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Applications of power to gas technologies in emerging electrical systems

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ABSTRACT

The energy sector is undergoing substantial changes in order to promote better efficiency, increase the use of renewable energy, reduce emissions and effectively deploy technologies to trade off costs and benefits One emerging solution is the application of the Power-to-Gas technology, which can be used for different purposes. In recent years, Power-to-Gas has been studied to understand the role it could play in the electrical system. This paper has the aims of analysing the existing literature about the Power-to-Gas technology in detail, by considering some solutions that have a direct impact on the electrical system (in particular electrolyser and CO_2 production) and applications in the different sectors of the electricity value chain (i.e., generation, transmission, distribution and utilisation). This paper sets out the conceptual aspects that are necessary to include Power-to-Gas facilities in a more comprehensive analysis framework of the operation of the electrical system in various sectors. Some perspectives concerning new Power-to-Gas applications are also presented for each sector, and some promising aspects that are expected to play a relevant role in the future technical and economic evolution of electrical systems are discussed.

1. Introduction

In recent years, the increase in the capacity of renewable energy sources (RES), together with the need to reduce the carbon emissions [1], have encouraged researchers to investigate new methodologies that could be used to fully exploit the production of RES to supply the energy system. Some studies have even been aimed at creating a 100% RES supplied energy system [2], and in particular a 100% RES-based electrical system [3].

A few years ago, after the nuclear accident that occurred at Fukushima in Japan, the German government announced the so-called "Energiewende" [4]. This term indicates the transition from a carbon-based energy system to a low-carbon energy system, with the aim of dismissing the nuclear energy plants still operating in the country. The presence of wind farms in the north of Germany, together with the presence of massive load in the south, created the conditions for the introduction of a proper means of energy transportation from north to south. However, as the construction of new overhead lines is often not accepted by the general public, novel methods have to be applied. Since there is already a gas network spread over all the industrialised countries in Europe, it could be used for energy storage, and the gas could represent an energy vector that could be used to exploit the potential of RES.

In this context, one of the main challenges is the necessity of introducing more flexibility to the existing bulk system in order to reduce RES curtailment as much as possible [5–7]. The Power to Gas (P2G) option represents a suitable solution for the long-term storage of the electricity produced by RES-based plants [8]. P2G is able to add more flexibility to the electrical system, and it allows the electrical system to be coupled to other energy systems, such as heating districts [9] and transport systems [10]. The idea of producing Synthetic Natural Gas (SNG) to store electricity was first introduced by Long in 1978 [11]. He described the possibility of converting electricity into gas (feeding the public gas network) and of obtaining enough electricity to satisfy the load peak. Several pilot and demonstration sites were installed throughout the world, thus demonstrating the great interest in this technology [12].

Gas and electricity are linked by means of both the P2G and the Gas-to-Power facility, i.e., Combined-Cycle Gas Turbine (CCGT) power plants and Open-Cycle Gas Turbine (OCGT) power plants. An example of the potential paths and connections is shown in Fig. 1. In the figure, the blue lines represent the *gas* vector, which can be provided to the

Abbreviations: CAES, Compressed Air Energy Storage; CC, Carbon Capture; CCGT, Combined-Cycle Gas Turbine; *HHV*, Higher Heating Value; HV, High Voltage; HVDC, High Voltage Direct Current; *LHV*, Lower Heating Value; LV, Low Voltage; MV, Medium Voltage; NG, Natural Gas; OCGT, Open Cycle Gas Turbine; OLTC, On-Load Tap Changer; P2G, Power-to-Gas; PEM, Proton Exchange Membrane, or Polymer Electrolyte Membrane; PHES, Pumped Hydroelectric Energy Storage; PV, Photovoltaic; RES, Renewable Energy Sources; SNG, Synthetic Natural Gas; SOEC, Solid Oxide Electrolysis

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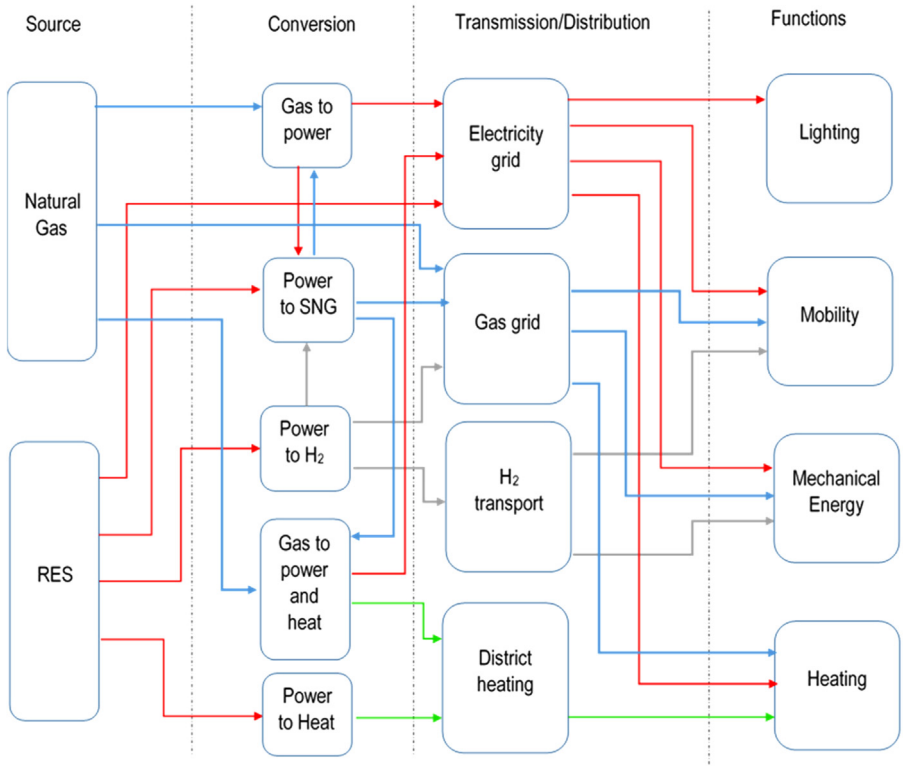


Fig. 1. Energy paths involving different vectors (i.e., electricity, natural gas, H_2 and heat).

customer as it is (for heating and mobility), or converted into electricity, heat or mechanical energy. The red lines represent the *electricity* vector, which is usually provided directly to the customers, but could be converted into either gas (SNG or H_2) or heat. The green lines represent the *heat* vector, which can be produced from both electricity and gas, and can be distributed by means of a district heating system. Finally, the grey lines represent the possible distribution of H_2, which can be used in the mobility sector, converted into mechanical energy and heat, or used as an element for the production of SNG. The link between H_2 and SNG means that the production of SNG could be made directly from H_2 stored in tanks (for example, for small power plants to SNG ones), without the need of including an electrolyser in the same plant. Further possible connections (such as the production of H_2 from gas and applying processes such as steam reforming) have not been highlighted in the figure for the sake of clarity. P2G in fact represents a significant new entry, which shows a growing integration within the multi-energy generation framework [13].

