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Implications of open eco-innovation for sustainable development: Evidence from the European renewable energy sector

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ABSTRACT

This study aims to look inside the vague construct of an open eco-innovation (OE) network to reveal underlying strategic factors of combining complementary resources to overcome complexity. Results show that uncertain economic outcomes might reduce the motives of certain partners to engage in OE. In this case, OE network transformation is needed to reduce risks of market failure, driven by bridging nodes. This transformation should focus on exploration and future complementarities of network members, instead of exploitation and existing complementarities, despite technological maturity. This study is the first to demonstrate the significance of future complementarities in OE network evolution.

1. Introduction

Over the past decades, sustainable development has been argued to induce environmentally beneficial technologies, strategic changes, and innovations by larger and smaller firms [1]. Indeed, sustainability terms have been combined with innovation, such as eco-, environmental, or green innovation, which are often interconnected with energy terms as well [2]. However, these terms are often used interchangeably, such as green or eco-innovation (EI), both of which can refer to products, processes, or methods contributing to environmental sustainability [3].

Recent research often approaches EI from an inter-organizational perspective, and highlights the effects of dyadic collaborations [4], inter-organizational networks [5], innovation ecosystems [6], absorptive capacity [7], and open innovation (OI) [8]. As confirmed by multiple literature reviews, these studies are quite consistent in their strategic assumptions about "what to do" and "why". Accordingly, EI initiatives should be realized through collaborations because of the diverse external resource- and knowledge needs, so, (eco-innovative) organizations must cooperate to overcome individual resource constraints [9–12]. Nevertheless, the dynamics of OE network evolution, which occurs owing to changing strategic or complementarity challenges in turbulent external contexts, is not evident. Consequently, this study, focuses rather on the "how" with a longitudinal approach and aims to answer (RQ) *how an OE network (should) evolve over time concerning complementary resources, to contribute to sustainable development.*

By answering this research question, the goal is to address a theoretically (and methodologically) relevant research gap. In theory, there are certain underlying strategic problems of ecological and green energy innovations, both of which are also related to the output side (i.e., commercialization), not only the input side (i.e., combining complementary resources within an inter-organizational OE network). A fundamental market problem of EI is that the "benefits of natural capital depletion are privatised, while the costs are often externalized" [4, p. 4] which leads to a higher risk of market failure. Also, the potential spillover of new and valuable knowledge can also discourage partners from heavily investing in EI [12]. Sectoral characteristics might induce further difficulties. For example, while the energy sector would need rapid and radical advancements, highly innovative solutions could be difficult to implement, because of the degree of novelty, system-wide consequences, and implementation windows with time constraints [13]. While these are serious strategic concerns for sustainable development, less is known about what happens within an OE network between sourcing inputs and producing outputs. Quantitative EI studies can provide suggestions only about certain casualties of – mainly

Abbreviations: CCUS, carbon capture, utilization & storage; EI, eco-innovation; EU ETS, EU emissions trading system; OE, open eco-innovation; OI, open innovation; P2G, power-to-gas; SNG, synthetic natural gas; SDG, sustainable development goal.

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knowledge related – input and output factors (e.g., based on external sourcing [8,7], regulation [14], or eco-innovation behavior [15]). At the same time, these studies are unsuitable to grasp the complex strategic (and not always knowledge-related) challenges of an OE network in a constantly changing external environment. In line with these observations, Sanni and Verdolini [12] noted that "the majority of the studies on OE are quantitative leaving […] in-depth qualitative and case studies few and far between. Meanwhile, qualitative approaches are known to have the potentials to advance theories on inter-organizational collaborations" [12, p. 9].

Our study directly responds to this call, as it aims to look into the "black box" of an inter-organizational OE network by using the extended case study method. The contribution of this research to the OE literature is twofold. First, based on the origins and the advancements of the resource-based view, our findings fine-tune a frequent underlying idea about complementarities in OE by highlighting the role of the time-horizon. In particular, the conclusions differentiate existing versus future complementarities as underlying factors of network evolution, which could be useful for theorizing and facilitating new collaborations of organizations for sustainable development. The qualitative nature of the study enables us to illustrate how the vague construct of an OE network is structured and evolves over time, which – to the best of our knowledge – prior quantitative and the few qualitative OE studies overlooked. Second, these theoretical questions have vast importance in practice. Understanding the structure and evolution of an OE network would be important to enable specific interventions of policymakers and ecosystem builders to engage and incite more and more actors to contribute to sustainable development. For example, strategic planning of sustainable development initiatives, such as EI projects, has an increased significance in the European energy sector, where geopolitical changes induced fundamental challenges, and the green transition and economic progress are heavily emphasized by policymakers (e.g., the REPowerEU Plan) [16]. This trend is also relevant on a corporate level, as energy companies should reconfigure their operations and innovate in line with the expectations about energy efficiency, renewable energy, or pollution prevention [17].

The study is structured as follows. In Section 2, it is summarized what we (do not) know about inter-organizational collaboration in the OE context, and propositional knowledge is developed for the missing parts, based on general management theories. Section 3 details the research context and methodological considerations are presented. After that, the results are presented in Section 4. Section 5 discusses the results from the resource-based view, moreover, implications for trending OE areas are also outlined, i.e., green absorptive capacity, circular economy, and EI intermediation [12]. Finally, conclusions, limitations, and further research directions are elaborated in Section 6.

2. Background

2.1. Inter-organizational collaboration in the OE context

OI and EI together seem to be important for sustainable development, as "open innovation positively affects firms' green product and green process innovation performance" [8, p. 21], moreover, collaboration and openness could have a crucial role in sustainability-focused technology development [18]. In the recent literature, the nature of collaboration and the type of outcomes are focal topics. For example, in case of dyadic collaborations, different actors could strengthen different types of EI, i.e., product- or process-EI [19], while cooperation with international or national actors might not increase the probability of successful EI to the same extent [20].

