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# Integration Opportunities of Power-to-Gas and Internet-of-Things Technical Advancements: A Systematic Literature Review

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**Abstract:** As renewable electricity integration generates grid-balancing challenges for network operators, new ways of grid resilience receive significant attention from the energy research community. Power-to-gas (P2G) applications could produce and use green hydrogen. Thus, they enable the integration of more renewable energy into the energy system. Meanwhile, Internet-of-things (IoT) solutions could optimize renewable energy applications in decentralized systems. Despite the strategic importance of both technologies in renewable-rich grid developments, opportunities for P2G advancements based on IoT and related solutions have not come to the forefront of renewable energy research. To fill in this research gap, this study presents a hybrid (thematic and critical) systematic literature review to explore how strategic co-specialization opportunities appear in recent publications. Findings suggest that P2G and IoT could be fundamentally linked within the proposed frameworks of multi-energy systems and energy internet, but further empirical research is needed regarding their operative and strategic integration (e.g., cost reduction, risk management and policy incentives).

**Keywords:** power-to-gas; Internet of things; smart grid; energy internet; smart energy system; strategy

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## 1. Introduction

A promising opportunity for developing multi-energy systems (MES) [1,2] with a holistic approach [3] is integrating electricity, gas, transportation and/or industrial sectors with power-to-X (P2X) technologies [4]. Among these, power-to-hydrogen (P2H) for green hydrogen production is already well-known and thoroughly discussed in the literature [5,6], and its further extensions towards developing power-to-methane (P2M) [7,8], power-to-liquid (P2L) [9,10] or even carbon capture, utilization or storage (CCUS) [11,12] value chains have been explored. From the aspect of power grid operators, these processes could relieve the burden of grid-balancing and maintenance if they convert renewable electricity into other energy carriers [13]. Along with this integration in the physical dimension, in the digital (or cyber) dimension similar efforts have been focused on the Internet of things (IoT) by creating new opportunities and virtual systems for simulation, optimization or design [14,15]. Despite P2G and IoT, both offer solutions for the strategic challenge of grid operators and volatile renewable electricity production [16], and even though it can be proposed that they could "meet" in the new era of the energy system, energy internet with energy, information and also business flows [17], little is known about the concepts of their integration. Moreover, there is no available widespread public information about corporate initiatives to integrate neither IoT nor other ICT solutions and P2G. A recognized opportunity, however, was in case of Microbenergy GmbH (biological methanation technology developer company) when back in 2019 it belonged to Viessmann Group, offering IoT solutions for energy transitions [18,19]. Open innovation-oriented ICT development was reported in the case of Power-to-Gas Hungary Kft. (P2G and CCU technology developer company), which was closely linked to prototype operations and knowledge management [20].

In general, the lack of industrial initiatives could be considered a missed strategic opportunity for companies and society as well, as co-specialization is generally considered an opportunity to innovate from a strategic perspective [21]. Co-specialization refers to activities through which one asset (e.g., a technology) will fit another or a strategy to a process to enhance value (innovation) by their joint use. For example, the development of tightly integrated systems could lead to highly differentiated products or services that could not be easily copied by competitors. This abstract theory of co-specialization is closely related to the practical challenges of green transition. For example, even Teece [21] (p. 1332) mentions as a common example that hydrogen cars need hydrogen filling stations. Moreover, co-specialization and complementary assets are important "in industries in which innovation might be characterized as cumulative" [21] (p. 1337), and the adequacy of this statement is apparent in the energy sector, which fights climate change. This is especially relevant from the perspective of energy companies, as "energy service providers, enablers, and operators [ ... ] should rethink their positions in Energy Internet ecosystem and remodel their development strategies and business processes to better satisfy the dynamic, personalized and diversified needs of users" [17] (p. 219). Based on the above, the goal of the manuscript is to integrate strategic aspects with P2G and IoT research, as their co-specialization could be a significant opportunity for actors who could contribute to MES development.

This emerging research area induces first a systematic literature review (SLR) to answer the following research question: *How do co-specialization opportunities of P2G and IoT appear in recent publications which could support the development of multi-energy systems?* Because of (a) the theoretical co-specialization potential of physical and digital solutions for strategic benefits, (b) the emerging research topic and (c) the lagging industrial development projects, the goal of the study is to explore and interpret current research results from a strategic perspective and outline future research and development directions. This study represents a hybrid SLR approach [22], as it aims to answer a research question for informing practice (i.e., thematic synthesis [23]) with a critical perspective on the presence or absence of strategic perspectives (i.e., critical review [24]), based on quantitative and qualitative analyses. By doing so, the main contribution of the study is to fill in the specific research gap of P2G from a strategic viewpoint and outline different levels, subjects, actors, and structures of co-specialization through which MES could be developed.

The rest of the article is structured as follows. Section 2 describes the research background and the methodology. Section 3 presents the results, while Section 4 discusses them considering prior literature. Finally, conclusions, contributions and limitations are summarized in Section 5.

## 2. Materials and Methods

In the following, the research background of P2G and IoT is introduced. After that, the process of the followed SLR method is described in detail.

### 2.1. Research Background

In line with the Paris Agreement [25] to mitigate climate change, global renewable electricity capacities could increase by 60% to 4.800 $GW_e$ by 2026, and this volume would be similar to global fossil and nuclear capacities [26]. Accordingly, one key mission of the European Union is to become climate neutral by 2050; thus, hydrogen economy development [27] and decarbonization [28] emerged as critical areas for this goal. Regarding these areas, literature and industrial actors are emphasizing the role of energy storage [3,29,30], grid balancing [31] and green hydrogen production by power-to-hydrogen (P2H) technologies due to the volatile nature of renewable electricity production [32]. Numerous studies discuss the role of other P2X technologies that could convert green hydrogen to other valuable fuels or energy carriers [4], as not only the production of large volumes of green hydrogen but its utilization in the hydrogen economy is also crucial by definition [33].