This paper has focused on the analysis of the *electrical* aspects of P2G. As such, for the sake of completeness, a brief presentation of the structure of the electrical system is provided. The structure of an electrical system is traditionally divided into four sectors (Fig. 2) that form an electricity production to utilisation value chain:

- Generation: this sector includes all the power plants necessary to produce the energy necessary to supply the sum of load and system losses. The power plants can be divided into two categories: dispatchable and non-dispatchable. The term dispatchable indicates all the controllable generators (i.e., with fossil, hydro and nuclear primary sources), while the term non-dispatchable indicates all the plants with non-controllable generators, including RES-based plants. The presence of a larger and larger share of non-dispatchable units is making the operation of the entire system more complicated [14], for a number of reasons, including a lack of controllability, the possible ownership by different entities with non-coordinated operation plans, a larger uncertainty in the outputs provided by these units (especially due to the uncertainty of the ambient variables in RES-based units), and exacerbation of the dynamic issues in the case of large disturbances due to the lower inertia of units with converter-based interface with the network.
- Transmission system: this is composed of High Voltage (HV) lines and represents the backbone of the entire electrical system. It guarantees the transfer of electricity over long distances. It is operated through a meshed structure to allow a high security level in the case of faults, with the possibility of excluding the faulted component and redistributing the power flows in the systems,

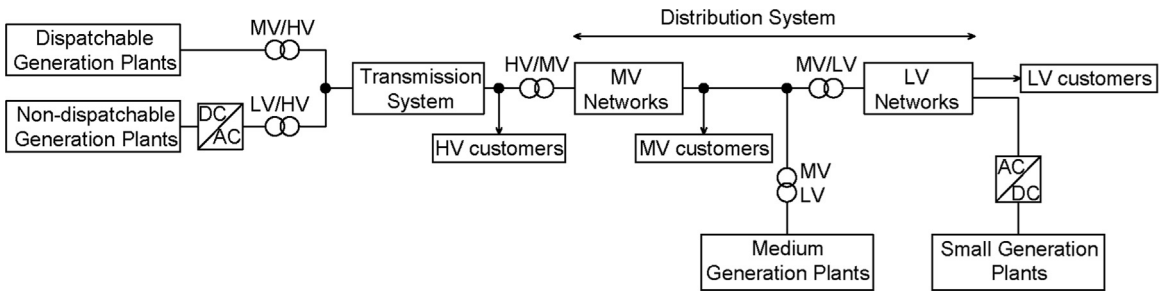


Fig. 2. The four typical sectors that make up the electricity value chain.

without service interruptions as a result of faults in individual components or faults in multiple components.

- Distribution system: this includes both Medium Voltage (MV) lines and Low Voltage (LV) lines, and it represents the portion of the network that falls between the transmission system and the loads. The MV distribution system normally has a weakly meshed structure and is operated with radial configurations to simplify the operation of the protection systems. The LV distribution system generally has a radial structure.
- Customer side: this represents all the loads that the electrical system has to supply. A distinction can be made between the different types of loads on the basis of the voltage level, the nominal power, the type of customers (e.g., residential, industrial, commercial), the shape of the load pattern, which indicates the evolution of the active power and reactive power over time, contract information, and so on. In general, the loads may be connected at the HV, MV and LV levels. The customers interact with the retailer to purchase the electricity supply and services.

In the past, in most countries, a single company owned and managed the entire value chain, or the largest part of it, in a so-called vertically integrated system. The unbundling of the electricity sector, which has been occurring in many countries since the end of the last century, has changed the previous situation completely and produced more than one actor along the value chain [15]. The existing generation companies were split up and had to become competitive with each other and with other new companies on the electricity market. However, the transmission system remained one single entity in each country, and it was managed by the transmission system operator, due to its meshed nature and interconnection at a transnational level. Moreover, specific transnational organisations were created to coordinate the operation procedures of the transmission system. The distribution system was partitioned into territorial areas, and each area was assigned to a single distribution system operator. Furthermore, electricity became a commodity, and more retailers were allowed to compete on an open retail market. The presence of markets increased competition among the players, with the goal of reducing the electricity price. In the current situation, different implementations of the electricity markets are in place in various jurisdictions. In the most advanced implementations, electricity can be traded on the *day-ahead market*, or on *intraday* markets, depending on the time frame between the transaction and the physical delivery of the electricity [16].

In this framework, the presence of smart metering and the collection of information are becoming crucial. From the technical point of view, the availability of more information guarantees better knowledge about the operation of the system, and this in turn makes it possible to better assess the correct deployment of the resources and infrastructures, and to check the security of the system and the provision of electricity with an adequate quality level. From the business point of view, the availability of more specific information on the customers' electricity usage is crucial to run the electricity markets, and to trade and market the retailers' activities with the customers [17,18].

However, the evolution of the electrical system is still ongoing. In fact, the future electrical system could be based on the *supergrid* paradigm [19], with a massive expansion of the transmission system, which could be attained in particular by building long High Voltage Direct Current (HVDC) lines to link distant regions. Conversely, another possibility is to have an electrical system composed of several *micro grids* [20] to serve autonomous communities in which the existing infrastructure would only be used as a back-up. The P2G technology, as a result of its scalability, could be used in both scenarios.

On the basis of what has been illustrated above, this paper presents a survey of the electrical aspects involved in the deployment of the P2G technology, and provides an overview of the applications reported in the literature. Furthermore, this paper indicates new proposals for the use of the P2G technology in electrical systems. The aim is the creation of a single vision that merges different aspects related to the connection and potential impact of P2G on electricity systems. This vision could help to unify the competences of operators working in different fields, in order to enable them to better understand the links between P2G and electrical applications.

Although the term P2G can indicate different processes, and consequently different final products (e.g., hydrogen [21,22], SNG [23,24], methanol [25], and so on), the production of SNG, which is also called methanation, is considered in particular in this paper. Furthermore, some applications that only involve H_2 are reported, and the possibility of upgrading these applications with a methanation plant, in order to produce SNG, is pointed out.

The next sections of this paper are organised as follows. Section 2 contains an overview of the P2G technologies and presents a general scheme and the characteristics of electrolysers, CO_2 production, and H_2 compression and storage. Section 3 reviews the applications illustrated in the literature and identifies new prospects for the incorporation of P2G in the typical sectors that make up the electrical system value chain (i.e., generation, transmission, distribution and utilisation). The last section contains the concluding remarks.

2. Technological overview: electrolysers, CO_2 production, H_2 compression and storage

In order to operate normally, a P2G unit needs a certain amount of power, which is taken from the electrical system to which it is connected. Thanks to the controllability of the electrolyser, P2G can reduce power to a minimum in order to participate actively in the operation of a system.

This section describes the devices of P2G plants that have a direct impact on the operation of an electrical network. The three parts of the P2G plant (i.e., electrolyser, CO_2 production, and H_2 compression and storage) are described in order to highlight their main aspects concerning power and energy, as well as their operational limits.

