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Review

Past, Present and Near Future: An Overview of Closed, Running and Planned Biomethanation Facilities in Europe

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Abstract: The power-to-methane technology is promising for long-term, high-capacity energy storage. Currently, there are two different industrial-scale methanation methods: the chemical one (based on the Sabatier reaction) and the biological one (using microorganisms for the conversion). The second method can be used not only to methanize the mixture of pure hydrogen and carbon dioxide but also to methanize the hydrogen and carbon dioxide content of low-quality gases, such as biogas or deponia gas, enriching them to natural gas quality; therefore, the applicability of biomethanation is very wide. In this paper, we present an overview of the existing and planned industrial-scale biomethanation facilities in Europe, as well as review the facilities closed in recent years after successful operation in the light of the scientific and socioeconomic context. To outline key directions for further developments, this paper interconnects biomethanation projects with the competitiveness of the energy sector in Europe for the first time in the literature. The results show that future projects should have an integrative view of electrolysis and biomethanation, as well as hydrogen storage and utilization with carbon capture and utilization (HSU&CCU) to increase sectoral competitiveness by enhanced decarbonization.

Keywords: biomethanation; power-to-methane; competitiveness; hydrogen utilization; decarbonization; Hungary

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1. Introduction

In line with the long-term strategy of the European Union to become climate-neutral, the energy storage challenge [1] that is induced by volatile renewable electricity production (e.g., with rapidly growing photovoltaic capacities) must be handled [2–4]. Power-to-gas (P2G), and especially power-to-methane (P2M), technologies, however, are capable of providing flexibility [5] and efficient seasonal energy storage [6] with the reuse of CO_2 and the utilization of the existing capacities of the natural gas grid [7]. Moreover, these technologies are not only present on a lab-scale or prototype level, but there are examples for commercial-scale implementation, with chemical [8] and biological methanation [9] as well. Widespread utilization of this technology, however, has not happened yet, despite the potential of P2G technologies [10,11]. To accelerate the implementation of the P2M technology on a commercial scale, further R&D&I activities and policy regulations are also needed [7]. Regarding the prior literature in the P2G field, the "research" and the "development" part of the R&D&I are often supported by new technoeconomic research results [12–14]. Moreover, the "innovation" part is already discussed from in-depth management aspects [7,15], and there are also analyses from policy perspectives [6,16]. Nevertheless, there is a lack of a high-level approach which can integrate these aspects for socioeconomic progress. Consequently, this study focuses on P2M facilities with novel biological methanation technology [17] and their potential connection to sectoral competitiveness in Europe.

Compared to previous project reviews [17–20], which have already collected P2M projects including chemical and biological methanation (and other P2X projects, as well), this study has a different approach with the following adjustments:

1. Narrowing the technological scope for biological methanation to generate a specific analysis;
2. Following a novel abductive methodological approach in this area with (1) using quantitative and qualitative data, (2) starting the analysis through the lens of a technology developer company, and (3) iteration with former theories and results to identify trends and gaps which can define the scope of future facilities;
3. Considering specific contributions of future projects to sectoral competitiveness in Europe.

This competitiveness-oriented approach is unique in the P2G literature. Even though Brunner et al. [21] analyzed the relationships of competitiveness and P2G, it had a different scope: they aimed to compare the competitiveness of different P2G operational concepts. Moreover, research usually focuses on the competitiveness of P2G technologies (e.g., compared to other energy storage technologies) [22,23] but rarely on the competitiveness-increasing opportunities by P2G (or P2M in this study). The importance of this topic, however, derives from the practical need and the context as well—similar to the competitiveness studies in general. For example, Fagerberg [24] argues that the "competitiveness" term also does not originate from theoretical researchers but professionals working around decision makers. The relevance of this topic has similar roots: the European Green Deal mentions several times the importance of supporting the economic competitiveness of the EU [25]. The document also declares that "new technologies, sustainable solutions and disruptive innovation are critical to achieve the objectives of the European Green Deal" (p. 18, [25]). As recent research focusing on biomethanation technology concluded that P2M can be disruptive in the future [15], the research question of this study is the following:

How can future P2M, and especially biomethanation facility development projects, increase sectoral competitiveness in Europe?

Figure 1 summarizes (1) why the research is relevant, (2) what is in the focus of the research, and (3) how the research was conducted.

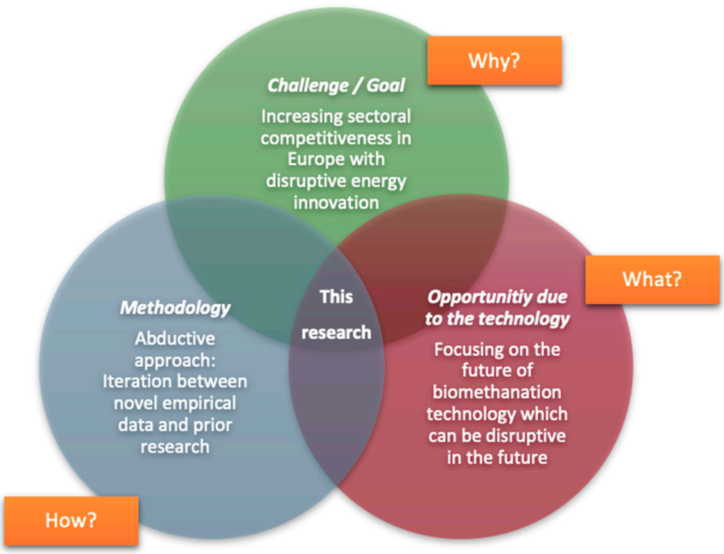

Figure 1. Relevance and scope of the research.

In sum, the study has a more future-oriented approach rather than a retrospective one, and this future orientation requires specificity regarding:

1. the technology (biomethanation);
2. the goal (supporting sectoral competitiveness by this technology);
3. the method (starting the investigation from the aspect of a concrete market player who may contribute to these goals).

Based on the abductive approach of this research with qualitative elements, hypotheses cannot be made, but underlying presumptions as propositional knowledge emerging from prior research [26] can be explicated that will be extended, modified, or developed further by empirical data gathering, analysis, and theory generation. Regarding the fundamental characteristics of the focal technology listed in the first paragraph, the underlying presumption for the research question is that future biomethanation facility development projects would increase sectoral competitiveness in Europe by providing flexibility, seasonal energy storage, and reuse CO_2 for synthetic natural gas production, thus integrating renewable energy sources and contributing to decarbonization efforts.

The study is structured as follows. First, the technical background of biological methanation, the research framework, and the applied data gathering and analysis methods are presented. In the Results section, biomethanation facilities are presented and key topics for future projects are revealed. After that, these topics are discussed in-depth according to former literature and research results. Finally, conclusions, limitations, and further research directions are outlined.

2. Materials and Methods

2.1. Technical Background

The study focuses on the methanation segment of P2G. In this case, the mixture of H_2 (from water electrolysis by renewable electricity) and CO_2 (e.g., from biogas, landfill gas or flue gas) can be converted to methane [27]: $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$.

There are four different solutions for methanation, two of them are already in use at the commercial scale: chemical and biological methanation. These solutions have different operational characteristics that are thoroughly analyzed in the literature (see, e.g., [19] or [28]). One of the main differences is that while chemical (catalytic) methanation needs high pressure and temperature to reach high CO_2 conversion, which can be 50–60% and 80–90% or higher in proper conditions, biological methanation needs lower pressure and temperature (ca. 60–70 °C) than catalytic methanation; moreover, the CO_2 conversion is often higher than 95% [17,29–32]. Furthermore, in the case of biological methanation, microorganisms catalyze the reaction in a multiphase system because the gaseous H_2 and CO_2 are dissolved in the liquid phase, in which the Archaea absorb them and produce CH_4 [33]. In contrast, chemical methanation needs other types of catalysts, e.g., ruthenium [34] or nickel-based catalysts, that are characterized by high performance and low cost [35]. The catalysts determine different opportunities and limitations as well. For example, fluctuations and impurities are less harmful in case of the biological process with the robust methanogens, thus it can provide simpler applicability in contexts where contaminants (e.g., hydrogen sulfide) must be considered; nevertheless, its main limitation is the gas-to-liquid mass transfer at a relatively low temperature [19].

The "biomethanation" and "biological methanation" terms are often used in case of biogas upgrading, as well, when additional hydrogen injection happens. In this case, hydrogenotrophic methanogens function as a catalyst in a mixed culture, and there is no need for a separate bioreactor and clear culture [36,37]. A novel method for the P2M process is the bioelectrochemical system for electromethanogenesis (EMG-BES). It uses electro-active microorganisms, and the reaction happens only at 25 to 35 °C [38].

In the case of the focal biomethanation technology, microorganisms can convert ca. 97–98% of the CO_2 into methane during the methanation phase in a separate culture, which is promising regarding the decarbonization efforts. The total efficiency of such a biomethanation plant (together with the electrolysis step) can be in the range of 55 to 60% [6].

2.2. Research Framework

While competitiveness is defined from several aspects in the literature [39], an innovation approach must be considered in this study. In this sense, sectoral competitiveness can mean such capabilities which are (partly) created by innovation and which are required for sustained economic growth in an (international) competitive environment [40]. As innovation can be interpreted as a process during which an opportunity becomes a useful solution in practice [41] and can be a positive-sum game because of the complementarities among contributors [42], a network approach can be also important to increase sectoral competitiveness.

