similarly, since there is little empirical evidence in the prior sustainability transition literature on the use of digital technologies [9], it is important to study the digitally mediated energy communities ecosystem and the interactions of the ecology of sociotechnical entities all within, between, and beyond energy communities.

Accordingly, this study aims to explore how digitalization enables energy communities to leverage various digitally mediated approaches, and to understand the perceptions of different ecosystem actors regarding digitalization's role in the emergence, coordination, and operational management of these communities. This study argues that an ecosystem perspective is particularly well suited to analyzing digitally mediated energy communities, as it involves several collaborative entities, resources, and means of coordination between different ecologies of actors and the digital platform. This also aligns with the notion presented by Fuenfschilling and Truffer [14] who argued that sociotechnical transition is conceptualized as an interplay between actors, technologies, and institutions, whereas actors and technologies are embedded within and shaped by institutions, thus contributing to the change. Thus, this research poses the following research questions: What are the current benefits of digital mediation for energy communities? How does the ecology of actors envision the role of digital mediation in the emergence of the EC ecosystem?

Our results are based on data collected from 22 semi-structured interviews with actors in ECs and among different stakeholders in those communities. The key findings indicate that regardless of the current state of a loosely connected ecology of actors, digital mediation supports ECs in monitoring and controlling their operations, and in addressing demand response and trading through data retrieval, exchange, and optimization. It further enables transparent communication and knowledge sharing among EC members and other actors, contributing to better decision-making. The current loosely coordinated ecology of actors envisions developed, digitally mediated EC ecosystem collaborations based on digital platforms that can function as the glue among actors and enable the sharing of experiences and peer-to-peer support in community planning phases and operations.

Literature review

Energy communities and digital mediation

Energy communities play a pivotal role in driving the energy transition from the grassroots level by increasing the share of renewable energy production, promoting energy efficiency, and reducing transmission losses [4, 9]. Recent research has focused on the EC concept to understand how such initiatives manifest in diverse socio-economic, societal, cultural, technological, and regulatory conditions [3]. The definition of the concept of energy community in the academic literature has been elastic and even vaguely expressed. Some definitions highlight aspects of locality. For instance, the widely used definition of Seyfang et al. [11] understands EC projects as formal or informal citizen-led initiatives that advocate for collaborative solutions at the local level to promote the advancement of sustainable energy technologies. However, the Clean Energy for All Europeans Legislative Package (CEP) has now been formalized, and defines "renewable" and "citizen" energy communities (REC and CEC) in the EU. These two concepts share a wide range of commonalities and imply promoting active citizen participation, enabling local communities to generate, consume, store, and sell energy. They emphasize a participatory governance model and prioritize social and environmental benefits over profit. While CECs focus only on electricity supply and distribution, RECs include electricity, heating, and cooling. These definitions also have differences in geographical locality and scope of technology, with CECs being agnostic regarding locality and technology, and RECs being limited to renewable technologies and local areas [15].

Historically, energy communities existed in the form of electricity cooperatives in many European countries [16], and many such types still operate as off-grid solutions in remote communities of developing countries with little or no digital infrastructure [17]. Without digitalization, these communities often face various operational challenges such as optimizing energy use, coordination among members, and managing administrative tasks [17]. Digital mediation has significantly impacted various sectors, including energy, leading to a creation of value for ECs [18, 19]. Through utilizing information and communication technologies (ICT) and digital platforms to enable users' interaction and communication, digital mediation can enhance the agency of ECs and make them economically viable within the existing energy system, as well as to design and negotiate the future energy system [9] which is predicted to enter a new phase of digital mediation [20, 21]. Digitally mediated communities connect peers in supporting a wide diffusion of energy solutions [22], and enabling citizens or communities to mutually engage in institutional work, energy management, and trading, and thus create a sense of collective ownership [9]. Digital mediation has also been identified as an important area to support effective, socially just, and economically worthwhile coordinating efforts from an assemblage of energy community actors to implement transformative policies. However, little evidence has been gathered to support this in the existing research. Furthermore, sustained energy community development requires the evaluation of meaningful actions, knowledge production, and communication practices [23] through digital mediation. Prior research has also considered internet forums as digitally mediated communities where geographically dispersed actors interact to share their concerns regarding different technological options [22].

Digital technologies play a central role in digital mediation as these technologies function as enablers in achieving the goals set for ECs. Well-designed mediation through digital technologies facilitates communication among EC members as well as other actors, emerging as a valuable tool to break the silos of traditional energy systems. Recent research has explored the role of digital mediation in energy systems, such as enabling energy sharing, fostering citizen participation, and peer-to-peer trading involving customers in smart local energy systems [24–26]. However, a decentralized energy system requires infrastructural changes with digital technologies and platforms playing a central role, linking consumers' innovative roles as prosumers and ECs [27]. ECs have started to utilize digital services in their operations, as recent developments in ICT and digitalization processes are considered to play a pivotal role in energy transition [9, 28]. Furthermore, ECs can benefit from digital tools and communication methods in collaboration [9] and technologies such as AI, big data analytics, and digital twin support in optimizing energy management and decision-making, while minimizing the complexities related to renewables [18]. Adu-Kankam and Camarinha-Matos [28] have proposed collaborative digital twins (CDT) as a replica of a household unit within a collaborating EC, supporting decision-making and promoting collaborative behavior. The use of CDTs positively impacts scaling development and promotes sustainable energy consumption within the community. Hiteva and Foxon [29] adopted the innovation ladder approach to explore innovations in digital energy services business models, finding that digital innovation is still limited in creating social and environmental values for ECs, although it is a useful technique for several stakeholders as it offers opportunities for collaborative action.

As the concept of EC is broad, the long-term objectives and means of reaching the objectives also have a broad range. The literature has recognized that communities are often motivated by the improvement of local energy self-sufficiency and greater autonomy [30]. Thus, different communities approach their goals via different approaches, ranging from the development of resilient and smart infrastructure, innovative practices, or establishing coalitions of actors by utilizing disruptive technologies and local networks [5, 20]. Gui and MacGill [20] linked regional innovation to ECs, highlighting digital innovation's role in facilitating community participation in initiatives. Hill and Duffy [13] designed a digital platform for large-scale community energy, fostering user confidence, project progression, and community connection through communication. This platform optimizes resources, promotes collaboration, and brings economic benefits by enabling communities to co-create value [21].