2.1. Scheme of the P2G plant

Let us consider a typical plant (exemplified in Fig. 3), characterised by at least four components [26]:

- An electrolyser, which allows H_2 to be produced;
- A methanation process device;
- A source of CO_2, which is necessary for the methanation step;
- Storage facilities, to allow the H_2, CH_4 and CO_2 to be stored safely and buffered.

From the same figure, it is possible to list both the inputs, (i.e., electricity, water and CO_2) and the outputs (i.e., SNG, O_2 and heat).

A further input is the work required to supply the auxiliary services, that is, the energy necessary for pumping the water, for pressurising H_2 and so on (only the CH_4 treatments are represented in the figure).

From the chemical point of view, methanation can be performed using either CO or CO_2 [27].

The production of SNG from CO_2 (shown in Eq. (1)) is a linear combination of two reactions, which are shown in Eq. (2) and Eq. (3), respectively [8,28], that lead to the release of the enthalpy $\Delta H°$:

$$CO_{2(g)} + 4H_{2(g)} \rightleftarrows CH_{4(g)} + 2H_20_{(g)} \quad \text{with} \quad \Delta H°_{@298\,K} = -165 \quad [\text{kJ/mol}] \tag{1}$$

$$H_{2(g)} + CO_{2(g)} \quad \rightleftarrows \quad CO_{(g)} + H_20_{(g)} \text{ with } \Delta H°_{@298\,K} = 41 \quad [\text{kJ/mol}] \tag{2}$$

$$CO_{(g)} + 3H_{2(g)} \rightleftarrows CH_{4(g)} + H_20_{(g)} \text{ with } \quad \Delta H°_{@298\,K} = -206 \quad [\text{kJ/mol}] \tag{3}$$

The reaction shown in Eq. (3) represents the process necessary to obtain SNG directly from CO, if a source of CO exists.

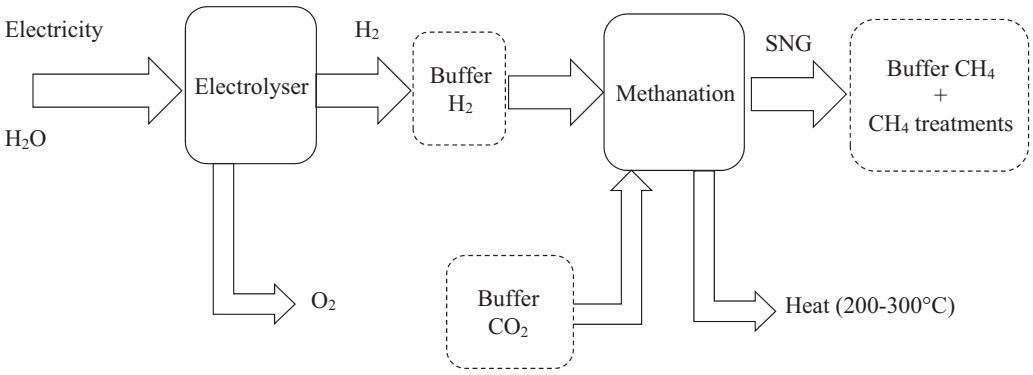


Fig. 3. Scheme of a typical P2G installation.

As can be noted from the sign of the reactions, Eq. (2) is endothermic, whereas Eq. (3) is exothermic.

The temperatures that facilitate the two reactions are different [28], and for this reason the process is composed of multiple stages (typical ranges fall within the 250 °C ÷ 400 °C range, with a pressure of 1 ÷ 80 bar [29]). A professional software package (such as ChemCad 6.3®) is needed to obtain an accurate design of the methanation process: an example of an integrated design that can be adopted to investigate the feasibility and the convenience of installing a P2G plant can be found in [30].

Three parts of the plant that have an impact on the electrical system (i.e., electrolyser, CO_2 production, and H_2 compression/storage) are presented briefly in the next sections.

2.2. Electrolysers

The electrolyser allows hydrogen to be produced by means of the dissociation of H_2O. From the chemical point of view, the endothermic reaction is:

$$H_20_{(l)} + energy \rightleftarrows H_{2(g)} + \frac{1}{2}O_2 \quad (4)$$

The consumption of energy for the reaction depends on the technology that is used, and it varies with the temperature and the pressure of the process [31].

In an ideal electrolyser, the production of hydrogen is proportional to the current that flows in the device (Faraday's law): for this reason, a high current density would be preferred, so that high current values could be reached for small cell surfaces.

An important parameter is the efficiency, which is defined as the ratio between the energy content of the produced hydrogen and the energy used to produce it. This calculation may be carried out by considering either the higher heating value $HHV_{H_2} = 3.54$ kWh/Nm^3, or the lower heating value $LHV_{H_2} = 3$ kWh/Nm^3, depending on the potential successive energy use of the produced hydrogen [32]. For the sake of clarity, and to avoid any confusion related to the heating value used to calculate the efficiency, manufacturers usually indicate the specific energy consumption (expressed in kWh/Nm^3).

Three main technologies can be used for a P2G plant:

- Alkaline electrolysers;
- Proton Exchange Membrane, or Polymer Electrolyte Membrane (PEM) electrolysers;
- Solid Oxide Electrolysis (SOEC).

The latter technology is still not at a mature stage. Therefore, only the first two technologies are described in the following sections. An overview of their characteristics is given in Table 1.

From the simulation modelling point of view, some models were suggested both in the early 2000s (such as in [33]) and more recently (such as in [34,35]). The mathematical models that describe the operation of the electrolyser can be focused on different aspects of the electrolysis, for example, the response of the electrolysis cells or stacks (addressed by means of electrochemical models), the electrical behaviour of the components that form the electrolysis system (described by the electrical model), or other aspects, such as the thermal behaviour or mass transfer. An exhaustive description of the models that exist in the literature regarding alkaline and PEM technologies can be found in [36].

2.2.1. Alkaline electrolysers

Alkaline electrolysers are the oldest and most well-known technology and they have been available for industrial purposes for many years. They are characterised by the use of aqueous alkaline solutions, which are extremely corrosive.

Some of the characteristics pertaining to alkaline electrolysers in the available literature (such as [23,31]) are listed in Table 1.

The different sizes of alkaline electrolysers cover a wide range of power (from tens of kW to a few MW) and they are characterised by different plant layouts [31].

However, some drawbacks still have to be overcome [21,23] concerning:

- The minimum load. It is not possible to operate the electrolyser over the 0 ÷ 100% P_n range: the minimum load usually falls within the 10 ÷ 40% P_n range [37], even though a case with 5% P_n is reported in [38]. This means that if the input is lower than these limits, the electrolyser has to be switched off.
- Transient operation is possible with this technology, but some problems can arise: in fact, the typical response time is seconds or minutes, but according to [37], these are not physical limits, but only design limits that depend on the absence of a fast response by the customers.
- The relatively long cold start time (10 min to h), which mainly depends on the purity of the gas [37].
- The long restarting time after shutdown. This is an important drawback, because the electrolyser takes 30–60 min before it can be switched on again (due to purging operations with nitrogen) [38].