Accordingly, as the literature highlights the importance of the know-how transfer among companies, universities, and state administration [40,43], this research not only focuses on biomethanation projects but the main areas on which future work is necessary to contribute to sectoral competitiveness. For this purpose, the projects are interpreted from the aspect of recent scientific research results and EU strategies and policies. Figure 2 illustrates the research framework.

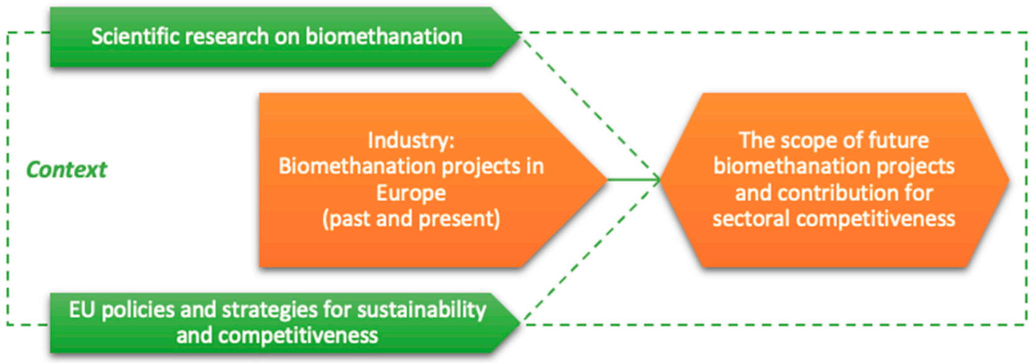

Figure 2. Research framework (Orange: Focus of the research; Green: Context of the research).

2.3. Research Methodology, Data Collection, and Analysis

An abductive approach was followed to answer the research question, which involved iteration between empirical data and theory. It means that empirical data can be analyzed to reveal regularities or phenomena, and then they can be compared to previous research results and theories to explain the revealed phenomena and develop new theories. This abductive approach and the iteration is emphatic in several research methods, such as grounded theory [44], extended case study [45], or more broadly, the abductive theory of method (ATOM) [46]. This research integrates elements from all of these methodological roots. As "ATOM itself as a grounded theory method that explicitly accommodates both quantitative and qualitative outlooks on research" (p. 106, [46]), this research involves both quantitative text analysis and their qualitative interpretation from the aspect of a disruptive technology developer company (an empirical case as a starting point).

The research is partly built on the digital R&D and open innovation platform of Power-to-Gas Hungary Kft., a Hungarian startup that developed an innovative biomethanation P2G prototype in cooperation with Electrochaea GmbH. The startup company consciously manages digital know-how flows within the organization and the inter-organizational network and continuously monitors the international P2G market and research results. On this platform, the company develops different kinds of knowledge elements with the involvement of employees, external professionals, stakeholders, and academic researchers. These knowledge elements include project descriptions, innovational and technological know-hows and analyses, e-learning materials, innovation problems, and ideas to solve them (idea generation). This platform, however, only represents the industrial "lens" for the study because research papers (indicating the scientific context) and EU policies and strategies (indicating the socioeconomic context) were also collected by the authors, while also considering the suggestions of the stakeholders of the company (interviewees, see below).

Table 1 presents the structure of data collection.

1. Focus: Relevant project descriptions were selected from the digital platform which meant direct benchmarking for the company for future project planning. These were collected based on the market monitoring activity by employees or suggestions by external professionals and other industry stakeholders. The selection criterion was that only European projects were within our scope.
2. Context:
    a. Scientific research can also affect the planning and implementation of future P2M projects with biological methanation [7]. The authors collected recent research papers and created a long list of potentially relevant publications from the aspect of the company and future biomethanation facility development (n > 250). The goal was to provide a broad horizon of opportunities (including power-to-methane (P2M), power-to-hydrogen (P2H), power-to-liquid (P2L), power-to-X (P2X), and carbon capture (CC)) and to avoid unintentionally narrowing the relevant themes, which could have limited the reliability of the research in an abductive sense. After that, the P2H-, P2L-, P2X, and CC-oriented contents were filtered out collaboratively with the interviewees. Facing the limited number of literature analyses focusing only on biological methanation, and as the term "biological methanation" is often used for novel biogas upgrading processes with H_2 injection and mixed culture, the potential contribution of biological P2M could be identified more reliably if less restrictions were applied and the whole P2M literature is considered (n = 63; see Appendix A).
    b. In line with the competitiveness approach of the study, the analysis of the project descriptions was compared to EU strategies for carbon-neutrality and their relations to competitiveness.

Table 1. Data collection for text analysis.

Data	Level of Analysis	Connection to the Research Framework	Relevance	Source/Suggested by	In Scope and Their Volume		Out of Scope (Examples)
Project descriptions	Micro	Focus	Review of industrial advancements	Employees, external professionals, and other industry stakeholders	Biomethanation projects in Europe (see the Results section)	21	Chemical methanation projects and/or out of Europe
Research papers, scientific publications	Meso	Context	Review of research directions and results	Employees and external academic researchers	P2M (see Appendix A)	63	P2H, P2L, P2X
Relevant policies and strategies	Macro		Outlining directions for technological innovations	EU websites	EU documents related to climate-neutrality policies and strategies and competitiveness: A Clean Planet for All: The European Green Deal [47–50]	4	Not EU or focusing on only economic competitiveness in general

The research involved quantitative text analysis with the JMP software, which is useful for text mining purposes [51]. After cleaning the data, recoding words and phrases (e.g., plurals, or "ptg" and "p2g" to "power to gas"), word clouds and trend analyses were generated, i.e., exploring the change of the most common terms according to different variables (time horizons, data sources (project descriptions scientific research or policies), and electrolyzer capacity in case of project descriptions). Moreover, trend analyses were combined with hierarchical clustering to reveal possible important underlying structures [52]. These quantitative analyses, additional qualitative interviews with company employees and stakeholders for interpreting raw data, and iterations with former literature indicated "key topics" for further elaboration. These key topics were iterated by more research results to generate an in-depth understanding and R&D&I directions for future biomethanation projects.

The relevance of these methodological choices is to look at the biomethanation projects not only through the lens of academia, but as a technology developer company as well. Power-to-Gas Hungary Kft. is known for its long-term mission to implement a 10 MW_{el} P2M plant. It would be the largest P2M plant with biological methanation, and the second largest regarding chemical methanation as well [18]; consequently, the potential contribution to sectoral competitiveness is high in its case.

To improve the validity, reliability, and generalizability of the research, the following steps were undertaken:

1. Creating balance in authorship regarding research perspectives and background (energy research, applied research and development, technical aspects, economic and management aspects);
2. Building on the quantitative text analysis of more than 80 texts (more than 6000 total terms). The data sources had similar volumes regarding the number of terms (project descriptions: 2501; research abstracts: 2258; EU documents: 2341);
3. Triangulation—Involvement of professionals through interviews to support the interpretation of raw data and results;
4. Iteration between the literature and empirical data allowed us to develop conclusions that are valid in a specific context [44].

3. Results

3.1. Biomethanation Projects and Industrial-Scale Facilities in Europe

Regarding list of the European P2M projects with biological methanation, while most of the projects were listed in recent reviews of Thema et al. [19] and Bargiacchi [18], there are three projects that were not listed previously.

1. In contrast to the well-known biogas-based biomethanation projects, the BIOCO$_2$NVERT project aims to implement a biocatalytic P2M facility at one of the largest bioethanol plants of Europe. According to the description of the Innovation Land Lab, installation and commissioning are the next steps of the project [53]. The project started in 2018, and the cooperation partners are Klärgastechnik Deutschland GmbH, MicrobEnergy GmbH, PRG Precision Stirrer Gesellschaft GmbH, and Südzucker AG [54].
2. The HYCAUNAIS project takes place in Saint-Florentin, France, and involves synthetic methane production with CO_2 from landfill gas through the development of biological methanation. The project started in 2018 and is being realized by five private and three public partners [55,56].
3. The CarbonATE project in Austria and Switzerland focuses on the optimization of microbiological methanation by the development of enzymatic CO_2 capture process to prevent the microorganisms from harmful contaminants (e.g., N_2, O_2) of potential input gases (industrial exhaust gases) [57,58].

Table 2 shows these projects with the other projects which are monitored by the company based on accessible information about their capacity or status. Besides these 21 projects, Thema et al. [19] listed other biomethanation (mainly research) projects without sufficient (accessible) information:

1. "Biological biogas upgrading in a trickle-bed reactor" (Tulln/Donau, Austria, 2013);
2. "Biocatalytic methanation" (Cottbus, Germany, 2013);
3. "Forschungsanlage am Technikum des PFI" (Pirmasens, Germany, 2013);
4. "BioPower2Gas-Erweiterung" (Allendorf (Eder), Germany, 2016);

5. “Biologische Methanisierung in Rieselbettreaktoren” (Garching, Germany, 2016);
6. “Einsatz der biologischen Methanisierung [. . .]” (Hohenheim, Germany, 2016);
7. “Biocatalytic methanation of hydrogen and carbon dioxide in a fixed bed bioreactor” (Helsinki, Finland, 2016).