Digital mediation has entered the EC domain in a rather surprising manner. The most common use case (and perhaps with the most significant impact on the energy transition at the household level) is related to information sharing, communication, and knowledge sharing, allowing geographically separated peers to exchange knowledge on the acquisition, operation, and improvement of the technology [19, 22]. These communication-related use cases have strengthened the agency of ECs and facilitated production and consumption through collaborative actions [9]. The technology improvements have included various ICT integration efforts, which were grassroot types of software development projects that enable overlooked service ideas. Institutional arrangements such as taxation or distribution fee structures have previously hindered such development. However, these barriers have been overcome in recent years, enabling experimentation and providing ECs with a better foundation for testing new digital technologies within the existing energy system [9]. In addition, digital mediation enables grassroot developments and experiments that can be institutionalized. In the case of ECs, efforts rely on community-level power generation, distribution, controlling, and metering, which is often referred to as a community-based virtual power plant (cVPP). The first-mover countries, such as the Netherlands, have already integrated digital cVPP solutions into national transmission system operators [9, 31]. However, energy systems are now entering a new phase with the new dynamics of digitally mediated ECs [20, 21], and development efforts are being directed at more advanced digitalization use cases co-created inside ECs.

While digital technologies developed through digital mediation empower ECs to participate in shaping the future energy system and strengthen the smart grid niche, the success of these communities and their configurations remains uncertain due to policy-practice gaps such as policies that are not fully utilized, financing and funding issues, technical limitations and grid integration issues, social acceptance, community participation, and a lack of knowledge sharing [9]. This uncertainty requires a further exploration of how technology operates, and of the current digitalization processes seen in energy markets. ECs have been actively incorporating digital technologies, requiring effective ecosystem interactions to destabilize the existing regime and establish a transformation pathway [22]. Table 1 summarizes the recent research on the use of different types of digital technologies in digitally mediated ECs.

Ecosystem actors' perspectives on digital mediation in ECs

In inter-organizational collaborations, entities unite around a common goal, sharing information, resources and responsibilities, and jointly planning activities [35, 41, 42], while promoting mutual benefits and enhancing actors' capabilities. In the energy sector, such collaboration can facilitate decisions and promote sustainable energy transition and behaviors [28]. While inter-organizational collaboration and knowledge acquisition can trigger innovation and strengthen the energy ecosystem [32, 37], relying solely on slow-changing partnerships is insufficient. In a shift toward a system-level orientation, the ecosystem perspective is considered as a strategic direction [43–45] for ECs.

In business and management, the term "ecosystem" is borrowed from biological studies, and refers to the interdependence between actors and the analysis of complex social phenomena [46]. Research inspired by James Moore's [44] work has focused on ecosystem-based concepts such as the business ecosystem [44], innovation ecosystem [47], entrepreneurial ecosystem [48], and knowledge ecosystem [49]. Different concepts can be further distinguished based on Adner's [47] ecosystem view describing affiliation and structure. The affiliation view proposes that ecosystem type and value creation

Table 1 Recent research on digital mediation in ECs

Publication(s)	General focus	Technology used
Adu-Kankam and Camarinha-Matos [32]	The objective is to address issues concerning ICT communication and tools that support VPP implementation	ICT
Van Summeren et al. [31]	Collaboration between ECs for shared digital technology to support the replication of initiatives	
Van Summeren et al. [9]	The use of ICT to change the way technology operates and strengthen collaboration to increase collective agency	
Hansen et al. [24]	The use of digital technologies and ICT to affect the governance of shared renewable energy systems	
Crosbie et al. [33]	Implication of ICT tools in demand response	
Valdivia and Balcell [34]	The potential role of blockchain technology in enhancing the governance of distributed energy transitions	Blockchain
Adu-Kankam and Camarinha-Matos [35]	How ecosystems interact with the power grid and the role of collaborations	
Kotilainen et al. [36]	Participation of prosumers in the future flexible energy ecosystem	
Adu-Kankam and Camarinha-Matos [18]	The use of digital twins in renewable ECs	Digital twins
Adu-Kankam and Camarinha-Matos [28]	The use of digital twins in the collaborative ecosystem	
Adu-Kankam and Camarinha-Matos [37]	Collaborative behaviors and the ecosystem's resilience and sustainability	
Hill and Duffy [13]	Development of a digital support platform for community energy: One-Stop-Shop architecture	Digital platforms and internet forums
Wittmayer et al. [38]	The agency of multiple actors, and the different types of social relations and activities pursued by energy system actors	
Kloppenburg and Boekelo [21]	The future of digital platforms in energy transition	
Hyysalo et al. [22]	The role of energy internet forums in accelerating energy transition	
Barber et al. [39]	A new collaboration method based on a digital ecosystem	Other digital and smart technologies
Ford et al. [25]	Incorporating smart technologies to accelerate energy system transition	
Fernandez et al. [26]	P2P energy trading using digital technologies	
Hiteva and Foxon [29]	The ability of digital solutions to deliver more social and environmental value	
Boait et al. [40]	The use of smart home technologies to change the community-based business model	
Gui and MacGill [20]	The impact of social, technological, and organizational contexts on clean ECs	

depend heavily on the actors and their interdependencies. But converse to the affiliation view, in later work, the selection of actors and interdependencies are seen to be dependent on the actor's relevancy and contribution to value [46, 50]. Regarding ecosystem structure, the broader literature on inter-organizational collaborations and their innovations highlights innovation ecosystems as being the central construct. Compared to inter-organizational and network-based collaboration, ecosystem-based collaboration is complex, as it includes the amalgamation of diverse and multiple actors that operate beyond the core business activities [4, 37, 46], including value chain partners [51] and intermediary organizations [52]. Thus, building on these concepts, this study conceptualizes the composition of a group of varied actors ranging from consumers to prosumers, ECs to utility companies, and intermediary organizations to research institutes, as interconnected ecologies of actors [6, 51] that work together for energy production, consumption optimization, trading, and storage.