But not only dyadic relationships could be needed for EI. Resource (or knowledge) sharing could be realized, for example across the supply chain to improve green innovation capability [21] but also within a network of focal developer firms, complementors, research centers, suppliers, end-consumers, governing bodies, or service providers [6]. Nevertheless, while network involvement and cooperation with research institutes are found to be essential for small firms, larger firms might have more knowledge and capabilities to eco-innovate independently [22]. Larger firms, however, are usually less capable to produce radical innovations alone, which is why they could benefit from collaborations [23].

Another important topic of OE research is the nature of resources and benefits which can or should be shared within an inter-organizational network. First, given the complexity of EI development [23], external knowledge sourcing and combination is repeatedly mentioned as key success factor. Thus, organizations collaborate to build and use their knowledge base containing analytical knowledge (e.g., new (often scientific) knowledge from universities or their own research and development unit), synthetic knowledge (i.e., combining existing knowledge, often through the interaction of customers or suppliers), and sometimes symbolic knowledge (i.e., creating only an impression, not a concrete solution) [12]. Second, besides knowledge, inter-organizational collaboration is also generally useful to involve missing financial resources and technologies, while sharing risks, improving process efficiency, increasing compliance with regulations, or getting information about disruptive changes can be also relevant [9].

Based on the above, scientific knowledge is mainly limited to the drivers, goals, and effects of inter-organizational collaborations, which is a more static description of casualties. In contrast, less is known about the evolution of an OE network, i.e., the dynamics of creating and ceasing collaborations based on one of the main underlying ideas of open innovation: complementary resources [24]. The few similar qualitative studies were focused on other OE aspects instead of complementarities, for example, creating innovation ecosystems through policy interventions [25], or intermediaries for small and medium-sized companies, e.g., local authorities and consultancies [26]. Since the effective management of the emerging multilateral dependencies within an ecosystem aimed at circularity or environmental innovation is frequently argued to be a success factor [27], the current insufficient knowledge about collaboration dynamics hampers to generate useful managerial implications.

Nevertheless, relevant theoretical perspectives might help to form an assumption for the research question. The resource-based view is not only the most dominant theoretical perspective of OE research [12], its prior application in general business and management research allows to induce assumptions for critical pillars of OE network evolution. These can include the drivers of changes in the network structure (e.g., missing resources), the directions of network growth (e.g., specific partner searching criteria), or the prioritized network activities (e.g., reshaped innovation goals).

2.2. Inter-organizational innovation network evolution from the resource-based view

According to the resource-based view of the firm, resource position barriers also exist besides entry barriers [28] and sustained competitive advantage could be built on valuable resources rather than (only) market positioning and external factors [29]. While one part of the resource-based literature explored the opportunities of tangible and intangible resources in gaining a sustainable advantage in a turbulent environment (e.g., knowledge-based view) [30], other studies oriented the attention to precisely differentiate resources from capabilities [31]. Furthermore, separating operational and dynamic capabilities [32] gave additional emphasis on environmental adaptation [33].

To ensure environmental adaptation, inter-organizational networks have vast relevance from the resource-based perspective, if valuable resources or capabilities needed for adaptation or innovation are spread out among firms and locations, which is characteristic in technology-intensive industries [34] (such as the renewable energy sector). Bridging nodes interconnecting certain elements, i.e., organizations within a network, could significantly affect OI [35] and might help single firms which are not able to control all required resources or capabilities to realize their innovation goals. Thus, organizations in the network need partners with preferably (1) similar or aligned goals, (2) opportunities to combine or exchange resources, (3) orchestrate actions, and (3) generate positive effects from the collaboration [36].

During the evolution of such networks, collaborating organizations might search for and select new partners, in which strategic, technological, and relational alignment could be relevant [37]. One can, however, differentiate project-related criteria (idea, organizational aspects) and partner-related criteria, as well (competence, attitude, relationship, resources) [38]. Specifically, exploration as an objective can induce the addition of a new tie in the inter-organizational network, which could be relevant to access a missing resource [34] or facilitate innovation [39]. As innovation performance and organizational ambidexterity are affected by OI [40], balancing between exploitative and explorative innovation (i.e., innovation ambidexterity) [41] might also affect the evolution of an innovation network. This evolution could induce strategic changes concerning present and future resource deployments [42] or new projects, and technologies coming from internal or external sources, i.e., OI [43].

Based on the above, our propositional knowledge is that OE literature suggests that accessing complementary resources within an inter-organizational network (what) could be key to overcoming individual resource constraints (why), and general management literature suggests that the size of network (e.g., involving new partners), partner selection criteria (e.g., strategic and/or technological alignment), innovation ambidexterity (e.g., following exploitative or explorative goals) could drive OE network evolution, i.e., these can be subjects of strategic decisions (how).

3. Methodology

3.1. Research context

The focal EI of this study is an innovative power-to-gas (P2G) technology for renewable energy storage and integration, which is a frequently mentioned topic for balancing renewable energy supply and demand [44]. Also, the technology is widely expected to play a significant role in the future energy sector [45,46]. Specifically, energy storage technologies will be crucial to provide flexibility for the European energy sector as well [47]. The main idea of the P2G is to integrate more renewable energy into the energy system by converting surplus electricity into hydrogen by water electrolysis and methane (synthetic natural gas – SNG) by chemical or biological methanation of hydrogen and carbon dioxide [48] (Fig. 1).

By enabling grid balancing by green hydrogen production, reusing carbon dioxide in the methanation step, providing seasonal energy storage through the natural gas grid, and coupling the electricity and gas sector, this technology could directly contribute to decarbonization [49]. Nevertheless, this potential also means high complexity because of the several infrastructural connections. For example, the needed input and output connections should involve preferably a local renewable electricity producer unit and/or connection to the power grid, carbon dioxide input from biogas or flue gas, connection to the natural gas grid for energy storage or local utilization of the produced methane [45,46]. Without these infrastructural connections, a commercial-scale P2G plan cannot operate.