These P2X technologies usually require $CO_2$ or CO to combine with $H_2$ in order to produce different hydrocarbons. For example, P2M technologies convert $H_2$ and $CO_2$ into $CH_4$ by biological or thermochemical processes [11], which leads to the opportunity of coupling electricity and natural gas sectors and long-term (seasonal) energy storage [30]. In contrast, P2L technologies focus on the production of diesel, kerosene or other liquid hydrocarbons by adapting Fischer–Tropsch or methanol synthesis processes [9], occasionally with high-temperature solid-oxide electrolysis (SOEC) or reversed water gas shift (RWGS) reaction to produce CO from $CO_2$ [34]. The need for carbon dioxide links P2G directly to decarbonization; thus, the integration with CCU technologies has been recently proposed. For example, well-known post-combustion carbon capture with amine scrubbing has been analyzed by Bailera et al. [11], and the potential use of oxygen from electrolysis was mentioned concerning oxy-fuel combustion [35].

Besides renewable electricity integration and decarbonization, P2G technologies have recently been considered important elements of circular economy development ambitions as well. One origin of this approach is that $CO_2$ could be efficiently sourced from biogas, especially in case of biological methanation with microorganisms [20], which is more robust against fluctuations and impurities [36] compared to chemical (e.g., nickel or ruthenium-based) catalysts, which has, however, less limitation regarding the gas-to-liquid mass transfer [37]. In this case, the P2M process could produce biomethane from hydrogen and biogas, and biogas production is closely related to other waste-to-energy processes, such as algae harvesting and utilization [38]. For example, co-fermentation of micro- and/or macro-algae and/or other feedstocks could lead to higher biogas volumes [38,39]. Another approach could be the deployment of the P2H process only and in situ biogas upgrading by the injection of green hydrogen [40]. Micro-algae could be utilized for photosynthetic biogas upgrading as well [38,41], which could be used together with ex situ P2G biomethanation [38].

In contrast to the emphasis on fuel production in the case of the P2G research, recent literature often discusses the role of IoT in the energy system closer to the electricity grids. For example, Motlagh et al. [42] pointed out that key components of an IoT platform (devices, applications, protocols, data storage and analytics) could be combined and utilized in a way which could create value in many areas, such as energy storage, smart grids (SG), electric vehicle charging, battery energy management, operation of district heating networks and/or virtual power plants, etc. Many of these areas point toward the energy internet (EI) concept [43], which means the extension of SG toward a multilayer system with other energy networks [17] (in the case of P2G, it could be the natural gas grid).

Recent publications offer a comprehensive overview of the relevant concepts, the advancement from SG to EI [44,45], the emerging technologies that underpin EI [46] and its benefits, challenges and future directions as well [47]. Several scholars have put forth EI management architectures for renewable energy delivery or hybrid systems [48,49]. Additionally, in order to push for the standardization of EI, Hussain et al. formulated a new, universal definition of EI based on the synthesis of the scientific literature: "a cyber-physical system in which physical energy infrastructures and physical distributed RERs (Renewable Energy Resources) are interconnected and managed via a software-defined cyber energy network using packetized energy management techniques" [50] (p. 183131). Accordingly, EI could also play a crucial role in the current energy paradigm revolving around renewable-based, decentralized, integrated and smart energy systems (SES) [51]. EI allows the effective harnessing, control and management of energy resources through the integration of various forms of energy in a highly flexible and efficient grid made possible by the advancement of information and communication technologies (ICT) [50].

Based on the above, it could be proposed that P2G plants as central elements in the physical energy infrastructure could be interconnected with other infrastructural components, efficiently managed by IoT applications integrated into an MES. This proposition oriented the SLR process, which focused on the exploration of more concrete concepts where P2G and IoT appear together and are potential subjects of co-specialization.

### 2.2. The Process of the Systematic Literature Review

SLR aims to answer a research question by collecting all relevant research outcomes that fit the pre-specified inclusion criteria, as well as by extracting and analyzing data through systematic methods [52]. SLR could be successfully applied for strategy-oriented renewable energy research (e.g., [53]). To ensure methodological transparency and replicability, minimize selection bias and enhance the validity of the research, the authors followed (and documented) an explicit methodology based on the guidelines provided in the literature [22,54–56], regarding: (1) formulating the research problem; (2) development and validation of the review protocol; (3) literature search; (4) screening for inclusion based on title, keywords and abstract; (5) quality and scope assessment based on the full text; (6) extracting data; (7) quantitatively and qualitatively analyzing and synthesizing data; (8) reporting findings. Regarding Step (2), inclusion and exclusion criteria are presented in Table 1.

**Table 1.** Inclusion and exclusion criteria (own construction).

| Time of Implementation | Criterion | Inclusion | Exclusion |
|---|---|---|---|
| Before the literature search | Publication | Journals ranked Q1 in the "energy" field of the Scimago database | Lower ranked journals in the same category<br>Journals in any other field |
| Literature search | Language | English | All other languages |
| Literature search | Date | Between 2010 and February 2022 | Published before 2010 |
| Literature search | Article type | Research and review articles | Other types of articles, such as short communications, editorial or correspondence |
| Quality assessment | Focus | Relationship between IoT and P2G (primary keywords: "Internet of Things/IoT, "Power-to-gas/PtG/P2G"; moreover, to integrate studies with relevant content but other terms, secondary keywords: "energy internet", "internet of energy", "power-to-X", "power-to-methane", their other versions and abbreviations) | Irrelevant for research question |

In SLR Step (7), the JMP software was used for quantitative text analysis purposes, as suggested in prior studies [57]. In this research part, word clouds, correlation matrices and thematic and time-series analyses were conducted based on the title, keywords, abstract and publication year of the selected articles. Before these analyses, data cleaning, tokenizing, phrasing and terming tasks were needed in the program.