Regarding future industrial-scale developments, it can be argued that the capacity of larger biomethanation facilities must reach at least 1 MW_{el} to satisfy the demand for electrolysis and also for methanation, which can exceed even 1000 GW_{el} globally [59], and even over 500 GW_{el} for P2M in very positive scenarios [60]. Based on publicly accessible data, six projects reached or are planned to reach the 1 MW_{el} capacity: Energiepark Pirmasens-Winzeln, BioCat Project, Dietikon Microbenergy, INFINITY 1, Power-to-Gas Hungary plant, and HYCAUNAIS. The first five received a detailed description recently by Bargiacchi [18], while the HYCAUNAIS project was introduced above.

Table 2. European biomethanation projects with sufficient accessible information about capacity or status, based on [18,19] and own research.

Projects	Country	City	Start of the Project	Electrolyzer Capacity (MW_{el})	Status	Source of Status Information
PtG-Emden	Germany	Emden	2012	0.312	Closed	[18]
PtG am Eucolino	Germany	Schwandorf	2013	0.108	In operation	[61]
P2G-Foulum Project	Denmark	Foulum	2013	0.025	Closed	[62,63]
SYMBIO	Denmark	Lyngby	2014	-	Closed	[64]
W2P2G	Netherlands	Wijster	2014	0.400	In operation	[65]
BioPower2Gas	Germany	Allendorf	2015	0.300	Closed	[66,67]
GICON-Großtechnikum	Germany	Cottbus	2015	-	In operation	[68,69]
Energiepark Pirmasens-Winzeln	Germany	Pirmasens	2015	1.800	In operation	[70]
Mikrobielle Methanisierung	Germany	Schwandorf	2015	0.275	-	[71,72]
Biogasbooster	Germany	Straubing	2015	-	In operation	[73,74]
BioCat Project	Denmark	Kopenhagen/ Avedore	2016	1.000	Closed	[75,76]
Power to Mobility (MicroPyros GmbH)	Germany	Weilheim-Schongau	2017	0.250	Under development	[77]
STORE&GO	Switzerland	Solothurn/ Zuchwil	2018	0.350	Closed	[78]
ORBIT 1st site	Germany	Regensburg	2018	-	Closed	[79]
BIOCO$_2$NVERT	Germany	Dörentrup	2018	-	Under development	[53]
HYCAUNAIS	France	Saint-Florentin	2018	1.000	Under development	[55,56,80]
Dietikon Microbenergy	Switzerland	Dietikon	2019	2.500	Under development	[81]
ORBIT 2nd site	Germany	Ibbenbüren	2020	0.001	In operation	[82]
INFINITY 1	Germany	Pfaffenhofen a. d. Ilm	2020	1.000	Under development	[83]
CarbonATE	Austria and Switzerland	Winterthur	2020	-	In operation	[57]
Power-to-Gas Hungary plant	Hungary	-	-	10.000	In planning	[84]

3.2. *Key Topics of Future Implementation*

In the following section, key topics are identified based on the quantitative text analysis, interviews, and the literature, for which overarching R&D&I directions will be suggested in the Discussion section.

3.2.1. Key Topic 1: The Role of Biomethanation in the Hydrogen Economy

Based on the short summaries of the listed projects (ca. 1–3 pages, 2501 total terms, 14,573 total tokens), the most common word is “hydrogen”. Similar influential words are “carbon dioxide” and “methane” (see Figure 3). This result refers to the importance of input factors in the biomethanation sector, and even though it is not particularly surprising, the relative dominance of hydrogen against the other key terms (e.g., methane, storage, biogas, natural gas) is conspicuous. Regarding the trend and advancements towards the hydrogen economy [85], the hydrogen orientation can be justified, but it can also be asked, for example, what could the role of biomethanation (biomethane or SNG production) be in the hydrogen economy? This might require further analysis later, based on other research results and EU policies.

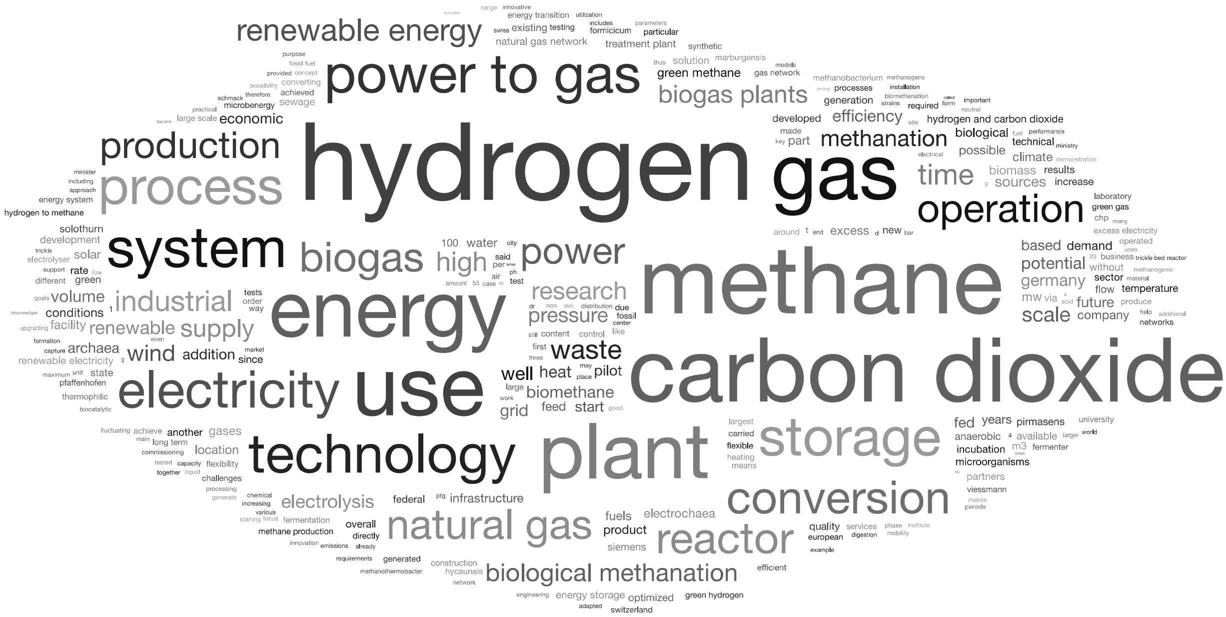

Figure 3. Word cloud from biomethanation project descriptions.

In addition to taking a static "snapshot" of the content of the biomethanation project descriptions (Key topic 1), quantitative characteristics of the projects provide opportunities for deeper insights. The next section (Key topic 2) considers the size of the facility (indicated by the capacity of the electrolyzer), while after that, Key topic 3 analyzes trends according to the start of the project (year).

3.2.2. Key Topic 2: Opening New Ways besides Biogas Plants to Store More Renewable Electricity/Hydrogen

The terms that appeared at least 15 times in the project descriptions were analyzed according to the size of the biomethanation facility. It can show how the focus of the R&D&I activities changes (or does not change) with the deployment of larger facilities. Considering the lessons of the interpreting interviews as well, Figure 4 suggests the following:

(a) at the small scale, the focus is on the "efficiency" of the "process", the "reactor" structure, the microorganisms ("archaea"), and the "biogas" input from "biogas plants", which contains "carbon dioxide" to "convert" it into "methane".

(b) at the large scale, the emphasis is on the "volume" of "wind" or other "renewable energy" and the "production" of "methane", which can be "fed" into the "natural gas" for "energy" "storage" purposes. (Words in quotation marks refer to the empirical data.)

The importance of the results shown by Figure 4 is that they interconnect the past and the future of biomethanation technology development from a purely technical aspect (without considering the time horizon, which is presented in the next section). Less abstractly, different issues are important at the small and large scales, and the gaps between these issues might generate new areas for research. Regarding the listed (a) and (b) points above, a step is missing between the efficient process in kW-scale with CO_2 from biogas and the purpose of storing high volumes of renewable electricity in the form of SNG in MW-scale. This missing step seems to be the sourcing of CO_2 in large volumes to develop multi-MW biomethanation plants. Accordingly, it is worth analyzing that if biogas plants cannot provide enough carbon dioxide for large-scale P2M plants [15], which could convert the vast volume of renewable electricity produced by wind or solar parks, what solutions can help to increase the capacity of biomethanation facilities to multi-MW_{el} level, which are needed in the future [59].

