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# Exploring the role of transdisciplinary research in accelerating sustainability transition: an empirical analysis of environmental innovation drivers in Central European energy sector

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## ABSTRACT

Energy transition requires environmental innovations (EIs), which, theoretically, could be accelerated by transdisciplinary research (TR). Although the recent literature also suggests that both EI and TR can be constrained in impact generation, the integrative view of TR and EI in the energy industry is overlooked. This study focuses on the top-down (policy) and bottom-up (inter-organizational) innovation drivers which could turn TR into EI in the fast-changing Central European energy sector. Results of a three-year-long transdisciplinary action research empirically demonstrate that TR and EI could be interconnected. In addition to prior findings, however, even the slight misalignment between the innovation drivers could constrain impact generation, as long-term complementors, e.g., biomethane and hydrogen, could become mid-term competitors for policy support. This is the first EI study which highlights the role of TR-based innovation interplays for the energy transition through the example of a biomethane-based process innovation and a hydrogen-based system innovation.

## 1. Introduction

New transdisciplinary research (TR<sup>1</sup>) approaches consider collaborative research and development to accelerate sustainability transition [1]. The urgency of sustainability transition in the energy sector has been argued for more than a decade [2], including innovations from transdisciplinary research and development [3]. According to the IEA's Tracking Clean Energy Progress, however, no area of the energy sector is "on track" to meet the Net Zero Emissions scenario by 2050. Most of the areas "need more effort" (e.g., renewables; hydrogen), and two are absolutely "not on track" (behavioural changes; and carbon capture, utilization, and storage - CCUS) [4].

Accordingly, environmental innovations (EIs) are critical for the

energy sector, for example, to increase renewable energy use and decrease carbon emissions [5]. In theory, TR has the methodological potential to solve the specific EI challenges of the energy sector. For example, green transformation requires new methods from other disciplines, e.g., economic modelling, and corporate strategies and management [6], which makes the transdisciplinary work and knowledge co-production relevant [7]. Likewise, EI often requires diverse knowledge sets and networks [8], external knowledge sourcing and open innovation [9]. In line with the impact barriers of transdisciplinary projects, such as lack of networks [10], EI projects could face commercialization challenges because of risk-averse investor behaviour, e.g., grounded in potential knowledge spillover [11] or the contrast between higher social benefits and lower market performance [12]. Specifically,

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### <sup>1</sup> Abbreviations

CCUS: Carbon capture, utilization, and storage.  
EI: Environmental innovation.  
P2G: Power-to-gas.  
R&I: Research and innovation.  
TR: Transdisciplinary research.

the energy sector often has a strong focus on stable and efficient operation, and strategic rigidity could hamper new technology adoption [13]. Radical novelty, system effects, time constraints could also restrain the implementation of EIs in the energy sector [14].

Despite this presumed potential of TR to accelerate EI, it is hard to find any answers in the literature regarding how TR and EI could interconnectedly drive sustainability transition, especially within the context of the energy sector (as detailed in the next section). This study focuses on drivers of innovation [15], concerning both top-down and bottom-up drivers, as previously differentiated by Rogge and Stadler [16]. In this study, top-down innovation drivers of the sustainability transition could mean policy instruments to reduce socio-technical barriers to innovations. These can include, e.g., strategic plans, taxes, demand creation [17], strategic investment to transform infrastructures by technological innovation [18], or addressing potential policy inconsistencies across local and regional energy systems [19]. In contrast, bottom-up innovation drivers cover the activities and outcomes of inter-organizational collaborations and networks. In these relationships, not only research institutes and start-up companies are relevant as perceived traditionally innovative. Incumbents, for example, can also realize intermediation functions (e.g., knowledge transfer, networking, innovation and diffusion, advocacy) [20], while civil society can act as early adopters of new solutions [21]. To be effective, top-down and bottom-up drivers should be aligned with each other, i.e., they should be directed toward the same issues [16]. Nevertheless, misalignment of top-down and bottom-up drivers can be often experienced in real-world context, for example, because policies change too slowly or benefit certain group of actors [16]. Another explanation of such misalignment derives from the complexity of the task: proper alignment of top-down and bottom-up drivers could result from the iteration between knowledge and action, scientific and policy experimentation, and the adaptive governance of complex systems [22].

The research questions are the following:

*RQ1: Which top-down and bottom-up innovation drivers are needed to turn TR into EI within the energy sector?*

*RQ2: What are the implications of the potential misalignment of top-down and bottom-up innovation drivers?*

In line with the nature of TR, research questions are answered by a three-year-long transdisciplinary action research in a Central European context. First, the study contributes to the literature by providing evidence about the possibility of TR-EI interconnection (i.e., EI comes from TR), presenting a case of an international and inter-organizational research programme, which focused on energy storage and decarbonization, and resulted in real-world technology development with patent and utility model applications. Second, the importance of proper timing of top-down and bottom-up innovation drivers was explored, since a slight misalignment could turn long-term complementors (e.g., bio-methane and hydrogen) into competitors, and thus, constrain impact generation. Third, the role of TR-based EI interplays (i.e., different types of EIs drive each other, building on TR results) to accelerate sustainability transition in a changing energy sectoral context (e.g., exploiting an environmental process innovation to advance environmental system innovation).

The study is structured as follows. Section 2 introduces the fundamental principles of TR in sustainability transition, elaborates on the research gap, and the approach through which this study aims to partially fill this gap. Underlying drivers in EI studies are structurally explored by a precursory systematic literature review. Section 3 presents the details of the research context, methodology, and data, focusing on four Central European countries and an inter-organizational network. Results are shown and discussed in Section 4, involving the TR- and EI-based interpretation of long-term transition directions of the focal countries, and related findings from the action research. Conclusions with managerial and policy implications, moreover, limitations and future research directions are outlined in Section 5.

## 2. Literature review

### 2.1. Energy sectoral background

In the energy sector, environmental innovations are crucial, defined as organizational implementations and changes, with different levels of novelty, aimed at reducing environmental impacts and related to products, processes, or marketing. [23]. In contrast, energy innovation is often linked to new technologies [24] for energy production, use, security, and sustainable energy system development [25]. Energy innovations include clean energy technologies to reduce CO<sub>2</sub> emissions [26], new solutions for energy-efficiency and renewable energy [27], and those new solutions which “ensure access to affordable, reliable, sustainable and modern energy for all” (SDG7) [28,29]. Scientific research sometimes specifies further their scope, e.g., community energy innovations involve citizens actively to increase renewable energy adoption [30].

Top-down and bottom-up drivers of innovation both play crucial roles in the decarbonisation of the energy sector. In the above-mentioned community-based context, Dall-Orsoletta et al. [31] highlight the relevance of social innovation for low-carbon and just energy transition. The authors also argue that such bottom-up initiatives, e.g., for local renewable energy deployment, can be useful to access and mobilise local resources, however, top-down financial and institutional support is often necessary to develop and implement new solutions (e.g., business models) [31]. Jamasb et al. [32], however, suggest that inadequate top-down regulatory mechanisms are at least partly responsible for the slow uptake of technological innovations in the European energy sector. Based on the European study of Capozza et al. [27], top-down policy drivers should rather focus on direct economic incentives instead of introducing strict regulations and taxes to encourage firms to develop energy innovations. Besides, stimulating market demand and cost-saving ambitions of firms are also viable opportunities for policy-makers to drive energy innovations [27].

In the Central European context of this research, EI and sustainable transition faces significant challenges within a rapidly changing environment. While Central European countries aim to build low-carbon or climate-neutral economies, in line with the ambitions of the European Union, nevertheless, their traditionally fossil-based industry structure [33,34], energy security concerns [6], the dominance of economic aspects [35], or specific challenges of a follower country [36] slow down the EI processes. Additionally, Prokop et al. [37] argue that low interest in environmental issues is historically coded in this region, and recently found that “companies in the considered CEE countries went through a similar process of ‘environmental transformation’ as many comparable firms in Western and Northern countries, but with a considerable time lag” ([37], p. 8).

Prior research, however, also suggests that TR could be relevant in practice of the energy sector, as well, to solve such EI challenges. For example, community renewable energy use could be approached with TR principles, such as integrating not only academic but non-academic knowledge streams in a collaborative research project [38]. Concerning the European Union, Prades et al. [39] point out that the interaction between different scientific disciplines and the network of researchers, practitioners, and civil groups are included in the EU-level climate policies and energy transition-aimed innovation programs.

