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Power-to-gas for injection into the gas grid: What can we learn from real-life projects, economic assessments and systems modelling?

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ABSTRACT

Power-to-gas is a key area of interest for decarbonisation and increasing flexibility in energy systems, as it has the potential both to absorb renewable electricity at times of excess supply and to provide backup energy at times of excess demand. By integrating power-to-gas with the natural gas grid, it is possible to exploit the inherent linepack flexibility of the grid, and shift some electricity variability onto the gas grid. Furthermore, provided the gas injected into the gas grid is low-carbon, such as hydrogen from renewable power-to-gas, then overall greenhouse gas emissions from the gas grid can be reduced.

This work presents the first review of power-to-gas to consider real-life projects, economic assessments and systems modelling studies, and to compare them based on scope, assumptions and outcomes. The review focuses on power-to-gas for injection into the gas grid, as this application has specific economic, technical and modelling opportunities and challenges.

The review identified significant interest in, and potential for, power-to-gas in combination with the gas grid, however there are still challenges to overcome to find profitable business cases and manage local and system-wide technical issues. Whilst significant modelling of power-to-gas has been undertaken, more is needed to fully understand the impacts of power-to-gas and gas grid injection on the operational behaviour of the gas grid, taking into account dynamic and spatial effects.

1. Introduction

Power-to-gas (P2G) is a key area of interest for decarbonisation and increasing flexibility in future energy systems, due to its potential to help integrate high penetrations of renewable energy. Combining P2G with the gas grid, primarily through direct injection of hydrogen, is one of several possible applications of P2G, and it has its own advantages and challenges.

When hydrogen is combusted it releases no carbon dioxide (CO_2); consequently any addition of hydrogen to the natural gas grid will result in lower CO_2 emissions at end use [1]. Provided the hydrogen is produced in a low carbon manner – either through steam methane reforming (SMR) with carbon capture and storage (CCS) or through electrolysis of “green” electricity – then overall CO_2 emissions will also be reduced. Many countries, such as the UK and the Netherlands, have extensive gas grids and there is interest in finding ways to continue to make of use these networks in a low carbon future, to avoid having to abandon these valuable assets altogether [2]. Furthermore, due to the ability of the gas grid to handle a range of gas pressures, it has an inbuilt flexibility which could be exploited by P2G, shifting some variability caused by intermittent renewables on the electricity grid onto the gas grid [3].

Nonetheless hydrogen injection into the gas grid (HIGG) has technical, economical and systems-level challenges [2,4,5]. Considerable work has been undertaken to understand these challenges through research, modelling and real-life demonstrator projects, and some effort has been made to establish a coordinated approach to expanding HIGG, for example through the HYREADY project [6]. However, many academic, industrial and policy studies have called for more to be done, particularly from policymakers [2,7–11].

Several reviews of P2G have previously been performed. Schiebahn et al. [12] performed a technological review of power-to-gas with

Abbreviations: $\%_{HHV}$, Efficiency based on higher heating value; CAPEX, Capital expenditure; CCS, Carbon capture and storage; CHP, Combined heat and power; CO_2, Carbon dioxide; HIGG, Hydrogen injection into the gas grid; LP, Linear programming; MIGG, Methane injection into the gas grid; MILP, Mixed-integer linear programming; MINLP, Mixed-integer nonlinear programming; NFCRC, National Fuel Cell Research Centre; NLP, Nonlinear programming; OPF, Optimal power flow; P2G, Power-to-gas; PEM, Proton exchange membrane; SMR, Steam methane reforming; vol%, Percentage blend by volume

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respect to the gas grid, including the technologies involved in the production, distribution and end use of the gas. Some reviews, including Haeseldonckx and D'Haeseleer [13], Dodds and Demoulin [14] and Götz et al. [15], have taken a broader assessment of P2G and the gas grid, assessing both the technological and wider system challenges. However, of these only Haeseldonckx and D'Haeseleer [13] considered partial HIGG: Dodds and Demoulin [14] considered a complete conversion of the gas grid to hydrogen, and Götz et al. [15] only considered synthetic methane injection into the gas grid (MIGG). Many similar studies have also been performed by private firms and regulatory and policy-making bodies [1,2,4,16,17]. The NaturalHy project [5] was a major study commissioned by the European Commission which assessed the practicalities of delivering hydrogen in the European natural gas network, considering production, transport and end use.

Reviews of real-life P2G projects have also been performed. Gahleitner [18] performed a wide-ranging study of P2G projects and found that there was a focus of projects in Germany, but that projects had not been running long enough to draw specific conclusions on performance. Garcia et al. [19] conducted an expert opinion analysis of the potential of renewable hydrogen storage systems in Europe, including highlighting significant projects. Bailera et al. [20] reviewed 46 projects, but only considered power-to-methane.