Regarding Step (6) and Step (7), the analysis applied the abductive coding technique of the grounded theory (GT) (open, axial and selective coding) [58]. Abductive methods generally focus on the exploration of patterns based on empirical data from the field and finding the best explanation based on the iteration of theory, other literature results and data [59] and are open to the application of quantitative and qualitative methods [60]. Table 2 summarizes the main characteristics of the data collection and analysis.

**Table 2.** Summary of the data collection and analysis process (own construction).

| Research Phases | Research Goal | SLR Steps | Main Tasks | Coding | Methodological Goal |
|---|---|---|---|---|---|
| I. | Exploring the IoT- and P2G-related literature | 1–4 | Preparation, protocol development, literature search and screening | - | Establishing methodological consistency and data collection |

**Table 2.** *Cont.*

| Research Phases | Research Goal | SLR Steps | Main Tasks | Coding | Methodological Goal |
|---|---|---|---|---|---|
| II. | Analyzing the IoT- and P2G-related literature | 5–6 | Qualitative coding | Open | Finding relevant data Preparation for quantitative analysis |
| | | | Quantitative text analyses and qualitative coding | Axial | Finding initial patterns in the data |
| III. | Finding strategic co-specialization opportunities for P2G and IoT | 7 | Qualitative re-coding, comparison to other literature results | Selective | Conceptual synthesis of the results and discussion from overlooked aspects |

## 3. Results

In the following, the results of quantitative and qualitative analyses will be presented. During the screening and scoping, three groups were developed: "less relevant", "more relevant" and "most relevant" (Figure 1). Appendix A presents the list of "more relevant articles", including the "most relevant" ones. As articles in the "less relevant" category were placed out of scope to avoid distortion of the results, the quantitative part represents a transition from the analysis of the "more relevant" articles ($n$ = 46) to the "most relevant" articles ($n$ = 10), focusing on the main results of quantitative analyses. "Most relevant" articles will be summarized qualitatively in the second part.

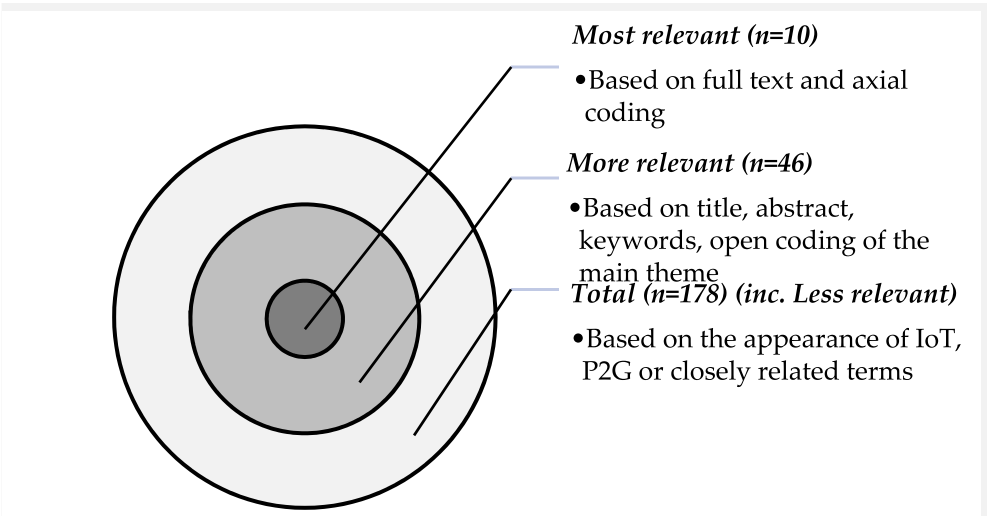


**Figure 1.** Results of relevancy assessment (own construction).

### 3.1. Quantitative Results

Regarding the "more relevant" category ($n$ = 46), since 2017, the number of relevant publications has been increasing slowly, which points toward a growing interest in the interrelationships between research on digitalization and alternative energy production. Additionally, strong growth can be expected soon, as evidenced by the number of papers published in 2022 (see Appendix A). Regarding these studies, high-level quantitative text analyses were undertaken to explore initial patterns in the literature.

Firstly, the title, keywords and abstracts of the articles were extracted as the most important article elements. Regarding these elements, we conducted a multivariate analysis on the 60 most common terms and phrases from the selected elements to explore which of those appear or do not appear frequently together, especially if the correlation is counter to obvious expectations. (The presence of obvious correlations, however, validates the method. For example, high correlation is between "storage—power", "problem—use", "challenge—research", "method—algorithm", "research—development"). Regarding our main terms of concern from the perspective of our research question, we found that:

- "Internet of things" has a low correlation score with "energy system" even though that was one of the most common terms in all the sources.
- "Power to gas" has a high correlation with several terms that relate to the technological performance of the process such as "optimization", "operation" and "improve". In contrast, it has a low correlation with terms such as "renewable energy", "flexibility" and "integrated energy system", which is unexpected as these also describe some of the defining characteristics of this technology. Additionally, it also scores relatively low with regards to terms such as "internet of things" and "energy internet", which could suggest that P2G literature is not analyzing actively the opportunities with digitization and its network benefits and vice versa.

