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An integrated techno-economic and life cycle environmental assessment of power-to-gas systems

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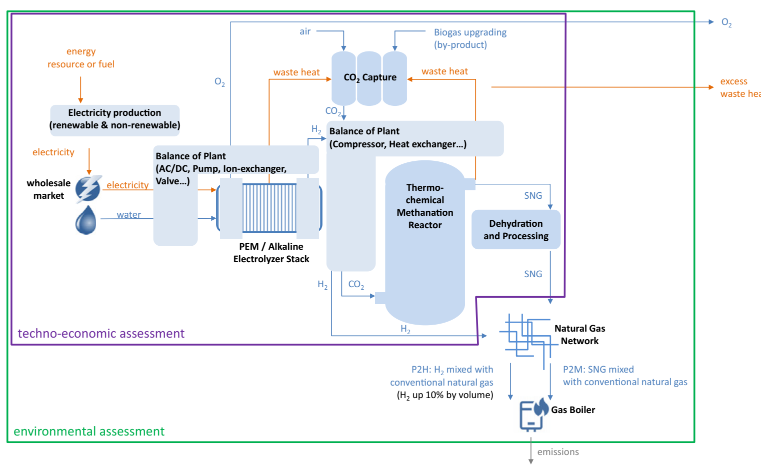
HIGHLIGHTS

- A PEM electrolyser only accounts for up to 25% of the total levelized cost.
- P2H offers lower environmental impacts than conventional production in most scenarios.
- P2H and P2M must use clean electricity in order to provide environmental benefits.
- Biogas upgrading reduces the environmental impacts by 2–9% regarding CO_2 capture.
- Increasing system scale improves both economic and environmental performance.

GRAPHICAL ABSTRACT



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ABSTRACT

Interest in power-to-gas (P2G) as an energy storage technology is increasing, since it allows to utilise the existing natural gas infrastructure as storage medium, which reduces capital investments and facilitates its deployment. P2G systems using renewable electricity can also substitute for fossil fuels used for heating and transport. In this study, both techno-economic and life cycle assessment (LCA) are applied to determine key performance indicators for P2G systems generating hydrogen or methane (synthetic natural gas – SNG) as main products. The proposed scenarios assume that P2G systems participate in the Swiss wholesale electricity market and include several value-adding services in addition to the generation of low fossil-carbon gas.

We find that none of the systems can compete economically with conventional gas production systems when only selling hydrogen and SNG. For P2G systems producing hydrogen, four other services such as heat and oxygen supply are needed to ensure the economic viability of a 1 MW P2H system. CO_2 captured from the air adds \$50/MW h_t of extra levelised cost to SNG compared to CO_2 supplied from biogas upgrading plants and it does not offer an economic case yet regardless of the number of services. As for environmental performance, only the input of "clean" renewable electricity to electrolysis result in

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environmental benefits for P2G compared to conventional gas production. In particular, more than 90% of the life cycle environmental burdens are dominated by the electricity supply to electrolysis for hydrogen production, and the source of CO_2 in case of SNG.

1. Introduction

In order to cut greenhouse gas (GHG) emissions, the power sector needs to be decarbonised. With substantial expansion of wind and solar photovoltaic (PV) power generation, there is a growing need for new technology which facilitates the integration of such stochastic renewable energy (RE) technologies in the energy system [1]. Among all the possible strategies such as grid expansion, curtailment and demand side management, energy storage (ES) is gaining much attention since it is an option which can: play a role of both energy generator and consumer [2]; be used for different time scales (e.g., short, mid and long-term ES) [3]; be installed at different scales (e.g., distributed (kW) versus bulk ES (MW)) [4]. For large-scale storage, technologies such as pumped hydro storage and compressed air storage which storage capacities are independent from power ratings are considered [5,6]. However, both technologies are highly dependent on local conditions. P2G is more flexible in this regard since it only requires access to the natural gas network or any other gas storage, while supporting a more integrated energy system connecting electricity and gas networks [7]. It can make use of excess RE and/or low-cost electricity, transforms it into gas while leveraging the existing natural gas network [8]. Moreover, P2G can provide ES capacity from minutes to months [9], with the largest plant so far reaching 6 MW (defined by electrical power input) [10]. Larger systems are expected to be deployed given the modularity of different components comprising a P2G system [6].