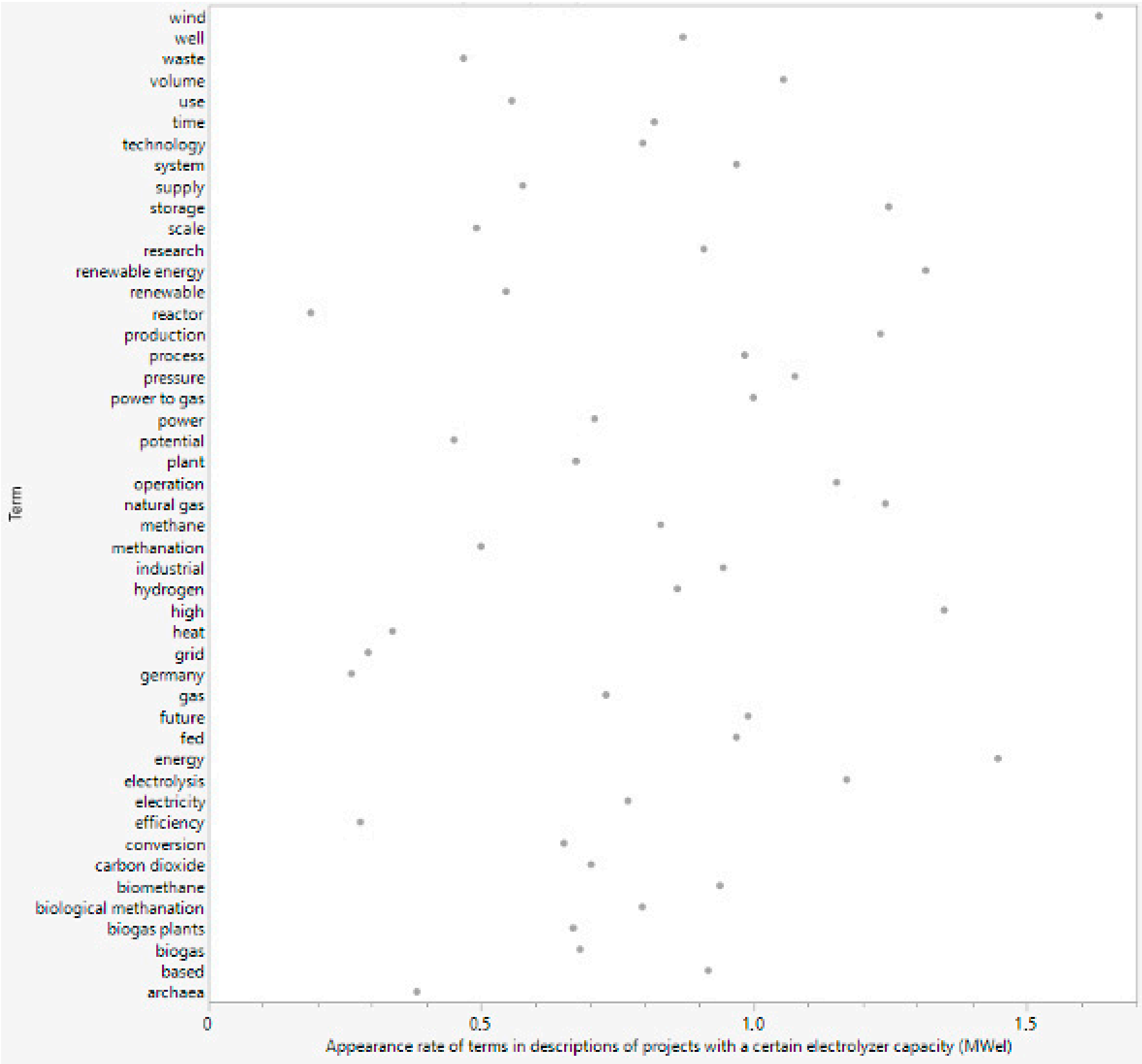

Figure 4. Appearance of the most common terms according to the size of the planned/implemented biomethanation facility. For example, the term "storage" appeared in project descriptions of biomethanation plants, which were 1.3 MW_{el} on average.

3.2.3. Key Topic 3: From Technology Development towards Achieving "Future" Benefits

The most common terms of the project descriptions may change according to the start year of the projects, not only their capacity. Accordingly, Figure 5 shows constellation plots of a hierarchical cluster analysis which might reveal some underlying structures (e.g., main terms of past and present; based on the 75 most common terms). Based on the collaborative interpretation with the interviewees, Figure 5 shows the following:

1. From 2013 to 2016/2017, the emphasis was on "research" and "pilot" implementation; moreover, the fundamental characteristics of the process (e.g., using "excess" "solar" energy, "conversion" into "gas", connection to the "grid", and/or "biogas plants").
2. From 2016/2017 to 2020/2021, broader themes appeared, such as the "future" "potential" of the "technology" realized by a "company", utilizing "renewable energy" and

"electricity", and producing "green methane", "biomethane", or other "fuels" that fit the "infrastructure" to fight "climate" change.

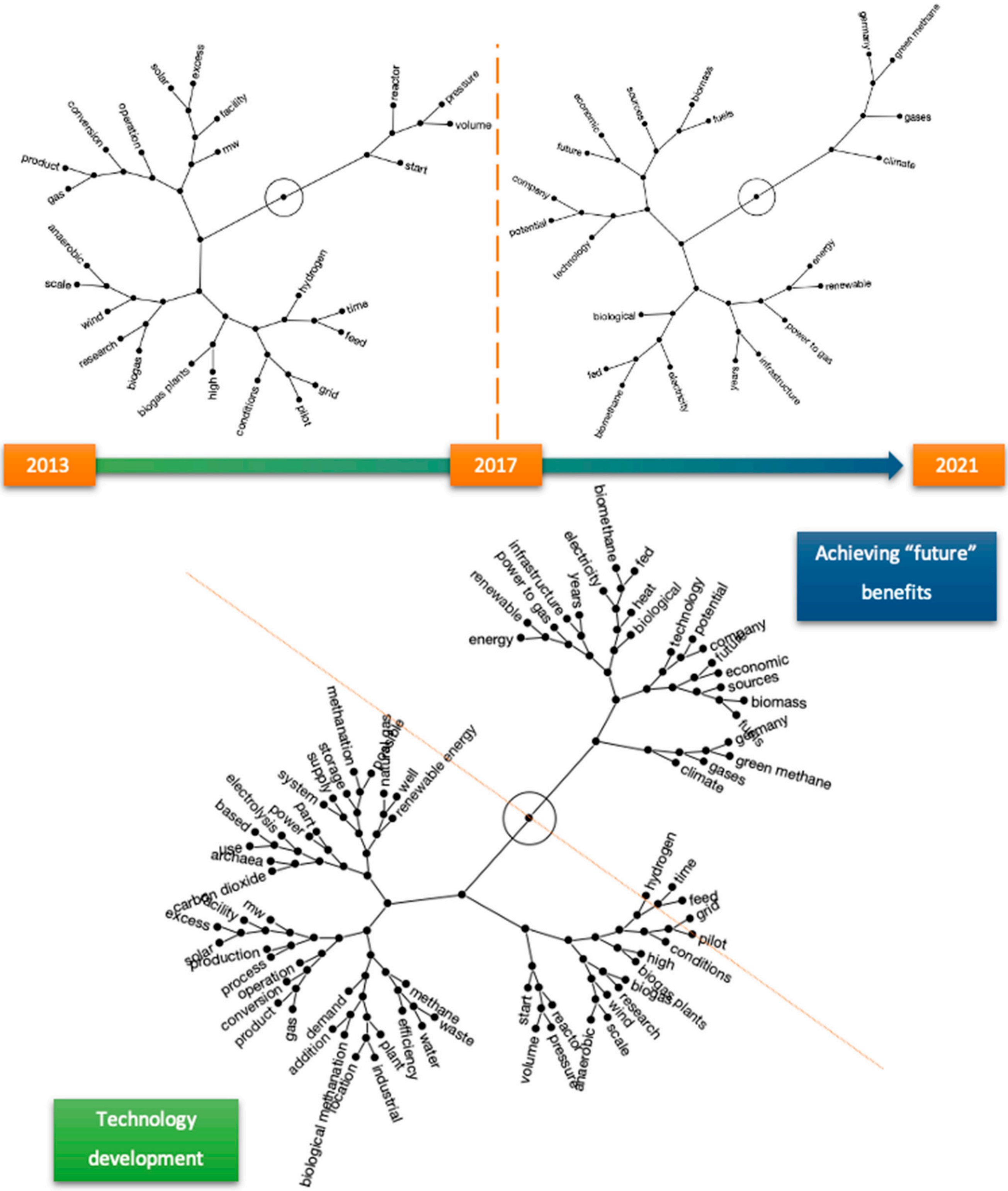

Figure 5. Constellation plots showing clusters of terms according to the project starts.

3.2.4. Key Topic 4: Future Project Planning in Line with Scientific Advancements and Policy Objectives

Based on the abstracts of the selected publications, a slightly different scheme can be seen on the word cloud than in the case of the biomethanation project descriptions. For example, while hydrogen and carbon dioxide are apparently important, carbon dioxide appears more often in case research papers, while hydrogen utilization appears more often in case of the project descriptions. Scientific research, however, deals more with the operative questions of the "system", the "process", or the "reactor", while biomethanation project descriptions write about "using" the "technology" for "energy storage" and the "production" of methane.

Figure 6 shows the comparison of the most common terms of research papers, project descriptions, and EU policies. In line with the mentioned trends, carbon dioxide (N = 116), hydrogen (101), methane (92), system (79), and power-to-gas (77) were the most dominant in a quantitative sense, in case of the abstracts of research papers. Project descriptions were also focused on these three terms, but with others: hydrogen (104), methane (90), carbon dioxide (80), use (80), energy (77), and gas (77).

