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# The role of inter-organizational innovation networks as change drivers in commercialization of disruptive technologies: the case of power-to-gas

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## ABSTRACT

Power-to-gas (P2G) technology is an emerging disruptive solution for renewable electricity integration and energy storage. Two significant challenges of its commercialization are the perceived risks associated to its scalability and the cost-benefit ratio of P2G versus other innovative energy storage technologies. Its emerging regulatory and business environment significantly limit the accuracy of the financial models, as well.

The authors have examined how strategic and innovation management could contribute to the commercialization of the technology despite the above-mentioned challenges. The authors performed action research between 2016–2019 at Hungarian technology developer startup Power-to-Gas Hungary Kft.

Research results show that dyad-level open innovation led to a significant opportunity to make new steps towards the commercialization of the disruptive technology. Because of the exploitative characteristics of the market environment and emerging regulatory framework, significant needs for complementary resources were identified that would drive successful commercialization. Inter-organizational P2G innovation networks and their role in shaping further innovation and the establishment of regulatory sandbox models might be essential to overcome barriers of commercialization of this disruptive technology.

***Keywords:***

Power-to-gas;
Technology development;
Inter-organizational network;
Innovation management;
Action research;

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## 1. Introduction

One of main trends of the transforming energy sector is the increasing use of renewable energy technologies [1]. Renewable energy technologies research [2, 3, 4] is significantly focusing on research areas, such as energy supplies and cost-efficiency [5, 6], regional level integration and coordination [7, 8], or system modelling and data analysis [9, 10].

This paper contributes to several research areas that drive the transformation of the energy industry: challenges related to the integration of renewables into the power system [11], technology investments and implementation [12], theories and tools to overcome these challenges [13, 14], with a special focus on organizational [15] and innovation management [16] perspective. The authors analyse the development and implementation of an innovative energy storage technology, power-to-gas (P2G) with biological methanation. An inter-organizational model of the core technological innovation is elaborated to overcome the challenges of the renewables integration in Hungary.

Nowadays, P2G technologies get increased attention from industry representatives, academia and public sector not only on national level, but on global level, as well. For

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example, the STORE&GO project, which is funded by the European Union's Horizon 2020 research and innovation programme, is focusing on three variations of power-to-gas implementation in three different countries – but still on demo sites. Since 2016, 27 European partners are collaborating in the project [17]. This fact justifies the critical role of inter-organizational innovation networks in case of power-to-gas technology development.

The scientific literature of energy storage elaborates the opportunities of P2G technologies for the transforming energy industry [18, 19, 20, 21] and its different technological R&D aspects [22, 23, 24, 25]. Based on the overview of Blanco and Faaij [26], P2G research focuses on levelized cost of energy, process design, time series, business models, technology review, cost optimization, life-cycle assessment and projects surveys, but does not focus on the managerial challenges of the technology development and commercialization. The P2G technology has not been widely commercialized, yet [27]. The authors believe that research focusing on innovation management aspects of P2G technology development would add significant value to the commercialization of this technology on a wider scale, as well as could serve as a benchmark to other disruptive technologies for successful commercialization.

Although this research has been undertaken in Hungary, focusing on local inter-organizational innovation networks, the research concept can be extrapolated internationally to countries and institutions collaborating to develop a disruptive technology and reaping similar benefits. Consequently, the findings of this research show how organizations could collaborate to exploit a disruptive technology and help decision-makers in supporting technology development according to the complementary resources on organizational, national or regional level.

Quantitative research in this field highlight important operative (e.g. efficient reactor structure) or system level (e.g. impact on the energy sector) cause and effect relationships between key variables. In contrast, this research enables a deep insight into the P2G technology development in a given context (Hungary) and highlights factors (opportunities, barriers, interests, perceived benefits) that lead to the formation of an inter-organizational P2G innovation network. A continuous iteration between the empirical research and management theory in this study is crucial because through this methodology the findings

a) emphasize the importance of inter-organizational networks in developing disruptive technologies
b) add "soft" management aspects to the P2G discourse
c) show that action research of new energy technologies is possible, and most importantly, not only possible but important and effective to generate social change.

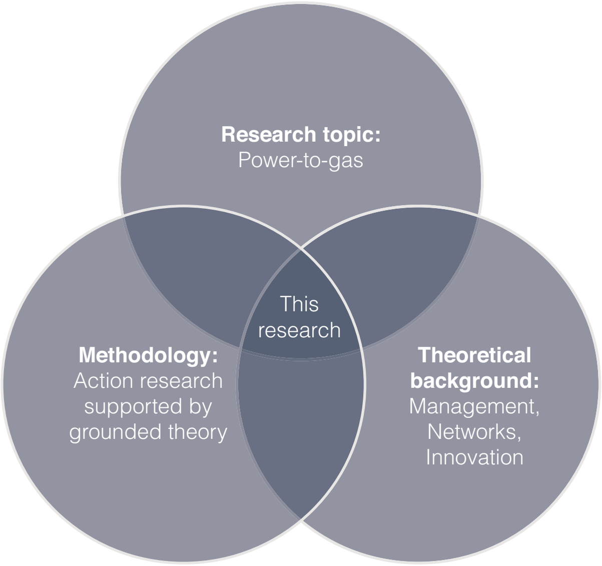

Figure 1: Characteristics of the research: research topic, theoretical background and methodology

Figure 1 shows the most important characteristics of this research. The combination of these managerial aspects in the power-to-gas research field is a significant research gap, and combining these methods could lead to answer the research question from the empirical research environment and lead to social change.