Like the radical energy efficiency innovations presented by Johansen and Isaeva [13], P2G innovation also seem to be highly transformative, but its commercial-scale implementation seems to be slow in practice. Accordingly, the radical novelty and complexity mean a commercialization challenge, driven by, for example, the uncertain variable financial prospects depending on the specific context and configuration [50,51], and the turbulent energy environment of nowadays which might decelerate green transition [52]. Because of the novelty and the technical complexity, usually, an inter-organizational network is needed for a P2G project [53].

Table 1 presents the data of the participating organizations in the focal P2G innovation network. Organizations are involved in the network from five countries: Croatia, Estonia, Germany, Finland, Italy, and Hungary. This inter-organizational network is mainly built around the biological methanation-based P2G technology, the operation of which has been already demonstrated in different locations and development phases (lab, prototype, and semi-commercial), and which is ready for large-scale commercialization [54]. The long-term goal of the network is to foster the diffusion of the technology and support climate neutrality by multi-MW_{el} commercial-scale plants. Based on this research context, the main proposition could be that the successful commercialization of the actual EI could be achieved by exploitative patterns and combining complementary resources, while explorative OE patterns might also appear over time based on the strategic interests of some partners.

3.2. Extended case study method

This research applied the extended case study method [55], which was already used in topics concerning strategic management and innovation [56–58]. Furthermore, case study research and qualitative methods have been successfully applied in EI-aimed collaboration research [59]. According to Burawoy [55], the extended case study involves four main extensions: intervention, process, structuration, and reconstruction. Table 2 presents how these extensions appeared in this research.

3.3. Data gathering and analysis

Qualitative data gathering involved 22 interviews and 13 personal or online meetings with organizations of the innovation network between

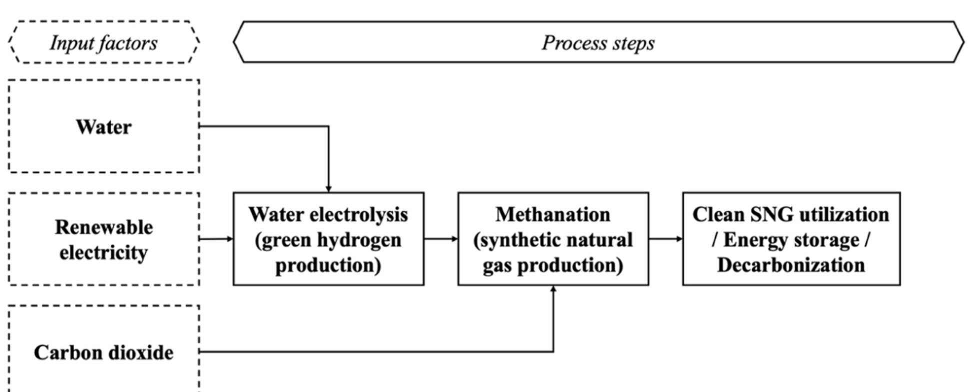

Fig. 1. Simplified P2G process diagram.

Table 1
Participating organizations in the focal OE network.

Organization	ID	Relevant activity	Top level of the network decisions
Industrial incumbent A	iiA	Natural gas and electricity distribution and trade	CEO
Industrial incumbent B	iiB	Natural gas distribution and trade	CTO
Industrial incumbent C	iiC	Chemical industrial processes, flue gas emission, methane use	CFO
Industrial incumbent D	iiD	Fossil and renewable electricity generation, distribution, and trade	Division Leader
Industrial incumbent E	iiE	Technology developer and manufacturer in the natural gas sector	Managing Director
Industrial incumbent E	iiE	Natural gas distribution	Division Leader
University A	unA	Bioscience research	Head of Department
University B	unB	Biology Research	Head of Department
University C	unC	Energy engineering research	Dean
University D	unD	Circular economy research	Dean
University E	unE	Energy systems research	Dean
University F	unF	Innovation management research	Rector
Start-up company A	suA	P2G and biological methanation development	CEO
Start-up company B	suB	P2G and Carbon Capture & Utilization development	CEO
Start-up company C	suC	Biological methanation development	CEO
Water utility A	wuA	Wastewater treatment, biogas production	CFO
Water utility B	wuB	Wastewater treatment, biogas production	CEO
Agricultural firm A	afA	Biogas- and bioethanol production	CEO
Agricultural firm B	afB	Biogas production	CTO
Research centre	rc	Techno-economic energy research	Division Leader
Financial investor A	fiA	Venture capital fund	CEO
Financial investor B	fiB	Venture capital fund	CEO
Non-profit Association	na	Hydrogen technology development and diffusion	Director
Public authority	pa	Energy authority and regulation	Head of department

Table 2
The application of the extended case study method (based on Burawoy, 1998).

	Methodological background	This research
Intervention	The researcher becomes a participant, not only an observer	Engagement in discussions about the OE strategy of the OE network by non-participant and participant observation
Process	Observations go beyond the close context of the research regarding time and space	Assessing the external environment of the OE network by supplementary quantitative data
Structuration	Wider social context and external forces also get attention, not only internal mechanisms which could be separated from the context	Concerning the collaboration patterns from the aspect of the technological characteristics and external environment
Reconstruction	Theory is not fixed, but evolving and reconstructed	Interpretation of network evolution is supplemented with new perspectives

2020 and 2022 (see Table A1 for details). Field notes from the interviews and meetings were triangulated by document analysis (project initiation documents, website, meeting memos) and quantitative data about the trends of the external environment. The data gathering and data analysis were partly parallel, and the first data analysis results informed further data collection [60]. 1–2 h-long semi-structured interviews were conducted, with multiple interviewers to balance between flexibility and consistency and a standard interview guideline as follows: Corporate strategy; High-level OE opportunities and challenges; Concrete techno-economic and business development opportunities and challenges; Existing, potential, and preferred partners; Planned and ongoing projects; Main technology development achievements and future objectives.