Figure 2 could offer new ideas for filling in this research gap. Among high correlations, "risk" and "optimization" appear often together, which could refer to the operative maintenance challenges which network operators will face in case of intermittent renewable energy integration without P2G [13] or IoT support [61]. Nevertheless, exploring and managing system-level or strategic risks might be a new avenue for P2G and IoT research and development.

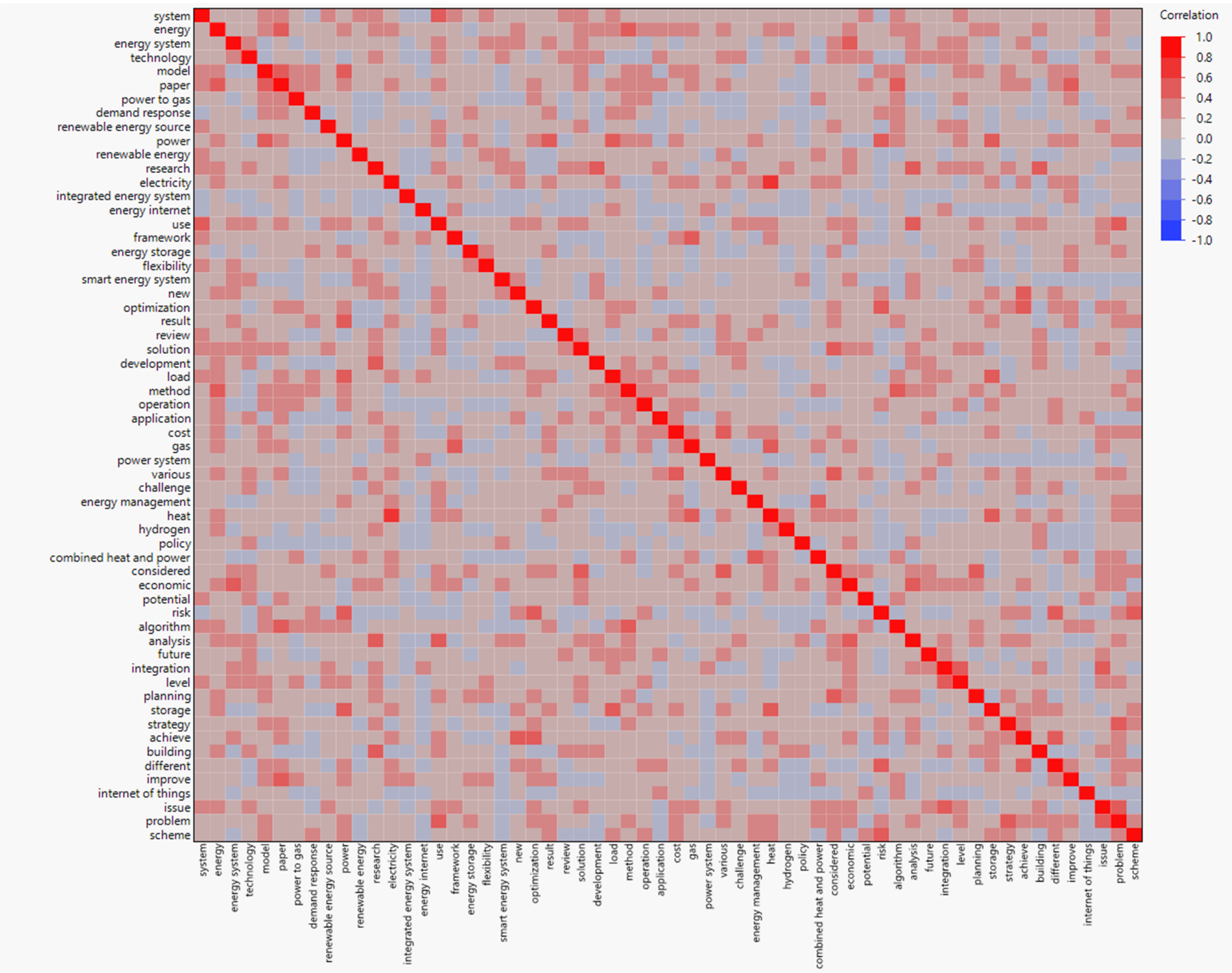


**Figure 2.** Map of correlation for the most common terms and phrases (own construction).

In relation to future orientation, surprisingly, "power-to-gas" and "future" appear rarely together, in contrast with the described potential in the P2G literature. For example, P2G studies often incorporate scenario analyses [5,62], or as Bailera et al. [63] (p. 292) stated, P2G is a "long-term solution" and "will play a significant role in the future energy storage scenario". Moreover, "costs" with "energy systems" and "policy" are also surprisingly underrepresented since these are generally important areas for P2G research [7]. Strategic perspectives and future orientation regarding, e.g., risk management, cost-reduction by the integration of P2G and IoT and policy interventions, could be interesting research topics.

The increased relevance of strategic topics, especially "cost" and "policy", is reflected in the development of key concerns of the literature by highlighting which terms were featured more prominently in which year (Figure 3). It is because "cost" and "economic" also show a steady rise in terms of appearance. Similarly, the changes in the appearance rate of "policy" mean that, besides the technological considerations, the utilization of innovative technologies and energy systems can affect or require effect from the social and political sphere as well. The terms most prominently featured in 2022 are likely to define research in the near future. "Smart energy system" appeared at a rate of 71% in 2022, suggesting that the research area is moving towards digitalization, integration and decentralization. In addition, while the appearance of "power to gas" and "hydrogen" decreased in 2022, "gas" was more apparent, which could indicate growing interest towards P2M processes and producing synthetic natural gas.