Sustainable energy transition necessitates the development of EC ecosystems involving various actors. The prior literature has emphasized the importance of understanding such collaborative interactions in an ecosystem [4]. Scholars [28] have explored these interactions to understand the engagement between actors and technology enablers in an ecosystem. They found that ecosystem members could collaborate to devise a common goal and engage in collaborative actions by forming a repeated and patterned value constellation, and that the penetration of different technologies (e.g., IoT, smart devices, intelligent applications, peer-to-peer networks, and blockchain) can play an important role in supporting the ecosystem. However, Adu-Kankam and Camarinha-Matos [32] have stressed that as ecosystem collaboration revolves around collaboratively sharing the resources and management of ecosystem operations, it is important to identify the most important partners and their roles in the ecosystem, in order to achieve common goals for the EC. The prior research has further introduced the concepts of a collaborative virtual power plant ecosystem (CVPP-E) and a cognitive household digital twin (CHDT) to support efficient energy performance and sustainability within the EC ecosystem, where CVPP-E is considered as a representation of the digital twin of the EC, and CHDT as an embedded cognitive intelligence platform for autonomous decision-making. Such collaborative behaviors in an ecosystem promote resilience and sustainability and offer mutual benefits and agility to the ecosystem [18, 32, 37]. The integration of certain technologies such as cyber-physical systems, the Internet of Things, and blockchain seems to lead toward future community scenarios where several networked partners, smart devices, and systems will coordinate and operate within an ecosystem in a more collaborative and dependable fashion. Members of such an ecosystem (which is self-sufficient and governed by stakeholders) are motivated by polycentric and decentralized economic, social, technological, and sustainability goals, which flexibly contribute to mutual achievement [35, 37]. In terms of the digitalization of ECs, Adu-Kankam and Camarinha-Matos [18] presented a collaborative digital twin application from an ecosystem perspective. They illustrated a collaborative environment composed of ecosystem actors such as municipalities, distribution and utility companies, business organizations, consumers, and prosumers, with four application layers. Following this model, they contended that an ecosystem-based environment of this kind facilitates sustainable energy consumption and optimization, where surplus energy can be aggregated into a virtual organization, injecting renewable energy into the grid.

Barber et al. [39] suggested that new solutions are needed to address the challenges in wind ECs, which enable co-innovation and co-creation between the different organizations of the digital ecosystem, utilizing emerging digital technologies to integrate and exchange knowledge and information. A collaborative setting of this nature accelerates the process of sharing knowledge and information and enables ecosystem actors to develop digital platforms for co-innovation activities. Adu-Kankam and Camarinha-Matos [35] focused on organizational and governance structures, roles and relationships between different ecosystem actors, and how they interact with the power grid. They found that ECs (including cooperative governance structures) often owned energy resources, and interacted with the grid by injecting the surplus energy from the community. Sustainable energy transition ecosystems and digital transformation can mutually benefit each other by developing solutions that support optimizing the integration of renewable energy. Different actors have different roles and responsibilities within an EC ecosystem, ranging from energy production for the community to achieving common community goals. Hellström et al. [53] explored how firms develop collaborative mechanisms to build business model innovation in distributed energy systems. They found that interaction between ecosystem actors helped design new collaborative mechanisms that supported the establishment of new roles for ecosystem actors, as well as business model innovation, increased collaboration and interdependencies among actors, and generating and capturing system value. Kotilainen et al. [36] presented a prosumer-centric digital energy ecosystem framework based on smart grid technologies, decentralized energy production, a complex network of new and incumbent actors, and business model processes. They argued that in addition to incumbent actors, new entrants from the energy sector are emerging in innovation ecosystems that utilize digital platforms. The authors outlined four layers of the digital energy ecosystem: human activity, value-adding, a digital layer of IoT, and energy processes. Vernay and Sebi [4] adopted an ecosystem perspective to study the characteristics that ECs must exhibit to fully realize their potential in energy transition. They argued that the ecosystem around the EC could help fully realize its potential, where the keystone actors play a central role and foster diversity, pool resources, coordinate their actions, and facilitate the energy sector's transformation through building relationships. Wittmayer et al. [38] conducted a comparative analysis of collective renewable energy prosumer initiatives from several European countries. They found that energy production did not happen in isolation, but rather in collaboration and networking with other ecosystem actors, through developing new digitalized energy infrastructure, new organizational and governance settings, and educational endeavors linked to renewable energy production and consumption.

In sum, the prior research on the ecosystem perspective regarding ECs has mainly focused on understanding how an ecosystem can or may function and support various actors [4, 18, 28, 32, 36, 37]. Information, knowledge, and resource sharing as well as their organization through different actors within an ecosystem are seen as critical activities in EC ecosystem collaboration. However, the present literature lacks an empirical understanding of how ECs are digitally mediated to present the potential benefits of digitalization to the EC ecosystem, and how ecosystem actors perceive the role of digitalization in the emergence and scaling of ECs.

Methods

The unit of analysis adopted in this paper is an EC ecosystem formed by various actors with a common interest in medium-scale collaborative energy-related initiatives, working in energy production, consumption optimization, trading, and storage. We conducted the study in Finland, which liberalized its energy market in the mid-90 s [54], with a 75% lower electricity generation carbon intensity than the EU average [55]. In Finland, dynamic electricity contracts have been available to residential consumers since the market opened in 1998, and nearly every energy retail company offers spot-based contracts for residential, commercial, and industrial users [56]. The country has been highly successful in household-level energy transition, and energy transition momentum has started to gather pace at the community level. The regulatory environment has recently become more favorable for collaborative initiatives, and follows the Clean Energy for All Europeans Legislative Package (CEP). In practice, electricity distribution companies (DCs) were obligated to offer a specific virtual net metering service to ECs from the beginning of 2023. Finnish electricity market regulation defines local ECs as “a legal entity that produces, supplies, consumes, aggregates, stores energy, or provides energy efficiency services, electric vehicle charging services or other energy services to its members or shareholders” [57]. In Finland, technical details (e.g., the proximity of properties – distance in meters) are not strictly defined in the legislation, and are determined by property boundaries (i.e., communities inside a single property or cross-property with the adjacent property are allowed). Three types of energy communities are recognized. Single-property energy communities and cross-property energy communities can be implemented according to the current regulations. However, the regulation of a third type of dispersed energy communities has not yet been finalized [58].

We started collecting data with DCs, and followed a snowball sampling strategy for interviews [59]. All interviewees were asked to give referrals that might identify other relevant actors who could provide valuable information for our study. We continued our data collection for as long as we could find new actor organizations to accept our interview requests.

First, we contacted the largest electricity distribution company in Finland, which had already provided balance settlement and metering services during the transition period of 2020–2022, prior to the new regulation that obligated the provision of balance settlement to local ECs in the country. We also selected two local DCs that had started EC-targeted businesses when the obligation entered into force.

Our final sample (Table 2) includes organizations that constitute an integral part of the value chain (i.e., involving monetary exchange within the interconnected value chain), and other actors who played intermediating and supporting roles without business relationships. Interviews were conducted with three ECs, one of which had a for-profit actor as a heat provider for the community. In addition, we interviewed other ecosystem actors, including other DCs, technology providers, for-profit intermediary organizations (companies working between sellers and users and providing consulting services), non-profit intermediaries, research institutes, and also a regulator. In all, we carried out 22 interviews with an average interview duration of 60 min. The interviews were conducted online between February and November 2023 with participants from across Finland.

Our research centers on understanding digitalization’s role, and its promising benefits in emerging organizational forms of ECs which may contribute to the decarbonization of the energy system. Digitalization is emerging in EC and business ecosystems, and changing various practices in regard to generation, consumption, and social interaction. Thus, our data collection strategy and interview guides focused on questions concerning digitalization: current offerings, coordination, information sharing and collaboration, business models, and future developments.