In the following chapters, the background, methodology, and key results of a three years long action research will be presented, as follows:

- Opportunities for deployment of P2G technology in Hungary
- Barriers of scaling-up and commercializing this disruptive technology
- Solution: formation of an inter-organizational innovation network.

In line with the fundamentals of action research and grounded theory, the authors are going to discuss the findings and draw conclusions iterated with related literature.

## 2. Background

In this section, the authors highlight those important characteristics of power-to-gas technology, the concrete research background, theoretical considerations and previous empirical results which had an impact on formulating the research question and framed the research.

### 2.1. Introduction of the power-to-gas technology

Energy storage is crucial to reach an increasing renewable energy supply [28]. The P2G technology is an emerging disruptive solution for renewable integration and energy storage by converting surplus electricity to biomethane which can be injected into the gas grid to store and transport it efficiently [26]. P2G also decreases the operating risks of TSOs by providing flexible balancing services. It contributes significantly to decarbonization efforts by using carbon dioxide in the methanation process [29].

According to Blanco and Faaij, P2G technology means "power conversion to hydrogen through electrolysis with the possibility of further combining it with $CO_2$ to produce methane" [26, p. 1049]. There are other definitions in the literature [29, 30, 31, 27], as well, however, this approach is best suited for this research, because it differentiates the two main market segments of the P2G industry: power-to-hydrogen (P2H) and power-to-methane (P2M). This approach also fits the areas of use of produced hydrogen [31]: direct utilization (e.g. as fuel), injection into the gas grid by its safety limits [32, 33], combining with carbon dioxide to produce methane.

This research focuses on the P2M segment, that is characterized by two dominant approaches: the catalytic (or Sabatier) and the biological methanation technologies [30]. The Sabatier process utilizes nickel- and ruthenium-based catalysts [31], while the biological methanation happens by methanogen microorganisms as biocatalysts [30]. The efficiency of biological methanation is higher (more than 95%) than in the case of the Sabatier process (70–85%) [26]. The product gas with high methane content can be directly injected into the gas grid, can be used for heating, fuelling or industrial processes [27].

Based on Baleira et al. [29], catalytic methanation has been known since the 1970s [30] and more projects have been running with catalytic methanation, than with biological methanation. Considering the higher efficiency of biological methanation, as well, one could argue that its innovativeness (which can be associated with newness, development, change, learning, improvement, value creation [34, 35, 36] ) is higher than the innovativeness of catalytic methanation.

### 2.2. Research background

The authors conducted action research with the involvement of P2G technology developer Power-to-Gas Hungary Kft. The company plans to build industrial-scale P2G facilities with biological methanation (up to 10 MW).

Power-to-Gas Hungary Kft. has been founded in 2016 and developed an innovative lab scale P2G prototype in cooperation with Electrochaea GmbH, the developer of the largest P2G facility in the world with biomethanation, located in Avedøre, Denmark (1 MW) [37]. In both cases, the P2G reactor contains a proprietary biocatalyst, which is an optimized strain of Archaea (Methanothermobacter thermautotrophicus). The robust, highly selective and efficient strain was developed at the University of Chicago [38, 39]. The conversion is carried out by basic reactions and mediated by the biocatalyst employing a unique set of enzymes [40, 41]:

- Power-to-hydrogen: $4H_2O \rightarrow 4H_2+2O_2+\text{Heat}$ (electrolyzer)
- Hydrogen-to-methane: $CO_2+4H_2 \rightarrow CH_4+2H_2O$ (biocatalyst)

The stoichiometry of the second reaction requires four moles of hydrogen and one mole of carbon dioxide to yield one mole of methane.

Using its innovative lab-scale prototype, Power-to-Gas Hungary Kft conducted R&D activities from April 2018 to July 2019. Based on the values of the product gas of almost 10 000 measurements within this period, Power-to-Gas Hungary Kft demonstrated the applicability of the technology in Hungary, collected and analysed empirical data for further development.

### 2.3. Research question

Both academics and industry experts agree that P2G technologies could play crucial role in the future of the energy sector. There are, however, two significant challenges of commercialization of P2G technologies: perceived risks associated to its scalability and the cost-benefit ratio of P2G versus other innovative energy storage technologies [30, 31, 27, 29]. The authors would like to contribute to addressing these challenges with this research.

On the other hand, the research is built on an inter-organizational network perspective, since several scholars argue that collaborations and networks among industry representatives could significantly increase innovation performance through combining complementary capabilities [42, 43, 44].

By following action research supported by grounded theory, not only the theory and the data were iterated and continuously forming, but the research question as well. While the initial question was rather a holistic strategic management question ("How to develop and commercialize P2G technology in Hungary?"), the final, narrowed research question was:

*How could inter-organizational networks and innovation management contribute to commercial development ambitions and scale-up of an innovative P2G technology, as well as to increase its efficiency?*

Based on action research, the authors aimed to build a bridge between technological, commercial and managerial aspects, as well as between theory and practice of P2G technology development and commercialization.

### 2.4. Research framework

There are significant changes in several energy market segments driven by global trends [45], especially sustainability efforts [1], decentralized and smart solutions [46, 47], energy efficiency and energy security [48]. Sustainability even appeared at many organizations as an additional goal besides profit-maximizing and growth [49]. Significant infrastructural challenges have also emerged in case of TSOs and DSOs, as decentralized energy production and consumption are not fully compatible with current physical and IT systems [50, 46].