**Figure 3.** Rate of appearance of most common terms in the selected elements regarding their time of publication (own construction).

### 3.2. Qualitative Results

Regarding the "most relevant" studies, P2G and IoT appeared usually within mostly integrative and smart energy frameworks which were, however, described by different terminologies (Table 3). For example, Nolting et al. [64] carried out an SLR on industrial digitalization in the sense of Industry 4.0 and scientific energy system analysis to explore the technologies that enable (digitized) industries to interact with the energy system in order to contribute to a future *smart energy system* (SES), which comprises the transportation, the industry and the heat sectors (in which P2G could be used). In contrast, Salehi et al. [65] wrote about a *multi-energy hub* (MEH), which involves different hubs for residential energy, commercial energy and industrial energy with different technologies (e.g., P2G) and is controlled by IoT. The term "energy hub" is defined by receiving energy carriers (inputs), their management (process) and supplying consumers (outputs), and the authors proposed an unprecedented cost-emission-based scheme for energy management of interconnected MEHs aimed at minimizing procurement costs as well as reducing carbon emission.

Other combinations in the terminology of the emerging frameworks also appeared, for example, Agabalaye-Rahvar et al. [66] presented a *smart multicarrier energy hub* (SMEH) coordinated with an integrated demand response program (IDRP) and hydrogen storage system (HSS) (for the hydrogen from P2G) as flexible resources. While reviewing the main existing and emerging flexibility options that can be deployed in power systems in order to support the integration of sustainable and variable power production technologies, Cruz et al. [67] discussed *multi-energy systems* (MES). Nevertheless, while considering P2G, they mention *multi-sectoral energy systems* (MSES) as well. Ramsebner et al. [68] was focusing on the development of *multi-energy and hybrid energy systems* (HES), changing the requirements from historically grown, isolated energy grids toward renewable HES and the associated potential and challenges. Their article describes P2G as a key tool for integrating variable renewable energy (e.g., by hydrogen and biofuel production), while IoT could support, e.g., energy efficiency.

The previously mentioned integrated demand response program (IDR) was also emphasized by Wang et al. [69], who presented a state-of-the-art review of IDR in *multi-energy systems* but in the context of the EI paradigm. The authors argued that one of the benefits of IDR is the enhancement of the reliability of energy systems and mentions P2G as a technique to use surplus electricity and ICT technologies for controlling the MESs. Similarly, the *energy internet* (EI) framework was the focus of Wu et al. [70], who broke it down into three subsystems (energy-oriented network subsystem, communication-oriented network subsystem and service-oriented management subsystem), in which P2G enhances decarbonization by enabling power-to-fuel processes, and IoT could support monitoring and automation in several areas (e.g., smart homes, smart grids, EI intelligence).

In addition, other contextual frameworks appeared as well. Regarding a partly spatial approach, Wang et al. [71] proposed an online optimization strategy for a *regional integrated energy system* (RIES) with heating, ventilation and air conditioning loads, in which P2G could support large-scale renewable energy storage while IoT could be used for real-time monitoring. Their proposed model was aimed at solving the energy management and control problem for energy management systems. From the aspect of the built environment, Tronchin et al. [72] stressed the importance of temporal and spatial decoupling of supply and demand as a solution to the challenges posed by inflexible production and inelastic demand in a renewable-energy-based energy system. In this approach, IoT could induce new perspectives through data analytics, and P2G could help interplay among different sectors. Finally, the broadest context was identified in case of Elavarasan et al. [73], who explored decarbonization opportunities for European climate neutrality but also the conflicts of interests among various social groups and lack of market formation as the prime barrier to the diffusion of P2X systems in Europe. Additionally, digitalization is argued to be an enabling tool for decarbonization as it can have significant benefits for decreasing energy consumption, but it brings also legal, cybersecurity and data protection risks.

**Table 3.** Emerging frameworks and roles of P2G and IoT in the literature.

| Emerging (Co-Specialization) Framework | Examples of Key Framework Characteristics | Potential Role of P2G | Potential Role of IoT |
|---|---|---|---|
| Multi-energy systems (MES) [69] | Integration of different forms of energy: electricity, thermal, natural gas, etc. | Overcoming the inertia of the natural gas grid by incorporating the surplus of electric power and converting electricity to hydrogen or methane | Maximizing operational efficiency by real-time information |
| Multi-energy hubs (MEH) [65] | Connecting residential, commercial and industrial energy hubs | Producing gas from electricity to supply the gas equipment when natural gas is calculated at a high tariff | Controlling the MEH and coordinating data and devices for optimal energy management of the whole system |
| Smart multicarrier energy hub (SMEH) [66] | MEH with novel technologies for flexibility and supplying multiple economic and environmental demands | Flexibility based on hydrogen production and storage | Communication tool in the IDRP-coordinated hub |
| Multi-sectoral energy systems (MSES) [67] | Integration of sectors to increase flexibility | Enhancing the flexibility of the network | Further integration of energy systems by improving their performance with automated responses |
| Smart energy system (SES) [64] | Offering energy services by automation and cross-sectoral integration | Integration of renewables, seasonal storage for PV integration, seasonal load shifting, reduction of required reserve capacity | Automatically controlled demand and integrated supply |
| Hybrid energy system (HES) [68] | Alignment of the operation of electricity, heating, cooling, transport fuels to improve system efficiency and reduce carbon emissions | Enabling hybrid energy systems by transformation technologies (P2X) | Enabling hybrid energy systems by advanced communication and information systems (IoT, ICT) |
| Regional integrated energy system (RIES) [71] | Multi-energy complementation and coordination of multiple energy subjects (source, network, load, storage) | Increasing the resilience of the power system | Real-time monitoring of the appliances, load management and power generation optimization scheduling |
| Energy Internet (EI) [70] | A new evolutionary stage of the smart grid by networks for energy sharing, data sharing and service sharing | Integrating power and gas grids, and improving flexibility, stability and reliability, as an energy conversion and storage technology | Playing a crucial role in communication- and service-oriented information networks |
| Built environment [72] | Intermediate scale of analysis in multi-level perspective planning (e.g., techno-economic and socio-economic aspects) | Opening new possibilities by combining the temporal and spatial decoupling of supply and demand with an interplay among different sectors in the energy system and multiple energy carriers | Data analytics and the use of robust and scalable computational techniques to respond to technical problems, supporting the emergence of innovative solutions |
| Decarbonization, climate neutrality [73] | Transitioning to low-carbon activities | Strengthening the climate action response, extending chains towards the industry | Enabling decarbonization in the area of energy consumption |