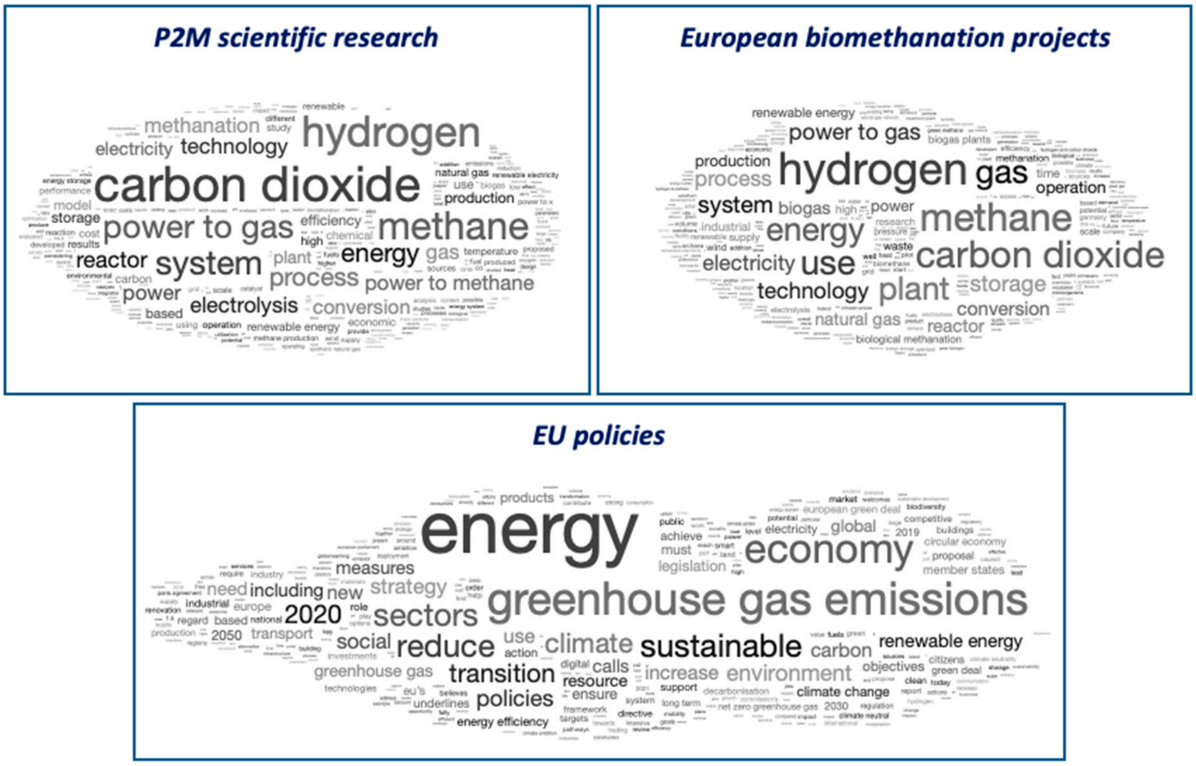

Figure 6. Comparing the word clouds of biomethanation project descriptions, P2M publications, and relevant EU policies.

In contrast to that, regarding the EU policies and strategies, the most common terms are energy (157), greenhouse gas emissions (88), economy (87), reduce (69), sectors (68), and sustainable (68). Accordingly, the main objective is to "reduce" the "greenhouse gas emissions" (GHG) through a "sustainable" "transition" with more "renewable energies". The "economy" and increasing "competitiveness" in a "global" "environment", however, is also important while fighting "climate change". For example, the document called "A Clean Planet for All" by the European Commission refers to competitiveness already in its subtitle: "A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy" [47]. The European Green Deal "aims to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy" (p. 2, [48]).

These results suggest that scientific research, industrial project development, and policies have common points, e.g., the GHG-reduction induces the scientific research on carbon capture and utilization (CCU) solutions and their industrial application at biomethanation facilities. These high-level interconnections, however, should be analyzed in-depth to identify how sectoral competitiveness can be supported in practice by new biomethanation facility development projects.

4. Discussion

In the following, possible R&D&I directions will be presented for the identified key topics. These directions are based on the European context on the one hand, and the mentioned EU documents and the extensive studies of the European STORE&GO project [86] were analyzed. This project included three P2G demonstration plants, and its studies are heavily based on empirical data, as well.

On the other hand, the Hungarian context was also considered. It was important because the whole research followed an abductive approach in which the aspect of the Hungarian technology developer company is central. In addition, the capacity of the gas-grid of Hungary—compared to most other European countries—is quite high, which is an important factor to choose P2M-based long-term energy storage. Consequently, its national environment must be taken into account to contextualize findings. Since the National Energy Strategy 2030 of Hungary states that the implementation of the strategy contributes to the improvement of Hungary's competitiveness (p. 13, [87]) and identifies the direct value-creating potential of power-to-gas in energy storage (p. 39), the contribution for competitiveness by P2M seems clear by deductive reasoning. Based on the abductive methodology, however, it must be supported by more empirical evidence and prior research results.

In the following, overarching directions are presented along with the key topics for future biomethanation facilities, which can directly or indirectly increase sectoral competitiveness.

4.1. Key Topic 1: The Role of Biomethanation in the Hydrogen Economy—An Integrative View of Electrolysis and Biomethanation for Carbon-Neutral Energy Production, Flexibility Services, and Hydrogen Storage and Utilization

Hydrogen is explicitly considered as a "priority area" (p. 8, [48]) in the EU. The more hydrogen is produced in the hydrogen economy, the higher the need will be to store or utilize it efficiently, especially because there are safety limits to the injection hydrogen into the natural gas grid [88,89]. Biomethanation can function as a chemical method for hydrogen storing and/or utilization "tool" in the form of methane (SNG) in high amounts and for a long term, or it can be a middle step towards utilization in other forms (e.g., LNG). This is also in line with EU strategies, for example: "Sustainable renewable heating will continue to play a major role and gas, including liquefied natural gas, mixed with hydrogen, or e-methane produced from renewable electricity and biogas mixtures could all play a key role in existing buildings as well as in many industrial applications" (p. 8, [47]). Biomethanation can be also dynamically coupled with electrolyzers because microorganisms are capable to produce methane in seconds [6] (unlike chemical methanation)—this means additional flexibility beyond the electrolysis for the coupled electricity and gas sector.

In the European context, flexibility by electrolysis and biomethanation can have a beneficial effect on the operation of the network. The presence of 7.2 GW_{el} P2M could significantly reduce the peak (~45%) and duration (>95%) of the imbalance. Due to P2M installation, reverse energy flow could be reduced by 67% or even 100% [90]. Furthermore, the prevalence of green methane is also expected. By 2030, according to scenarios that can be considered optimistic in this regard, the 4% share could increase to 12% [91]. With P2M technology, the ratio of imported gas and total gas consumption could be reduced by up to 30–40% by 2050 [92]

In the Hungarian context, carbon-neutral methane production can also reduce natural gas imports, which is relevant because ca. 80% of the natural gas demand is covered by imports (p. 14). Encouraging the use of biogas, biomethane and non-natural-gas-based hydrogen (p. 12) also include the production of these energy sources. Hydrogen and methane can be used to produce biofuels or "green" fuels, which can be the part of the green transportation program (p. 13, [87]).

4.2. Key Topic 2: Opening New Ways besides Biogas Plants to Store More Renewable Electricity/Hydrogen—Enhanced Decarbonization by the Co-Specialization with Carbon Capture Technologies

Decarbonization is one of the main objectives in the EU, as "further decarbonising the energy system is critical to reach climate objectives in 2030 and 2050" (p. 6, [48]). In this area, an important challenge emerges in case of biomethanation because methanation requires efficiently useable CO_2 sources, which are reachable at biogas or bioethanol plants, but these plants sometimes do not have a close connection to the natural gas grid for energy storage, nor enough CO_2 for multi-MW_{el} P2M plants [6]. Moreover, carbon capture solutions for flue gas are considered expensive and immature in commercial-scale yet [15], despite the numerous research on different CC solutions (e.g., post-combustion [93] or oxyfuel-combustion [94]). A promising direction can be, however, the joint R&D on carbon capture technologies and biomethanation, similar to the research of Bailera et al. [95,96]. In addition to the co-specialization of resources, technologies can lead to competitive advantages in general in a competitive environment [97], and the context is also supporting this purpose. For example, by implementing P2M systems, pollutant emissions can be reduced, thus their environmental impact is positive and most of the positives can be detected in the field of climate change [98]. Synthetic methane offers outstanding greenhouse gas savings when biogenic carbon dioxide sources have been used in the methanation process or when hydrogen is generated by electrolysis by renewable energy [99], but it can be further be enhanced with efficient carbon capture solutions for flue gas.

Strictly speaking, P2M is not carbon-neutral because, during the use of biomethane, the previously "captured" CO_2 will be emitted again. However, one should realize, for example, that by using the flue gas of an energy-producing gas turbine for methanization and by reusing the new biomethane again in the same gas turbine, one carbon atom will be used twice (or thrice or even more) before emitting it as CO_2.

In the Hungarian context, by 2030, 90% of domestic electricity production is planned to be CO_2 emission-free (p. 42). Installation alongside GHG-intensive industrial activities and the use of industrial carbon dioxide are also promising in the methanation step, to increase the competitiveness of GHG-intensive industrial activities (p. 50). The production and purification of biogas can also contribute to the achievement of decarbonization goals (p. 20, [87]), and it is particularly true if carbon dioxide can be converted into methane.