During the meetings, we have varied non-participant and participant researcher roles in the discussions better understand relationships between actions, goals, and social processes. The meetings were focused on research, development, and innovation opportunities; moreover, upscaling roadmap of the P2G technology.

Regarding the data analysis, specific contextual factors and timing were considered by combining multiple coding schemes [55], i.e., theoretical coding (writing theoretical notes, comparison of data and prior theories); context-specific coding (comparison of internal (qualitative) and external (quantitative) data); timeline-oriented coding (historical interpretation of patterns). To improve validity, reliability, and generalizability, literature patterns [57,56] were also followed in terms of the volume of interview data, which was needed to reach theoretical saturation, we have iterated the qualitative data with theories and quantitative contextual factors and validated of emerging theoretical concepts at the end of final meetings to receive direct feedback.

4. Results

4.1. Exploitation-oriented OE phase: existing complementarities but several challenges

The core network structure was built around technical universities and technology developer start-up companies. The initial growth of the network was towards efficient input providers, i.e., agricultural biogas plants and wastewater treatment plants with biogas plants to access easily useable carbon dioxide input for a grid-scale plant (biogas contains ca. 40–50% carbon dioxide and 50–60% methane which is an inert gas in the biomethanation process). Industrial plants with flue gas emissions, which would be their main alternative as potential sites, were not in the scope of core OE partners. Although flue gas is produced in larger volumes than biogas, its carbon dioxide content is much lower (ca. 10–15%) and might contain impurities, nitrogen, and oxygen which would be disadvantageous for the biological conversion process of carbon dioxide. The CTO of *suA* put it this way in the middle of 2020:

> 'Flue gas use would be promising only in theory. However, our current technological know-how and experiences fit more the utilization of biogas, especially because the methane content of the biogas is inert during the methanation process, and there is a large volume of carbon dioxide that could be converted. […] Even in this case, we will have to deal with the complexity and the uncertainties of optimization of hydrogen production, biogas production, methane production and methane storage or local storage, in grid-scale.'

Consequently, biogas plants were involved in the discussions, especially wastewater treatment plants, because of other potential technical synergies (the oxygen produced in the electrolysis step could be utilized during the wastewater treatment while handling the wastewater of the biomethanation step could be also easily solved there). Many technical details were discussed (e.g., the volume and composition of biogas production, infrastructural connections, local energy needs, etc.), and some of the potential sites showed serious interest in joint research and development, thus prior techno-economic analyses were conducted.

Besides, OE partners made efforts to involve strategic investors, i.e., larger energy companies from the electricity and/or the gas sectors to get infrastructural and knowledge support to generate sector-level benefits (grid balancing, seasonal energy storage). Furthermore, they paid attention to building a broader research and development network with other university research centres to establish scientific excellence, thus, credibility for OE. Moreover, the partners were in connection with financial investors, non-profit professional organizations (e.g., for hydrogen technology), and relevant energy and public utility authorities. The Head of Department of *unC* highlighted the role of network building at the end of 2020:

> *'It is crucial to raise awareness about this new technology which is a remarkable opportunity for seasonal energy storage. Accelerating scientific research and professional discussions might support the state administration to recognize the socio-environmental potential.'*

Nevertheless, several challenges emerged during this first phase of OE which were focused on the exploitation of the core technology. It would have meant the implementation of a grid-scale plant. Other main challenges were related to regulatory issues and the financial prospects of such a plant. For example, even though renewable electricity would be a cheap resource, in theory, to produce valuable biomethane / low-carbon SNG from it, operating with only (surplus) renewable electricity would lead to a slow return because of the high capital expenditures. If electricity would be sourced from the grid, its growing price and system usage fees would affect the business model negatively in the absence of discounts, e.g., for supporting seasonal energy storage. While this challenge could be solved by policy interventions, such as feed-in tariffs for biomethane, it has not been introduced yet in the focal European area where the grid-scale plant deployment would be planned. Furthermore, a comprehensive and detailed regulatory framework for renewable or low-carbon gases in the EU would also help the marketing of the end product and the financial planning. So, uncertainties in the external environment meant a significant obstacle to organizing and financing such exploitative OE for commercial-scale implementation.

4.2. The turning point: absorbing knowledge about the market and not the solution

According to main input and output factors, the focal EI could be financially attractive if electricity prices are low and natural gas or renewable gas prices are high (e.g., because of a green premium or feed-in tariffs, to support or incite renewable energy integration and storage). Based on average monthly data, Fig. 2 shows that in the middle of the case study time horizon (2021 Q1), electricity prices in the network member's countries were much higher than natural gas prices, which justifies the concerns of financial investors and would induce the support of state administration due to potential environmental performance. Nevertheless, the Figure also shows that the growth of electricity and natural gas prices were (are) mainly in line with the growth of CO_2 prices, which was previously disregarded. Its growth rate, however, amplified the interests of the industrial partners who are involved in the EU Emissions Trading System (EU ETS) (unlike biogas plants) to find a solution, through which future challenges of CO_2 prices could be reduced. Thus, based on the recognized trend illustrated by Fig. 2, realizing OE in a way which creates value for an overlooked segment emerged as a new opportunity. This task would have required modifications in the OE pattern though, the start of which became even more important in 2022, when the volatility of energy markets generated additional interest for clean technologies which help to reduce not only emission costs but uncertainties of energy sourcing by local renewable electricity and gas production.