### 2.2. Transdisciplinary research and sustainability transition

In the last decades, scholars introduced many different perspectives of transdisciplinarity, e.g., from a multi-level coordination concept of research, innovation, and education to going beyond interdisciplinarity to reframing scientific and societal relationships [40]. TR principles are also related to knowledge production for practical and contextual application for managerial problem-solving [41]. Lang et al. [42] developed the following definition: “Transdisciplinarity is a reflexive,

integrative, method-driven scientific principle aiming at the solution or transition of societal problems and concurrently of related scientific problems by differentiating and integrating knowledge from various scientific and societal bodies of knowledge” ([42] pp., 26-27). More recently, Renn [43] pointed out that a common understanding is necessary between researchers and practitioners and integrating different scientific reasonings of disciplines to enable concrete actions for societal benefit. The author underlines that “bridging the gap between different pools of knowledge, social orientations and collective action” could a main goal of TR, with addressing complex questions and generating practical solutions, as well ([43], p. 2).

For more than a decade, TR has been also argued to be a driver of sustainability science [44]. Nevertheless, its diverse challenges are not only associated with framing and methodological elements but also impact generation. For example, it is fundamentally defined by Brandt et al. [7] in the geographic dimension, i.e., focusing on local, regional, supra-regional or global scale, developed and/or developing countries. Impact constraints, however, can be interpreted in other dimensions, as well. For example, transdisciplinary research-for-development programs try to bring outcomes closer to the practice of sustainable development [1], but the lack of political will, time and resource constraints, the lack of networks, or even problems with know-how exploitation strategies have been reported [10]. Since TR aim to solve real-world problems [45], understanding and overcoming the challenges of turning research outcomes into, e.g., innovative prototypes, then applicable products and services with socio-environmental benefits [42] is an inevitable task for the sustainability transition.

### 2.3. Underlying innovation drivers in the environmental and energy literature

This study assumes that TR-based EI is possible, but top-down and bottom-up innovation drivers could affect impact generation. This assumption is reinforced by the systematic re-interpretation of several influential studies which are related to the focal topic, as presented in Table 1. Based on the recommendations in the literature [58–60], the process of the precursory systematic literature review was the following:

- a) Developing a research protocol:
  - a. Searching literature in the Scopus database
  - b. Focusing on the reviews and original research articles which are closely related to environmental or energy innovation. (The latter is relevant because of the empirical research context.)
- b) Assign search keywords: Search keywords included eco-innovation, ecological innovation, and sustainability-oriented innovation, as well, to ensure a high volume of potentially relevant articles, based on title, abstract, and keywords. Although this narrow keyword list could have been further extended, the precursory systematic literature review only aimed to gather an initial understanding of the field and strengthen the underlying assumption. Moreover, closely related alternative keywords had organically appeared in the results (e.g., cleantech, green innovation). Since other alternatives with broader meanings (e.g., responsible innovation) were not included, the interpretation context is limited to energy and environmental aspects.
- c) Citation-based prioritizing, i.e., finding the most influential studies which might shape the present and future thoughts on environmental and energy innovation.
- d) Content-based filtering by title and abstract, focusing on relevance (i.e., excluding too narrow technical topics, but including studies which (can) have interconnections with innovation, TR, and strategic change or transition).
- e) In-depth qualitative analysis according to the following aspects: Transdisciplinary aspects principles (e.g., collaboration), top-down policy drivers (e.g., economic development), bottom-up (inter-)organizational drivers (e.g., business models).

- f) Interpretation of the results in the light of empirical data.

Table 2 shows that many highly cited articles explicitly or implicitly refer to the necessity or benefits of transdisciplinary collaboration and innovation interplays among disciplines (e.g., digital innovation can also increase energy efficiency). From a top-down policy perspective, parallel economic and environmental relevance of EI can be seen, for example, to enhance circularity or reduce the negative environmental impacts of economic growth. Regarding the organizational level, responding to external pressure by business model reconfiguration is a frequently mentioned driver of sustainability transition. These themes provide theoretical perspectives for discussing the empirical results in Section 4.3.

### 2.4. Research gap

Based on our literature review, first, there is a spatial gap in the focal topic, i.e., Central Europe is insufficiently studied in terms energy-focused TR and EI processes. Second, more importantly, there is also an empirical gap with missing evidence about the drivers to turn TR into EI in the energy sector, which would demonstrate their theoretical relationship. Specifically, three related streams of the literature could be identified, which inform but do not answer the research questions:

1. *Discussing TR with top-down or bottom-up innovation drivers separately, for example:*

EI-focused transdisciplinary studies highlight the need for customizing the design of climate research programmes based on specific societal needs (top-down driver) [46] or encourages to reorganize a specific knowledge stream during environmental research, instead of directly pressurizing the production of usable results (bottom-up driver) [47].

2. *Lack of innovation viewpoints in TR studies conducted in the energy sector, for example:*

Energy-focused TR studies are conducted also in scientific contexts, e.g., concerning the relevance of those researchers in socio-environmental change who could integrate technical and social aspects [48]. Other recent energy studies focus on community perspectives, such as the human dimension of the engagement [49], the complex environment of energy system modelling [50], and iterative approaches to energy planning [51]. Other, more transition-focused studies discuss the role of transition management [52] and power dynamics [53], but without explicitly focusing on innovation.

3. *Integrative TR and innovation studies in the energy sector with different scope, for example:*

There are studies which followed integrative approaches but did not focus on the differentiation and (mis)alignment of top-down and bottom-up innovation drivers. For example, Ramiller and Schmidt [54] who also analysed the Danish energy system and the national strategy while elaborating on the importance of scale effects. Besides, Medved et al. [55] argue that clean energy communities could play an important role in social change by co-producing knowledge and testing and implementing radical energy innovations.

## 3. Material and methods

### 3.1. Research approach

Following these first steps within this field, this study focuses on the alignment of top-down policy strategies and bottom-up technological advancements by inter-organizational collaboration. By the analogy of going “from science to policy through transdisciplinary research” ([56], p. 46), this study aims to find those innovation drivers which enable going from transdisciplinary research to EI in (the energy) industry. This ambition is paired with the structured iteration of prior literature findings and empirical data to allow theoretical reflection as well (but