In our analytical process, we first separated the data based on actor groups into ECs, for-profit organizations, intermediaries, research organizations, and regulators. We used NVivo and Excel software to code and organize the data. We coded all of the interviews, constructed thematic categories by actor, and retrieved illustrative quotes for each thematic category. Within the coding, we followed an inductive coding process for the main categories of digitalization, collaboration and business models, and future development. In our thematic analysis, we constructed emerging themes [60, 61] to build a foundation for theorization.

Results

Our study provides considerable insights into the role of digital mediation regarding ECs from the ecosystem actors’ perspective. Although the interviewed actor groups have different roles, responsibilities and interests in the context of ECs, all of them emphasized the importance of digitalization and digital platforms for the evolution of the EC ecosystem. Thus, we first look at the benefits of digitalization for the actors identified in this early phase of EC ecosystem evolution. Second, we analyze what kind of EC platform would nourish and enforce

Table 2 List of interviewees and their organizational background

Interviewee's organizational role	Organization in detail	Organization type	Goals/actions
CEO	Heat and power company	For-profit, (EC1)	Fostering community engagement in renewable energy projects
Project Manager	EC	(EC2)	
EC member	EC	(EC3)	
Energy Manager	DC	For-profit (FP1)	Facilitating the formation of energy communities and integrating surplus energy supply
Head of New Ventures	DC	For-profit (FP2)	
Product Manager	DC	For-profit (FP3)	
Product Manager	Technology provider	For-profit (FP4)	Offering various technologies and solutions to the energy communities
Sales Director	Solar solution provider	Intermediary, for-profit (IFP1)	
Development Manager	Solar solution provider	Intermediary, for-profit (IFP2)	
CEO	Energy consulting	Intermediary, for-profit (IFP3)	
Executive Director	An advocacy group of homeowners	Intermediary (I1)	Advocacy, promoting energy community related solutions, and supporting collaboration among actors
Advocacy Manager	An advocacy group of local energy companies in Finland	Intermediary (I2)	
Executive Director	Association promoting local energy	Intermediary (I3)	
Expert, energy, energy politics, energy markets, bioenergy, and international climate policy	The Central Union of Agricultural Producers and Forest Owners (MTK)	Intermediary (I4)	
Leading Expert, Energy and Climate	The Finnish Real Estate Federation (FREF) (central association for property owners in Finland)	Intermediary (I5)	
Specialist	Energy counseling organization	Intermediary (I6)	
Senior Specialist, Energy Markets	Energy industry advocacy group	Intermediary (I7)	
Senior Advisor, Energy Markets	Energy markets regulator	Intermediary (18)	
Senior Specialist	Research institute	Research (R1)	Conducting advanced research in the energy field
Professor	University	Research (R2)	
Post-doctoral Researcher	University	Research (R3)	
Professor	University	Research (R4)	

the EC ecosystem, and foster scaling the number and level of operations of ECs.

The benefits of digital mediation in the early phase of the EC ecosystem

In the current emerging state of the EC ecosystem, there are actors who contribute to its evolution, but the connections between them are often ad hoc and not well-enough established to solidly support the evolution. Digitalization is seen by all actors as an essential element in the pathway to a successful EC ecosystem. However, the interviewees all stated that the digital platforms and tools currently used for intermediation in the context of ECs are only partial solutions. Thus, EC managers and other ecosystem actors use separate tools for communication, and many other tools for operational functions. Several data interfaces exist to retrieve and exchange data, while a separate service may be used to monitor EC operations, and other digital tools to control operations. Thus, a digital base for an EC has to currently be constructed from several separate and often non-interoperable or non-standardized digital tools, for a variety of purposes and for diverse connections between actors. The interviewees stated that there is a lack of digital service providers and consequent services for ECs and other ecosystem actors. This may be due to the ambiguity of the conceptualization of ECs, and the increasingly complex and rapidly changing energy policies, regulations, technologies, and wider business environment. In the currently nascent EC ecosystem, it is not clear who the users of the digital platform would be, and for what purpose they might need the digital platform. Moreover, the discourse is even more confused since there are different yet ill-defined layers within the EC that are characterized by diverse requirements, attributes, functions, and relevant actors [62].

That said, according to the interviewees, the existing tools already benefit ECs and various actors. In the following, we explore the main benefits of digitalization that emerged from the interviews (Table 3) and illustrate the benefits with quotations from the interviews.

Monitoring energy generation, consumption, and balancing: Currently, ECs are provided with the possibility to monitor the generation, consumption, and

Table 3 The main benefits of digitalization with empirical examples

Benefits of digitalization	Examples of benefits	No. of organizations showing strong evidence
Monitoring energy generation, consumption, and balancing	Fingrid net metering solution service based on Datahub that provides ECs with access to customer data on generation, consumption, and selling via the Datahub customer portal	FP2 EC3 IFP1
Data retrieval, exchange, and optimization	Digital services provide ECs with data that are used to estimate the optimal energy generation capacity, and for planning and controlling EC's operation. External data: e.g., day-ahead hourly market prices, balancing reserve market calls and price information, weather forecasts from Finland's National Weather Institute, and the status of the national electricity grid from the transmission system operator (TSO). Internal data: e.g., energy generation, consumption, diverse energy assets, and economic transactions and balances	FP3 I1 I7 IFP3
Digital commerce and contracts	Following energy selling prices and energy bidding market prices, and management of contracts with utilities, energy companies, service providers, and within the EC. Participation on reserve markets	EC1 IFP1
Communication between EC members and other EC ecosystem actors	Use of standard tools such as Teams and Zoom for communication between actors, and for knowledge sharing, discussion, and joint initiatives,	EC3 FP4 I6
Decision-making support	Planning and managing EC, and making decisions on investments and development based on data of EC energy generation and consumption	FP2 I4

balancing of the EC energy. In 2023, the regulation of ECs changed in Finland, aiming to enable ECs and prosumer processes. The national transmission operator Fingrid offers all 80 distribution companies in Finland a "virtual EC" via a net metering solution service, enabling the easy set-up of ECs within single land plots and flats [63]. It is based on Datahub, which is a centralized data exchange system for the electricity retail market, and provides consumers and communities with access to customer data on generation, consumption, and selling via the Datahub customer portal. Also, users may follow potential results on selling to the reserve balancing markets.