The system costs about 1000 €/kW [32], whereas the entire system has a lifetime of 15 ÷ 30 years [23,31,39].[1] The cell temperature falls within the 65 ÷ 100 °C range [23]

As final remark, it should be noted that the purity of the hydrogen production lies within the 99.8 ÷ 99.9% range and on occasion can even reach 99.999% with an additional purification system [31].

[1] It is important to note that both [23,39] referred to the same study (in German) for their indications. The study has been listed in the reference as [40].

Table 1
Summary of the characteristics of the available electrolysers*.

type	rated power [MW]	rated production [Nm^3/h][a]	energy consumption [kWh/Nm^3]	efficiency [%][c]	cold start time	deployment time (from stand-by)	operating pressure [bar]	operating temperature [°C]	cost [mu/kW][d]	hydrogen purity [%]
alkaline	< 0.055	0.4 ÷ 10	7.5 ÷ 5.4	47.2 ÷ 65.5	min to h	s to min	1 ÷ 30	65 ÷ 100	≈ 1000	99.5 ÷ 99.9
	0.055 ÷ 0.25	10 ÷ 43	5.4 ÷ 5	65.5 ÷ 70.8						
	0.25 ÷ 0.50	43 ÷ 100	5 ÷ 4.87	70.8 ÷ 72.7						
	0.50 ÷ 1.5	100 ÷ 330	4.87 ÷ 4.3[b]	72.7 ÷ 82.3						
	1.5 ÷ 3.5	330 ÷ 760	≈ 4.3[b]	≈ 82.3						
PEM	< 0.012	0.53 ÷ 1.05	6.7	52	min	s	10 ÷ 30	20 ÷ 100	> 2000	> 99.99
	0.022 ÷ 0.070	2 ÷ 6	7.3 ÷ 6.8	48.5 ÷ 52.1						
	0.1 ÷ 0.275	10 ÷ 30	6.2 ÷ 5.8	57.1 ÷ 61.1						
	1 ÷ 2	200 ÷ 400	not available	not available						

[a] 1 Nm^3/h = 0.0899 kg/h.
[b] These two values only refer to the electrolysis system.
[c] The efficiency is mainly obtained from [31]; for PEM, it has been calculated as the ratio between HHV_{H_2} = 3.54 kWh/Nm^3 and the energy consumption.
[d] The cost has been expressed in mu/kW because some references use €/kW, while others use $/kW. The reported cost should be considered as indicative.
* References: Alkaline: [23,31,32,37–39]. PEM: [21,31,39,43,44].

Table 2
Cost and energy consumption for CO_2 capturing.

Source	Cost [€/t_{CO_2}]	Energy consumption [kWh/t_{CO_2}]	Reference
CC	20–60	100–350	[8,50,55]
biomass	35–80	–	[8]
industrial processes	45–150	–	[51]
air	1000	3000–5000	[8,41]

2.2.2. PEM electrolysers

The PEM technology for water electrolysers was developed in 1966 by General Electric, and was then put on the market in 1978 [8,31]. It is based on the use of a polymer membrane as an electrolyte [8], and because of the acidic regime provided by the proton exchange membrane, noble materials (basically platinum group metals) have been successfully adopted as catalysts [39]. This aspect is a drawback as far as the cost is concerned, because it has been estimated to be at least double (> 2000 €/kW) that of the alkaline technology [37,41]. However, the better exploitation that can be achieved with noble materials (usually platinum-group metals), could lead to a cost reduction [32,39]. Moreover, the development of a technology based on rare materials can lead to material availability constraints, and alternative materials, such as nickel, could be valid substitutes [42].

The operating temperature lies within the 20 ÷ 100 °C range [23].

PEM electrolysers allow a high-pure hydrogen (> 99.99%) to be produced, without the need for any further purification equipment [31]; this can be confirmed from the data available on the manufacturers' websites (such as [43,44]), where a higher purity level than 99.998% is indicated.

Furthermore, dedicated solutions for storing the electricity produced by RES [43] allow up to 450 Nm^3/h of hydrogen, delivered at 30 bar: this means that the PEM technology is gradually becoming comparable with the alkaline technology. Furthermore, PEM electrolysers can be completely ramped up and down in just a few seconds and they can work in the 0 ÷ 100% range; moreover, a cold start can be completed in just minutes [43].

As a final remark, it is important to point out that the lifetime of a system based on the PEM technology is shorter than that of a system based on alkaline technology and falls within the 5 ÷ 20 year range [21,39].

2.3. CO_2 production

One of the positive aspects of SNG production is the possibility of using CO_2, and hence of delaying its release into the atmosphere [45].

However, the purity of the CO_2 affects the quality of the produced SNG and strict parameters have to be verified (e.g., minimum value of the Wobbe Index [46,47]) before it can be integrated in an existing gas network.

The main CO_2 sources are [8,48]:

- CO_2 from Carbon Capture (CC);
- CO_2 from biomass, obtained by means of fermentation, gasification and combustion;
- CO_2 from industrial processes, obtained as a by-product;
- CO_2 from air.

Table 2 reports the energy expense, the cost and the production process used to capture CO_2 from the different sources.

Three different methods can be applied to capture CO_2 in power plants [49]:

- Post-combustion, where the CO_2 is extracted from the gas produced by combustion;
- Pre-combustion, where the fuel is pre-treated before being fired;
- Oxyfuel combustion, where combustion is performed with pure oxygen instead of air.

In the case of existing plants, the best option for implementing CC is post-combustion. The main technologies used to implement post-combustion are [50,51]:

- Chemical absorption;
- Physical absorption;
- Adsorption;
- Gas particle reactions;
- Membrane separation;
- Cryogenic separation.

The best performing technology for gas-fired power plants is the amine-based capture system [51], which is a chemical absorption system.

The exploitation of a post-combustion technology implies knowledge of the CO_2 content of the gases, as well as the partial pressure of CO_2. Both aspects are in fact important for CO_2 extraction; data related

Table 3
Content of CO_2 for gas-fired plant emissions.

Gas from	CO_2 emissions [kg/MWh_e]	%volume CO_2	Partial pressure CO_2 [MPa]
CCGT	340 ÷ 400	3 ÷ 4	0.003 ÷ 0.004
OCGT	480 ÷ 575		

to CCGT and OCGT are reported in Table 3 [52,53].

The implementation of any CC technology implies an increase in fuel consumption, due to the request for more energy to supply the system. According to the indications in the literature, the additional consumption, due to the use of a CC system, is expressed either in terms of primary energy (2.9 ÷ 4 MJ/kg_{CO_2} for post-combustion) [48,54], or in terms of additional produced electricity (0.308 − 0.354 kWh/kg_{CO_2}) [50,55]. Other estimations indicate 0.100 − 0.240 kWh/kg_{CO_2} [8].

The nominal efficiency of the system (in terms of amount of captured CO_2 over the processed CO_2 flow) lies within the 85–90% range [51].