**Table 1**  
Examples of potential innovation drivers from influential environmental and energy innovation studies.

Type	Citations <sup>a</sup>	Scope	Transdisciplinary drivers <sup>b</sup>	Top-down drivers (policy)	Bottom-up drivers (organizations)	
[61]	Review	866	Sustainability-oriented innovation (SOI) of SMEs	<b>Collaboration</b> Interaction with external actors to increase SOI performance and root the whole business model in sustainability (p. 57)	<b>Economic and environmental relevance</b> While the concept of cleaner production focuses on environmental impact, eco-efficiency emphasizes economic gain (p. 66)	<b>Business models</b> Business model transformation for SOI (p. 70)
[62]	Review	794	Reusing food waste in industrial symbiosis	<b>Collaboration</b> Industrial symbiosis would be possible (p. 39)	<b>Circular economy</b> Industrial ecology, circular economy, and zero waste economy are the leading principles for eco-innovation (p. 28)	<b>Stakeholder management</b> Need for stakeholder involvement, inter-organizational collaboration (p. 39)
[63]	Research article	650	Green innovation and financial performance	<b>Innovation interplays</b> Green process innovation supports the development of green product innovation (p. 697)	<b>Economic and environmental relevance</b> Green technology innovation is relevant for the business sector (p. 697)	<b>Production</b> Green process innovation generates deep changes in the production (p. 702)
[64]	Review	565	Circular economy (CE) indicators	<b>Shared knowledge</b> CE strategies require shared and augmented knowledge, know-how (p. 556)	<b>Circular economy</b> Circular economy objectives (reduce, reuse, recycle) are different from the traditional linear economy, i.e., new measurement methods are needed (p. 543)	<b>Business models</b> CE strategies require new organizational and business models (p. 556)
[65]	Research article	444	Ecological footprint	<b>Innovation interplays</b> Technological innovation can reduce ecological footprint (p. 8)	<b>Impacts of growth</b> Economic growth and ecological footprint are associated according to an inverted U-shape (p. 3)	<b>Sustainable behaviour</b> Implementing sustainable management practices because of the depletion of natural resources, pollution, climate change (p. 2)
[66]	Research article	441	Drivers of eco-innovation	<b>Environmental capabilities</b> Green product design is an environmental organizational capability (p. 111)	<b>Encouraging innovation</b> Environmental policies can induce technological innovation activities of firms (p. 111)	<b>Production</b> Sustainable development induces new green products (p. 115)
[67]	Research article	413	CO <sub>2</sub> emissions	<b>Collaboration</b> International cooperation and research should be increased for better energy efficiency (p. 185)	<b>Economic and environmental relevance</b> Industrial structure must be reshaped to maintain growth and reduce emissions (p. 187)	<b>Sustainable behaviour</b> Environmentally friendly consciousness should be improved (p. 187)
[68]	Research article	315	Energy efficiency	<b>Innovation interplays</b> Domestic and foreign technological innovation has the potential to improve global energy efficiency (p. 9–10)	<b>Impacts of growth</b> New technologies must decrease carbon emissions which are associated with economic growth (p. 9)	<b>Knowledge absorption</b> International knowledge spillover could be highly important in tackling energy and environmental problems (p. 9)
[69]	Research article	169	Circular business models	<b>Innovation interplays</b> Circular economy is driven by creative individuals, entrepreneurs, new technologies (p. 738)	<b>Economic and environmental relevance</b> Decoupling production and growth from dependence on natural resources (p. 738)	<b>Production</b> Many companies started to develop environmentally sound products to remain competitive (p. 738)
[70]	Research article	153	ICT and carbon footprint	<b>Innovation interplays</b> ICT as an enabler of energy efficiency through other smart solutions, ICT changes patterns of production and consumption (p. 2)	<b>Impacts of growth</b> Growth-related research, development, and innovation can increase carbon dioxide emissions (p. 12)	<b>Sustainable behaviour</b> Careful management of rapid digitalization to avoid increased energy consumption (p. 2)
[71]	Review	152	Photovoltaic trends and growth	<b>Collaboration</b> Need for innovative policies, energy cost reduction, social acceptance, capacity building and collaborations (p. 589)	<b>Technological advantage</b> Renewable energy is a better option for a sustainable future and global economic contribution compared to other technologies (p. 591)	<b>Business models</b> Reconfiguring business activities for the social environment (p. 608)
[72]	Review	129	Corporate eco-innovation (EI)	<b>Social contributions</b> Design for the bottom of the pyramid (BOP) to reduce poverty (p. 216)	<b>Circular economy</b> Circular economy development is a key future direction of EI technology development (p. 216)	<b>Business models</b> Changing culture, behaviour, interests and designing sustainable business models (p. 211)
[73]	Research article	126	Life cycle assessment	<b>Innovation interplays</b> Eco-design for lower environmental impacts can mean eco-innovation, eco-redesign, or ecological system innovation (p. 236)	<b>Environmental assessments</b> Eco-design-related environmental assessments can drive changes (p. 237)	<b>Production</b> In certain cases, new design or eco-innovation is used to develop completely new products (p. 236)
[74]	Research article	110	Green socio-technical transition	<b>Collaboration</b> Cluster strategy can impact social learning and social change, technical innovation, and technical change (p. 224)	<b>Regional economic development</b> Green energy clusters can support economic development (p. 213)	<b>Sustainable behaviour</b> Overcoming path-dependence which promote incremental changes over transformative ones (p. 218)

(continued on next page)

Table 1 (continued)

	Type	Citations <sup>a</sup>	Scope	Transdisciplinary drivers <sup>b</sup>	Top-down drivers (policy)	Bottom-up drivers (organizations)
[75]	Research article	101	Venture capital and cleantech	<b>Innovation interplays</b> Cleantech requires diverse actors and innovation models (p. 394)	<b>Encouraging innovation</b> Public policy can encourage participation in cleantech innovation (p. 394)	<b>Business models</b> Clean energy could not only induce new technologies but also new business models to commercialize (p. 386)
[76]	Research article	100	Ecoscape	<b>Innovation interplays</b> Cultural innovation can be aimed at reaching sustainability, pathways toward sustainability require not only technological and institutional innovation, but cultural innovation (p. 28)	<b>Circular economy</b> Ego-industry must be changed to a function-oriented and closed-loop eco-industry (p. 27), the driving forces are physical force, i.e., energy; social forces, i.e., money (economic incentives), power (social integration), spirit (cultural innovation) (p. 19)	<b>Production</b> A participatory transition path is to develop easy-to-change processes (p. 27)

<sup>a</sup> Based on Scopus, June 2024.

<sup>b</sup> To remain brief, no verbatim quotes are used in the table, but page numbers are shown to ensure reliability.

limited only to the research context).

Fig. 1 presents the research framework, which concentrates on two dimensions of the sustainability transition: the innovation dimension (i. e., generating new solutions through research, development, and commercialization) and the change dimension (e.g., change in institutions, technologies, or business models) to increase environmental performance [2]. (1) As TR aims to solve real-world problems, accelerating the sustainability transition through EI could be targeted, i.e., TR can produce outcomes which can be further turned into applied EI in practice. This represents a linear transdisciplinary research and innovation (R&I) process, following a classic “need pull” innovation model [57]. (2) Public policymakers must introduce new strategies and measures to meet socio-environmental needs, i.e., they drive top-down changes to increase innovation performance. (3) Organizations with heterogeneous knowledge base sense stakeholder-related and/or business potential, problems, or a shapable, emerging context. They collaborate in inter-organizational networks to produce EI, i.e., they drive bottom-up change with innovation. (4) Top-down and bottom-up innovation drivers interact with the linear transdisciplinary R&I process, symbolizing a coupling innovation model [57]. Top-down and bottom-up innovation drivers should be aligned but can be misaligned with each other and with real-world problems, solutions, and innovation opportunities [16]. In other words, what happens in the intersection of the linear R&I process and the multi-directional change process is key to

turning TR to EI.

### 3.2. Geographical and technological context

The sampling of the study follows a deepening approach regarding the geographical scope. Accordingly, top-down innovation drivers are analysed on the level of a Central European region, consisting of four countries: the Czech Republic, Hungary, Poland, and Slovakia. This sampling for Central Europe has been quite frequent in the literature for decades [77,78], owing to similar socio-environmental characteristics and their regional alliance called the Visegrád Group. Specifically, the similarities of these countries' energy sectors, such as import dependence, and potential synergies of coordinated energy policies [79] further justifies this sampling.

The first phase of the action research was focusing on the top-down drivers, which, in line with the literature, was only used to frame the problem [42]. On the one hand, this phase included the analysis of the indices of the European Innovation Scoreboard [80], since prior innovation performance provides a context to interpret future ambitions. On the other hand, a qualitative document analysis was conducted (for detailed results, see the Supplementary Material), as reliable managerial and policy recommendations can be made by considering the existing strategic priorities of the chosen Central European countries. To ensure consistency, the national energy and climate plans were analysed in the case of all countries, specifically:

1. National Energy and Climate Plan of the Czech Republic [81]
2. National Clean Development Strategy 2020–2050 of Hungary [82]
3. National Energy and Climate Plan for The Years 2021–2030 of Poland [83]
4. Integrated National Energy and Climate Plan for 2021 to 2030 of Slovakia [84].

During the document analysis, we followed an inductive approach with gathering in vivo codes and interpreting, synthesizing them to explore (1) the conditions and (2) frameworks for EI. The analysis separated (a) the environmental aspects as the focal perspective of, and (b) the social and economic aspects as other dimensions of the sustainability transition. The reliability of the qualitative coding was ensured by conducting the draft analyses of two co-authors, while the other two co-authors were responsible for supervision and finalization. Nevertheless, since the qualitative nature of the coding could lead to varied operative results in case of different research groups, results are more applicable to explore patterns in strategic change directions rather than operative details. Detailed analyses of the strategies can be found in the Supplementary Material.

The bottom-up innovation drivers are analysed, however, on the level of an international inter-organizational network in the second

Table 2

Basic information about the transdisciplinary action research.

