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Comparative life cycle assessment of power-to-gas generation of hydrogen with a dynamic emissions factor for fuel cell vehicles

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ABSTRACT

Power-to-gas, an excellent energy storage technology, is also useful for the role it can play in producing hydrogen for fuel cell vehicles. The replacement of the existing transportation infrastructure and the end of society's reliance on carbon-based fuels is dependent on the development of efficient, cleaner technologies as well as 'smart energy networks'. One of the most touted technological advances is the replacement of internal combustion engines with 'green' hydrogen fuel cell vehicles. Hydrogen fuel cell vehicles do not emit any greenhouse gases or other emissions as such do not directly contribute to climate change or urban air pollution during their operation. With green hydrogen as the fuel, the emissions from the fuel production become dependent not on the vehicle type or electrolyzer technology, but on the sources of electricity being used to generate the hydrogen. In this study, the authors examine the use of electrolytic hydrogen to power vehicles and compare this with its internal combustion counterpoint. In this analysis a dynamic electrical grid emissions factor, based on the total grid mix of energy generation technologies at any given time, is determined. In this case study, the province of Ontario, Canada is used. Unique to this work is that the simulation of the generation of hydrogen is via electrolysis under different control strategies; the strategies considered, specifically, are continuous electrolyzer operation, price threshold operation, or operation based on an emission factor threshold based on the mix of energy generation technologies feeding the grid at any given hour. With the introduction of new policy tools to reduce greenhouse gas emissions, such as carbon taxes and cap-and-trade, the monetization of emissions provides an even greater incentive for industry to reduce their greenhouse gas emissions. In this study, it is illustrated that by using the dynamic emissions factor to control the production of hydrogen, emissions can be significantly reduced over the life of the vehicle.

1. Introduction

Power-to-gas, an energy storage technology that provides flexibility and integration to the electrical and natural gas grids, can also be used to produce green hydrogen for fuel cell vehicles. Although hydrogen is currently used mainly as an industrial commodity for the production of ammonia and petroleum, it is clearly becoming a viable solution to use hydrogen as an alternative fuel [1]. At this time, the Department of Energy's Office of Transportation Technology and the automotive manufacturers clearly see fuel cell vehicles as the path to hydrogen vehicle commercialization vehicles likely to be brought online in the 2015-2020 timeframe [2]. As nations and provinces move to monetize their reduction of CO_2 emissions, through carbon taxes and cap-and-trade programs, the market for this technology will only increase. An excellent technology for the production of hydrogen is power-to-gas [3–6]. Power-to-gas is an effective way to generate emissions-free hydrogen fuel while utilizing cleaner power and can also compliment the function of the electrical grid by providing load flexibility and provision of other ancillary services. As the sources of energy into the electrical grid have changed substantially in many jurisdictions from more carbon-based sources to an increasing amount of intermittent, renewable energy sources that compliments significant a significant base load of nuclear, thus there is a definite need to provide this flexibility. Energy storage through hydrogen generation is a clear alternative.

Another important advantage of power-to-gas is its ability to provide energy storage which allows utilities to better manage excess base load power. When the majority of the electricity from the grid is generated by nuclear energy, there is a constant energy

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base [7]. At peak demand times, other sources of energy are drawn on to support the base load power and increase the energy supply. At off-peak times, however, the supply of energy exceeds the demand and, as nuclear facilities cannot easily reduce their output, the excess energy is exported to neighboring jurisdictions. In Ontario – the focus of this case study – these jurisdictions include Quebec, Manitoba, New York, New Jersey and Pennsylvania. In 2013, for example, approximately 18.3 TWh was exported to these jurisdictions at a significantly undervalued price by Ontario, potentially costing the utilities up to $1 billion in lost profits [8]. Some other energy storage technologies which can be considered to provide this type of support to the grid include flywheels, lead-acid batteries, lithium-ion batteries, compressed air energy storage (CAES) and pumped hydro energy storage [9,10]. These energy storage technologies are compared in an earlier work by Walker et al. [11].

The main purpose of power-to-gas, however, is the production of hydrogen. In Fig. 1, below, a number of power-to-gas energy utilization pathways are shown. The supply of energy, on the left hand side, comes from the electrical grid and can be from specifically renewable sources, excess base load energy during off-peak periods or the basic electrical grid mix. Next, the electrolyzer takes water and splits it into H_2 and O_2. Following the H_2 can either be injected into the natural gas infrastructure or stored by tank for immediate use. The H_2 stored for immediate use can be used for industrial processes or to power hydrogen fuel cell vehicles, or vehicle fleets [12]. The rest of the H_2 is added to the natural gas grid creating Hydrogen Enriched Natural Gas (HENG) [13]. In order to avoid the embrittlement of the materials the pipelines are made with, it is necessary for the H_2 concentration to remain below 5% by volume at this time [14].