Meeting these challenges are limited by general management related factors and by industry-specific factors. From managerial aspect, realizing strategic ambidexterity is difficult because exploitation (efficient operation on current business areas) and exploration (searching for new opportunities, innovation) are competing for the same resources and are contradictory from several aspects [51]. Organizations tend to follow their exploitative routines because of their path dependency [50, 51]. From the industrial aspect, Nisar et al [52] found that the strict regulation and the rigid institutional background in the national energy markets result in less open, less collaborative, less innovative structures at large energy companies. Costa-Campi et al [48] argued that large company size means slow, and long decision procedures related to R&D&I activities. This problem is widely spread in the energy sector, where market concentration and company size is usually high. Moreover, several studies concluded that the dominance of current technologies obstructs the development and implementation of new, renewable energy technologies [53, 54, 55]. Consequently, the development and implementation of new technologies (e.g. P2G technologies) could be limited by exploitative routines and path dependency of large energy companies.

According to management literature, collaboration with external partners [56] could add, however, significant value in such cases. Complementary resources can be essential for profiting from technological innovations, which can be ensured by collaboration partners, as well [42]. As a consequence, a network-based innovation approach could significantly contribute to competitiveness and efficiency [57].

Change aspects also emerge concerning innovation [58, 59, 60], as the dynamic reconfiguration of organizational capabilities could result in strategic actions and innovations which could shape the business environment [61, 62, 63]. Internal organizational capabilities can be combined with the capabilities of external partners, that could result in even disruptive innovations that are able to generate change in the industry [64].

Figure 2 summarizes the theoretical framework of the research:

1. The changing environment (here: higher share of renewables in the energy sector) means an adaptation challenge [65, 66, 67, 42] for energy companies.
2. Energy companies should facilitate exploration for renewal [68, 69], for example searching for new opportunities and technologies (here: P2G). Facilitating exploration and innovation generate internal (organizational) change [60], which is needed because of path dependency and exploitative routines [51, 51, 56].
3. Energy companies need to build inter-organizational collaborations (e.g. with start-ups or research centres) and to combine complementary resources [42] (e.g. core power-to-gas technology, scientific knowledge and extended energy infrastructure) [56, 44], and they should perform innovation management practices [70] (e.g. technology development) together.
4. Combining capabilities can shape the business environment [61, 62, 63], and disruptive innovation can be achieved which highly impacts the environment [64] (e.g. efficient, implemented, grid-scale P2G technologies contribute to the higher integration of renewables because of the long-term energy storage function).

In sum, inter-organizational networks contribute to the environmental adaptation of organizations, and they have the potential to generate change within the competitive environment.

The two main elements of this framework are the strategic approach (the resource-based view) and the innovation approach (network-based, or open innovation). The alternative model of the applied strategic approach could be Porter's framework, according to which the strategy

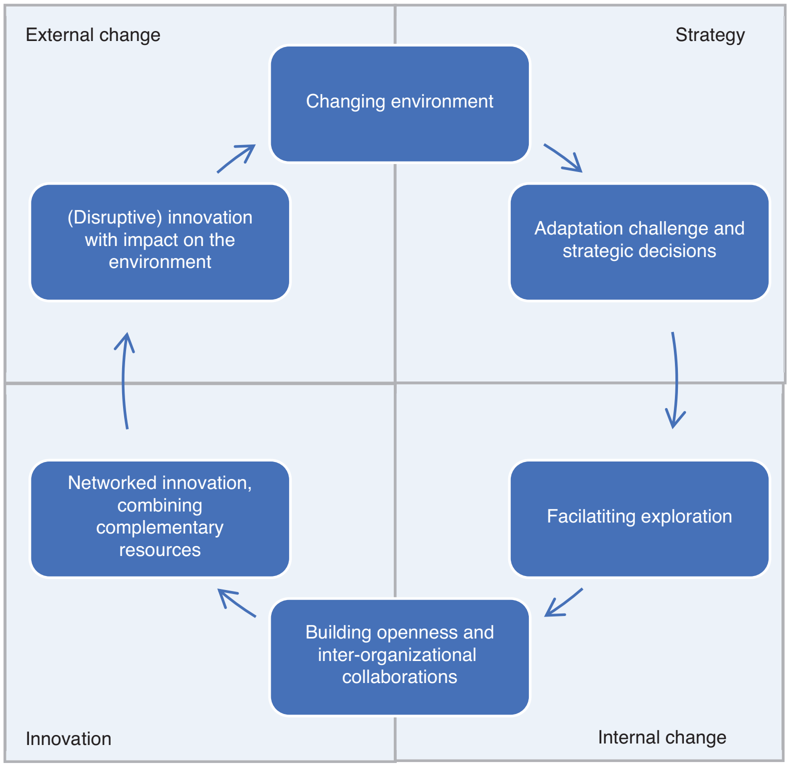

Figure 2: Network-based innovation as internal and external change driver (theoretical framework)

should be formulated based on the industry structure and the competitive positioning in the industry. In this case, the organization should focus on low-costs or differentiation [71]. In contrast, the resource-based view is based on the consideration that the pace of the change in the external environment is so high that sustainable competitive advantage can be only built on the organizational resources and capabilities [62]. In this case, the strategy should focus on developing and utilizing unique, rare, valuable and embedded capabilities [61]. The resource-based view is more appropriate in this research than Porter's framework which is more about positioning and competing than developing and utilizing something unique. In the researched case, the core P2G technology is given, it cannot be discarded, and at the time of the research, no competitors have been identified in Hungary in the P2G segment. Moreover, scholars have demonstrated in different technology-related cases that focusing on the development of capabilities can facilitate adaptation and innovation [72, 73].