Action research	Subject of actions (What?) Methods (How?)	Environmental R&I activities in the energy sector Collaborative technology development and knowledge sharing, involving corporations, universities, and other partners
	Motivations (Why?)	Contribute to green transition in Central Europe
	Time horizon (When?)	2021–2024
Transdisciplinary research	Background of the core researcher group (authors)	Business and management studies (2 researchers) Research and innovation policy (1 researcher) Technology development, engineering (1 researcher)
	Other engaged actors (Detailed in Section 4.2.1)	5 local universities 5 local companies 6 other local partners (research centre, research lab, regulatory authority, individual experts) 7 foreign universities 4 foreign companies 1 other foreign partner (research centre)

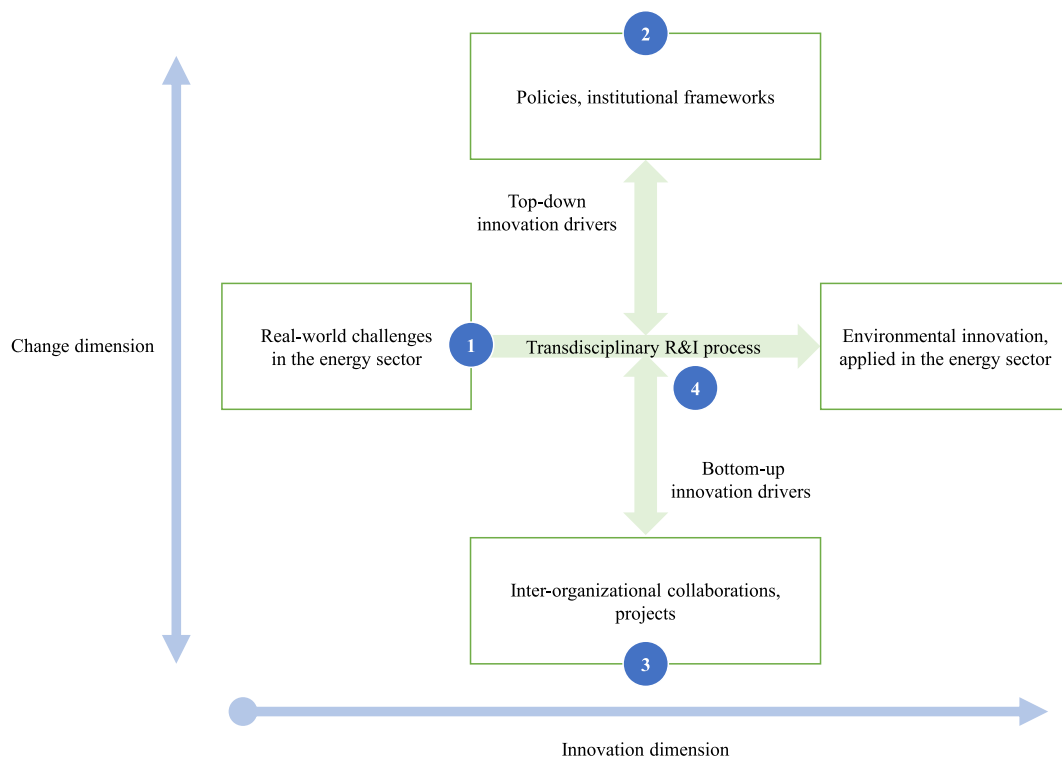


Fig. 1. Research framework.

phase. The core country of the network is Hungary, with partners from other countries for specific projects. The collaboration is framed by a program initiative to accelerate long-term energy storage and decarbonization in Central Europe, by developing solutions which can be applied and preferably commercialized (by corporate partners) in the analysed countries. Participants of the network are presented in Section 4.2.1.

The focal EI was focusing on decarbonization through renewable energy integration and long-term storage, i.e., power-to-gas [85] combined with a CCUS system [86]. These sectoral areas got “more efforts needed” and “not on track” statuses in the Tracking Clean Energy Progress Report [4], which indicates the relevance of further R&I. Technological details of the EI are presented in Section 4.2.2.

### 3.3. Transdisciplinary action research: process and limitations

Following the TR principle which aims to interconnect scientific work with socio-environmental needs, the authors of this study have been actively engaged in the R&I processes. This engagement was framed by the methodology of action research. This approach is also in line with the participatory action research concept, presented in the energy sector by McGookin et al. [50]. While the research framework (Fig. 1) considers more abstract innovation mechanisms to improve fundamental understanding, the combination with transdisciplinary action research enables the generation of socially useful contributions [87].

In terms of scientific rigor, qualitative researchers need to detail and reflect on their research design and the limitations of their methods, as follows:

#### 1. Research design

The researcher group and the fundamental information of the action research [88] are introduced in Table 2. Despite the large number of participants, the research focused on a single but spatially and temporarily extended case of collaborative R&I, and rather the activities and

outcomes (i.e., impact generation in the theoretical background), than on the individual contributions of the partners.

#### 2. Inherent limitations

The applied qualitative data collection and analysis methods belong more to the interpretive paradigm of energy social science research, which can have risks and limitations, such as (1) the amount of time required to gather in-depth understanding, (2) perspective-based biases, or (3) misinterpretations [87]. The methodological roots also put emphasis on internal validity and limit external validity. Consequently, unlike quantitative research, insights from a qualitative and highly context-specific study will not be generalizable.

#### 3. Actions to increase ensure rigor in a qualitative sense

To minimise the above-mentioned risks, (1) our research took three years to gather enough data and reach theoretical saturation, (2) included authors from three different disciplines to confront perspectives, (3) actively compared empirical data with prior findings (Table 1) following an abductive approach [89]. This approach, deriving from the grounded theory methodology [90] allows us to make theoretical extensions valid in a limited social context (the Central European energy sector). To further increase rigor, a clearly structured research process was formed. Considering the dominant change and management aspects in the research framework, we applied a combined process of Lüscher and Lewis [91] for the action research and Lang et al. [42] for TR, as detailed in Table 3.

#### 4. Results and discussion

In the following, first, top-down drivers are introduced which, from a TR perspective, framed the problem, i.e., challenging context and insufficient EI performance. The analysis of these top-down drivers includes quantitative and qualitative as well. Second, the bottom-up innovation drivers are explored, with a detailed list of collaborative EI

**Table 3**  
Details of the transdisciplinary action research.

Action research phases [91]	TR phases [42]	Focus	Data and analyses
Groundwork (2021)	Phase A: Framing the problem	Top-down innovation drivers	Qualitative content analyses – Climate and energy strategies of Central European countries Sample: - Czech Republic - Hungary - Poland - Slovakia
Interventions (2021–2023)	Phase B: Co-producing solutions-oriented knowledge (and initial solution)	Bottom-up innovation drivers	- Technology development, lab-scale prototype development (with individual experts) - Industrial project planning, techno-economic analyses (with corporate partners) - Organizing research conferences (with university partners) - Research and innovation project planning (with corporate, university, and other partners) - Preparing patent applications (three of the four authors)
Theoretical iteration (2024)	Phase C: Applying knowledge in scientific and social practice	Top-down and bottom-up innovation drivers	Iterating empirical data and theory through the thematic coding of EI literature (see Section 2) and comparing findings with data, based on the abductive theory of scientific method [89]

initiatives and outputs. Considering TR, this part concentrates on the co-production of knowledge and solutions and presents concrete examples and data about TR activities and their outputs. Third, the relationship of TR and EI is discussed from theoretical perspectives.

#### 4.1. Exploring top-down innovation drivers

##### 4.1.1. Prior innovation performance

The innovation performance of Central Europe and the focal countries can be compared by using The European Innovation Scoreboard. Table 4 shows that Austria and Germany belong to Strong Innovators, while other Central European countries belong to Moderate Innovators or Emerging Innovators, including the Czech Republic, Hungary, Poland, and Slovakia.

Besides, there are certain output sub-indicators which might help to

**Table 4**

Categorization of countries based on the Summary Innovation Index of The European Innovation Scoreboard – (based on European Commission, 2023).

Category	Country	Central Europe (EU)	Focal countries in this study
Innovation Leaders	DK - Denmark		
	SE - Sweden		
	FI - Finland		
	NL - Netherlands		
	BE - Belgium		
Strong Innovators	AT - Austria	X	
	DE - Germany	X	
	LU - Luxembourg		
	IE - Ireland		
	CY - Cyprus		
	FR - France		
	EE - Estonia		
Moderate Innovators	SI - Slovenia	X	
	CZ - Czechia	X	X
	IT - Italy		
	ES - Spain		
	MT - Malta		
	PT - Portugal		
	LT - Lithuania	X	
	EL - Greece		
	HU - Hungary	X	X
	HR - Croatia	X	
Emerging Innovators	SK - Slovakia	X	X
	PL - Poland	X	X
	LV - Latvia		
	BG - Bulgaria		
	RO - Romania		

generate a nuanced picture of EI performance (Fig. 2). For example, there is an “Eco-Innovation” index, according to which Slovenia and Czechia have a quite high performance, while Poland and Hungary have a quite low performance. The “Environment-related technologies” index shows a similar picture, but in this case, Slovakia has the largest score. Consequently, top-down changes might or should drive improvement in EI in the focal countries.