4.3. Key Topic 3: From Technology Development towards Achieving "Future" Benefits—Finding Ways for Realizing and Communicating Business, Societal and Residential Value Creation

Research results suggest that even though there is still a need for research on biological methanation to increase its TRL [100], it is already worthwhile to analyze how future biomethanation can achieve future socioeconomic benefits. Realizing benefits is possible by scaling up the technology, but it requires capital investments, the returns of which might not meet the expectations of market players in the present [6,7]. Consequently, supporting regulations and profitable business models must be developed to "attract support from "patient" capital (i.e., long-term venture capital)" (p. 24, [47]), but significant public funding could be also necessary to scale up the technology. Public funding, however, can be justified if broad social and residential benefits are also explicit. Research results of the STORE&GO project show, for example, that a potential supply shock in the energy market will have less of an impact on social welfare if P2M technology is used [98]. Moreover, solar parks and P2M infrastructure increase the acceptance of the energy system by local energy communities [101].

In Hungary, rapidly growing photovoltaic capacities to 6000 MW by 2030 is a priority (p. 14), which can be technically supported by the integration function of P2M technology.

Converting surplus electricity to methane and its storage, however, can be important from broader socioeconomic aspects as well, because it can contribute to the affordable and steady energy supply (p. 10, [87]).

4.4. Key Topic 4: Future Project Planning in Line with Scientific Advancements and Policy Objectives—Building and Supporting Innovation Ecosystems for Efficient Know-How Transfer

Most of the biomethanation projects are realized in consortia of heterogeneous stakeholders, such as universities, startups, and large energy companies, while funding is often provided by the state administration [17,18]. As such, an inter-organizational network can have heterogeneous stakeholders, and an R&D&I ecosystem might be needed to bring and hold them together. An innovation ecosystem is a dynamic and adaptive system, the participants of which have different roles, motivations, and capabilities, but they all contribute to the success of an innovation process [102]. It means that an innovation ecosystem can involve not only companies from a certain sector but also from supporting sectors and regulators, since government policies also affect competitiveness [103]. Accordingly, the literature deals with the state support of R&D&I ecosystems as well. For example, government interventions that focus resources for grand challenges such as climate change facilitate the formation of networks beyond sectors and encourage scientific and technological improvements and the introduction of new or existing technologies [104]. These ecosystems can be the key for the economic growth after the COVID-19 pandemic according to the World Economic Forum, who also stated that supporting ecosystems can contain incentives for venture capital investments, R&D process and spreading new technologies [105]. Even though "green" R&D and creating balance among economic, ecological, and societal aspects must be supported by public financial sources, recent empirical studies showed that advancement in one dimension (e.g., ecological) does not necessarily happen at the cost of another dimension (e.g., economic) [106]. Biomethanation-focused innovation ecosystems may obtain support from the Horizon Europe programme, in which "partnerships with industry and Member States will support research and innovation on transport, including batteries, clean hydrogen, low-carbon steel making, circular bio-based sectors and the built environment" (p. 18, [49]).

Consequently, know-how transfer in biomethanation-focused innovation ecosystems with startups, universities, and state administrations can facilitate the previous three R&D&I directions. Figure 7 summarizes the findings and shows them according to the research framework.

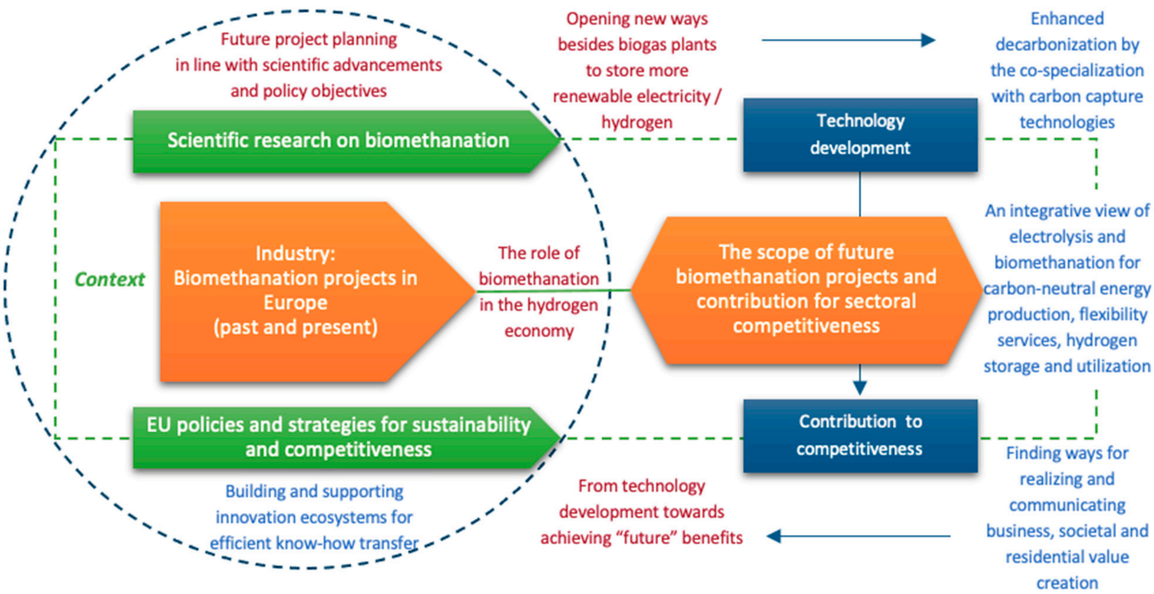

Figure 7. Findings aligned by the research framework (Orange: Focus of the research; Green: Context of the research; Red: Key topics; Blue: Suggested R&D&I directions).

4.5. Comparing the Results to Other Relevant Topics

As stated before, the list of the analyzed project descriptions and research papers was formulated from the viewpoint of a startup company (which might contribute to sectoral competitiveness with the deployment of large biomethanation plants). In addition, raw text data and interview data were iterated with former theories and research results. This approach, on the one hand, can be considered as a pragmatist one, which is in line with the roots of competitiveness studies [24], and one aimed to generate conclusions representing "cognitive usefulness in the world" (p. 18, [46]) and actionable knowledge [107]. This actionable knowledge is represented by the suggested R&D&I directions. Moreover, the conclusions would be supported by the coherence theories of truth, as well, according to which the propositions must be coherent with other scientific propositions [46]. This is because the empirical data was processed with comparisons with previous research results.

On the other hand, findings generated by this approach cannot cover every aspect and do not mean a positivist, general, theory [44]. It means that because of this abductive methodological approach, there can be areas that did not emerge during the research, i.e., the empirical data did not orient the parts of the ATOM, such as phenomena detection, analyses, and theory development [46]. Consequently, even though the synthesis of new empirical data and former research results into a coherent (but not full) set of theoretical propositions, it is worth comparing the results to some other topics which might be considered "key topics" in different contexts.

For example, (1) circular economy models can be relevant. Based on the analysis of Kircherrr et al. [108] on circular economy definitions, the main elements are central in circular economy models: the combination of reduction, reuse and recycling, and systemic shifts. These elements can be supported by biomethane production with P2M technology, as follows:

1. reuse of carbon dioxide happens in the methanation step;
2. the share of fossil energy sources can be reduced by the higher integration of renewable electricity and its storage in the form of methane;
3. coupling of the electricity and gas sectors means a system-level novelty, so the parallel function of energy storage and gas production of P2M.

Taking a closer look at biomethanation, research on the relationship with circular economy outlined some opportunities and challenges already. Baena-Moreno et al. [109] discussed that the combination of biological processes and renewable energy production can be the main pillar of the paradigm shift towards the circular economy, but incentives and/or cost-reduction-oriented technology developments are still needed. In a similar area, Eggemann et al. [110] argued that power-to-fuel processes producing methanol can contribute to the circular economy, but technology adoption might be influenced by the economic performance of these systems compared to other technological options. D'Adamo et al. [111] showed how biomethane can integrate effective management of renewable energies and municipal waste, thus contributing to the circular economy development. Their research leads to another important area of potential competitiveness developments, as well. The authors pointed out that biomethane can be used as fuel for vehicles, so (2) the green revolution in the transportation sector might be also supported by converting biowaste into clean fuels [111]. For example, biomethane can be compressed (CNG) or liquefied (LNG) for these purposes. Finally, competitiveness can be researched from (3) policy perspectives. Wall et al. [112] pointed out that recent EU legislation incites third-generation biofuels, and it creates a foundation for the integration of different solutions, e.g., anaerobic digestion, gasification, P2G, or algae as feedstock. Nevertheless, there is still further need for policy interventions to support green transitions with biomethane, for example, fueling stations in the case of the transportation sector [111], feed-in tariffs supporting seasonal energy storage [6], or carbon taxes [7] or certifications for green premiums [113] influencing the diffusion of the biomethanation technology and the production of biomethane.

These areas (circular economy, green transportation, impact of policies) did not emerge empirically during this research, but their related research results are mostly in line with the key topics and/or suggested R&D&I directions. For example, circular economy development is often focused on decarbonization which can be supported by the co-specialization of biomethanation and carbon capture technologies. Regarding green transportation, finding the role of biomethane in an area dominated by electric and hydrogen vehicles is also an important task, while incitive policies are important in the case of the formation of efficient national or international innovation ecosystems as well. The main novelty of the findings compared to previous literature, however, is related to the urged adaptation to the hydrogen economy and carbon capture of the future biomethanation project planning, as discussed below.