4.3. Exploration-oriented OE phase: the promise of future complementarities

Based on the emerging opportunity for industrial decarbonization and saving costs of carbon emissions for industrial plants, a reshaped OE emerged as a promising opportunity during the inter-organizational discussions, focusing on carbon capture and utilization (CCU). The exploration, first, resulted in new collaborations, a new prototype, and patent applications. CCU can be considered a new capability through which P2G plants could be implemented in different sites compared to existing international projects. The integration of the two technologies could also result in larger plants. Moreover, focusing on the local utilization of product (low-carbon SNG for heating, electricity generation or other chemical processes), makes the regulatory uncertainties irrelevant (i.e., P2G could be used as a process-EI instead of a product-EI). The new capability to utilize flue gas as a carbon source would help to achieve the long-term goal of the network, i.e., building multi-MW_{el} plants.

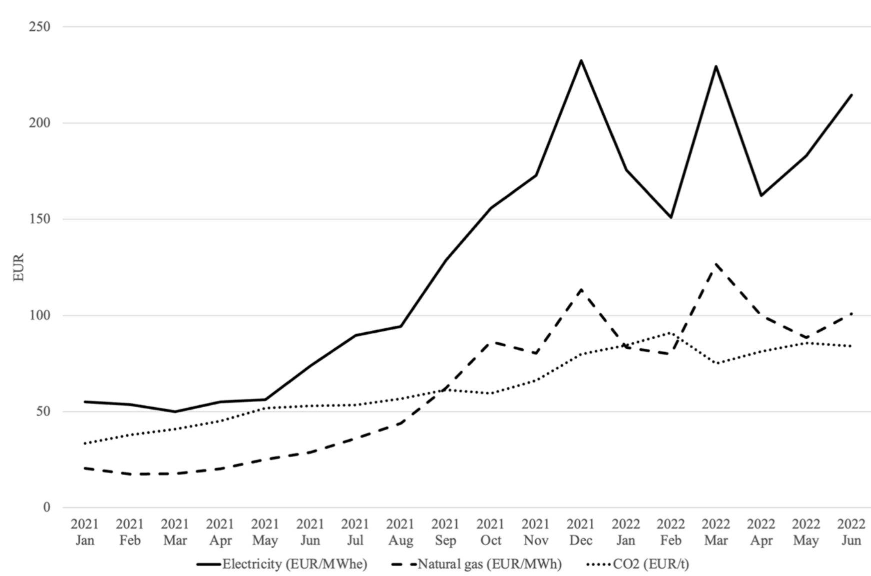

Fig. 2. Changing average electricity, natural gas, and CO_2 prices in 2021–2022 Electricity price: Monthly average, wholesale day-ahead prices of Croatia, Estonia, Germany, Finland, Italy, and Hungary. Concrete prices varied per country. The standard deviation was low in the first half of the time horizon and increased in line with the growing prices and volatility, starting from the end of 2021. Natural gas prices: Monthly average, TTF DAM (end of day); CO_2 prices: Monthly average, EUA (EU-ETS) (Own construction based on: Ember 2022a; Ember 2022b; EEX AG 2022).

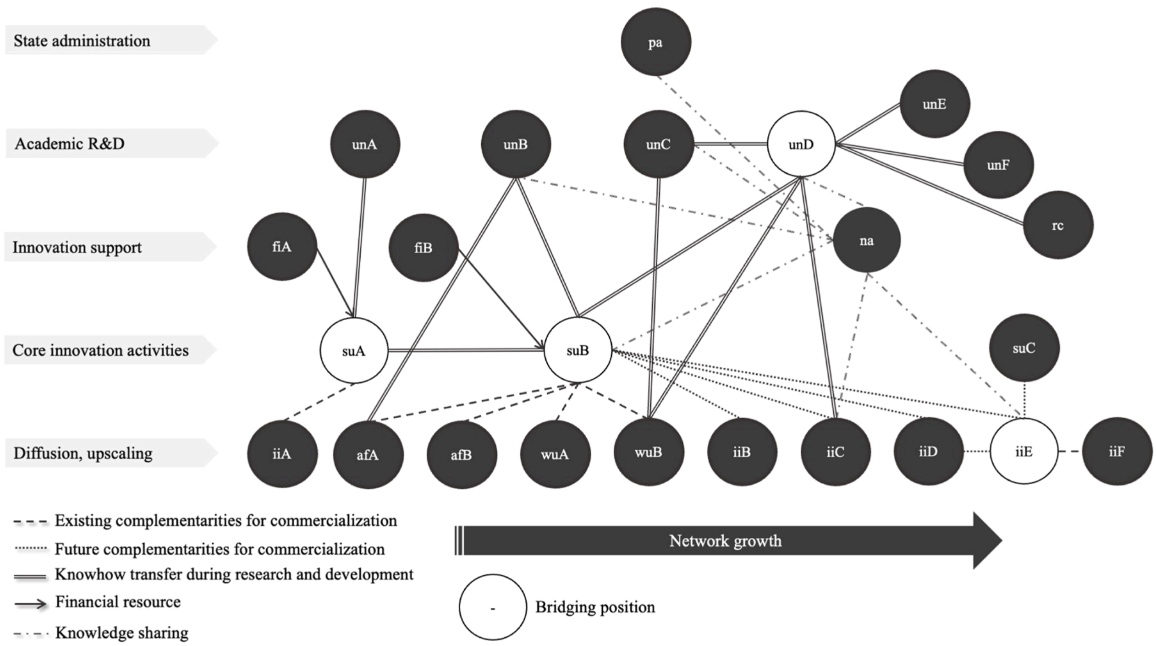

Fig. 3. Evolution of the analysed inter-organizational OE network.