Regarding the innovation approach, the alternative model of the open innovation is the closed innovation, where companies perform their innovation activities strictly inside, without involving external actors. Chesbrough [44] pointed out that innovation processes could result, however, in higher innovation performance (especially in case of technology development) if they would not stop at organizational or even industry boundaries, involving other organizations or groups such as suppliers or customers [44]. Open innovation paradigm is not only a trending practice but a viewpoint of analysis, as well. The authors take Vanhaverbeke's [74] categorisation as a starting point, which identifies dyad-level open innovation and inter-organizational networks as levels of analysis of open innovation.

## 3. Research methodology

The authors performed action research between 2016–2019 at Power-to-Gas Hungary Kft. Action research is a useful tool in management and organization research [75, 76, 77, 78] and has been used in the energy industry, as well [79, 80, 81]. Action research is a participatory and empirical process, meaning a constant iteration between social actions and the research of the actions undertaken, connecting theory and practice, and acquiring new knowledge to solve complex problems by generating change [82, 83, 84].

The conducted action research is close to the collaborative inquiry concept [85], as authors of this paper have been fully involved in the process as co-researchers aiming to improve their propositional knowledge (introduced in the second chapter) through practice and experience. Following McNiff's [84] guidelines, the authors must define that

- (1: What we do?) they develop and implement the P2G technology on grid-scale in Hungary
- (2: How we do this?) by analysing the role of inter-organizational networks and pro-actively engaging in inter-organizational networks in relation with P2G technology development and commercialization
- (3: Why we do this?) to contribute to the sustainability and energy security efforts on the national and global level.

As the research approach to this topic is managerial and involves change aspects, as well, the authors built the three years research process on the three phases model of Lüsher and Lewis applied in their similar managerial research topic [75]:

1. In the *groundwork* phase, building on findings of a literature review about innovation management challenges in the global energy sector, the authors aimed to create an overall understanding of the changing energy sector in Hungary. 15 semi-structured interviews were conducted in this first phase with local industry experts. As secondary data, corporate documents were analysed, as well.
2. In the *interventions* phase, three main milestones were undertaken, as follows:
    - an innovative P2G prototype has been developed in Hungary in collaboration with Electrochaea GmbH and started intense R&D activity;
    - new partnerships, inter-organizational networks have been built with potential stakeholders of the large-scale implementation of P2G technology;
    - an own digital, P2G R&D platform has been developed facilitating open innovation.

These activities can be considered as social actions through the lens of action research.

All these actions were continuously combined

- with semi-structured interviews of the potential partners and stakeholders (more than 30 interviews in this second phase);
- with the analysis of publicly reachable and confidential documents (more than 500 pages), as the triangulation of the primary interview-data;
- iteration between the data and the theoretical framework.

The authors followed qualitative methodology and iterated the empirical experiences in line with grounded theory fundamentals (e.g. making theoretical memos besides field notes, reaching theoretical saturation) [86, 87] to prepare the third phase.

3. In the *theory-building* phase, the authors synthesized the empirical findings with previous theories. To improve validity, the findings were presented to other scholars from different disciplines (engineering, biotechnology, management, legal) and industry partners (as potential collaboration partners in innovation). According to their feedback, findings and conclusions were finalized.

In-line with qualitative research methodology, in order to improve

- validity, the authors explored the research area deeply – that is why the research lasted three years and it was enough to reach the theoretical saturation
- reliability, the authors fine-tuned the conclusions after consulting with other scholars and stakeholders
- generalizability, the authors iterated the data with theory to create a substantive theory which is only valid in a given context and might be applied in similar cases.

## 4. Results

In line with the iteration between action and research, empirics and literature, the authors are going to summarise the findings while highlighting the relations and contributions to the current literature. The following results show what happened (happens) on the field (in Hungary with power-to-gas) and/or how it appears in the literature, while conclusions will connect these results with the theoretical framework to create a substantive theory.

### 4.1. The opportunity: Importance of P2G technologies in Hungary

The development of P2G technologies are in line with local industry trends and existing infrastructure. According to the new National Energy Strategy 2030, the installed capacity of electricity generating units from photovoltaic sources will exceed 6 000 MW by 2030 from ~1 000 MW of 2018 [88, 89]. Considering the volatility of the dominant ratio of the photovoltaic panels in this 6 000 MW (around 85%), and the planned increase of nuclear capacities, the development of large-scale energy storage technologies is a high priority [88, 89]. Even if the storage capacity of the accumulators could reach 100 MW [90], it is an extremely small volume compared to the 6,33 billion m$^3$ storage capacity of the Hungarian national gas grid [88, 89].

In terms of $CO_2$ sources, the theoretical P2G potential in Hungary is around 1 $GW_{el}$, based on the $CO_2$ output of anaerobic digestion plants ($CO_2$ in raw biogas) and bioethanol plants ($CO_2$ as a by-product) [91]. If one takes into account that "Hungary imports 80% of its natural gas" [89, p. 16], P2G technologies might have great importance in Hungary for large scale energy storage, and also for reducing the dependence on natural gas import.