5. Conclusions

This research aimed to answer how could future biomethanation facility development projects increase the sectoral competitiveness in Europe. The propositional knowledge of the research based on prior literature was that future biomethanation facility development projects would increase sectoral competitiveness in Europe by providing flexibility, seasonal energy storage, and the reuse of CO_2 for synthetic natural gas production, thus integrating renewable energy sources and contributing to decarbonization efforts. Based on the empirical data collection, analysis, and iterative theory generation, however, this proposition must be modified. It viewed the relationship of biomethanation projects and sectoral competitiveness too narrowly, and ignored their contribution to the hydrogen economy and the synergies with another technology development area: carbon capture. The specific conclusion for this proposition is that in addition to the important energy storage potential, biomethanation facilities would increase sectoral competitiveness mainly due to their connective role between the two most important terms (or areas) of European strategies about economic and environmental progress: hydrogen economy and decarbonization.

Findings suggest that by building on the know-how of past and present projects, future biomethanation projects could take significant steps towards multi-MW_{el} capacities. Moreover, they should take these steps to satisfy the growing demand for their outputs and positive externalities. These improvements could support sectoral competitiveness in Europe if these projects have an integrative view of electrolysis and biomethanation for carbon-neutral energy production, flexibility of services, and hydrogen storage and utilization. In other words, biomethanation should be interpreted in the future as a hydrogen storage and utilization (HSU) solution, on the one hand. On the other hand, as biogas plants sometimes cannot provide enough CO_2 for multi-MW_{el} plants, enhanced decarbonization can be only achieved by co-specialization with carbon capture technologies. Consequently, future industry-scale biomethanation facilities should integrate hydrogen storage and utilization and carbon capture and utilization functions (HSU&CCU) to increase sectoral competitiveness in Europe. This direction, however, requires strategic alignment and know-how transfer among universities, startups, large energy companies, and state administration in biomethanation-focused innovation ecosystems.

The main limitation of the research is that it was built on abductive methodology, i.e., conclusions are not confirmed in a positivist sense by testing hypotheses. Because of the specific environment and the integrative, high-level of the analysis, the study might not cover every aspect of biomethanation technology development and competitiveness. For example, future research could identify the competitiveness-increasing potential of biomethanation in future energy systems, or maybe compare it to the potential of chemical methanation. The abductively revealed key topics, however, such as the role of biomethanation in the hydrogen economy or integration with carbon capture technologies, the alignment of technology development, scientific research, and policies might induce other thoughts and future research that facilitates the broad utilization of this innovative technology.

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Z.C.; visualization, M.Z.; supervision, A.R.I.; project administration, Z.C. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: Two of the authors perform their P2G research at Corvinus University of Budapest, and they have founded the innovative startup company Power-to-Gas Hungary Kft. in order to perform industrial R&D and further develop the technology in pre-commercial and commercial environments.

Abbreviations

ATOM	Abductive theory of method
CNG	Compressed Natural Gas
CCU	Carbon Capture and utilization
EMG-BES	Bioelectrochemical system for electromethanogenesis
EU	European Union
GHG	Greenhouse gas
HSU	Hydrogen storage and utilization
LNG	Liquified natural gas
P2G	Power-to-gas
P2H	Power-to-Hydrogen
P2L	Power-to-liquid
P2M	Power-to-methane
P2X	Power-to-X
R&D&I	Research, development and innovation
SNG	Synthetic natural gas

Appendix A

Table A1. Selected publications for quantitative text analysis.

Author	Year	Title	Keywords
Agneessens et al. [37]	2017	In-situ biogas upgrading with pulse H_2 additions: The relevance of methanogen adaption and inorganic carbon level	Acetate, CO_2 affinity, H_2, Hydrogenotrophic methanogenesis, In situ biogas upgrading
Alitalo et al. [114]	2015	Biocatalytic methanation of hydrogen and carbon dioxide in a fixed bed bioreactor	Hydrogen, Hydrogenotrophic methanogens, Methane production, Methanogens, Power to gas
Amez et al. [115]	2021	Underground methanation, a natural way to transform carbon dioxide into methane	Sustainable energy, Energy storage, Underground hydrogen storage, Green hydrogen, Underground methanization, Methanization
Ancona et al. [116]	2020	Numerical prediction of off-design performance for a Power-to-Gas system coupled with renewables	Power-to-Gas, Co-electrolysis, Methanation, Storage system, Off-design performance, Renewables
Bacariza et al. [117]	2019	Power-to-methane over Ni/zeolites: Influence of the framework type	CO_2 methanation, USY, BEA, ZSM-5, MOR, Nickel
Bailera et al. [118]	2021	Lab-scale experimental tests of power to gas-oxycombustion hybridization: System design and preliminary results	Power-to-Gas, Oxycombustion, Methanation, Lab-scale facility

Table A1. *Cont.*

Author	Year	Title	Keywords
Bareschino et al. [119]	2020	Feasibility analysis of a combined chemical looping combustion and renewable-energy-based methane production system for CO_2 capture and utilization	Thermal power plants, chemical looping combustion, CO_2 capture and utilization, methanation, numerical model
Bareschino et al. [120]	2020	Life cycle assessment and feasibility analysis of a combined chemical looping combustion and power-to-methane system for CO_2 capture and utilization	CO_2 capture and utilization
Bargiacchi [18]	2021	Power-to-Fuel existing plants and pilot projects	Carbon capture, Green ammonia, Green methanol, Electrolysis, Energy storage, Power-to-ammonia, Power-to-fuel, Power-to-methane, Power-to-methanol, substitute natural gas
Bargiacchi et al. [121]	2021	Power to methane	-
Bedoić et al. [122]	2021	Synergy between feedstock gate fee and power-to-gas: An energy and economic analysis of renewable methane production in a biogas plant	Biogas, Food waste, Optimisation, Uncertainty, Renewable gas
Biswas et al. [123]	2020	A Review on Synthesis of Methane as a Pathway for Renewable Energy Storage With a Focus on Solid Oxide Electrolytic Cell-Based Processes	Renewable fuel, Power-to-X, Hydrogen, Methane, Solid oxide electrolyzer
Blanco et al. [124]	2020	Life cycle assessment integration into energy system models: An application for Power-to-Methane in the EU	TIMES, Ecoinvent, Consequential LCA, Environmental impact, Ex-post analysis, Power-to-Gas
Böhm et al. [59]	2020	Projecting cost development for future large-scale power-to-gas implementations by scaling effects	Power-to-gas, Electrolysis, Methanation, Scaling effects, Technological learning
Carrera & Azzaro-Pantel [125]	2021	Bi-objective optimal design of Hydrogen and Methane Supply Chains based on Power-to-Gas systems	Power-to-Gas, Methanation, Hydrogen, MILP, Augmented epsilon constraint, GAMS, Optimization approach
Chellapandi & Prathiviraj [126]	2020	Methanothermobacter thermautotrophicus strain ΔH as a potential microorganism for bioconversion of CO_2 to methane	Methanogenesis, Methane, Methanothermobacter, Biogas, Systems biology, Power-to-Gas
Csedő et al. [6]	2020	Seasonal Energy Storage Potential Assessment of WWTPs with Power-to-Methane Technology	Seasonal energy storage; Power-to-methane; Wastewater treatment plants; Techno-economic assessment
Dedov et al. [127]	2018	Partial Oxidation of Methane to Synthesis Gas	Synthesis gas, Partial oxidation of methane, Neodymium–calcium cobaltate–nickelate
Fózer et al. [128]	2020	Bioenergy with carbon emissions capture and utilisation towards GHG neutrality: Power-to-Gas storage via hydrothermal gasification	Carbon dioxide utilisation; Power-to-Gas; Carbon Neutral; Catalytic Hydrothermal Gasification; VRE storage; LCA
Gantenbein et al. [129]	2021	Flexible application of biogas upgrading membranes for hydrogen recycle in power-to-methane processes	Power-to-Gas, Biogas, Membrane, Upgrading, Flexibility
Ghaib & Ben-Fares [29]	2018	Power-to-Methane: A state-of-the-art review	CO_2 recycling, Demonstration plants, MethanationPower-to-Methane, Water electrolysis
Giglio et al. [130]	2021	Dynamic modelling of methanation reactors during start-up and regulation in intermittent power-to-gas applications	Power-to-Gas; CO_2 methanation; Synthetic natural gas; Reactor design; Dynamic modelling
Gong et al. [131]	2021	Power-to-X: Lighting the Path to a Net-Zero-Emission Future	Electrical energy, Power, Fossil fuels, Electrocatalysts, Solar energy
Guilarte & Azzaro-Pantel [132]	2020	A Methodological Design Framework for Hybrid "Power-to-Methane" and "Power-to-Hydrogen" Supply Chains: application to Occitania Region, France	Power-to-Gas, Hydrogen, Methane, MILP, Gams
Hermesmann et al. [133]	2021	Promising pathways: The geographic and energetic potential of power-to-x technologies based on regeneratively obtained hydrogen	Energy storage, Wind power, Hydrogen, Carbon dioxide, Power-to-Xfuels
Hervy et al. [134]	2021	Power-to-gas: CO_2 methanation in a catalytic fluidized bed reactor at demonstration scale, experimental results and simulation	Power-to-gas, CO_2 valorization, Catalytic methanation, Demonstration reactor, Fluidized bed reactor