Fig. 3 shows the structure and the main connections of the OE network. It could be seen that universities and start-ups transfer knowhows during research and development projects, the non-profit association is central in terms of general knowledge flows, while investors are in direct connections only with start-ups. Furthermore, there are four organizations (two start-ups, a university, and an industrial incumbent) in bridging positions that create network connections at least to two other otherwise disconnected organizations. The OE network transformation was the result of a reshaped OE after the top management of the partners, especially the ones in bridging positions, faced the above-mentioned challenges and opportunities (regulatory challenges, uncertain business environment).

The figure also illustrates that after the initial goal to exploit the core EI of two start-ups with a strategic investor (i.e., industrial incumbent from the energy sector) and a biogas plant, new collaborating universities were involved in the discussions of the reshaped OE. Moreover, which is the most important from EI commercialization aspects, industrial plants with flue gas emissions became the main potential partners and primary target groups of network building, as detailed by the research group leader of *unD* in early 2022:

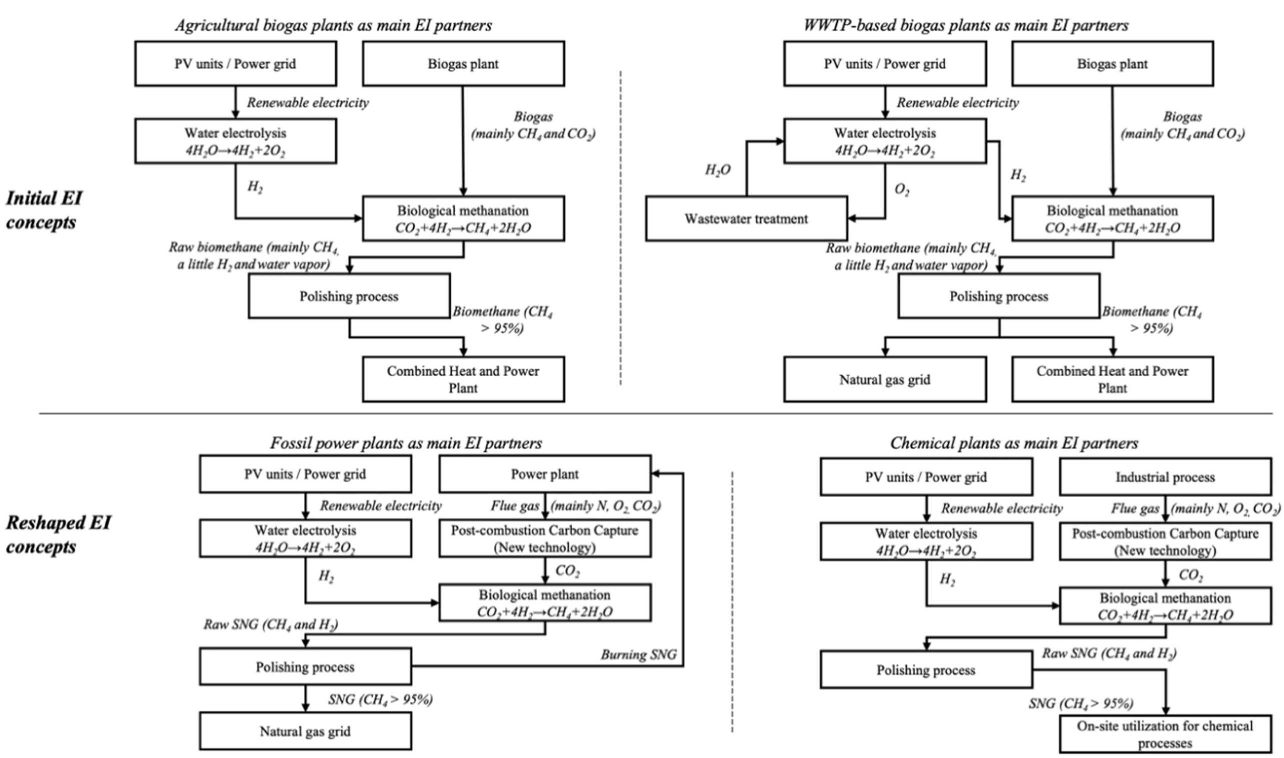

Fig. 4. P2G technological concepts according to different main EI partners.

'Even though industrial plants have fewer technological benefits compared to biogas plants, for example, no easily usable and cheap carbon source, and no obvious technical synergies for using the by-product oxygen, they have an expected financial challenge because of their carbon emissions. They are motivated partners to contribute to the innovation process because of the growing carbon prices which would endanger their profitable business model if they do not reduce their emissions and/or invest in CCUS, and because of other uncertainties of the energy market, for example, the costs of electricity and natural gas sourcing.'

Solving site-specific technical challenges for upscaling and additional investments (e.g., local solar energy production to decrease the volume of the electricity sourcing from the grid) will also require collaborative development, and the involvement of university research centres to help in optimizing auxiliary processes and developing other promising technological system concepts. The technical comparison of the initial and the reshaped EI concepts is presented in Fig. 4.

Network transformation was also reflected in the dominance and the temporality of the commercialization-focused project- and partner-related criteria. Table 3 shows that project-related criteria defined how OE could focus on the exploitation of the actual EI or exploration (i.e., strengthening ambidexterity), while partner-related criteria reflected the strategic fit of certain types of plants.

5. Discussion

5.1. Market uncertainties, internal capability building, and complementarities

Our empirics suggest that dynamically responding with capability building to market uncertainties of the EI *and* complementary resources might be similarly important to form EI partnerships, avoid market failure, and maintain the specific opportunity for sustainable development in a turbulent context. This generates a more elaborated description of the assumption which would simply suggest that complementary capabilities could be primary drivers of OE network evolution. For example, Teece [24] argued that the commercialization of a novel and core technological know-how might require complementary assets which could be provided by other entities and not by the innovator itself. This argument explains why the collaborating partners who were interested in EI commercialization focused their initial EI partner search on the owners of critical assets, such as the cost-effective source of a key input factor or a central infrastructure. Nevertheless, it does not fully explain the change in the network evolution because of market challenges. This evolution was rather based on rather 'a promise' than existing complementarities at that time. The closest argument to ours about the significance of future complementarities also comes from Teece [61], i.e., tapping complementary innovation is important in turbulent contexts, however, the emphasis on its non-existing nature and its relevance in network evolution represents novelty.