As discussed earlier, there are a number of advantages of using power-to-gas energy storage including a high energy density, the ability to transport the energy efficiently and the ability to store and distribute the energy in existing natural gas infrastructure for long periods of time. Additionally, the hydrogen can be used as a mixed gas with natural gas and shipped to existing natural gas customers.

As shown in Fig. 1, power-to-gas is a multi-faceted system which can have a number of different pathways from energy input to deliverable electricity or gas outputs. In addition to power-to-gas's ability to provide efficient, high density energy storage, it can also be used to meet the demand for industrial hydrogen. Although the vast majority of hydrogen is currently used as a commodity, which makes up a $60 billion industry, the future of hydrogen production will be to provide a clean fuel for fuel cell vehicles [2,15]. There have been a number of works that have considered the well-to-wheel (WTW) emissions of electrolytic hydrogen for vehicles [16–18]. Most notably McCarthy and Yang [19] consider electrolysis in a comprehensive fashion, however they do not consider different control strategies for the electrolysis operation, specifically control strategies based on an electrical grid dynamic emissions factor.

As billions of kilograms of hydrogen will need to be produced daily to meet the needs of hydrogen fuel cell vehicles, the potential for CO_2 equivalent reduction through the substitution of petroleum with electrolytic hydrogen is quite large. In the pathway to producing industrial hydrogen, electricity is used to power an electrolyzer and the hydrogen is then sent by a dedicated pipeline to the customer. Due to the high demand that will accommodate the use of hydrogen as a transport fuel, substituting electrolytic hydrogen for hydrogen from the more commonly used steam methane reformatted hydrogen generation represents an excellent opportunity to reduce greenhouse gas emissions. For example, Simons and Bauer [20] find that in a grid mixture dominated by nuclear energy approximately 3–5 kg CO_2 equivalent is emitted per kilogram of H_2 produced by electrolysis, while other technologies, such as steam methane reformation, emit approximately 13 kg CO_2 equivalent per kilogram of H_2. Additionally, the electrolysis of hydrogen can be accomplished in significantly fewer energy-intense steps than steam methane reformation [21].

To encourage these types of reductions in CO_2 emissions, a number of carbon reduction policy tools have been proposed. Carbon taxes have been proposed whereby organizations are made to a pay a premium for the carbon emissions that they are responsible for [22,23]. One criticism of the carbon tax, however, is that it generally increases the costs of energy and transportation for consumers without encouraging innovation [24]. Cap-and-trade systems, however, have been successfully implemented in the European Union and North America [19,25]. Cap-and-trade

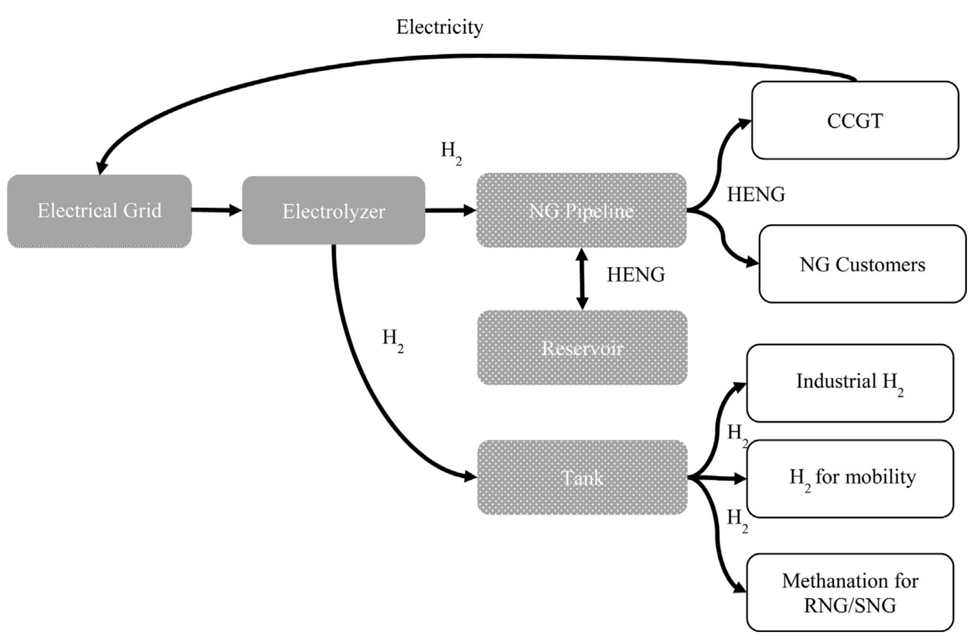

Fig. 1. Hydrogen economy and power-to-gas energy flow.

Adapted from [3].