##### 4.1.2. Policy frameworks for energy transition and innovation

The document analysis highlighted that the analysed countries have similar strategic frameworks and innovation opportunities. Overlapping strategic directions include low-carbon or climate-neutral economy development, significant transformation of the energy sector, developing low-carbon solutions, and focusing on energy efficiency, nuclear energy capacities, renewable energy, and bioenergy. Innovation directions include, for example:

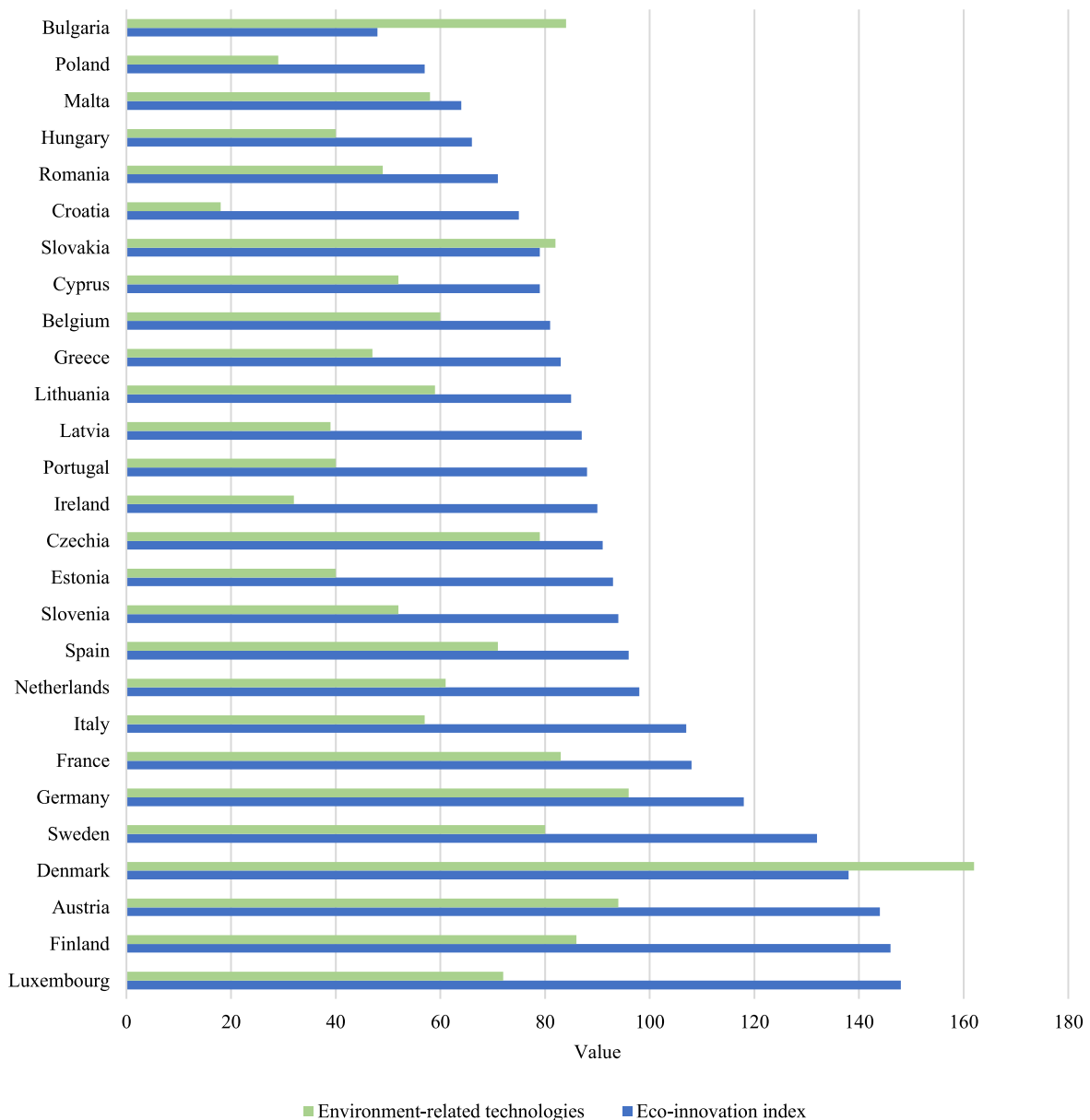
- Czech Republic: “Priority areas of &I: Renewable (alternative) energy sources, Nuclear technologies, More efficient use of fossil energy sources, Increasing efficiency and reliability of energy systems and distribution networks, Energy recovery of waste, Transport systems” ([81], pp., 72-73)
- Hungary: Energy efficiency improvement; Electrification; Hydrogen, CCUS, RES, and energy storage technologies; Bioenergy, biofuels; Modern agriculture, Natural sink capacities ([92], pp., 12-13)
- Poland: “...reducing emissions in transport, construction and agriculture, taking into account the beneficial effects of CO<sub>2</sub> absorption by ecosystems and the flexibility associated with land use, land use change and forestry”; “Advanced biofuels, wind energy, RES micro installations” ([83], pp., 2-3)
- Slovakia: “The optimal use of renewable energy sources, nuclear energy, decarbonised gases and innovative technologies” ([84], p. 10)

Besides, certain statements indicated the need for a transdisciplinary approach, as indicated in the precursory systematic literature review:

- Economic and economic performance: The transformation of the energy sector must provide not only environmental but economic benefits in all countries. For example, the Czech strategy lists not only energy R&I directions but more general national priorities, such as creating an environment for quality life.

The national priorities for oriented research, experimental development, and innovation include Competitive knowledge-based economy, Environment for quality life, Social and cultural challenges, Healthy population, Secure society ([81], p. 72).

The Polish strategy mentions the ambition to reduce their gap



**Fig. 2.** Eco-Innovation Index and Environment-related technologies according to the European Innovation Scoreboard (based on European Commission, 2023).

compared to economically more developed countries. Illustrative statements, for example:

- a. “Development of a competitive (energy) market”
- b. “Reduce the civilization gap between Poland and economically highly developed countries” ([83], p. 4)

b) Innovation interplays: The documents suggested an increasing need for combining diverse knowledge bases. For example, the Hungarian strategy mentions that technological innovation should be combined with business model innovation and social innovation.

“there is also a need for regulations and policies that encourage innovation as well as innovative business models”; “...there is a need to pursue a holistic approach that emphasizes the importance of interaction between technological and social innovations” ([92], p. 115).

The Slovak strategy emphasized industrial and digital technologies, especially to improve energy efficiency, but also to drive economic development.

“Establishing a technological lead in alternative energy and reducing energy consumption will create huge export and industrial opportunities. It will also support growth and jobs”; “The Slovak Republic has the

potential to use knowledge and domestic expertise acquired through Big Data in the processing, analysis, prediction and visualisation of large volumes of data in real time, as well as to use artificial intelligence...”; ([84], p. 14).

#### 4.2. Exploring bottom-up innovation drivers

##### 4.2.1. Participants

The activities, results, and participants of the focal TR-based EI are detailed in Table 5. As the table shows, several universities and university departments were involved in projects, representing different disciplines (energy engineering, energy economics, biology, business and management, and agricultural economics). Besides, multiple corporate partners were also engaged in prototype development, feasibility studies, and further project planning. The authors participated in the action research on the side of the cleantech system developer company. In addition, individual experts, and external universities, and companies also participated in certain projects and initiatives, from Central Europe (Germany, Austria, Croatia), and outside Central Europe