Our results suggest that OE partners would decide the potential targets for commercialization partnership based on the exploitative or explorative project-related criteria, moreover, complementary resources and aligned strategic interests. Accordingly, even though the initial target group could provide a cheap input material for the original network goal, because of the market uncertainties concerning the financial model, the OE was forced to a more difficult path with a new technology development to reduce the risk of market failure. As the network analysis explored, this transformation was driven mainly by the bridging nodes, which sensed the emerging opportunity of industrial decarbonization and took further steps to seize it and transform the network structure.

Consequently, some extensions could be also argued from a resource-based network perspective. For example, empirical data suggest that exploration as a driver for building new network connections could concern not only resources [34] but also internal capability building based on the financial threats of the potential partners. Furthermore, project-related searching and selection criteria could be more important because of the idea to reduce market uncertainties (i.e., strategic alignment) than resources (i.e., technological alignment) among the partner-related criteria [38]. Indeed, the empirical data points rather toward that *market uncertainties in the present* and *complementarity capabilities in the future* could drive OE network evolution, instead of purely the existing complementarities. This is in line with the argument of Markard and Hoffman [62] about complementarity dynamics in the energy transition. The authors mentioned the potential future complementarities in the context of alternative sectors as "vehicles depend on the stations and stations depend on the vehicles, and none of the elements is available in sufficient numbers" [62, p. 70]. Nevertheless, while they interpret future complementarities on sector- and technology-level, our study showed that future complementarities have significance in the

Table 3
Changing patterns in connection-building criteria to foster OE.

	Criteria	Time horizon	Connection building for OE		Technical explanation
			Biogas plants	Industrial plants	
Project-related criteria	**Accessing missing resources for *exploitative* OE**	Present	Primary	Secondary	…with existing P2G technology
	Accessing missing resources for *explorative* OE	Future	Secondary	Primary	There are non-existing but promising technologies **Biogas plants:** Power-to-liquid **Industrial plants:** Carbon capture & utilization
Partner-related criteria	**Volume of existing complementary resources**	Present	High	Low	**Biogas plants:** Cheap CO_2 source, oxygen utilization **Industrial plants:** Additional technology needed for CO_2 sourcing
	Aligned strategic interests	Future	Moderate	High	**Biogas plants:** Increasing calorific value of the biogas **Industrial plants:** Avoiding growing CO_2 and volatile natural gas prices
Temporality of the OE pattern Commercialization-related results so far			2018- Delivering 1 semi-commercial P2G plant is in progress	2021- Delivering 1 semi-commercial integrated CCU and P2G plant is in progress 2 other variations are planned	

OE network evolution as well. Table 4 summarizes how propositional knowledge could be reinterpreted or extended based on empirical data.

5.2. The impact of green absorptive capacity, circular economy development, and intermediaries

This sub-section briefly reflects on the emerging areas of the OE research landscape, recently identified by Sanni and Verdolini [12]. First, the authors highlighted that future studies might focus on the moderating effect of green absorptive capacity on external knowledge appropriation and EI performance. Concerning this topic, our findings suggest the interpretation of concerning threat rigidity theory [63] and absorption capacity [64] on a network level. Accordingly, strategic partners might not only help a firm in maintaining growth [65], but new connections could help an inter-organizational network within a challenging environment: the threat of failing the upscaling process was overcome by the absorption of new knowledge about the market need and technological opportunity which resulted in stepping back to exploration and sourcing resources for the new EI after that.

Second, the authors argued that the effects of green R&D networking and management capabilities on circular economy adoption should be also in the scope of future OE research [12]. As the focal EI of this research can contribute to circular processes (e.g., producing carbon-neutral fuel from waste), our results might be relevant in partially answering this question as well, from a resource-based perspective. The findings suggest that dynamic capabilities [61], especially sensing the collaboration opportunity with new partners, seizing it by internal capability development, and transforming the network might be more important in challenging times than insisting on the original EI opportunity based on existing complementarities.

Third, the impact of the intermediaries was mentioned as an interesting research topic [12]. The results showed that organizations in bridging positions were responsible for the above-mentioned network transformation, which came with building new connections to help avoid market failure and maintain the momentum for sustainable development.

Table 4
Comparison of propositional knowledge and empirical findings.

	Theoretical assumption and supporting literature		OE-related extensions based on empirical data
What to do and why?	Collaborate and combine complementary resources with external partners to increase EI performance to strengthen product- or process EI to access external resources and knowledge as a tool for environmental adaptation	[8,6,4,19,40,26,12,9]	Not only combining complementary resources but developing new (future) complementarities can be relevant
How?	by adding new ties to the network and forming strategic partnerships with aligned goals and coordinated contributions	[34,36]	Adding new ties should be driven by bridging nodes which sense the urgency for network transformation
	by evaluating potential partners by technological, strategic, relational, project- and partner-related criteria	[37,38]	Strategic alignment can be more important than the volume of complementarities, i.e., differentiation between present and future technological alignment is useful
	by maintaining the balance between exploitation and exploration during innovation activities	[40,41]	Market uncertainties might induce a novel exploration phase to extend the use cases of the focal EI

5.3. The impact of inter-organizational networks

In a broader sense, EI contributes to sustainable development by improving environmental performance [59]. This is in line with several other definitions from the scientific literature, as presented by Díaz-García et al. [66]. These definitions usually concern (1) motivations (drivers), e.g., contributing to sustainable development, and/or (2) effects (outcomes), e.g., reducing environmental harm [66].