Based on the above, P2G and IoT technologies were discussed from slightly different perspectives in the different frameworks. Table 3 presents the (potential) role of the P2G and IoT technologies that were mentioned in case of these frameworks. The main ideas, however, could be synthesized in the following way:

- P2G is an energy conversion technology which could play an important role in the energy network through energy storage and thus support the integration of renewables, providing flexibility for the power grid and temporal and spatial decoupling of supply and demand.
- IoT is an information and communication technology which could play an important role in communication- and service-oriented information networks by real-time monitoring, control and optimization of demand and supply, supporting efficient energy consumption and data-based system management.

## 4. Discussion

Even though the most relevant studies are heterogeneous in terms of the discussed energy frameworks, they are mostly similar regarding the level of analysis, which could be called "a system perspective" (except the work of [73] Elavarasan et al.). Compared to the other areas of integrated and multi-energy system research, this is in line with the continuous progress of this discipline. For example, Jin et al. [74] discussed the need for intelligent dispatch methods concerning a hybrid energy microgrid integrated with renewable generations, dispatchable distribution generators and low-carbon buildings; Wei et al. [75] considered thermostatically controlled appliances as the solution to the issue of power fluctuations tied to renewable energy utilization and put forth a hierarchical and distributed management strategy focused on resource maximization and improved control performance; or Ju et al. [76] proposed a two-phase DR based on coordinated purchase and sale transactions considering the uncertainty of wind power and photovoltaic (PV) power and the power consumption behaviors of different customers, respectively. From a broader perspective, Wang et al. (2018) [77] summarized the available research about an integrated energy distribution system (IEDS), based on which they present an integrated model and evaluate the related concerns since IEDS is central to the research and development of regional energy internet and future energy strategy in China. On the one hand, the benefits of IEDS-oriented integrated generalized demand side management (IGDSM) are highlighted as IGDSM employs advanced technology and economic strategies to coordinate and optimize the supply and the demand side within the EI.

Because the results suggested that some aspects of P2G and IoT integration are not or are only partially covered, potential micro-, meso-, and macro-level drivers and research areas of co-specialization are presented in the following sections, based on the iteration of the results and prior studies, some of which did not appear during the SLR process because of the filtering criteria.

### *4.1. Micro-Level Drivers of Co-Specialization*

Regarding the technical aspects, the uncertainty of P2G modeling could be reduced by precise data results, and the "design of smart management" for P2G was suggested [78] (p. 203). Even though the P2G process, without limitations of energy storage capacity and rigid production demand, allows controllable load, further developments of the optimization and control strategy must be achieved concerning auxiliary equipment, such as pumps, heat exchangers, power electronic converters, compressors and hydrogen storage tanks, especially in case of special operating situations (e.g., grid fault or quick ramping) [79].

Managing P2G in a "smarter" way by IoT support, however, must involve multiple layers [43], and its initial research concept could integrate (1) sensor-embedded things that could include local renewable electricity producer units (PV and wind turbines), short-term electricity storage battery units, carbon dioxide sources (biogas or flue gas), hydrogen and natural gas storage units, with sensors for power, temperature, light, gas, pressure, humidity, etc.; (2) interconnection among network layers, data management, smart meters and other IoT applications, e.g., tracking and controlling MESs of PV and hydrogen generation plants and/or refueling stations; (3) automation in the volume of absorbed electricity by electrolysis and switching between end-products (hydrogen or methane) based on the actual renewable electricity production, battery loads, carbon dioxide sources, gas storage levels, market conditions or local gas needs. These IoT-based development directions could mean additional novelties in case of P2G demonstration plants. It is because their IoT support has not been reported yet, despite gas flows needing to be continuously metered, pipelines and compressors must be supervised by leakage detection (e.g., in the case of a P2G plant in Falkenhagen [80]), which generates large amounts of data for advanced analytics and the potential need for automated intervention.

### *4.2. Meso-Level Drivers of Co-Specialization*

The role of IoT in P2G development could be argued from system-level techno-economic optimization and control aspects as well. For this goal, several communication technologies and sensors could be used. For example, a supervisory control and data acquisition (SCADA) system could be used for optimizing energy storage [81] based on data from different regions, while wireless networks (e.g., 5G [43]) and wired power-line communications (PLC) could support bidirectional communications between electricity system operators and P2G operators as key consumers in the system [82]. In addition, smart meters focusing on load management, and wind or solar sensing focusing on environmental parameters, could be implemented in the transmission system, which could support the optimization of P2G-based grid balancing [78].