2.4. H_2 compression and storage

Information regarding H_2 compression and storage is given in [37]. The energy expense of passing from atmospheric pressure to 200 bar (the pressure of the tank considered in the study) is 3.6 kWh/kg_{H_2}, whereas the energy expense is 1.3 kWh/Nm^3 when a suction pressure of 1 bar and a discharge pressure of the compressor of 8 bar are assumed for injection into the gas network.

The calculation of the capital cost for storage leads to about 900 €/kg_{H_2}, which means 24 €/kWh_{H_2} stored.

3. P2G in the electrical sector

This section has the aim of showing how P2G facilities can be used correctly in the current and future electrical systems. An overview of P2G applications to the generation, transmission, distribution and utilisation of electricity is reported, by synthesising the current solutions and discussing a number of perspective applications. This aim of this kind of discussion is to illustrate the current and future exploitation situations of the P2G technology in a context in which the practical applications involving the electrical system are still at an early stage of development.

3.1. Electricity generation

Fig. 4 provides a categorisation of P2G applications to the electricity generation side. The first distinction is between dispatchable and non-dispatchable units, as indicated in the Introduction. In both cases, the common goal is to allow for a more efficient use of the plants, from both the technical and the economic points of view. The use of P2G for dispatchable units can in fact provide:

- More flexibility, because of the increase in the energy-shifting possibilities from electricity to gas and vice versa [56]. This is helpful for the system when variations in the electrical power injected into or drawn from the electrical network are needed for control purposes or to provide reserve services to the system.
- Arbitrage opportunity, considering the economic terms associated with the provision of services through a system that may be supplied either by fuel or power [57].
- CO_2 emission reduction, which also leads to the possibility of participating in energy-related markets [58] based on greenhouse gas emission allowance trading [59].

On the other hand, two different types of applications exist for non-dispatchable units:

1. Reduction in renewable energy curtailment, with the possibility of accessing RES support schemes [60].
2. Introduction of an integrated energy system, based on renewable energy.

Both the state of the art and new proposals are reported below for each point.

3.1.1. Dispatchable units

The exploitation of P2G, together with dispatchable units, has been treated in the literature by investigating a number of different applications.

In [61], the Authors presented the possibility of integrating the P2G technology with existing nuclear power plants, so that the production profile from nuclear power plants could be kept as flat as possible.

The economic feasibility of a biomass-fired CHP integrated with

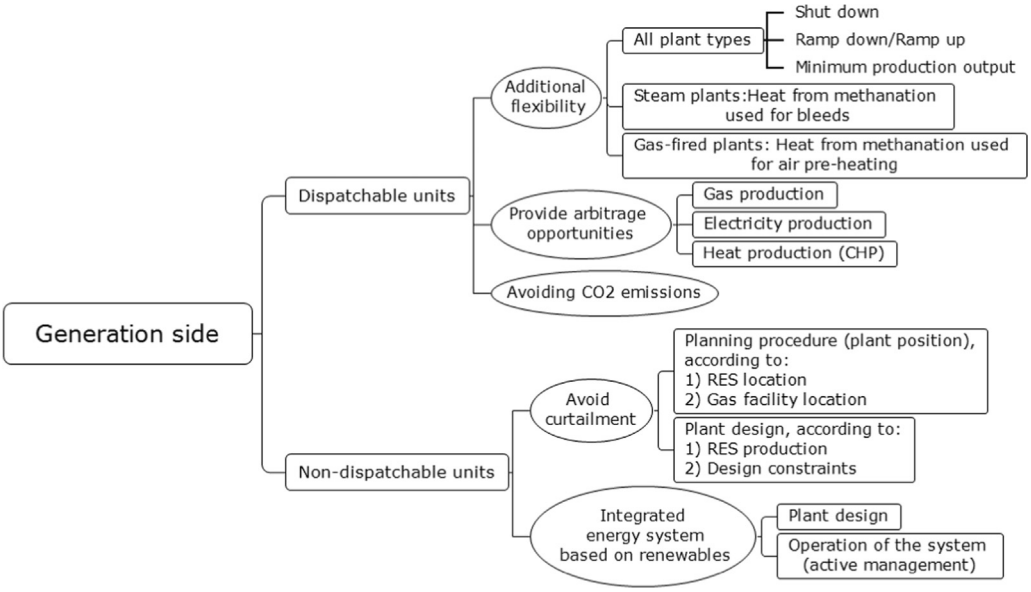


Fig. 4. P2G applications to the generation side.

P2G is reported in [62]: the biomass plant size is about 300 MW_{fuel}, and some aspects of the CH_4 plant (such as a methanation plant, CO_2 production, and so on) are modelled in a simplified way. In this case, the production of oxygen is also considered. A novel P2G-biomass oxyfuel hybrid system has been presented in [63].

Two SNG plants, integrated with CC technology, have been compared in [64] by focusing on the design of the process part.

A potential new application is the use of P2G facilities, together with a CHP plant, to reduce the mismatch between the actual production of the power plant and the scheduled production (the latter is obtained from the trading performed on the Day-Ahead market).

3.1.2. Non-dispatchable units

Most of the renewable energy-based plants (except for hydroelectric ones) are non-dispatchable, as their production is not directly controllable by the system operator [65,66]. One of the goals that has emerged in recent years is the reduction of the curtailment of renewable energy [1] using different storage technologies [67,68]. In [69], an energy and economic evaluation has been performed to improve the dispatchability of wind turbines. In this case, the P2G facility has the purpose of producing hydrogen instead of methane, and the entire facility is coupled to a gas turbine, but the case study could also be extended to a methanation facility.

The elimination of the curtailment of renewable energy becomes more important when the system under analysis is an island. An analysis of the Irish case has been presented in [70]. The results show that the installation of a P2G facility could reduce the total energy curtailment on the island. In this case, the CO_2 source considered the most suitable is that of a biogas plant. A study dealing with the use of P2G to produce methane in the Spanish framework has been presented in [71]: a design of the process part has been proposed together with an economic assessment that has considered the costs of electricity and the purchase of gas.

A new application with RES should consider not only the energy balance (i.e., with a defined amount of potentially curtailed energy, it would be possible to supply a number of P2G plants), but also the existing constraints (gas network structure and operational limits, the presence of CO_2 sources, and so on). Furthermore, the model of a P2G facility should be as close as possible to that of a real plant, and should also consider the different dynamics of the components.

3.2. Electricity transmission

Fig. 5 provides a categorisation of P2G applications to the electricity transmission side, which distinguishes between ancillary services, storage and RES integration, and system management.

3.2.1. Ancillary services (filtering RES production)

The electrical response of P2G plants is essentially provided by the response of an electrolyser. For this reason, the possibility of providing ancillary services is connected directly to the performance of the electrolyser. Thus, in this case, the production of SNG is has no influence.

For this reason, few of the papers in the literature do consider ancillary services as possible applications of P2G (for the production of methane).