The first step of a P2G process is splitting water into hydrogen and oxygen by electrolysis. Hydrogen can then be injected into the natural gas network up to a maximum volumetric limit depending on country-specific regulations [11], or it can meet any hydrogen demands (e.g., transport with refuelling stations). Such a system is known as power-to-hydrogen (P2H) system. Or alternatively, the generated hydrogen can further react with CO_2 to form SNG. These systems are referred to as power-to-methane (P2M) systems. CO_2 used for methanation can be obtained from various sources but certain contaminants and water need to be removed before it can be fed into methanation to avoid catalyst poisoning [12]. Once SNG is produced from methanation, it can be injected into the natural gas network or it can be directly consumed as a fuel [6,13].

1.1. Previous techno-economic studies on P2G

Some implications of different technological options within a P2G system (e.g., electrolyser technology or source of CO_2), different products and services provided (e.g., gas for mobility, gas being injected to the natural gas network, etc.) in a given regulatory context have been part of the previous P2G technology assessment. Felgenhauer et al. analysed the economic feasibility of P2H with alkaline and PEM electrolysers for mobility [14], and they found that hydrogen could be competitively supplied by on-site alkaline electrolysers at costs ranging from \$4.96–5.78/kg[2] (in particular with capacities above 25 kg/h), in comparison with liquid hydrogen delivered from a central steam methane reforming plant with a cost ranging from \$5–8/kg. A report commissioned by the "European Union Fuel cells and Hydrogen Joint Undertaking" evaluated the cost of P2H for three different services (small systems for transport applications, medium systems for industrial applications and large systems for energy storage applications) under the regulatory context of five different European countries [15]. Among these three different applications, small P2H systems (up to 20 MW) for transport applications was found to be the best economic case, with cost of \$4.8/kg for a 5 MW system generating 2000 kg H_2 per day for vehicle in an hypothetic German scenario in 2030.

Cost, value and/or profitability have been selected as key performance indicators (KPI) in previous techno-economic analyses evaluating ES under different regulatory contexts [16], among which the latter KPI was less assessed for P2G systems so far. For example, Schiebahn et al. quantified the levelised cost for hydrogen as fuel for transportation, and for hydrogen and methane to be injected into the natural gas network in Germany [17]. Likewise, the levelised cost and value have also been analysed for grid injection in Switzerland [6] and six different European countries [15].

1.2. Previous environmental studies on P2G

Limited number of studies have addressed the environmental performance of P2G systems. Bhandari et al. reviewed 21 LCA studies of hydrogen production technologies with a focus on hydrogen production via electrolysis [18]. They concluded that the impact on climate change is most frequently quantified, followed by acidification potential, while the other impacts are often not addressed. They also identified electricity supply to have a dominant impact on the results, and found that electrolysis with renewable energy sources is beneficial to reduce the life cycle GHG emissions. The global warming potential of hydrogen produced by grid electricity supply to electrolysis in Germany can be up to 30 times higher than the production with wind energy, due to the 54% share of fossil fuels in the German grid electricity supply. By comparing P2G with conventional hydrogen and methane production technologies, Reiter et al. found the break-even point for the GHG emissions of electricity supply, so that P2G systems could be competitive with conventional gas production: 190 g of CO_2 equivalents per kWh for P2H, and 113 g of CO_2 equivalents per kWh for P2M if CO_2 is considered as a waste product, or 73 g of CO_2 equivalents per kW h if separation of CO_2 is accounted for [19]. In another study, they evaluated different sources of carbon dioxide in Austria, including power plants and industrial processes, with different capturing technologies, thereby accounting for the additional energy consumption and the associated GHG emissions [12]. It was concluded that biogas upgrading facilities and bioethanol plants are the best suited sources of CO_2 for Austria. The quantity of CO_2 produced from fermentation in bioethanol plants is large and no additional energy is required for capture or purification while for biogas upgrading, CO_2 was considered as a waste product without requiring additional energy.

1.3. Research gaps from previous literature

Three key research gaps have been identified within the previous literature on P2G systems. Firstly, there are no comprehensive methodologies and studies consistently covering the

[2] Conversion rates of 1.07 and 1.00 are used between CHF/EUR, and CHF/USD respectively.