> *"There's one management interface available for whoever's the manager of the EC, and then there are separate interfaces for each of the members of the EC, so they can follow up on how much they get… or on their share of the distributed energy." (FP2).*
> *"These ECs have a digital platform where the EC is managed. This is currently offered mainly by the utilities because they must, by law. I mean [they offer] the billing platform, […], but it does not offer other functions [related to the EC]." (IFP1).*

Data retrieval, exchange, and optimization are growing in importance, especially according to EC and research actors. Digital services provide ECs with information that may help them estimate the optimal energy generation capacity. To do so, ECs retrieve data from multiple external sources, for example, day-ahead hourly market prices, balancing reserve market calls and price information, weather forecasts from Finland's national weather institute, and the status of the national electricity grid from the transmission system operator (TSO). These data are used for planning and controlling the EC's operation.

> *"And this is also offered to the housing company, […] [to estimate] what size would be suitable for the housing company panel system, when net billing is used." (FP3).*

Furthermore, the ECs generate internal data on generation, consumption, diverse energy assets, as well as economic transactions and balances. With digital tools, ECs share internally generated data with members, investors, utilities, TSOs, service providers, and in piloting cases with research organizations.

Digital commerce and contracts. Actors follow energy selling prices and energy bidding market prices, and can easily modify their contracts with utilities, service providers, and within the EC using digital tools. In other words, market participation is emphasized by the actors. However, ECs go the extra mile to optimize their system size to avoid excess generation. The system's profitability is defined by self-consumption, and although a community can obtain revenue from selling electricity to markets, it is typically not very profitable for the communities. Accordingly, while communities participate in markets and benefit from markets at some level, their main aim seems to be to maximize operations that take place outside of the market within the community's borders.

"We're getting weather forecasts daily, and energy price forecasts. We can then create a production plan and calculate whether it's viable to produce electricity at all [...]. And with this electricity, we're able to participate in the Nordic energy market [...]" (EC1).

Communication between EC members and other EC ecosystem actors. Standard tools such as Teams and Zoom are used for communication and collaboration within ecosystems. Communication with all actors is crucial in creating and strengthening the EC ecosystem, since there are numerous interlinkages between actors, and many open questions that require knowledge sharing, discussion, and joint initiatives, for example, business case-related work and setting standards and rules for the EC ecosystem. These aspects are particularly important in the early stages of setting up an EC. According to intermediaries, communication and consulting networks for communities exist, and intermediaries have a significant role in this function. However, focal communities and research organizations expressed a lack of support when setting up, monitoring, controlling, and optimizing EC operations.

"We want to disseminate the knowledge we've learned here. We want to let the people know this is technically possible at the moment. And you could benefit from this—with some restrictions and with some good implementation and good engineering you could benefit a lot from this type of microgrid or EC. So, this is just to let everybody know this is possible, how we've done it, and so on." (EC3).

Decision-making support. Historical data on EC energy generation and consumption help in planning the future management of the EC and investment decision-making.

"Also, our service allows collection of historical consumption data that could be useful when establishing the EC or planning solar power investments." (FP2).

Figure 1 demonstrates how ecosystem actors are currently connected with each other and within an EC using multiple digital solutions for communication, data exchange, and energy management. The existing solutions are rarely interoperable and fully integrated. Gaps and weak or irregular digital mediation appear between actors. If any business models are implemented on the digital platforms, they are incomplete and there is a lack of support for EC planning, monitoring, and communication.

Besides the benefits described, there are several existing challenges in the current state of digitally mediated EC ecosystems. Despite the importance of digital platforms and applications to the evolution of the EC ecosystem,

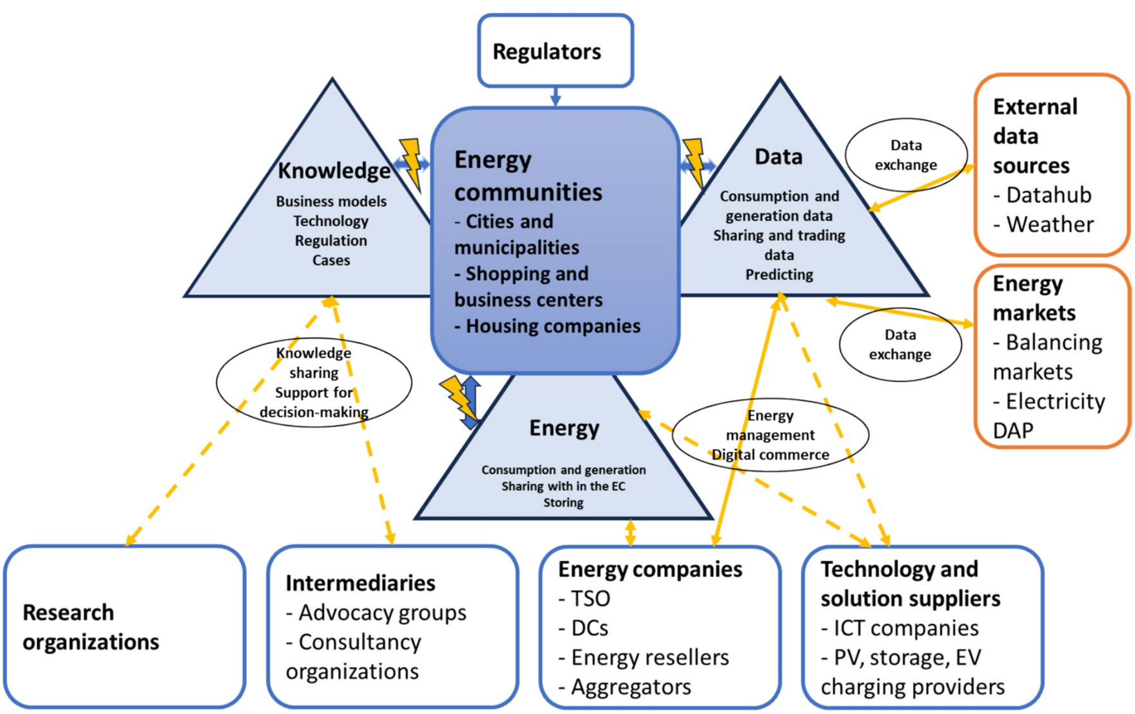

Fig. 1 The benefits of digitalization for the EC

actors were unaware of the specific digital EC platforms, services, and software that are available. According to the interviewees, current digital tools used in the emerging ecosystem by ECs and their collaborators for EC planning, monitoring, control, and communication comprise scattered and often non-interoperable solutions. There is a significant need to develop the services toward interoperable, comprehensive, and easy-to-use products. Some of the interviewees noted a lack of actors who could possibly take responsibility for developing and maintaining a digital platform that would take digital mediation to the next level.