In [6], grid ancillary services are listed with respect to their duration, i.e., very short (from milliseconds to 5 min), short (5 min to 1 h), intermediate (1 h to 3 days) and long (seasonal). The characteristics of hydrogen production can be useful to substitute traditional power plants for the spinning reserve, or as a source for a black start (both with a short duration). Other applications for which hydrogen production is suitable are classified as intermediate services:

- load following (i.e., a continuous service provided to match loading and generation [72]);
- load levelling (which allows a load to be as uniform as possible [72]);
- unit commitment (to cover the mismatch between a forecasted renewable production and a real one, if this mismatch is due to completely different weather conditions over a period of several hours [73]).

However, according to [22], some cases show the capacity of P2G to provide voltage and frequency regulation. From the literature review, it has emerged that only recent contributions [74] have reported response times that are compatible with the frequency response (800 ms to turn on and 140 ms to turn off), which indicates the potential of P2G as a RES production filter.

3.2.2. Bulk energy storage and RES integration

Different contributions in the literature suggest using P2G for energy storage and to integrate RES, in order to improve the flexibility of the system (for a review about flexibility see [7]).

For example, [6] indicated P2G and Pumped Hydroelectric Energy Storage (PHES) as the most suitable solutions for seasonal storage, whereas [75] investigated both P2G and power-to-liquid as options for a better integration of RES in the German electrical system (even though some simplifications and some future technologies were considered in the study). In [76], P2G was considered one of the key factors to reach a 100% renewable energy-based system in North-East Asia.

An economic analysis (based on the revenue of a storage plant, and not on the overall efficiency of the system) was suggested in [77] for load-levelling operations. From the remuneration point of view, the P2G technology is currently only suitable for seasonal storage, whereas other technologies (such as pump hydro plants) are more suitable for daily load levelling.

Large-scale storage facilities were studied in [78] to reduce the overall cost of an electrical system, and P2G resulted to be the third most suitable choice, after PHES and Compressed Air Energy Storage (CAES).

A comprehensive model of the German energy sector has been proposed in [79], in which the P2G technology was considered one of the conversion components necessary to properly manage different sectors together (i.e., electricity and heat). An analysis performed from the photovoltaic (PV) plant point of view, with the use of hybrid storage, has been presented in [80]. The study points out the necessity of

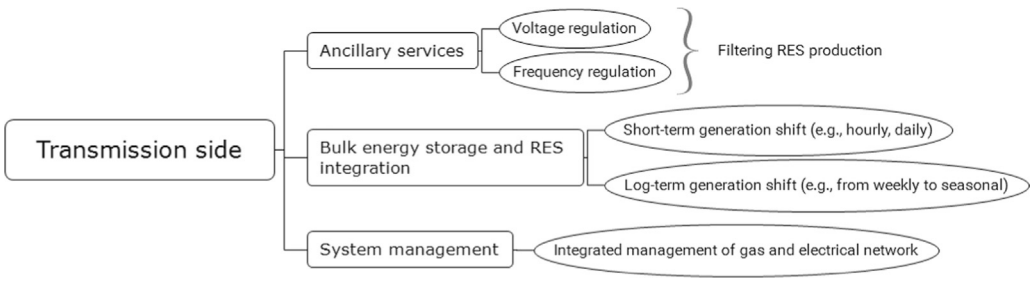


Fig. 5. P2G applications to the electricity transmission side.

carrying out a detailed analysis to ensure the profitability of the installed storage, shows a negative economic profitability for the case study (due the high capital cost of the electrolyser) and provides a sensitivity analysis to help recognise the conditions that would make the design profitable.

A geographically bounded modelling framework (i.e., the Baltic region) aimed at balancing a power grid in the presence of a large wind power with hybrid storage (based in part on P2G) has been presented in [81]. The results show that the methanation of the biogas in the region would require an enhanced wind production to achieve an important reduction in both fossil fuel and electricity.

Another geographically bounded study, limited to the German region of Baden-Württemberg, is presented in [82]. The study presents the potential of P2G in that region, considering residual loads of grids operated at 110 kV for the different municipalities, as a result of an increase in RES production in the region. The paper highlights how the current limits on hydrogen injection into the gas network lead to considering the production of SNG as a suitable solution. Nevertheless, it is recognised that the study is limited by uncertainties, such as an increase in RES, and the obtained results should only be considered as an indication of the upper bound of the actual potential.

The installation of P2G facilities can change the dispatch of generation units. The operation of P2G facilities (of different sizes and on different sites) installed in a simplified version of the Danish transmission system has been studied in [83]. The results indicate that the use of P2G leads to a reduction in wind curtailment, as well as a reduction in the network congestion time.[2] It should be pointed out that no connections with neighbouring countries, whose presence could reduce the benefit in the installation of P2G facilities, were considered.

The results reported in [85] for an 85%-renewable German electrical system show that P2G facilities can successfully integrate the excess of feed-in power produced by renewable sources in the system, as it allows to pass from 70 TWh/year to 30 TWh/year.

3.2.3. Integrated management of electrical and gas networks

The two main infrastructures in developed countries are the transmission system and the gas network: their joint analysis [86], considering interactions between different countries, could open up new perspectives, for example from the *resilience*[3] point of view [87].

The interactions between gas and transmission grids pertaining to the price of electricity and gas, due to transfer limits, are shown in [89]. The model allows both the electricity production cost and the gas cost to be optimised, when both vectors (i.e., gas and electricity) have to satisfy a given load level.

An integrated model that can be used to assess the impact of P2G on electrical and gas transmission networks has been suggested in [90]: the paper considers large P2G facilities (i.e., 1 GW) that produce both hydrogen and SNG. The most tangible effect is the alleviation of gas network congestions. The presence of storage facilities has been considered in [91], where the impact of the production of SNG on the cost of natural gas (due to a reduction in the gas demand) has been modelled. A model that considers gas and electrical systems, together with a carbon dioxide-related sector, has been proposed in [92]. The study shows that the presence of P2G links all the above sectors, and that the prices of gas and electricity can be modified when P2G is the marginal unit.[4] The probabilistic approach proposed in [93] investigates the available transfer capability of transmission lines, taking into account the security constraints of a gas network, and highlights the potential security threat that results from forced outages in the electrical system, due to an interruption of the gas supplied to gas-fired plants.

A unified approach to the steady state analysis of a system containing a gas network and an electrical network with bidirectional converters (i.e., P2G and gas-fired power plants) has been presented in [94]. Neither system had large dimensions (i.e., an IEEE 9-node electric network and a 7-node natural gas network). The tests showed that the presence of both P2G and gas-fired units reduces electrical power losses and improves the characteristics of the gas network (for example, reducing the consumption for gas compression).

A multi-linear approach to solving an integrated electrical and gas system is presented in [95]. In this case, the networks are larger (i.e., an IEEE 39-node electrical grid [96] and an NGS 48-node gas network [97]). The approach is based on Monte Carlo simulations, and it models variations in the energy demand as correlated Normal distributions, whereas the uncertainties in the wind speed are represented by the Weibull distribution with a known correlation matrix. The results show that the simple linearisation of gas flow equations can lead to some concerns, while the multilinear formulation allows these issues to be overcome.