### 4.2. Barriers of scaling-up and commercializing this disruptive technology

The authors found industry-specific and technology-specific barriers in Hungary which hampers the scaling-up and commercialization of the P2G technology.

#### *4.2.1. Industry-specific barriers of innovation*

Despite the opportunity created by an innovative technology for large-scale energy storage, there are several factors which limit further technology development. In line with Teece [42], innovative developers would need complementary resources (such as capital, infrastructure, knowledge and experience related to the grid operations) to scale-up the technology. Even though these resources could be granted by other industry partners (e.g. traditional large energy companies), which could also profit from accessing new technologies [92], there are industry-specific factors associated with systems, culture and knowledge, both inside and outside energy companies, which impede the development of any disruptive technology.

Table 1 shows those impeding factors which were identified by the 15 semi-structured interviews with industry experts who are/were working for power or gas companies (e.g. DSOs, TSOs) and are/were participating in innovation-focused initiatives. "Industry" in this case covers only the gas and the power industry segments (and does not cover the oil companies). These two segments are the most relevant from the aspect of the P2G, as these technologies can connect the power and the gas systems. The listed elements in Table 1 are common impeding factors in the power and the gas industry segments.

**Table 1: Impeding factors of innovation in the power and gas industry segments**

| | **External factors** | **Internal factors (in case of traditional energy companies)** |
|---|---|---|
| Systems | Rigid institutional background and strict regulations | Strong hierarchy and control<br>Incentives for stability and good short-term performance |
| Culture | Low motivations for entrepreneurship | Risk aversion<br>Low willingness to collaborate |
| Knowledge | Decreased access to innovative ideas on expert level | Missing knowledge about managing highly innovative projects |

Based on the interviews, many of these impeding factors derive from the rigid institutional background of the industry. In a market environment with such a high need for stability on short-term, large industry players are not incited to invest their resources for exploration and disruptive innovations.

#### *4.2.2. P2G technologies-specific barriers of further development*

Synthesizing the literature with empirical data, not only industry-level challenges limit the development of P2G technologies, but P2G technologies-specific factors as well:

a) Despite the biomethanation technologies are highly efficient (the rate of carbon dioxide conversion can be above 99% under optimal circumstances based on the data of the prototype), there are two efficiency challenges in different levels.
   1) *On sector-level*, the problem with efficiency is the higher electricity input upstream, higher pace of RES deployment (on top of what is already needed for electricity demand growth) and possibly reaching the maximum potential in some areas. High pace of RES deployment

also increases maintenance costs of TSOs, which could be solved by deliberate sizing and location of more P2G facilities.

2) *On technology-level*, the *efficiency of overall energy conversion* could be increased. For example, the utilization of waste heat for power generation could be another source for biomethane production. The produced waste heat at 70 C°, however, is currently too low for efficient electricity production which indicates the development of new technology solutions [93]. Moreover, there are other uncovered research areas in case of new biomethanation solutions: other types of reactors, stirring or nutrition of biocatalysts could also affect the overall efficiency of energy conversion.

b) Regarding *scalability*, also two key points should be discussed:

1) *Financing*: Assuring a reasonable return of investment is an important challenge because of the high costs of new technologies involved. The return of investment (mainly because of the high prices of electrolysers [94]), can be realized only over 10 years. Industrial-scale P2G facilities need low cost electricity [94], the electricity costs being the highest amount (43%) of the full production costs/kg methane. This meant 0,83 €/kg methane for electricity [94].

2) *$CO_2$ availability*: Finding ideal sites for P2G facilities might also be challenging because of large volumes of carbon dioxide are needed: For example, a 2 MW P2G facility would need ca. 105 $Nm^3$ carbon dioxide per hour. The access for proper carbon dioxide sources (gathered, efficiently useable, without harmful contaminants for biocatalysts) might be also difficult. This amount could be sourced only at larger wastewater treatment plants, agricultural biogas plants or bioethanol plants since current costs of carbon capture and storage technologies are rather high. Furthermore, a P2G facility would need a nearby connection for the natural gas grid for efficient storage and transport. If there is no connection for the natural gas grid on the site, compressing the biomethane to CNG fuel would require new investments, meaning higher operation costs, as well. [30, 26]

c) P2G technology could contribute to reaching national and regional energy policy objectives and could solve significant challenges of grid balancing [31]. There are, however, significant legal and regulatory barriers.

1) Hydrogen production, storage and injection into the natural gas grid are challenged by safety and administrative requirements in some countries (e.g. Spain), but there are also incentives for production or usage in other countries (e.g. Belgium) [95]. Regarding the biomethane production, feed-in tariffs were introduced in many EU member states as incentive (e.g. France, Germany). There are several legal and regulatory details which should be answered to support P2G technologies: e.g. clarification of the aim of the technology (energy storage and/or gas production), harmonisation of quality standards, shaping a system for network tariffs for energy storage [96].

2) The regulation of the mentioned feed-in tariffs and energy storage tariffs as revenue streams could be critical because of price disparity between the electricity and the biomethane. This could lead to very small incentives for such energy conversion. Financial sustainability also depends on the price of the sourced $CO_2$ as well [97], regarding which a favourable trend could help the spread of the P2G technology. If "carbon tax" [95] and similar additional costs of $CO_2$ emissions increase, large $CO_2$ producers will be interested to find alternative solutions which increases the bargaining power of the P2G operators on the $CO_2$ price.