Here, there is a chicken-and-egg problem with digitalization in the EC ecosystem. Various actors underlined that the main reason for their unmet needs is that there is no business case, given the small number of ECs and the uncertainty of profitable business for commercial actors. At the same time, the lack of services slows the scalability of the EC concept. In this scenario the regulator's role could be influential, but is focused on facilitating solutions through market dynamics instead of providing financial support that would allow business models to evolve independently.

Envisioning the future—the potential of digitalization in ECs

A comprehensive digital platform that combines multiple existing partial solutions is expected to be the basis for all three dimensions of sustainability: economic, environmental, and social. As shown in Table 4, all actors expressed the need for a platform from which to operate an EC for data management and the optimization of the EC's production and consumption. Also, commercial providers and research organizations especially emphasized the benefit of a digital platform in the planning phase of the EC to estimate the return on investment and to design the business model. Furthermore, the digital platform should include governing structures, regulation, and data exchange with other stakeholders, and enable communication within the EC, as well as with external data sources and stakeholders.

Next-generation trading and storage system. The emerging EC ecosystem opens up opportunities for new kinds of energy trading markets, and commercial providers paid particular attention to the role of digital mediation in enabling automated energy trading systems. The members of the EC might have different kinds of contracts with diverse parameters, and the system would optimize the sharing of energy within the community by combining contract data with the data on generation, energy prices, and consumption to meet the varying needs of each EC member.

> *"Creating additional value for the ECs by optimizing the share of the energy distributed among the members, [...] there might be some kind of internal energy trading within the EC, so that there isn't any fixed share, [...], but it's just based on the needs of the members of communities, so those with a bigger need could buy a bigger share of the production within this internal market, within the EC.[...] to maximize the value created of their own generation in that way." (FP2).*

Also, representatives of ECs, intermediaries, and research organizations underlined a need to optimize energy generation and consumption, storage, and possibly other energy assets within the EC. Digitalization is a necessary enabler for that, and would add value for community members and foster the scaling of the EC ecosystem.

> *"The status of the system might become even more important if we have a future system where we have EV charging, their batteries, and maybe some stationary batteries at the EC, and when you have this kind of storage system, whether it's the stationary battery or EV, then it's no longer about just the generation and the consumption, but also the battery capacity within the system." (R3).*

ECs emphasized that a digital optimization system of this type should be transparent and fair, and agreed on and understood by all community members. The optimization principles and data, near real-time operation, and results should be communicated and easily monitored by all community members. Research organizations were further concerned about the amount of data needed for optimization, and how to keep the optimization interface open, simple, and attractive.

Digital communication within and across EC boundaries was considered to be one of the most essential aspects of digitalization in the EC ecosystem by ECs, research organizations, and commercial providers. Communication between all actors is required to strengthen and scale the EC ecosystem, and digitalization enables that process. Also, the actors raised a point about multi-level communication needs for discussions, automated or discussed agreements, data retrieval, sharing and exchange, and informing community members and external actors.

> *"There will be someone who then combines all these different services as a one-stop shop principle for the customer in the same way, then the EC gets this energy and flexibility and energy management, and so it would be easiest for the EC if someone combines all this." (R4).*

Table 4 Envisioned benefits of digitalization

Digitalized element	Envisioned benefits	Examples of benefits	Number of organizations showing strong evidence
Next-generation trading and storage system	Developing an automated energy trading system	The members of the EC might have different kinds of contracts with diverse parameters, and the system would optimize the sharing of energy within the EC to meet the needs of each member	FP2
	Storage system and cost optimization	Optimization of energy generation and consumption, storage, and possibly other energy assets within the EC	FP1 FP2 IM7 EC3 R3 R4
Digital communication within and across boundaries	Digital communication system	Communication between EC members and other actors in the EC ecosystem. Multi-level communication needs discussion, automated or discussed agreements, data retrieval, sharing, and exchange of information within the EC and with external actors	EC1 R4 FP2
	Interaction between communities	Virtual EC for trading and sharing information between ECs	FP2
Platform economy-based new business models	Return on investment	Measuring investments in the EC, calculating pay-back time	FP2
	Planning aid for an EC	Relevant parameters of EC operation models, scenario testing	R2
	New business models	Innovations, new business opportunities. Merging of separate services and products as service packages. Change of roles of actors, new roles, new actors	IFP2 IFP3 FP4 I4 I6 R4 I7
	Possible integration of different technologies and data at the community level through digitalization (platform economy)	A comprehensive digital platform to integrate separate services and data for EC business, management, and optimization models, agreements, and regulations. Sharing data and information for and between ECs. Built-in structures and tools to plan and operate the EC	FP4 EC1 R3 R4 I7
	Demand response	Demand flexibility within the EC, locally and nationally	EC1 R3 R4

Intermediaries were expected by other actors to function as important hubs for communication, to inform and activate other actors, and to participate in the development and standardization of the field. However, intermediaries themselves saw their role as one-way informants, as opposed to providing the ecosystem with digital tools or space for communication.

Platform economy-based new business models. Energy trading markets and communication enabled by digitalization are closely related to the third key role of digitalization in the EC ecosystem that actors brought up – namely new platform economy-based business models. According to commercial providers, intermediaries, and research organizations, digitalization fosters the emergence of new business models, as well as changes in actors' current roles. For example, solar panel providers have already expanded their business into storage and other energy assets. They are also expanding into software, thus redefining their role and the whole EC business model.

> *"Well, in any case, I believe the individual companies (currently hardware sellers) will expand their business into software, too. That's inevitable. And in order to survive in the market, they have to expand their role in the whole value chain." (IFP2).*
> *"[T]hese digital services [...] start from the fact that there's data which is then combined in some way, and from there we get some added value from the data. There must be a new opportunity where different actors have different roles and opportunities. So, when [new] data-based services arrive, these again introduce different needs to different customers." (R4).*

Research organizations expect the digital EC platform or tool to support ECs' planning activities. At this time, EC business, management, and optimization models, agreements, and regulations are not implemented in any single digital tool or service. There is also a lack of a centralized service for sharing data and information for and between ECs. Information has to be collected from websites, and by inquiry from other actors in the ecosystems. Research organizations envisioned a digital platform providing ECs with built-in structures and tools to plan and operate the EC. One commercial provider and one researcher thought that the digital platform or tool might be used for business and investment planning, for example, calculating return on investment. Besides business planning and management, a digital platform should provide ECs with an integrated set of services and technologies. In the current situation, there is a lack of integrability and interoperability, and all actors expressed both a lack of and need to integrate current and future digital services and technologies. The integration of digital solutions, interfaces, and standardization is also required to realize demand response in the EC.