Table A1. *Cont.*

Author	Year	Title	Keywords
Hidalgo & Martín-Marroquín [135]	2020	Power-to-methane, coupling CO_2 capture with fuel production: An overview	Biological CO_2 methanation, Chemical CO_2 methanation, Catalityc CO_2 methanation, Carbon capture, Energy storage, Power-to-Gas
Hoffarth et al. [136]	2019	Effect of N_2 on Biological Methanation in a Continuous Stirred-Tank Reactor with Methanothermobacter marburgensis	Biological methanation; CSTR; Methanothermobacter marburgensis; Methane; Carbon dioxide; Dinitrogen; Hydrogen; Power-to-gas
Inkeri et al. [137]	2018	Dynamic one-dimensional model for biological methanation in a stirred tank reactor	Biological methanation, Gas–liquid mass transfer, Power-to-gas, Dynamic model, Stirred tank reactor
Inkeri et al. [138]	2021	Significance of methanation reactor dynamics on the annual efficiency of power-to-gas -system	Power-to-gas; Energy storage; Methanation; Modeling; Wind; Solar
Jentsch et al. [139]	2014	Optimal Use of Power-to-Gas Energy Storage Systems in an 85% Renewable Energy Scenario	Power-to-Gas, Methane, Long-term electricity storage, Economic optimization, Unit commitment
Kassem et al. [140]	2020	Integrating anaerobic digestion, hydrothermal liquefaction, and biomethanation within a power-to-gas framework for dairy waste management and grid decarbonization: a techno-economic assessment	-
Kirchbacher et al. [141]	2018	Process Optimisation of Biogas-Based Power-to-Methane Systems by Simulation	-
Kummer & Imre [142]	2021	Seasonal and Multi-Seasonal Energy Storage by Power-to-Methane Technology	Power-to-Gas; Power-to-Fuel; P2M; P2G; P2F; Biomethanization
Lecker et al. [143]	2017	Biological hydrogen methanation—A review	Biogas, Molecular hydrogen, Carbon dioxide, Power-to-Gas, Energy storage
Leonzio & Zondervan [144]	2020	Analysis and optimization of carbon supply chains integrated to a power to gas process in Italy	CCUS and CCU supply Chain, Mathematical model, Optimization, Reduction of CO_2 emissions
Liao et al. [145]	2020	A Recent Overview of Power-to-Gas Projects	Power-to-Gas, Power-to-Hydrogen, Power-to-Methane
Lin et al. [146]	2020	Geometric synergy of Steam/Carbon dioxide Co-electrolysis and methanation in a tubular solid oxide Electrolysis cell for direct Power-to-Methane	Solid oxide electrolysis cell (SOEC), Steam/carbon dioxide co-electrolysis, Direct power-to-methane, Geometry optimization, Pressurization, Electricity-to-methane efficiency
Liu et al. [147]	2020	The economic and environmental impact of power to hydrogen/power to methane facilities on hybrid power-natural gas energy systems	Power to hydrogen (P2H), Power to methane (P2M), Hydrogen energy, Hybrid power-natural gas energy systems, Renewable energy
Lovato et al. [148]	2017	In-situ biogas upgrading process: Modeling and simulations aspects	Biogas upgrading, Hydrogenotrophic methanogens, Mathematical modeling, Sensitivity analysis
Luo et al. [149]	2018	Synchronous enhancement of H_2O/CO_2 co-electrolysis and methanation for efficient one-step power-to-methane	Solid oxide electrolysis cell, One-step power-to-methane, In-situ thermal coupling, Pressurized
Meylan et al. [150]	2017	Power-to-gas through CO_2 methanation: Assessment of the carbon balance regarding EU directives	Power-to-gas, CO_2-fuels, Carbon balance, Renewable Energy Directive, Carbon capture and utilization, CO_2 valorization
Michailos et al. [151]	2021	A techno-economic assessment of implementing power-to-gas systems based on biomethanation in an operating waste water treatment plant	Biomethanation, Power to gas, Biogas upgrading, CO_2 utilisation, Techno-Economics, Carbon footprint assessment
Momeni et al. [152]	2021	A comprehensive analysis of a power-to-gas energy storage unit utilizing captured carbon dioxide as a raw material in a large-scale power plant	CO_2 utilization, Power-to-gas, Process design, Reaction kinetics, CO_2 methanation, SNG
Monzer et al. [153]	2021	Investigation of the Techno-Economical Feasibility of the Power-to-Methane Process Based on Molten Carbonate Electrolyzer	Molten Carbonate Electrolysis Cell, CO_2, Power-to-gas, Methane synthesis, Economic assessment
Morgenthaler et al. [154]	2020	Site-dependent levelized cost assessment for fully renewable Power-to-Methane systems	Synthetic natural gas, Power-to-Methane, Energy systems modeling, Sector coupling, Carbon capture and utilization (CCU)

Table A1. *Cont.*

Author	Year	Title	Keywords
Mulat et al. [155]	2017	Exogenous addition of H_2 for an in situ biogas upgrading through biological reduction of carbon dioxide into methane	In situ biogas upgrading, H_2 addition, Power to gas, Homo-acetogenesis, Stable isotope, CO_2 reduction
Ortiz et al. [156]	2020	Packed-bed and Microchannel Reactors for the Reactive Capture of CO_2 within Power-to-Methane (P2M) Context: A Comparison	Methanation, Microreactor, Packed-bed reactor, Hot spot formation, Computational Fluid Dynamics
Patterson et al. [157]	2017	Integration of Power to Methane in a waste water treatment plant—A feasibility study	Biomethanation, Power to Gas, Power to Methane, Biogas upgrading, Grid balancing
Pieta et al. [158]	2021	CO_2 Hydrogenation to Methane over Ni-Catalysts: The Effect of Support and Vanadia Promoting	CO_2 hydrogenation; methanation; Ni-catalyst; SMR catalysts; vanadium oxide catalysts
Pintér [5]	2020	The Potential Role of Power-to-Gas Technology Connected to Photovoltaic Power Plants in the Visegrad Countries—A Case Study	Power-to-gas; regulation; Energy storage; Biogas; Biomethane
Pörzse et al. [15]	2021	Disruption Potential Assessment of the Power-to-Methane Technology	Power-to-methane; Disruptive technology; Seasonal energy storage; Decarbonization; Innovation
Sánchez et al. [159]	2021	Optimal design of sustainable power-to-fuels supply chains for seasonal energy storage	Power-to-fuels, Chemical energy storage, Power-to-X, Renewable energy
Savvas, et al. [160]	2018	Methanogenic capacity and robustness of hydrogenotrophic cultures	Hydrogenotrophic methanogenesis, Biofilm, Power to gas, Energy storage
Schlautmann et al. [161]	2021	Renewable Power-to-Gas: A Technical and Economic Evaluation of Three Demo Sites Within the STORE&GO Project	Demo sites, Dynamic operation, Efficiency, Future cost development, Investment costs, Power-to-Gas, Production costs
Sinóros-Szabó et al. [162]	2018	Biomethane production monitoring and data analysis based on the practical operation experiences of an innovative power-to-gas benchscale prototype	Biomethane production, Power-to-gas, Prototype, Monitoring and analysis
Stangeland et al. [163]	2017	CO_2 methanation: the effect of catalysts and reaction conditions	Sabatier reaction, CO_2 methanation, energy storage, biogas upgrading, reaction conditions, nickel catalyst
Straka [164]	2021	A comprehensive study of Power-to-Gas technology: Technical implementations overview, economic assessments, methanation plant as auxiliary operation of lignite-fired power station	Power-to-Gas, Energy storage, Electrolysis, Methanation, CO_2 source
Vo et al. [165]	2018	Can power to methane systems be sustainable and can they improve the carbon intensity of renewable methane when used to upgrade biogas produced from grass and slurry?	Life cycle assessment, Sustainability criteria, Advanced biofuels, Power to gas, Biological methanation, Co-digestion
Wang et al. [166]	2018	Optimal design of solid-oxide electrolyzer based power-to-methane systems	Energy storage, Power-to-gas, Power-to-methane, Solid-oxide electrolyzer, Co-electrolysis, CO_2 utilization
Wang et al. [167]	2020	Reversible solid-oxide cell stack based power-to-x-to-power systems: Comparison of thermodynamic performance	Electrical storage, Power-to-x, Reversible solid-oxide cell, Ammonia, Methanol, Sector coupling
Welch et al. [168]	2021	Comparative Technoeconomic Analysis of Renewable Generation of Methane Using Sunlight, Water, and Carbon Dioxide	Atmospheric chemistry, Hydrocarbons, Membranes, Electrical energy, Electrolysis
Xie et al. [169]	2020	Optimization on Combined Cooling, Heat and Power Microgrid System with Power-to-gas Devices	Combined cooling, heat and power, Microgrid, Power-to-grid, Hydrogen natural gas blends
Zoss et al. [170]	2016	Modeling a power-to-renewable methane system for an assessment of power grid balancing options in the Baltic States' region	Excess power, Methanation, Power-to-gas, Power-to-methane, Renewable methane, Stochastic energy

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