Based on the iteration of the perceptions, experiences of the stakeholders in the power-to-gas segment of Hungary and the power-to-gas literature, Table 2 summarizes the complex challenges and the required actions, which should be realized to exploit the potential of the technology.

### 4.3. Solution: Overcoming barriers of innovation with an inter-organizational innovation network

According to Power-to-Gas Hungary Kft's business model, the primary value propositions [98] are providing innovative energy storage solutions and producing biomethane, as the environment-friendly

**Table 2: P2G technology-specific challenges in Hungary and required actions**

| Level of challenges | Topics | Examples of subtopics | Required actions |
|---|---|---|---|
| Micro-level | Technology:<br>The efficiency of overall energy conversion | Reuse of waste heat<br>Reactor structure<br>Nutrition of biocatalyst | Further R&D |
| Meso-level | Efficiency on sector-level | High pace of RES-deployment<br>Maximum potential | Scenario analyses, deliberate location and sizing |
| | Scalability | Financing: Investment volume | Raising capital |
| | | $CO_2$ availability: Sourcing carbon dioxide<br>Finding distribution channel | Involving experts from other energy market segments |
| Macro-level | Legal and regulatory environment | Clear definitions and regulations<br>Financial incentives for renewable energy storage<br>Financial incentives to produce green gas | Change of legal environment |

alternative of natural gas. The key resources of value creation are knowledge capital that is achieved from R&D and prototype operations, as well as financial and technical resources for plant establishments. As Power-to-Gas Hungary Kft. is a technology start-up founded in 2016 focusing on its core business (technology development and related project management), these resources could all be assured with the involvement of key partners.

The need for key partners is not unique in the P2G industry. According to the analysis of Baleira et al [29] of more than 40 P2G projects, 3–4 partners have collaborated on average. Considering the newer and more efficient biomethanation technology [26] the need for partners might be even higher. For example, Electrochaea, strategic partner of Power-to-Gas Hungary Kft., or MicrobEnergy, subsidiary of Viessmann Group established their biomethanation facilities with the participation of seven other organizations: strategic and financial investors, professional service providers, state administration institutions, traditional energy companies, research centres [29].

To make a step forward in the research of P2G, the authors identified those motives and conditions that frame the collaboration of potential partners.

a) P2G technology developer companies do not own all financial and infrastructural resources to scale up the technology but have disruptive core solutions, based on that profitable business models could be built. If complementary resources (broad industry-specific knowledge, infrastructural equipment, and related investment) are granted by strategic and financial investors, innovation and business opportunities could be realized:
   a. profits for P2G developer companies;
   b. synergies with core business for strategic investors;
   c. high returns for financial investors;
   d. high impact on local energy system management and sustainability targets.

b) There are many uncovered, or not fully covered topics related to the technology for further research and development (e.g. utilization of by-products, nutrition of biocatalyst, modified reactor structures), which could increase the efficiency of the technology. These areas cannot be individually researched by a start-up with limited resources and clear strategic focus, but research centres, other start-ups or consulting companies could participate in developing further such improvements of the technology.

The local energy sector is strongly regulated, the rigid institutional background and stability-focused short-term incentives do not support the utilization of disruptive innovations. That is why governments are always key stakeholders regarding the commercialization of P2G technology in grid-scale. It is found that two actions could lead to favourable changes of the legal environment:

a) Collaboration partners need to demonstrate the viability of local business models and future development opportunities of P2G technology with the involvement of local research and development, and local commercialization of the technology in small-scale.

b) A regulatory sandbox model would be a great first step to test the viability of local business models in a real business environment. A regulatory sandbox model means a unique legal framework for disruptive technologies in which certain laws and obligations could be applied in a modified version for the test period of the technology. The concept originates from the UK where FinTech solutions needed special conditions to prove their value. In 2019, there were more than 50 operating or planned regulatory sandboxes in different sectors, such as telecommunication, data or environment protection, globally [99]. There are examples in the energy sector as well: the Energy Market Authority in Singapore has introduced a regulatory sandbox for new energy products and services to leverage new technologies [100, 101]; the Netherlands also created a local experimental environment for innovative energy services [102]. Even though the regulatory sandbox model is relatively new, the volume of available data is limited, so measuring its impacts is difficult, it is expected that open and active dialogue between regulators and innovators can result in better regulatory assessment for innovations, and can decrease uncertainty for investors [99].

Although the current Hungarian legal and regulatory environment does not contain incentives for the development and operations of innovative energy storage technologies yet, the new National Energy Strategy 2030 of Hungary (introduced in January 2020) aims to develop a regulatory environment which supports the commercialization and utilization of the P2G technology. Furthermore, other actions are assigned which can be financially supported as well:

a) Installing a pilot P2G facility which is capable to inject biomethane into the natural gas grid
b) Building a 2,5 $MW_{el}$ P2G facility
c) Developing a mandatory national purchasing system for biomethane to incite biomethane production [89].

The appearance of the P2G technology in the new national energy strategy can be considered as a significant achievement and recognition of the work of the Hungarian P2G technology-oriented inter-organizational networks.