The assessment of the security of the supply in a coupled gas/electricity system has been addressed in [98]: the authors implemented a tool that combines a transient hydraulic model of the gas network with a full AC model of the transmission system. The equations are solved simultaneously to capture the effects of different control strategies on the two interconnected systems.

The short-term economic dispatch of the integrated gas and electricity system is shown in [99]: the problem is solved by means of a bi-level optimisation, where the upper-level problem is the economic dispatch to the electricity systems, whereas the lower-level problem refers to the optimal allocation of natural gas when more than one natural gas supplier exists. The security constraints of both the electricity and gas systems are considered.

A scheduling of electricity and gas systems has been proposed in [100]: the paper considers the possibility of the two infrastructures belonging to different owners and provides a methodology that is based on a limited exchange of private data.

An expansion planning of an integrated system has been considered in [101]: again, a bi-level programming has been used to minimise the sum of the investment and operational costs. The algorithm was applied to the Danish network and it considered bidirectional interactions resulting from the installation of P2G and gas-fired power plants.

3.2.4. Congestion management

In the case of large renewable power plants connected to an electrical network, the resulting high production could cause congestions of the lines [5]. In order to solve this problem and to avoid the curtailment of energy production, it is necessary to install storage systems close to the plant (as has happened in Italy, with batteries installed by the Italian TSO [102]). A cost evaluation of different storage options for the case of a high share of network congestions has been presented in [68]. The paper shows cases about both the transmission network and the distribution network, and considers different technologies (batteries, CAES, hydrogen and methane). The study (carried out from a grid perspective) shows that the use of storage technologies to only exploit the energy that can be curtailed is not convenient, due to the high investment costs and the low utilisation of the storage facilities.

3.2.5. Perspective applications

In this framework, the work should be concentrated on accurately modelling the bulk system at different scales (regional, country, European), together with a realistic model of the P2G facility (both the size and the dynamics), taking into account the constraints due to the availability of the gas network and of the CO_2 sources. Another field that may be investigated is the development of hybrid storage systems [103] that are capable of integrating short and long storage devices in

[2] The term *congestion* pertaining to an electrical line indicates that the current flowing in the line has exceeded its physical or operational limits [84].

[3] The term *resilience* indicates the capacity of a system to "withstand a major disruption within acceptable degradation parameters and to recover within an acceptable time and composite costs and risks" [88].

[4] The *marginal unit* is the most expensive generator in operation adopted to satisfy the load demand [16].

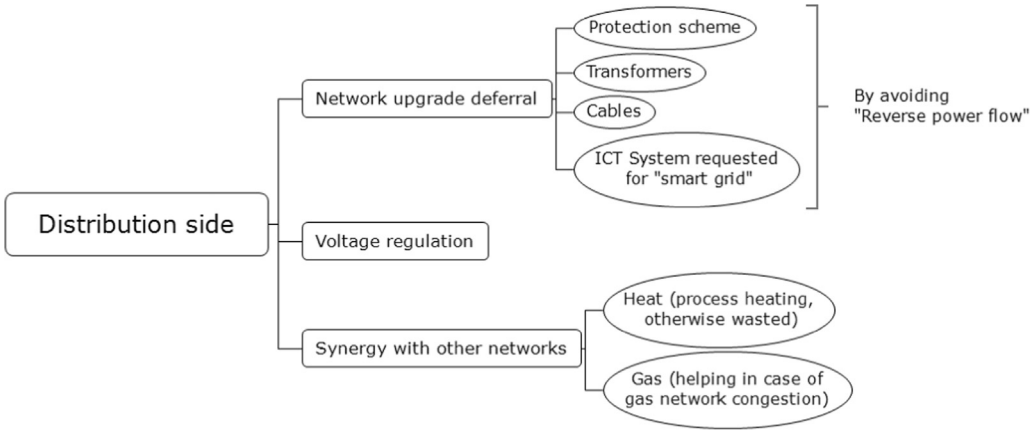


Fig. 6. P2G applications to the electricity distribution side.

order to offer the service at a different time scale.

3.3. Electricity distribution and utilisation

3.3.1. Introduction of P2G facilities

In the past, distribution systems were passive networks, because they only provided energy to the customers, and only received active power from a single supply point (while the reactive power was already supplied from both a main supply point and from local power factor compensation devices).

On the other hand, most renewable energy-based plants are now connected to a distribution system. This is changing the way distribution systems are operating, as they are becoming *active networks* that receive multiple active power inputs from local generation and other distributed energy resources (storage and demand response) [104].

The feasibility of the implementation of several P2G facilities in a German region, where there is high solar energy penetration, has been investigated in [105]. By considering the load profiles and the expected capability over the 2015–2025 period, the analysis highlights that it could be feasible to absorb about 20% of the excessive solar energy by installing many P2G facilities throughout the region.

The results of a study on a distribution network with a large number of congestions, due to the installation of a large number of RES plants, are reported in [68]. The study considers a dataset that refers to congestions that occurred over several years in real networks. The congestions were divided into permanent and temporary, with the aim of finding the most suitable storage technology to avoid their occurrence. Again in this case (in the same way as for the transmission system), the recovered energy did not justify the investment cost. However, it was necessary to consider not only the cost, but also other implications, related to system security, considering, for example, a margin that would ensure operation of the system in the case of large disturbances.

Till now, distribution systems have not been controlled as much as transmission systems, due to their different developments and designs. However, the approach to the operation of the system is changing, and is moving towards an active control of the network. An example of voltage control that takes into account On-Load Tap Changer (OLTC), renewable sources (i.e., wind and PV) and an alkaline electrolyser has been presented in [106], where a distributed coordination strategy has been developed to maintain the voltage within its operational range.

An example of optimisation, based on an economic objective function, where the sum of different objectives has been considered to plan P2G facilities with both MV and HV lines, has been reported in [107]. The optimal sizing and siting of P2G facilities in a distribution network has been shown in [108], where the objective function is a combination between network losses and the number of installed P2G facilities. In this case, the P2G facility is composed of an alkaline electrolyser, which was previously modelled in [109].

An application, aimed at the optimal management of an LV distribution, a gas network and heat systems, has been reported in [110]. The paper proposes an energy management system, based on nonlinear model predictive control, which has the aim of minimising the power that flows through MV/LV transformers, with a consequent decrease in the amount of electricity supplied by the MV network.

As far as the utilisation side is concerned, several applications refer to the use of hydrogen at the consumption level [111]. The incorporation of P2G in a local energy system, connected to energy networks, generally contributes to extending the concept of electricity prosumer (that is, both a producer and a consumer of electricity with respect to the electrical network, over different time periods) to a more general global energy prosumer that operates multi-energy facilities in a coordinated way. This view is consistent with the energy hub approach [112], whose original formulation has been extended to incorporate P2G [113]. In the analysis presented in [114], P2G is included in an energy hub model, and its convenience as a storage option is compared with that of thermal energy storage for application at a district level. P2G emerges as the better solution to minimise greenhouse gas emissions, although it continues to be limited by the high economic cost, compared to thermal energy storage.