**Table 5**  
Timeline of the intervention phase of the action research.

Timeline	Activities, results (with evidence and reference, if applicable)	Departments from local universities (scientific area)	Local companies	International and other local partners
- 2021 (Baseline)	P2G prototype operations since 2018, focusing on biomethane production [98] Two Hungarian power-to-gas conferences organized in 2019 and 2020 [99] [100]	– Energy engineering; Biology; Energy economics; Business and management	Cleantech system developer; Integrated energy company Cleantech system developer; Integrated energy company; Manufacturing company	Biotechnology developer Energy research centre; Chemical research lab
2021	Q1: Cooperation on the National Hydrogen Technology platform [101] Q1-Q4: International P2G research project with biogas focus [102] Q2-Q4: Searching and finding new paths of P2G development; Engagement to CCUS development and integration; Plans for CCUS prototype development; CCUS prototype development and first experiments Q4: Third Hungarian power-to-gas conference in 2021 [103]	Energy engineering; Biology; Energy economics; Agricultural economics Energy economics; Agricultural economics Energy engineering Energy engineering; Biology; Energy economics; Business and management; Agricultural economics	Cleantech system developer; Integrated energy company Cleantech system developer; Integrated energy company Cleantech system developer Cleantech system developer; Manufacturing company	Non-profit professional organization (hydrogen technology) External university partner (India) Individual experts (engineering) Energy research centre
2022	Q1: Feasibility study for commercial-scale P2G implementation at a wastewater treatment plant [104] Q1-Q4: CCUS prototype development and integration tests with P2G prototype; Patent application for P2G-CCUS integration Q2-Q4: Feasibility study for commercial-scale P2G-CCUS implementation at an industrial site Q3-Q4: Planning two international research projects (solar fuel generation, decarbonization of the chemical processes) Q4: First Central European Power-to-Gas Conference [97]	– – – Energy engineering; Energy economics Energy engineering; Energy economics; Biology; Business and Management; Agricultural economics	Cleantech system developer; Water utility company Cleantech system developer Cleantech system developer; Integrated energy company Cleantech system developer Cleantech system developer; Manufacturing company;	– Individual expert (engineering) – External university partners (Estonia, Finland); External research institute (Croatia) Regulatory authority; Energy research centre; External university partners (Croatia, Austria, India) External research institute (Croatia); External company (Germany, UK)
2023	Q1-Q2: Application for utility model protection of P2G-CCUS integration system; finalization of the patent application Q2: New biocatalyst experiments Q2-Q3: Planning an international research project (waste-to-biofuel system development)	– Biology Energy engineering; Energy economics	Cleantech system developer Cleantech system developer Cleantech system developer	– – External company (Estonia); External university partners (Turkey, Bulgaria)

(Estonia, Finland, India, UK, Turkey, Bulgaria). While it would be theoretically beneficial to involve participants from the Czech Republic, Poland, or Slovakia, “real-world” conditions constrained research opportunities.

#### 4.2.2. Activities, challenges, and results

Before the start of the intervention phase of this action research, initial partners were working on the development and operation optimization of a P2G prototype. Its primary function was to produce biomethane as an end-product, which can be injected into the natural gas grid for long-term energy storage [93,94]. Research partners aimed to establish a solid scientific basis to increase credibility in the eyes of high-level policymakers, since upscaling the technology faced a common challenge of EI – as some of the created value is externalized, it does not clearly meet investors' expectations [12]. Thus, the ultimate goal of impact generation by up-scaling the P2G technology would need financial support from the state administration. Consequently, domestic P2G conferences were organized where several universities and disciplines appeared, followed by publications in peer-reviewed journals.

While discussions with large energy companies and policymakers were in progress to establish a regulatory sandbox model for a pilot P2G plant with biomethane production, the middle of 2021, however, meant a turning point in this transition from research to practice. At the beginning of 2021, many of the network members had been already engaged in the National Hydrogen Technology Platform. It organized discussions about the domestic hydrogen technology development opportunities and directions, supporting state administration to prepare and finalize the national hydrogen strategy, which was published in May 2021 [95]. Prior to that, the national climate and energy strategy suggested that bioenergy, biofuels, and energy storage are similarly important areas as hydrogen ([92], pp., 12-13). Nonetheless, the formal hydrogen strategy meant a clear message to the energy sector about preferred technology development directions. In other words, the initial biomethane-based pathway for impact generation was challenged by the national hydrogen strategy which included specific targets for 2030, for example, “20 thousand tons / year low-carbon hydrogen, 16 thousand tons / year green and other carbon-free hydrogen, 240 MW electrolyser capacity, and 20 hydrogen refuelling stations / 40 refuelling points” ([95], p. 3).

Policy emphasis, consequently, meant a challenge for the ongoing R&I and upscaling activities. A new technological pathway must have been found, which is still in line with the prior biomethane-focused knowledge base, the regional context, and more in line with the hydrogen-heavy impact generation opportunities. Thus, besides continuing the “traditional” P2G activities (e.g., a feasibility study at a wastewater treatment plant and an international research project on biogas upgrading), a new R&I process has been started. The scope of the new R&I was carbon capture and utilization (CCU). The assumptions behind this choice were the following:

- a) Regional perspective: CCUS is inherently important for industrial decarbonization, as highlighted in the national climate and energy strategies (see the Supplementary Material). Nonetheless, the map of the International Association of Oil and Gas Producers [96] showed no existing or planned CCUS project in Hungary, Slovakia, or the Czech Republic, and only two were under planning in Poland, in October 2022.
- b) Environmental perspective: Biomethane / synthetic natural gas will be important in the energy storage mix as an environmentally friendly alternative to natural gas, despite the current context being challenging for commercial-scale deployment. The large capacities of the Hungarian natural gas grid would enable efficient and seasonal energy storage as well. Besides, the emissions of traditional hydrogen generation can be reduced by CCUS (i.e., producing blue hydrogen).

- c) Technological perspective: Biomethane / synthetic natural gas can be produced from green / blue hydrogen and CO<sub>2</sub> using the existing technology (knowledge base).

Table 5 shows that these assumptions were generated and validated through multiple projects (feasibility studies, R&I project planning), involving the companies and universities. An important milestone of this new pathway's scientific dimension was the organization of the First Central European Power-to-Gas Conference at the end of 2022, the subtitle of which already included CCUS: “Regional perspectives of power-to-methane and carbon capture technologies” [97].

Knowledge absorption from and ideation within these international scientific relationships was necessary to reshape the R&I strategy toward CCUS. Accordingly, the initial EI pathway was extended, and not replaced. The inventive activity identified an opportunity to directly integrate chemical CO<sub>2</sub> absorption with biological methanation of CO<sub>2</sub> and H<sub>2</sub> to produce synthetic natural gas (CH<sub>4</sub>) without a desorption phase but reusing the metabolic waste. Thus, the solution enables to reduce deployment costs, and transform a cost factor (CO<sub>2</sub>) into a valuable end-product (synthetic natural gas). The schematic process of the system is shown in Fig. 3. Photos of the prototypes can be found in the Supplementary Material.

The industrial part of the R&I consisted of three main phases to date: (1) CCUS prototype development, (2) CCUS prototype integration with P2G prototype, and (3) patent and utility model applications. In parallel, a feasibility study was conducted in 2022 about the upscaling potential of the technology in an industrial environment, in collaboration with a large energy company. Finalized patent and utility model applications were submitted in 2023, and accepted in 2024 by the Hungarian Intellectual Property Office (patent ID: P2200190; utility model ID: U2300161) ([105], pp. 329–330). These performances are, on the one hand, concrete and significant steps toward large-scale impact generation (i.e., decarbonization, energy storage). On the other hand, they generate small-scale impacts on the industry (i.e., the availability of a new solution for incumbent companies to develop further and exploit).

### 4.3. From transdisciplinary research to environmental innovation

#### 4.3.1. General transdisciplinary principles

First, the activities of the network could be evaluated whether they are in line with the general TR characteristics [42]. In Phase A, collaborative problem framing, and research team building happened twice:

- 1) Solving the challenge of long-term energy storage by P2G and biomethane production;
- 2) Solving the challenge of industrial decarbonization, thus, focusing on the integration of P2G and CCUS.

Both areas are real-world problems, especially considering the climate and energy strategies of the focal Central European countries. Even so, energy transition strategies must consider not only the technological but the economic and social conditions, as well. In countries which are more dependent on fossil fuels, CCUS and natural gas (biomethane) are valuable bridging technologies [106], but reducing uncertainties and finding new opportunities is necessary.