## 5. Discussion: Understanding the role of inter-organizational innovation networks in the P2G technology development

Taking a step back, one could see that the research and development results achieved with a special Archea strain created economic and environmental opportunity [103]. This opportunity led to a dyad-level open innovation, developing a P2G prototype with a proprietary biocatalyst and demonstrating the viability of the business model. The exploitation of P2G technology innovations, however, requires more than that: an inter-organizational innovation network. Its commercialization requires significant complementary resources, further development of the technology on related fields, and changes in the local legal environment.

Results imply that dyadic collaborations and inter-organizational innovation networks can have different characteristics of open innovation. Dyadic collaboration is rather temporary to solve a clear problem or create a new solution, while inter-organizational innovation networks could mean a long-term commitment or continuous collaboration for further incremental development on complex areas related to the previously created core solutions, driving the commercialization of the technology, and might also be able to have significant impact on legal and institutional environmental changes.

Table 3 illustrates the characteristics of open innovation based on P2G technologies development and commercialization, the needed inputs from partners for a scaled-up and efficient P2G technologies, and potential outputs which would add value to them. The table is built on empirical data from the interviews, it does not contain every possible combination of actors or inputs/outputs, but it highlights the clear need for collaboration. It means that this is not a prescriptive but a descriptive table, as it shows that what was needed to have an impact on the institutional environment.

Table 3 shows that exploiting the technological innovation requires complementary resources which can be granted by several stakeholders. If one or more stakeholder is missing from the network, it can (1) increase investment costs (e.g. if there is no strategic investor who is interested to share its infrastructure expecting future synergies), (2) lead to lost opportunity (e.g. if there is no scientific research, which could increase efficiency), (3) make the project impossible (e.g. there is no core technology, financial resources or supporting legal and regulatory environment).

Table 3: Collaborations leading to scaled-up and efficient power-to-gas technologies in Hungary

| | | **Dyadic collaboration** | | | | **Inter-organizational innovation network** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Theoretical aspects** | **Number of collaborators** | 2 | | | | More than 2 | | | | | |
| | **Temporality** | Temporary/Short-term | | | | Continuous/Long-term | | | | | |
| | **Development problems to solve** | Clear, focused | | | | Unclear, diffused | | | | | |
| | **Number of development problems to solve** | Few | | | | Many | | | | | |
| | **Goal of development in general** | To create something new, disruptive solution | | | | To utilize and develop a disruptive solution incrementally | | | | | |
| | **Location** | Outside Hungary | | | | Inside Hungary | | | | | |
| **Empirical data** | **Collaborators** | University/ Research centre | Biotechnology—P2G developer company | | P2G technology developer company | | Strategic investor (e.g. TSO or DSO) | Financial investor | University/ Research centre | Other start-ups, Management consulting companies | Government, State administration |
| | **Goal of development in the case of P2G technology development** | 1) Discovery of the proprietary biocatalyst | | 2) Development of a prototype | | 3) Scaling-up and commercialization of the technology<br>Increasing the efficiency of the technology<br>Achieving favourable legal and institutional environmental changes | | | | | |
| | **Input** | R&D knowledge and capacities | | Core technology | Local expert knowledge, business development | Innovative technology and project management | Extensive infrastructural resources, sector-specific knowledge | Financial resources | R&D knowledge and capacities | Expert knowledge, innovative services, social capital | Supporting legal environment |
| | **Output of the single organization** | Publishable research results, patent | Market-able patent | Inter-national business | Innovative technology | Innovation and profit | Synergies with core business | Profit (exit) | Publishable research results | New projects and business opportunities | Reached energy policy objectives |
| | **Output in broader sense** | Economic and environmental opportunity | | | | Exploited technological innovation (exploited opportunity) with impact on the energy sector | | | | | |

## 6. Conclusion and contribution

This paper analysed the role of inter-organizational networks and innovation management related to P2G technology development and commercialization. Based on a three years long action research, two dyadic collaborations led to the development of an innovative P2G prototype, representing a significant opportunity for industry-scale local energy storage, grid-balancing and higher integration of renewables. It has been shown that industry-specific and P2G technology-specific challenges might limit the exploitation of the innovation potential of this disruptive technology. To overcome innovation barriers, the dyad-level open innovation seems not enough. The research results demonstrated that inter-organizational innovation networks might be essential to achieve breakthrough results in increasing the efficiency of P2G technologies, scaling them up and prove their value for local decision-makers in small-scale. These actions are also needed to initiate legal environmental changes locally. The rigid regulatory environment and incentives for short-term performance are the most significant limiting factors of further innovation and commercialization. Figure 3 summarizes these findings.

In case of these networks, a rather cyclic than linear model could be drawn. The appearance of the P2G technology in the national energy strategy could be interpreted as a new opportunity. This means that the inter-organizational innovation network had an impact