In a specific sense, literature results provided significant advancements in understanding drivers of EI by using econometric models [67] and also focusing on different European countries, e.g., Germany [68,69], UK [70], France [71], or Spain [72]. These findings usually mention internal and external drivers and provide evidence about their significance. For example, among internal drivers, environmental management systems [68], technological, organizational capabilities, and R&D [69], recognized cost-saving potential [71] are highly relevant, while external drivers mostly involve environmental regulations [72], meeting market expectations [70] and accessing external knowledge sources [73]. Our research approached the topic from the perspective of external knowledge sources, which can be accessed by inter-organizational networks and OI. Nevertheless, our results demonstrated that an OE network is a dynamic construct, and thus, its effective management has a contingent nature not only in space (e.g., a region [73]), but also in time.

Regarding the specific outcomes of EI, the literature argues that it can improve not only environmental but also financial performance [74,75]. It suggests that EI could contribute to multiple sustainable development goals (SDG), for example, climate action (SDG 13) and economic growth (SDG 8), or other SDGs as well, for example clean energy (SDG 7), as presented in this study. These insights are in line with Gente and Pattanaro [76] who suggested that EI discussion should go beyond its traditional view of circular economy and waste management to accelerate sustainable development. Accordingly, even though there is a positive relationship between the level of sustainable development and EI activities [77], the assessment of sustainable development and the subsequent planning should have an integrative and context-specific approach [78]. For example, recent research reinforces that environmental problems could be closely connected to social and economic conditions [79], and Liu et al. [80] highlighted that “integrating evenness might also help governments to match adaptive strategies to places” (p. 1). Consequently, policymakers might assess SDGs according the future EI opportunities, and not only incite OE collaborations with heterogeneous input profiles to solve a specific problem but encourage multi-faceted problem-solving by an OE network.

However, not only governments but firms need adaptative strategies to support sustainable development by EI. For example, Lee et al. [81] found that “eco-innovation generates the appropriate dynamics for firms to manage rapid changes both internally and externally” (p. 127) and Wu et al. [82] found that “launching eco-innovation helps develop DOC” (p. 439) [Dynamic Operational Capabilities, which enable the reconfiguration of resources]. In contrast, our findings suggest its opposite within a network context. In particular, it was articulated above that strategic flexibility could be the driver and not the outcome of EI in a turbulent context, which suggests a bidirectional effect worth further research.

6. Conclusions

This study focused on the evolution of an OE network and approached its ongoing sustainable development activities from a strategic perspective, framed by the extended case study method. The results showed that the OE network had to transform because of the uncertain market environment of the core OE direction. The development of a new, but related technology was necessary through which it could create value for other potential OE partners who have fewer complementary resources but also face serious market uncertainties. This result suggests the reinterpretation of the propositional knowledge and it confirms only partly the main proposition for the research question. Accordingly, the commercialization of a technologically already advanced EI could not be always fostered by exploitative patterns based on (existing) complementarities but first, by switching to explorative patterns and other (future) complementarities to reduce the risks of market failure and enable contribution to sustainable development. This transformation could be considered rather a network-level ambition and not an autonomous organizational goal, however, bridging nodes played a key role in sensing growing risks of market failure and the new opportunity, moreover, to build capabilities and network connections based on future complementarities.

The main theoretical contribution of the research was that it looked into the vague construct of an OE network and demonstrated the relevance of future complementarities in OE network evolution, which was previously only mentioned regarding certain sectors and technologies of sustainable development. These conclusions also suggest that ecosystem-builders might need to rethink their partner-searching strategies when market uncertainties challenge the economic potential of the EI. Furthermore, not only the large-scale implementation of new technologies but supplementary developments could be incited by policymakers which would extend the potential EI use cases.

Nevertheless, these findings have limitations which induce further research. First, such a qualitative study cannot result in a general theory, but the theoretical extensions could be valid in the specific research context [83]. Consequently, considering our findings during new – OE-focused – econometric model development (as presented in Section 5.3) might be a promising research direction. Second, this research showed how collaboration patterns could transform during OE. In the focal case, even though bridging nodes drove and coordinated the transformation by explorative EI, further research might unveil cases where a newly connected, peripheric partner's technology reshapes the OE. Third, as these findings are heavily context-specific because of the followed methodology, finding similar or different cases would be useful to reinforce or refuse the complementarity-based and market risk-averse OE strategies.

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CRediT authorship contribution statement

Zoltán Csedő: Conceptualization, Data curation, Investigation, Supervision, Validation, Writing – review & editing. **Máté Zavarkó:** Data curation, Formal analysis, Methodology, Visualization, Writing – original draft. **József Magyari:** Conceptualization, Data curation, Investigation, Validation, Writing – review & editing.

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.

Data availability

Relevant quantitative data is uploaded as a supplementary file.

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Appendix

Table A1

Table A1
Details of the data collection.

Organization ID	Interviewee	Number of individual interviews	Meetings with the participation of the authors												
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
iiA	–	–	x												
iiB	–	–							x						
iiC	CFO	1									x				
iiD	Innovation Expert	2													x
iiE	Managing Director	2												x	
iiF	–	–													
unA	Associate Professor	1					x								
unB	Professor	1								x					
unC	Head of Department	2				x	x	x						x	
unD	Research Group Leader	2				x		x				x	x		
unE	Project manager	2										x			
unF	–	–													
suA	CEO, CTO	1, 1	x												
suB	CTO	2	x	x	x		x		x	x	x			x	x
suC	Senior Process Engineer	1												x	
wuA	CTO	1		x											
wuB	CEO	1						x							
afA	–	–													
afB	CTO	1			x										
rc	Project manager	1											x		
fiA	–	–													
fiB	–	–													
na	–	–													
pa	–	–													

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