Various approaches have been used to model P2G, but very few reviews of P2G modelling methods and their results have been performed. Typically, reviews that have been performed focus on general energy systems modelling techniques, with no interest in P2G. For example, Connolly et al. [21] reviewed models with a focus on integrating renewables into energy systems; Hall and Buckley [22] reviewed models in the UK context; and Pfenninger et al. [23] reviewed energy system models, questioning what the requirements are for these models in the twenty-first century. Blanco and Faaij [24] and Robinius et al. [25] both reviewed studies which included P2G, but only as one of a number of flexibility options, and were only concerned with the study results, not the modelling techniques.

The aim of this work is to provide a review of P2G and HIGG that for the first time considers both real-life projects and modelling studies and compares them based on scope, assumptions and outcomes. Furthermore, the interaction of P2G with the gas grid, primarily through HIGG, is of specific interest, due to the unique technical, economic and modelling characteristics associated with it. Inevitably, many P2G projects and studies include multiple P2G applications, so these are given consideration where necessary. MIGG is an alternative, or possibly complementary, pathway to HIGG which has its own set of strengths and weaknesses that are also assessed where appropriate.

The methodology comprises three elements:

1. An examination of over 130 reported real-life P2G and HIGG projects worldwide, in order to understand the historical trend in the scale and types of technology employed, as well as the types of application and the global distribution of the projects to identify what the impacts of P2G and HIGG are and where they are taking place;
2. An investigation of economic assessment studies performed for P2G and HIGG, comparing the different assumptions made about the level of hydrogen injection allowed, identifying specific business cases for the technologies and assessing the resulting levelised cost and the wider system cost; and
3. An evaluation of energy systems models that considered P2G and/or HIGG and classifying them based on: the modelling approach employed; how the gas-electricity interface, storage and linepack were represented; how the spatial and temporal dependencies of system properties were captured; and what the objectives and the key design decisions of the models were.

The results from the three steps above were synthesised and categorised based on the scope, assumptions and outcomes of this wide range of studies, in order to obtain insights about the current status of the technologies and make recommendations for future research.

The remainder of this paper is structured as follows. Section 2 discusses the practical issues concerning producing hydrogen, injecting into the transmission and distribution gas grids, and its end use. Section 3 surveys the P2G projects worldwide, with a focus on HIGG projects. Following that is a literature review of modelling studies on P2G with a focus on HIGG: Section 4 reviews economic studies with an interest in the costs and business potential of HIGG, and Section 5 surveys studies that have used optimisation to assess P2G and HIGG from a whole system perspective. Finally, Section 6 summarises and compares the scope, assumptions and outcomes of the real-life projects and modelling studies.

2. Practicalities of P2G and HIGG

This section provides a brief summary of the pathways and technologies of power-to-gas. A large number of studies and reviews have been carried out in this area: Schiebahn et al. [12] and Haeseldonckx and D'Haeseleer [13] are particularly recommended for more detail on this subject.

2.1. Production

Fig. 1 shows an overview of the gas grid injection pathways, including power-to-gas. Hydrogen can be produced from electrolysis or SMR, and injected directly into the gas grid. Provided that the electricity source used for electrolysis is low-carbon, such as wind or solar energy, electrolysis has very low environmental impact. There are many references available for details of the electrolysis process [12,26,27]. Several different electrolysis technologies exist and are used in P2G applications, as each has its own advantages and disadvantages. The most common technologies are: alkaline; proton exchange membrane (PEM); and solid oxide. Alkaline and PEM electrolysis have been used commercially for several decades in industrial applications. In recent years, manufacturers have also begun to produce commercial alkaline and PEM electrolysers capable of the more flexible operation regimes associated with P2G, although so far at a smaller scale [28]. Although solid oxide technology has been in development since the 1970s, it is less commercially established, mostly at the demonstration or pre-commercial stage [28,29]. The technologies and sizes of P2G projects are discussed further in Section 3.1.

As an alternative to direct injection, hydrogen can be combined with CO_2 to produce methane, by methanation (for example using Sabatier synthesis [30]). Methane is a versatile and easy to store substance, and it forms the majority of natural gas [31], however when used as an energy source the CO_2 will be re-released. There is considerable interest in power-to-methane as it has fewer barriers to implementation than power-to-hydrogen. However, its potential for significantly reducing CO_2 emissions in the long term is limited.

2.2. Distribution and transmission

A concern with direct injection of hydrogen into the natural gas network is hydrogen embrittlement, which can occur in pipes made of iron and steel, and can lead to propagation of cracks in the pipework [32]. It is broadly agreed that hydrogen can be injected into the distribution network at a low concentration with no serious safety issues. Although the exact level is disputed, several studies suggest that up to 15–20% hydrogen blend by volume (vol%) should be allowable [4,5,13]. Meanwhile, many regulators have seemingly arbitrarily low allowances on the amount of hydrogen in the blend. In the UK for instance the allowable limit is 0.1 vol%, whilst in the Netherlands up to 12 vol% is permitted [17]. Nowadays, polyethylene, which is not susceptible to hydrogen embrittlement, is being used more commonly in distribution networks. In the UK, for example, a major scheme is