In Phase B, the co-production of transferable knowledge was realized in scientific conferences, international research projects and further project planning, like other transdisciplinary collaborations for environmental sustainability [107]. Moreover, technical problems were involved by the collaboration of corporations, universities, and individual experts. In Phase C, valuable knowledge was integrated into both societal and scientific practice. Regarding the socio-environmental context, recent research underlines the value of conceptual models and design prototyping in transdisciplinary processes [108]. Nonetheless, the focal R&I process was able to go even further. The P2G-CCUS prototype integration was a key milestone in the impact generation

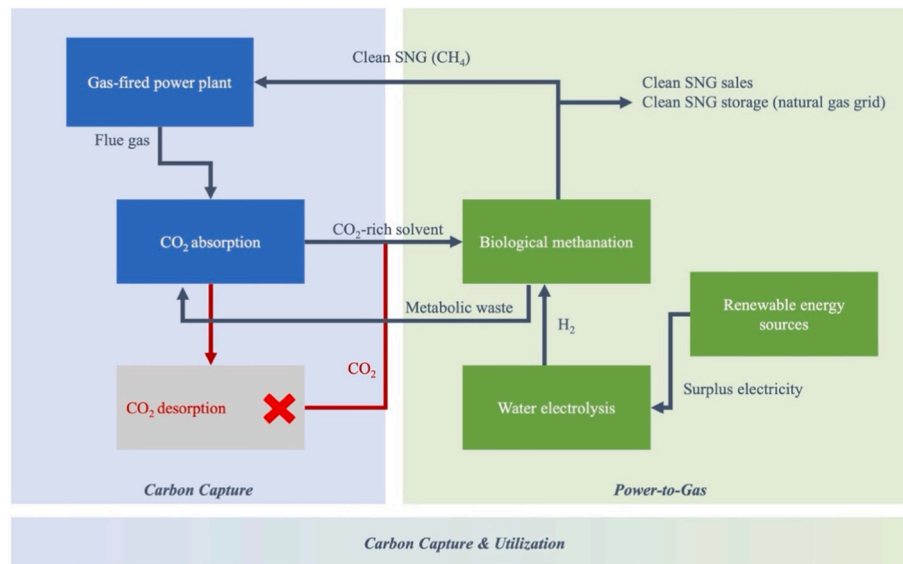


Fig. 3. Technological system concept of the focal EI – Avoiding CO<sub>2</sub> desorption in an integrated CCUS system.

pathway. It led to new discussions with corporate stakeholders about its commercial-scale deployment and contribution to the decarbonization of the energy sector. In the case of scientific discourse, both P2G and CCUS research was lack of not only economic and management studies, but also technical ones (e.g., auxiliary equipment, processes), owing to the novelty of the area.

Regarding the potential barriers of impact generation, however, previously listed barriers [10], such as problems with political will, networks, and know-how exploitation strategies were not present in the analysed case. Even time and resource constraints are only relevant if these are not interpreted as internal conditions of the TR programme, but external forces which affect the alignment of innovation drivers, as elaborated in the following.

#### 4.3.2. Top-down and bottom-up drivers for EI

The first research question focused on exploring top-down and bottom-up innovation drivers are needed to turn TR into EI within the energy sector. Several drivers of the sustainability transition from the literature review could be identified in the empirical data, as well. For example, top-down drivers elaborated in the national climate and energy strategies include the relevance of parallel economic and environmental performance improvement. In the analysed Central European strategies, cleaner production for reducing environmental impacts is represented by the importance of industrial decarbonization with CCUS, while eco-efficiency for economic gain [61] is also prioritized, e.g., with digital innovation. Likewise, the transformation of the energy industry is also targeted in Central Europe, which would allow maintaining growth and reducing emissions [67]. Furthermore, the strategies contained lists of priority R&I areas to encourage cleantech innovation [66,75]. In particular, the empirical R&I case was not only oriented by long-term climate and energy strategy until 2050, but an ensuing “sub-strategy” for hydrogen energy until 2030.

Considering bottom-up drivers, the lessons from the precursory systematic literature review strongly suggested that reconfiguring business models [61,64,69,71,72,75] and forming a sustainable behaviour [65,67] could drive EI. These drivers, however, were not identified in case of the focal inter-organizational R&I process. Instead, new production patterns [63,66,73,76] were relevant by turning waste (CO<sub>2</sub>) into valuable end-product (biomethane or synthetic natural gas). Also, extensive stakeholder engagement [62] were critical during the R&I process. For example, interaction with external actors indeed increased EI performance [61]. In particular, these interactions were partly based

on (1) a green cluster-like [74] domestic inter-organizational R&I network, (2) international cooperation [67] and (3) knowledge sharing [68].

#### 4.3.3. Implications of potential (mis)alignment of drivers

The second research question aimed to reveal the implications of the potential misalignment of top-down and bottom-up innovation drivers. Consequently, the above-mentioned top-down and bottom-up drivers should not be analysed only independently but also concerning their mutual influence. As our empirical data showed, bottom-up drivers support top-down drivers, and vice versa, for example:

- 1) The biomethane-focused pathway had been strengthened by scientific research and conferences, and biomethane and P2G became included in the top-down climate strategy; moreover, the hydrogen-focused pathway was amplified by the creation of a hydrogen technology platform, supporting the decision-making about the relevance and content of a national hydrogen strategy.
- 2) The national hydrogen strategy challenged the biomethane-focused bottom-up initiative. This influence led to a new concept with a higher relevance for policy (decarbonization through CCUS), and scientific research as well, e.g., bioenergy coupled with Carbon Capture and Utilization (BECCU) [109].

Nevertheless, empirical findings also revealed the dynamics of this interconnection, which meant an *alignment – misalignment – realignment* process from the perspective of the focal EI concept (Table 6). Implications of this process can be interpreted from (1) innovation and (2) change dimensions, as proposed in our research framework (Fig. 1).

(1) Concerning the innovation dimension, Gaddy et al. [75] argued that cleantech requires not only diverse actors but also innovation models. This statement from a purely economic context (venture capital investments) is relevant in this research, as well, which is more socially embedded because of the TR perspective. Besides the large number of participants in the empirical data, both innovation models of the research framework appeared. First, TR-based EI fundamentally belongs to the linear models, as it responds to a “need pull”, i.e., tries to solve a real-world problem. In the empirical case, the need pull is associated with the challenges of long-term energy storage and industrial decarbonization. Second, the coupling model is also relevant, but its iterative and non-linear approach is different from the “co-creation” concept in traditional TR. In scientific context, the emphasis is on social learning,

**Table 6**  
Implications of the misalignment of top-down and bottom-up EI drivers, from the aspect of the focal case.

	Phases:	Alignment	Misalignment	Realignment
Empirical data	Top-down drivers Bottom-up drivers	High-level climate strategy, including both biomethane and green hydrogen Biomethane-focused (P2G) pathway for energy storage	Emphasis on hydrogen and operationalized green hydrogen-focused strategy and targets	
Implications	Change dimension	A TR-based, pro-active, bottom-up change approach was followed	Driving changes pro-actively by TR comes not only with opportunities but serious risks of misalignment if top-down drivers even slightly change	Green hydrogen and CCUS-focused pathway for industrial decarbonization Re-alignment required a shift from a pro-active bottom-up change approach to a re-active one
	Innovation dimension	Significant scientific and industrial R&I results in biomethane-based energy storage (P2G), responding to a socio-environmental “need pull”	Even complementary solutions in the long term (i.e., biomethane and green hydrogen) can become competitors in medium term	TR-based interplays could concern natures, fields, and types of innovation (i.e., from P2G-based process innovation to P2G-CCUS system innovation), using feedback loops in a coupling innovation model

and even practical and pragmatic, or empowering “co-production” is limited to the knowledge level, despite involving non-academic stakeholders [110].

Instead, the focal R&I process in the coupling model is framed by interactions and feedback loops from (1) state of the art in technology and science, and (2) market and societal needs. Moreover, it focuses not only intangible but tangible outcomes (i.e., environmental system innovation). These feedback loops are relevant because both the precursory systematic literature review and the top-down policy drivers highlighted another important perspective: innovation interplays, i.e., innovation in a specific field supports innovation in another field, e.g., digital innovation enables energy innovation.

Accordingly, a former technological innovation (P2G for biomethane production) was initially developed to solve long-term energy storage challenges. Nevertheless, it became the basis of another new technological system, the integration of P2G-CCUS for industrial decarbonization. This interplay is like turning environmental process innovation into environmental product innovation [63], however, in this case, an environmental process innovation (P2G) was turned into an environmental system innovation [73] by the combination of two technologies to ensure alignment with hydrogen initiatives (P2G and CCU). In a broader interpretation, prior innovation for large-scale energy storage enabled innovation for industrial decarbonization.

Based on the appearance of innovation interplays, recent literature suggests that different (a) natures of innovation could be combined, i.e., policy mixes for social innovation could be useful for socio-technical system change [16]. The analysed strategies also mentioned the combination of technological and non-technological innovations, but (b) also multiple technical fields of innovation, i.e., using innovations in ICT for energy efficiency improvements. Nevertheless, the empirical case showed that innovation interplays should not overlook (c) the types of innovation (from process innovation to system innovation).