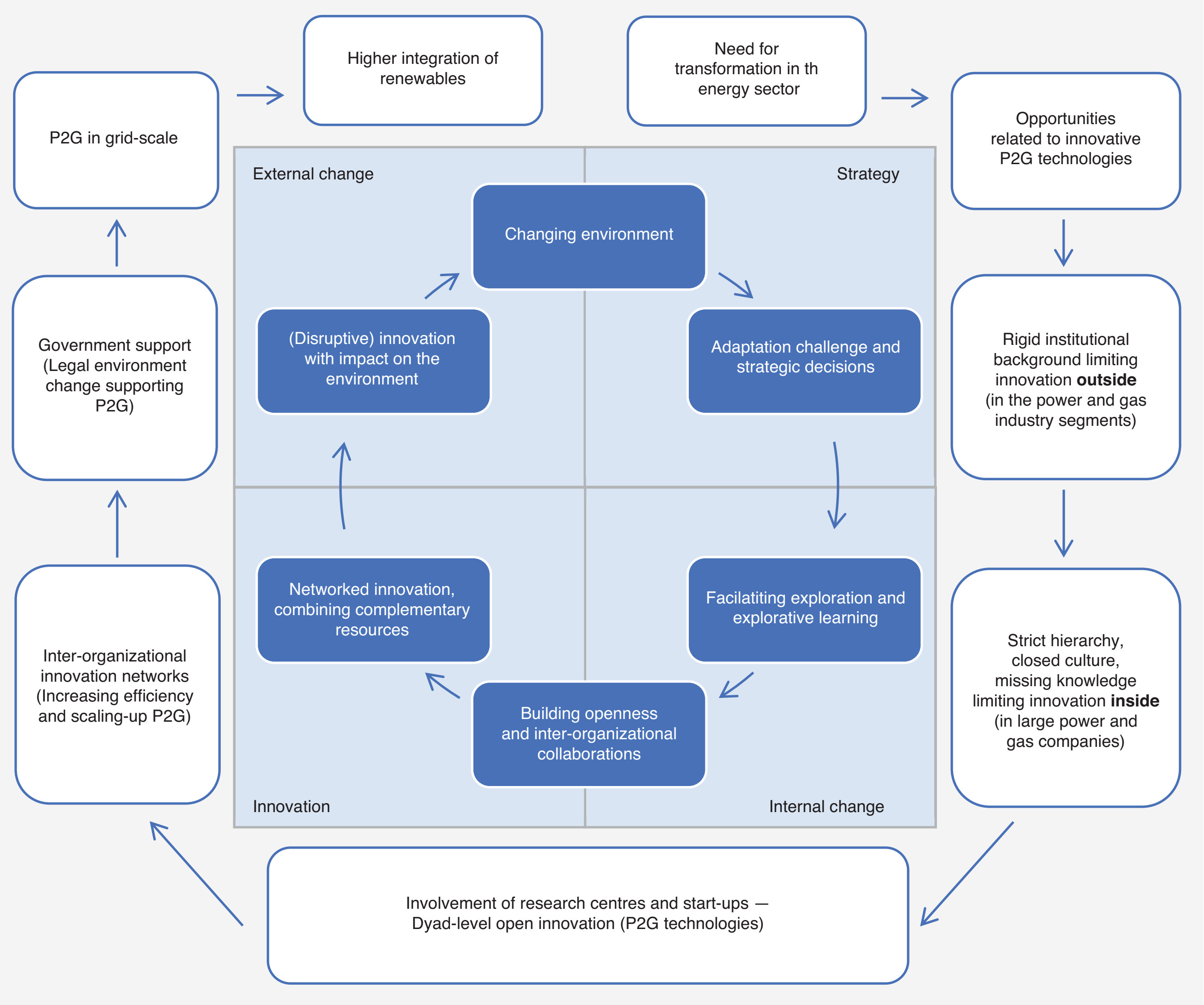

Figure 3: Innovation and change opportunities in the energy sector through P2G technology development and commercialization (Empirical findings aligned with the theoretical framework of the research)

on the institutional environment, and the new environment will mean new opportunities for the actors of the energy sector (and maybe challenges to others).

These findings emphasize the importance of inter-organizational innovation networks in facilitating the development of a more favourable socio-economic environment that would incite P2G technology development and commercialization.

This study shows that action research, iterating theory and practice is important to generate social change in the energy sector. For example, the micro social actions which have been undertaken (e.g. prototype development, business development, IT development, searching for partners, forming alliances) assured a solid local basis for the Hungarian P2G know-how and competencies, and had an impact on the institutional environment.

## 7. Limitations and future research

Building on the theory of action research, as well as grounded theory, the conclusions can be considered as a substantive theory [86], which is valid in a given research context. Nonetheless, there are many other complementary areas which could be researched with different methodologies or in different research contexts. The findings of this paper could serve as opportunities for further research in other countries about the role of inter-organizational networks in the improvement and exploitation of P2G or other innovative technologies.

The research was based on general management theories and iteration of empirical data with international sector-specific literature. The country-specific factors (e.g. current energy policies, infrastructural resources) could modify, however, the role and the structure of inter-organizational innovation networks in the development of P2G technology.

The authors focused only on the innovation management side of P2G technology, but its effect on the future of the local energy sector could also be researched with quantitative methods.

There are limits and future research opportunities which derive from the followed methodology. This qualitative study gave an insight to key factors that lead to the formation of an inter-organizational P2G innovation network. A future quantitative analysis could be applied to examine the power-to-methane segment for example with the technological innovation system (TIS) model [104]. Similarly, as action research was focusing on generating new research results and social change parallelly, some interesting points have not been covered, such as evaluating the performance of the network and its impact on the environment [105], identifying its critical success factors with statistical methods [106] or exploring how inter-organizational governance could or should work in this segment [107].

Finally, the 'ideal' framework of a local regulatory sandbox model could also be analysed much deeper, which would certainly require a detailed overview of the local regulatory environment.

Despite these issues for further exploration, the authors believe that their findings would contribute to the commercial implementation of P2G technologies by the establishment and pro-active management of well-focused inter-organizational networks.

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