> *"[I]t is the platform economy and this mentality that will certainly be part of this world, too, and just as I mentioned, our accelerator ecosystem shows we're also going more and more into this platform world. Yes, it's significant, and it's part of this, part of this whole. That's how these digital services are structured, how to offer the customer the benefits." (FP1).*

All actors indicated that demand flexibility and participation in demand flexibility markets require a cross-cutting and open digital system for ECs. Commercial providers envisioned the possibilities that communication between ECs could bring, including optimization and demand flexibility. However, when it comes to participation in the energy markets (e.g., balancing reserve markets), there seems to be a discrepancy between the goals and visions set for ECs by other actors, and those set by the ECs themselves. The ECs emphasized their aim for optimal self-consumption within the EC, rather than seeking profit from external energy markets.

Discussion

This study has examined the role of digital mediation in ECs navigating energy transition. The contribution of the paper is two-fold. First, this study contributes to the energy community literature by identifying the benefits of digital mediation among the ecology of actors that interact with ECs. Second, our paper contributes conceptually to the ecosystem literature by demonstrating how the early stages of EC ecosystems characterize a loosely connected ecology of actors, rather than an EC ecosystem. This research elaborates on how the actors envision the future ecosystem with interdependent and collective value creation to scale the energy community within the energy system. In doing so, this study reveals the crucial role of platformization in the EC context.

Contributions to the energy community literature

Prior research has addressed digital tools to support energy technology implementation for EC functions [18, 34]. Our broad empirical inquiry on the role of digital mediation in ECs brings to the fore digital mediation's diverse range of benefits for ECs. These are visible regardless of the present state, which is based on loosely connected actors [6, 64] rather than an ecosystem per se. These benefits also go well beyond the operational, such as using digital tools just to implement energy technologies.

Our findings confirm earlier discoveries on how digital mediation enhances and expands the operational possibilities to raise EC performance through data retrieval, exchange and optimization. ECs can share data with diverse groups of actors such as investors, utilities, TSOs, and service providers, maximize sustainable self-consumption [9, 33, 38], and optimize how surplus energy is aggregated and injected into the grid [18]. Digital mediation enables market transactions between energy communities and other energy providers and users. As the Nordic power market is based on the principle that electricity production and trading should be market based, the electricity market also allows households and communities to generate and sell energy on the market. Thus, digitally mediated ECs ensure effective peer-to-peer trading and demand response technology, for example, energy storage [40], and utilize digital platforms to harness energy management techniques which support better decision-making and minimize potential complexities related to renewables [18]. The decision-making involved further links to questions related to the expansion of the system, profitability calculations, and estimations, which are crucial to higher performance and system optimization.

Contributions to ecosystems literature

Our analysis reveals the current state of the EC ecosystem, which is characterized as a loosely coordinated ecology of actors that interact with the focal communities. These interactions are mostly based on traditional energy supply chain transactions, involving intermediaries who promote policies and collaboration for scaling energy communities, and research organizations that advance scientific knowledge and technological innovations through interdisciplinary projects. Distribution companies play a crucial role by facilitating the integration of energy communities with the national grid providing necessary infrastructure and services, while for-profit companies deliver the essential technologies and offer installation and maintenance services tailored to the needs of these communities. Energy communities themselves form the core of this ecosystem, in the form of grassroots initiatives by individuals to produce, consume, and manage energy resources sustainably. All ecosystem actors appreciate and value the generic digital platforms that are available for coordination and communication. But while these technologies are undoubtedly of assistance, they are not optimized for discovery or for other participants, or tailored for efficient information exchange in the EC ecosystem context. In other words, there is a need to share experiences and for peer-to-peer support in planning phases and community operations through a joint platform for all the ecosystem actors that properly supports the current modes.

Prior research has focused on digital platforms in terms of energy provision [21], advancing projects, and connecting and sharing experiences with other communities [13]. Our findings emphasized the essential need to develop digital platforms for future EC ecosystems, with the potential to form a functioning EC ecosystem where different actors are interdependent and coevolve [65]. Digital platforms are considered as spaces that enable users to communicate and interact, and facilitate access to products, services, or resources [21]. A digitally mediated platform can function as the glue among different ecosystem actors through utilizing joint digital platforms and transactions, and support clarification of the roles and responsibilities of different actors [9]. A holistic digital platform can enable transactional architecture linking all community actors [13] and support accurate planning and calculation of the size and capacity of renewable energy technology, as well as its related return on investment. The benefits of platformization include tools for EC managers to draw from various digital sources, in order to assess goal prospects. In practical terms, an ecosystem manager may query aspects such as weather forecasting systems, distribution service operators, the energy market, and bidding market prices [32]. Upon identifying an opportunity, the manager formulates the community goal and invites ecosystem members to establish an energy production plan, calculate the size and capacity of renewable technology, and develop contracts.

In scaling ECs, digital mediation can offer new entrants increased transparency, which helps them overcome their initial struggles to understand the EC ecosystem objectives and operations, and also to collaborate with different stakeholders [36]. Similar peer-to-peer support networks exist for individual users and households [19, 22], but not for ECs. Particularly, in a large country with a sparse population such as Finland, digital tools that bring together ECs for social learning and peer support would be crucial to scaling this nascent organizational innovation.

The evidence from this study points toward the idea of a framework for an EC digital platform that integrates customized tools and interfaces based on knowledge, data, and energy as layers within the platform, rather than as separate entities. Digital platforms aggregate distributed resources and do not own those assets (for example, in the cases of Airbnb or Uber) [21], but enable digital transactions between peers. A digitally mediated EC ecosystem platform can share these characteristics by connecting all of the ecosystem actors. In line with the suggestions of Silvast et al. [62], the evidence of this study indicates that a layered platform structure enables diverse actors to form a true ecosystem. As illustrated in Fig. 2, one comprehensive yet flexible digital platform enables