(2) Concerning the change dimension, first, we conclude that reshaping R&I processes represents flexibility, and it is beneficial to remain relevant. Recovery from a partial failure of R&I, however, also requires significant resources, e.g., learning costs or preparation time for re-entry [111,112] that could have been avoided. In this sense, the core network members took a proactive approach to drive a sustainability transition toward biomethane-based energy storage. While the relevance of this solution was indeed mentioned in the national climate and energy strategy and has not been challenged since then, yet the sub-strategy for hydrogen with more concrete targets and actions challenged the biomethane initiative.

This phenomenon can be explained not only by the alignment of change directions but also by the timing of innovation drivers. Accordingly, TR theory fundamentally advocates initiating changes pro-actively, shaping the external environment for socio-environmental benefits. As shown empirically, it can be an environmental process innovation to improve environmental performance [113]. Nevertheless, there are other three possible attitudes toward change, i.e., being

passive, re-active, or pre-active. A pre-active R&I group can prepare a new solution in line with the anticipated changes. For example, they can focus on digital technologies that are increasingly adopted in green supply chains [114]. A re-active R&I group can find the response for an explicit problem, e.g., based on the recognition of market demand and a subsequent environmental product innovation [115]. The passive behaviour can hardly be associated with any initiative for change or innovation. From a traditional adaptation perspective, passive and re-active behaviour is usually associated with more risk compared to pre-activity and pro-activity [116]. Instead, the presented case for energy transition explored the risk of a pro-active change strategy in TR-based EI: despite scientifically grounded arguments, even complementary solutions can become competitors and be preferred in the medium term in the energy sector, because of resource constraints (or power plays) on a policy level. Consequently, the pro-active change attitude must have been turned into re-active after the release of the sub-strategy for hydrogen, and step back to research and prototyping.

## 5. Conclusions

This study focused on top-down (policy) and bottom-up (inter-organizational) innovation drivers to turn TR into EI and support sustainability transition within the Central European energy sector.

First, top-down and bottom-up innovation drivers were explored in the research context. Top-down innovation drivers of the analysed countries are similar in terms of the content of the expected changes: significant transformation of the energy sector with focusing on energy efficiency, nuclear energy capacities, renewable energy, and bioenergy. Further similarities were explored regarding the importance of parallel economic and environmental performance improvement. In addition, encouraging innovation interplays were also present in the analysed documents, in line with the suggestions of the EI literature. Regarding the bottom-up innovation drivers, the study explored drivers which were not expected based on the literature review. Instead of business model reconfiguration and forming a sustainable behaviour, which are more related to the corporate contexts, extensive and international stakeholder engagement and innovation interplays emerged as main success factors of TR-based EI.

Second, implications of possible misalignment of top-down and bottom-up drivers were analysed. Empirical results highlighted the risk of driving changes pro-actively by transdisciplinary R&I in the energy sector, since complementary solutions in the long term (i.e., biomethane and hydrogen in the energy storage mix) became competitors in the medium term, which challenged the relevance of less prioritized R&I process.

These Central European empirical results shed light on certain success factors which appeared in other TR studies from different regions. For example, Bergmann et al. [117] explored 11 success factors of real-world labs for sustainability, focusing on Western Europe, mainly Germany. Our findings underline the importance of the 9th success factor, i.

e., “be prepared for adaptability” ([117], p. 549), to ensure the relevance of the bottom-up initiative in a changing policy context. Schwarz et al. [118] summarized the findings of 15 case studies from Europe, concentrating on the transition to agroecology. Compared to their results, our findings only reinforce the role of “strengthened collaborative actions” ([118], p. 47) through the extensive international network, while social capital, the practitioners' knowledge, and the required changes in consumer behaviour were not relevant in this Central European and energy-focused context.

Outside Europe, Schneider et al. [119] conducted case studies on TR in Asia, Latin America, and Africa. While two of their success factors was not reflected in our empirical data (localized research and communication, and socially embedded long-term partnerships), the other two factors were reinforced for TR, i.e., “become more adaptive, flexible, and resilient in its design” ([119], p. 2342).

Compared to the extant research, three theoretical contributions can be identified. First, it empirically demonstrates that TR and EI can be and should be interconnected in the energy sector. It represents novelty, because, to date, innovation viewpoints have been overlooked in TR studies conducted in the energy sector. Second, prior studies explored top-down and/or bottom-up drivers by “taking a snapshot”, while this longitudinal study identifies a new perspective (i.e., timing) for understanding the (mis)alignment of top-down and bottom-up innovation drivers. Third, this study highlights that top-down drivers can encourage different kinds of EI interplays for the energy transition. While innovation interplays appeared as underlying success factors in previous EI research, this is the first study to explicitly elaborate on their significance in the adaptation of TR processes, and highlight that the interplay is possible not only among natures (e.g., technological and business model) and fields (e.g., ICT and energy), but also types (e.g., process and system) of innovation.

### 5.1. Implications for policy and management

From a societal perspective, the empirical data shed light on the risk of losing scientific and industrial R&I outcomes which would be valuable in the long-term energy mix (biomethane pathway), owing to changes in top-down innovation drivers (prioritized hydrogen pathway). Consequently, policymakers can benefit from introducing institutionalized platforms to monitor new TR programs and EI pilots which inform the operationalisation of climate and energy strategies. Such institutionalisation will help evidence-based policymaking, which is usually challenged by uncertainties and reliability issues in the environmental area [120].

Furthermore, in the presented case, the transition from biomethane-based process innovation to hydrogen-based system innovation exemplifies the role innovation interplays in turning TR into EI. Consequently, a practical contribution of the study is that it encourages policymakers to incite innovation interplays to accelerate sustainability transition, and offers innovation interplay as a way of forward-thinking for contextually challenged inter-organizational innovation initiatives.

From a managerial perspective, while pre-activity has less potential to transform the energy sector and leads to limited benefits compared to the pro-active strategy, it also comes with fewer risks, which is important in a resource-scarce environment. In a pressurizing public context and business climate to be pro-active and shape the external conditions, understanding the risks of this approach should also be the part of responsible management. Since bottom-up initiatives can only influence but not control top-down change drivers, risk management should focus on producing flexible innovations with a wide range of reconfiguration options [121].

### 5.2. Limitations and future research

The main limitations of the study derive from the applied qualitative methodology. First, this research was conducted by a multi-disciplinary

research group, and the background of co-authors inherently influenced the focal points of the analyses. In particular, co-authors from the business and management field draw attention to adaptation challenges of the bottom-up projects, the co-author from the research and innovation policy field oriented the research to the alignment of top-down and bottom-up drivers of innovation. Finally, the co-author from the engineering field ensured to bring research and action, theory and practice (i.e., technology development) as close as possible. Even though we transparently disclosed our theoretical lens and assumptions, and detailed our methods, self-reflecting qualitative researchers must recognize that other researcher groups could interpret empirical data differently.

Second, the followed abductive approach enabled us to find a strong fit between theory and the empirical phenomenon, and to find the most promising explanation, but formal theory construction would require quantitative methods [89]. Consequently, our findings might fine-tune existing theories and can serve as hypotheses for further quantitative research. In other words, the findings of this study are not generalizable owing to its strong context-specificity. Consequently, replicating the study in other geographical contexts could contribute to gather further insights about TR-based EI processes. The nonlinear nature of this process, however, cannot guarantee the reproduction of the same outcomes, nor the challenges and the solutions (e.g., realignment of drivers through innovation interplays). So, building on the same trans-disciplinary action research phases (i.e., groundwork with problem framing, intervention with knowledge co-production, theory building and application [42,91]) is the most promising opportunity to establish a reliable basis to compare empirical results. Besides, future research might analyse similar projects in other industries since the complexity of the energy sector can strongly influence the theoretical reflections. Similar contextual preconditions, however, such as existing inter-organizational innovation networks, climate ambitions, and policy changes can increase the chances to explore similar patterns. For example, Western European scores in eco-innovation and environmental technologies indices are higher, but regulatory pressure on EU companies to disclose and increase the environmental, social, and governance (ESG) recently started to decrease (see e.g., the first Omnibus package). These future works could explore, for example, how innovation interplays and driving bottom-up changes pro-actively could accelerate the sustainability transition there.

### CRedit authorship contribution statement

**Zoltán Csedő:** Writing – original draft, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Máté Zavarkó:** Writing – original draft, Methodology, Formal analysis, Data curation. **Zoltán Sára:** Writing – review & editing, Visualization, Validation, Software, Methodology, Data curation. **Gábor Pörzse:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition.

### 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.

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### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.erss.2025.104222>.

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## Data availability

Data will be made available on request.

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