Nevertheless, by approaching the integration primarily from the side of IoT (and not P2G), Salam [78] suggested another paradigm, "sustainable energy IoT", which could interconnect sustainability (energy) things in the whole system. Following this approach, P2G opportunities were discussed for sustainable energy IoT development. While flexibility was indeed mentioned because of the fast response time of P2G, two other strategic aspects were also outlined. (1) Reducing carbon emissions by the integration CCU and methanation is an emerging area of P2G research, and the optimization and modeling of these integrated systems (e.g., with CHP units, CC, P2G, and considering system boundaries, such as wind turbines, PV units, natural gas sources, micro-gas turbines [83]) could induce the use of advanced information and communication technologies. Furthermore, (2) managing congestion by realizing P2G-based energy storage close to renewable power plants is also mentioned as a strategic opportunity for renewable energy integration. In this sense, prior research on on-site energy storage presented that uncertain market conditions could influence the economic performance of P2H-based energy storage [84], which suggests that integrated and real-time monitoring of production units and market conditions by IoT in an MES (e.g., with electricity, hydrogen, natural gas and liquid fuels) could result in improved economic performance (besides environmental benefits). Switching between operation modes and end-products in an MES (e.g., hydrogen, methane, or liquid fuels), however, would require careful decision making because of the technical and economic complexity of the energy system. So, further research could focus on the decision-making algorithms and protocols of IoT-supported P2G applications to increase their techno-economic viability, because many of the related studies concern only battery energy storage systems [85–87] or smart grids [88,89].

In case of economic aspects, besides reducing investment costs of P2G [8], the pricing mechanisms of flexibility services also seem to be an important research area. It could be further elaborated based on the integration of P2G and IoT in an MES, however, because that pricing and market conditions of P2G systems [90,91] and IoT-enabled smart- or microgrids [92] are discussed separately, while IoT-based P2G and MES would require a holistic approach. Future research of these integrated (sub)systems could be based on the classification of Miletić et al. [93], who differentiated strategic and non-strategic price-modeling approaches based on the size of the focal energy storage systems.

### *4.3. Macro-Level Drivers of Co-Specialization*

Finally, from a management and policy perspective, the development of IoT-supported P2G would affect and require resources from many industry actors (e.g., distribution and transmission systems operators and energy producers in both segments) that induce open innovation. In other words, individual companies might be unable to generate a competitive advantage in such a complex segment despite having beneficial autonomous characteristics (e.g., market orientation, customer orientation [94]). Investment into such renewable energy technologies, however, might not meet the risk appetite of the main stakeholders [95,96]. It is because that novelty and innovation adoption means not only opportunities but potential technical, financial, operational and implementation risks as well [97,98]. For example, (a) traditional energy activities of incumbent energy companies, (b) P2G and (c) IoT operations are distant areas regarding the needed capabilities, developing and managing such integrated systems lead to complex outsourcing and risk management tasks that could be researched. Because innovation risks might hamper the engagement of such companies, reconfiguration of assets [21] might need to be incited by new policies. However, successful technological integration could shape the environment and create competitive advantage on the corporate, national or international levels. As environmental and economic performance are important for corporations and also policymakers (e.g., for the European Union [28]), pathways through which P2G and IoT could jointly support social, environmental and economic progress could also be the topic of future research.

### 4.4. Synthesis of Cospecialization Aspects

Based on the iteration of the research background, the quantitative and qualitative results, cospecialization of P2G and IoT for developing MESs could be interpreted in case of technical developments (micro-level), energy system design and management (meso-level), and strategic management (macro-level), from which, meso-level approaches are dominant in the literature. Table 4 summarizes the relevant levels, subjects, goals, actors, and examples for uncovered research areas of cospecialization for MES development from the aspect of the integration of P2G and IoT. By comparing the results of this study to our results to the other areas of P2G, IoT and MES research, at least two other research perspectives seem to be overlooked:

- operative, direct technical cospecialization of these two technologies, i.e., how IoT could be used in concrete P2G plants;
- strategic, competitiveness-oriented cospecialization of these two technologies, i.e., how the operative or MES-level integration of IoT and P2G could be supported from a corporate or policy aspect.

**Table 4.** Cospecialization aspects of P2G and IoT to support MES development.

| Level | Micro | Meso | Macro |
|---|---|---|---|
| Cospecialization perspective | Technology | Techno-economic system | Strategy |
| Cospecialization goal | Direct technical integration, optimization | Multi-energy system design and efficient system management | Competitive advantage and socio-environmental contribution |
| Cospecialization subject 1 | P2G | Integrated P2G and IoT applications or other sub-system | Corporate Strategies and Risk Management |
| Cospecialization subject 2 | IoT | Other sub-systems | National/International Strategies and Regulations |
| Examples from the P2G- and IoT-related literature | - | [64–72] | [73] |
| Examples for P2G- and IoT-related future research areas | Cost-reduction or improved payback time, energy efficiency, reducing uncertainties, optimizing operation with auxiliary equipment | System-wide and multidirectional data flows, pricing mechanisms, decision-making protocols, open innovation, operations and risk management of the complex systems | Policy incentives and soci-economic contribution of innovators |

**Table 4.** *Cont.*

| Level | Micro | Meso | Macro |
|---|---|---|---|
| Cospecializing actors | Technology developers (engineers) | System integrators (engineers and economists) | Strategists of corporations and policymakers |
| Structure of cospecialization (open innovation) | Individual projects (e.g., with engineering teams) | Strategic partnerships (e.g., with companies of the electricity and gas sector) | Inter-organizational networks (e.g., with state administration) |

However, given the novelty of these technologies, many future research areas also appear also in case of the meso-level, as listed above.