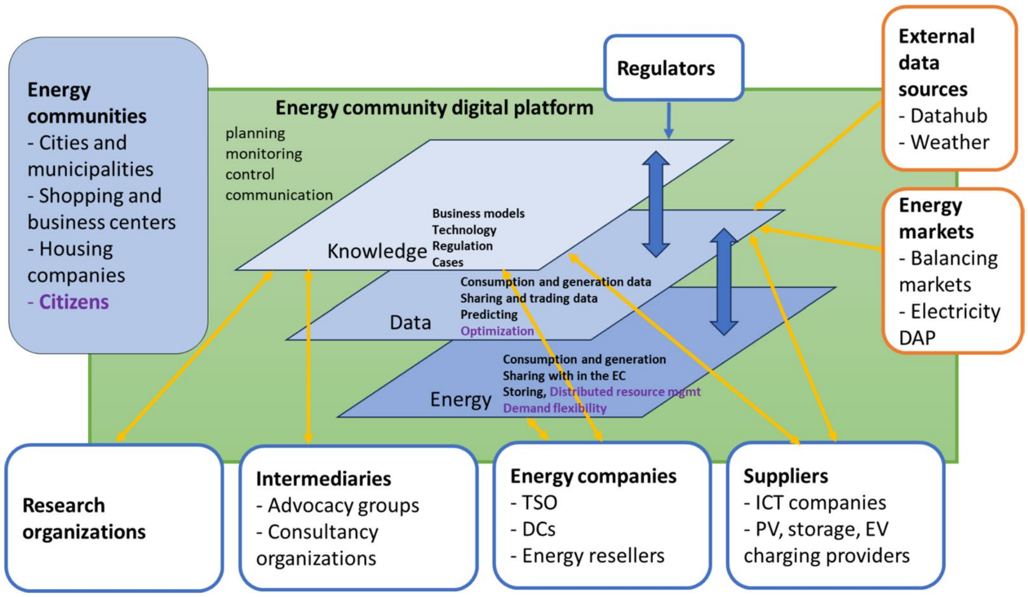

Fig. 2 Envisioning the future EC ecosystem digital platform

and eases the planning and optimization of energy communities. It also facilitates more efficient communication among energy community actors and with other ecosystem actors, thus strengthening the entire EC ecosystem. A digital EC platform will strengthen the EC ecosystem and lower the barriers for citizens to initiate and join ECs, as well as enable advanced digital technologies in the EC, such as optimization of energy generation and use in the EC, smart distributed resource management, and demand flexibility.

However, the exact choice of business model remains an open question. The regulatory environment is very particular, offering not only opportunities but also, for instance, legal limits related to the monopoly positions of key actors such as distribution companies. The context impacts the roles of different actors and the business opportunities of platform organizers. For example, the internationalization opportunities related to a platform may be limited by country-specific regulatory environments. In other words, a successful EC platform in one market may not succeed in another, at least not without modification. This is because the electricity sector is deeply regulated with country-specific features, compared to the more typical sharing economy applications which are based on the facilitation of the use of underused assets [66]. In the case of energy, the central part of the platform and sharing is about a consumable commodity with immediate use value shared over highly regulated infrastructures.

Our findings on the lack of digital service providers and consequent services for ECs highlight the importance of developing an unambiguous conceptualization of ECs and their related energy policies, regulations, and business environment, and we discuss these aspects in our implications for practice and policy.

Conclusions

This study underscores the importance of digital mediation in scaling and strengthening the EC ecosystem. Based on 22 interviews with EC representatives and the ecology of actors in Finland, the findings of this study highlight that digital mediation supports ECs in monitoring and controlling their operations, and in addressing demand response and trading through data retrieval, exchange, and optimization, so contributing to better decision-making. The existing ecology of actors envisions a developed digitally mediated EC ecosystem that can enable the sharing of experiences, peer-to-peer support in planning phases, and the operations of EC communities. The findings demonstrate that the early stages of EC ecosystems are characterized more by a loosely connected ecology of actors, rather than a fully developed EC ecosystem. In so doing, this research highlights the crucial role of platformization in the EC context.

While this study has revealed several valuable insights, it is important to acknowledge some study limitations. This research studied the ecology of actors around ECs, the actors' subsequent interactions through digital mediation, and how they envision a well-functioning EC ecosystem. Future research could study a business case of a digitally mediated EC ecosystem to better understand the nature of interdependencies between actors and the related interoperability issues. Such a study would enhance our understanding of how the role of digital mediation varies in different settings, and how contextual factors influence the process of developing a digitally mediated EC ecosystem. Furthermore, increased digitalization brings with it several opportunities and challenges for businesses, which necessitates new modes of operation and business models for EC ecosystem actors. This underscores the need for further research to explore the transformative impact of digital mediation on the business models of ecosystem actors, as well as ECs as a whole. Further research could also study the ownership level and operational capacities of digital platforms, as our study offers a limited understanding of these issues.

Practical implications

Our findings imply that there is a lack of awareness, availability, and standardization of the digital tools used by ecosystem actors and ECs. Based on our analysis, our findings underscore that it is difficult for any single community to independently place itself in a position to achieve its operational goals and that it would require systematic engagement with the various actors to turn collaboration into a well-functioning ecosystem. EC managers should explore and develop mechanisms to observe the emergence of EC ecosystems, not only to envision how an ecosystem must be structured while mapping the actors but also to exploit the full potential of ECs in contributing to sectorial change. EC managers can lead the responsibilities for coordination, opportunity brokerage, and the administration of digitally mediated ecosystem collaborations by sharing data with the diverse ecology of actors, in order to ensure sustainable self-consumption, profitability calculations, and optimization. Given that this study found no digital solution provider for ECs to enhance their operational capacities, actors who actively develop such solutions for the energy system can facilitate setting up a digitally mediated EC ecosystem. EC managers should determine their community's objectives and business model, utilizing digital platforms to evaluate prospects—for instance in regard to weather forecasts, distribution services, and market prices.

Policy implications

To address data privacy and security challenges, policymakers need to set precise requirements for the utilization and management of data generated by ECs. Increased access to data would not only enable the emergence of various data-driven services and solutions but also stimulate the overall digital transformation of the energy sector. The lack of essential solutions for ECs calls for the entry of new digital service providers to accelerate the development of new solutions. Governments should consider providing incentives and implementing a favorable regulatory framework to encourage more actors to experiment with new solutions and seize opportunities beyond the scope of their conventional business. In addition, the results show that a comprehensive digital platform is essential to provide ECs with the services they require, and to strengthen collaboration between the ECs and supporting actors. Establishing a platform of this kind would allow ECs to access all of the required services on a single platform, thus simplifying the formation and management of the ECs themselves. It would be more effective if government agencies were at the forefront of developing and promoting such a platform. In order to avoid path dependency, governments should take the lead in collectively defining a shared vision of digital transformation for ECs and the energy sector. This clarity would enable EC and other actors to mobilize their resources and align their digitalization priorities with the industry-level vision.

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Author contribution
KS contributed to conceptualization, methodology, supervision, investigation, validation, and writing—reviewing and editing. ST contributed to data curation, visualization, and writing—original, reviewing, and editing. JJ contributed to conceptualization, methodology, supervision, investigation, validation, writing—reviewing and editing, and funding. HY was involved in writing—reviewing and editing, data curation, and analysis and results writing.

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Availability of data and materials
The datasets generated and/or analyzed during the current study are not publicly available due to the respondents' anonymity and privacy but are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
Since the manuscript does not report any data on human or animal, the human participation (through reporting their statements) was ethically approved and the respondents' anonymity was ensured prior to conducting research.

Consent for publication
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Competing interests
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