Nevertheless, no specific application exists regarding the use of methanation at the customer level. One of the main limitations of this application is the need to construct an infrastructure for H_2 storage and distribution to the methanation equipment in the utilisation system.

3.3.2. Perspective applications

A significant outcome for distribution systems could be updated deferral of the investments to extend their infrastructures, as shown in Fig. 6. In a large distribution network, where the reverse power flow[5] is somewhat continuous, the substitution of transformers, the upgrading of the protective schemes, and the introduction of infrastructures for communication between devices, all lead to increased costs. For this reason, it is possible to evaluate whether the construction of storage facilities (and in particular P2G) would alleviate the problem, by delaying the need for structural interventions to the network [116].

Conversely, if the aim is to move towards a “smart network”, a control could be implemented (as in [106]) to take into account the real evolution of the quantities (e.g., with the use of a real time controller and smart metering).

Another line of research exploits the synergy between different energy sectors (i.e., electricity, heat and gas [117]) in which P2G can

[5] The expression *reverse power flow* indicates that the active and reactive power flow from the load to the supply point of the feeder, due to the high production of RES and low load of the feeder [115].

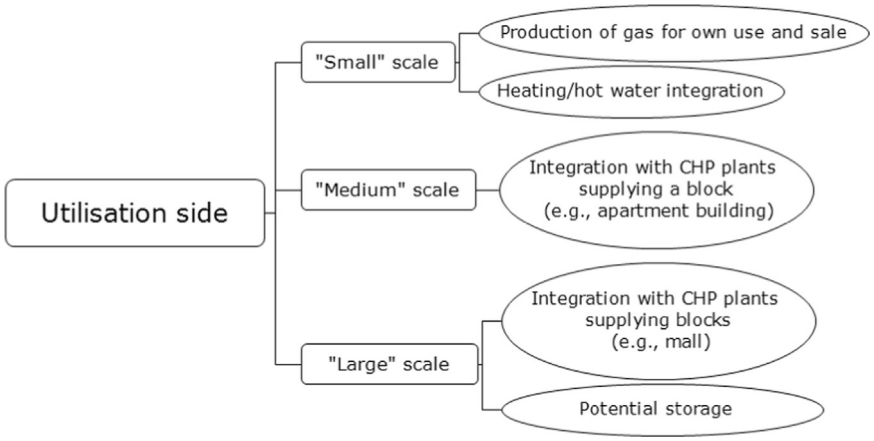


Fig. 7. P2G applications to the electricity utilisation side.

play a main role as the coupling facility. In the same way as for the transmission system shown in Section 3.2.3, the coupling of different systems can lead to improvements in both the gas network and the electrical network. Considering the voltage level of the distribution network, bidirectional conversion can be guaranteed by using a small sized gas turbine, together with small-scale P2G facilities.

As far as utilisation is concerned, the suggestions reported in Fig. 7 could be investigated. Applications at the customer side can be divided by considering the size (small, medium, and large – although the numerical ranges associated with these dimensions have not been defined in the literature). The initial hypothesis for all the considered cases is the existence of an oversized renewable energy-based plant, whose energy can be recovered by aP2G facility.

In general, the following indications about the size can be introduced:

- *Small* size refers, for example, to semi-detached houses that share private facilities (such as a courtyard, the heating system, and so on). In this case, one application could be the production of gas for their own use and sale, with heating and hot water integration (due to the heat lost by the methanation plant).
- *Medium* size indicates a block of buildings (e.g., an apartment building), with the possibility of installing a small CHP, which could be coupled to a P2G system.
- *Large* size refers to the case of large-scale applications, such as a shopping centres or industrial sites; another application is the production of car fuel, which can either be sold or used to supply company cars.

If electricity has to be bought on the market, the convenience of P2G has to be evaluated carefully in order to avoid the case in which the profit is not enough to cover the investment costs, due to the limited spread between the cost of electricity and the cost of gas [113].

4. Concluding remarks

This paper has provided a conceptual framework that can be used to help understand the role and potential of deploying P2G applications for the generation, transmission and distribution of electricity, and for the utilisation sector.

One of the most promising applications refers to the integrated management and optimal operation of gas and electricity transmission infrastructures. P2G has recently gained the attention of many institutions, due to its potential role in guaranteeing the long-term storage of electricity produced by RES-based plants. P2G can filter the RES production and assist in the optimal operation of the electrical system. For this purpose, the combined exploitation of electricity and gas infrastructures could alleviate constraints on the usage of the energy networks, and make it possible to deploy more electricity when the gas network is close to its constraints, and vice versa. In this way, P2G is used as a multi-energy storage system, and synergy among the different energy vectors is improved. However, a detailed comparison with other available storage technologies is necessary. This comparison should not be based only on the total costs necessary to provide the electricity storage service; in this case, P2G would not be competitive with other storage technologies, such as electrochemical batteries. In fact, a reliable comparison also has to take into account the possible benefits P2G could provide to other system services, such as energy-shifting possibilities from electricity to gas and vice versa, arbitrage opportunities for systems that can be supplied with different energy vectors, and the usage of the methane produced in a gas network.

Similar benefits appear at the electricity distribution level. In the case of an excess of RES, the use of the P2G technology can defer investments on expanding/reinforcing the infrastructure of the distribution system. The introduction of P2G also implies an active role for the distribution system operator. In practice, the distribution system operator could become both the owner and the manager of a grid-connected P2G system, or could procure network services from P2G systems owned by other entities.

From the utilisation point of view, the exploitation of P2G to produce SNG is still under study. The potential applications can range from home customers to large customers such as shopping centres, food industries, and chemical/process industries.

From the environmental point of view, the deployment of the P2G technology in any application allows the release of CO_2 into the environment to be deferred. This is important to avoid the impact of further ambient temperature increases on global warming. Moreover, the diffusion of P2G could lead to an improvement in the carbon capture technology, by reducing both the overall costs and the energy demand for carbon capture applications.

At the moment, the P2G technology is still rather costly. However, significant enhancements can be expected to take place as a result of the development of modular components, which may be combined to obtain different sized P2G systems. The scaled production of all the components could lead to a significant cost reduction, thus making this technology competitive on the energy market. This could be achieved by following the current trend of producing distributed generation and resources at smaller and smaller sizes in order to reach larger groups of consumers. The progress being made is in line with the idea of enlarging the scope of electricity prosumers in order to create global prosumers that could handle multi-energy facilities in a coordinated way. Global prosumers will also have more opportunities on the energy markets, on energy-related markets based on greenhouse gas emission allowance trading, and from access to RES support schemes.

In short, P2G will probably become an important part of future energy systems. For this reason, the impact on electrical networks and the potential applications shown in this paper represent a step forward towards a more comprehensive understanding of the benefits and limitations of the P2G technology.

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