## 5. Conclusions

This study aimed to outline integration opportunities of IoT and P2G technologies, which could support the development of multi-energy systems, by conducting a systematic literature review, following a strategic approach and interpreting the data with the help of quantitative and qualitative analysis. While quantitative results showed some ambiguities regarding the direction of P2G and IoT research, qualitative results highlighted that these technologies are mainly discussed as separate elements of different energy frameworks or more complex technological systems (e.g., MES, SES, EI). The results, however, confirm the initial assumption that IoT and P2G appear jointly in recent publications, but their direct integration seems to be overlooked for now. Parallel with the dominant system-centric approach, the strategic, macro-level aspects are also peripheric in the related P2G and IoT literature. Thus, findings suggest future research be conducted on different levels, including the operative technical issues of integration (e.g., IoT-supported P2G). Drivers of this co-specialization could be identified in micro, meso and macro levels as well, for example, reducing costs and uncertainties, optimization of on-site or system-level energy storage, pricing mechanisms and decision protocols in MES operations, strategic risk management to handle complex MES and heterogenous actors and policy incentives for MES-focused innovation and socio-economic contribution.

From a theoretical perspective, the contribution of this study is that it applied an influential strategic management theory (co-specialization) in an innovative, technology-intensive research area to identify the presence or absence of strategic orientation in the literature and outlined future research areas which might accelerate the development of MES based on P2G and IoT advancements. From a practical aspect, this study argued that such advancements could require collaborations on multiple levels, as co-specialization of technological solutions and techno-economic sub-systems and strategies are equally relevant.

While this review explored the potential roles of P2G and IoT in different conceptual energy frameworks, a main limitation is that the concrete technical opportunities of IoT and P2G were going beyond the scope of study because of the contents of the reviewed articles. Thus, this study could only be considered one of the first steps toward a new technology development direction (IoT-supported P2G) which could accelerate the development of MES. Nevertheless, by outlining different levels of analysis and development, conclusions might induce new P2G-, IoT- and MES-oriented initiatives and collaborations between academia, state administration and the industry.

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## Abbreviations

| | |
|---|---|
| CCUS | Carbon Capture, Utilization or Storage |
| EI | Energy Internet |
| GT | Grounded Theory |
| HES | Hybrid Energy Systems |
| ICT | Information and Communication Technologies |
| IDR | Integrated Demand Response |
| IEDS | Integrated Energy Distribution System |
| IGDSM | IEDS-oriented Integrated Generalized Demand Side Management |
| IoT | Internet of Things |
| MEG | Micro Energy Grid |
| MEH | Multi-Energy Hub |
| MES | Multi-Energy System |
| MSES | Multi-Sectoral Energy System |
| P2G | Power-to-Gas |
| P2H | Power-to-Hydrogen |
| P2L | Power-to-Liquid |
| P2M | Power-to-Methane |
| P2P | Peer-to-Peer |
| P2X | Power-to-X |
| PV | Photovoltaics |
| RIES | Regional Integrated Energy System |
| RWGS | Reversed Water Gas Shift |
| SCADA | Supervisory Control and Data Acquisition |
| SES | Smart Energy System |
| SG | Smart Grid |
| SLR | Systematic Literature Review |
| SMEH | Smart Multicarrier Energy Hub |
| SOEC | Solid-Oxide Electrolysis Cell |

## Appendix A

**Table A1.** "More relevant" articles regarding the integration of IoT and P2G.

| Author(s) | Year | Author(s) | Year |
|---|---|---|---|
| Xue, Y. [99] | 2015 | Grigoriev et al. [100] | 2020 |
| Alanne et al. [101] | 2017 | Ju et al. [102] | 2020 |
| Song et al. [103] | 2017 | Tan et al. [104] | 2020 |
| Wang et al. [69] | 2017 | Ju et al. [105] | 2020 |
| Luo et al. [106] | 2017 | Dou et al. [107] | 2020 |
| Luo et al. [108] | 2017 | Wu et al. [70] | 2021 |
| Cruz et al. [67] | 2018 | Ahmad et al. [109] | 2021 |
| Paiho et al. [110] | 2018 | Wang et al. [71] | 2021 |
| Tronchin et al. [72] | 2018 | Ramsebner et al. [68] | 2021 |
| Koirala et al. [111] | 2018 | Hoang et al. [112] | 2021 |
| Cao et al. [113] | 2018 | Saeed et al. [114] | 2021 |
| Andoni et al. [115] | 2019 | Yang et al. [116] | 2021 |
| Salehi et al. [65] | 2019 | Chen et al. [117] | 2021 |
| Yang et al. [118] | 2019 | Feng et al. [119] | 2021 |
| Cheng et al. [120] | 2019 | Agabalaye-Rahvar et al. [66] | 2021 |
| Piacentino et al. [121] | 2019 | Ding et al. [122] | 2022 |
| Qu et al. [123] | 2019 | Zhu et al. [124] | 2022 |

**Table A1.** *Cont.*

| Author(s) | Year | Author(s) | Year |
|---|---|---|---|
| Zhang, X. and Yu, T. [125] | 2019 | Razmjoo et al. [126] | 2022 |
| Ju et al. [127] | 2019 | Erixno et al. [128] | 2022 |
| Nolting et al. [64] | 2019 | Elavarasan et al. [73] | 2022 |
| Zheng et al. [129] | 2020 | Wang et al. [130] | 2022 |
| Cambini et al. [131] | 2020 | Xu et al. [132] | 2022 |
| Dranka et al. [133] | 2020 | Shen et al. [134] | 2022 |

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