Chapter 2

Literature Review

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Chapter 2

Literature Review

This section explores the economic feasibility of hydrogen as an energy carrier, based on the review of the academic literature. The study (i) summarises the prospects of hydrogen produced from RESs as an energy carrier, (ii) examines the feasibility of using RESs and hydrogen in remote locations such as islands, and (iii) reviews the potential of using hydrogen for FCEVs.

1. Hydrogen as Storage for Renewable Energy in the Power Sector

Renewable energy is becoming a key component in the energy mix to meet increasing electricity demand and reduce GHG emissions. Renewable energy's expansion, however, is limited by intermittency and peak-hour mismatch. Energy storage technologies must be developed to ensure that renewable energy is fully absorbed by the energy system. We review the economic feasibility of hydrogen storage for electricity produced from RESs.

Academic studies are divided on the profitability of hydrogen storage for RESs. Many studies stress that hydrogen storage is still far more expensive than fossil fuels and demands a lot of upfront investment. Hydrogen storage might not, therefore, be profitable in the end. APERC (2018) shows that producing hydrogen from RESs (US$0.22–US$0.55 cents/normal cubic metre [Nm^3]) is twice as costly as producing it from fossil fuels and carbon capture storage (CCS) (US$0.07–US$0.23/Nm^3).

Nagashima (2018) estimates that hydrogen produced in Japan from renewables is not competitive because of their high cost. The intermittency of renewables decreases the capacity factor of electrolysis and raises the marginal costs of hydrogen production. Hydrogen produced from RESs, therefore, remains more expensive than hydrogen made from natural gas and CCS, and hydropower.

Combining wind power and a hydrogen storage system for power plants is deemed economically unviable, as a mixed system of wind–hydrogen would increase investment costs in infrastructure components and significantly decrease profits (Loisel et al., 2015). Besides, the benefits of energy storage for hybrid wind–hydrogen power plants are limited by the decrease in overall efficiency. Therefore, hydrogen production costs from wind-powered electrolysis are higher than those of steam methane reforming (SMR) and SMR with CCS (Olateju et al., 2016). Eypasch et al. (2017) advised industrial power plants to convert excess energy to heat, rather than store it using liquid organic hydrogen carriers (LOHCs).

Other studies, however, indicate that hydrogen is an economically viable way to store hydrogen produced from RESs. Seyyedeh-Barhagh et al. (2019) attempted to satisfy economic and environmental conditions in optimising the performance of hydrogen storage systems, and prove that it is feasible to have an environmentally friendly and profitable hydrogen storage system that meets demand. However, these studies usually consider off-grid systems. Some conclude that the most beneficial configuration of offshore wind farms with hydrogen systems is to sell hydrogen directly to users, if there is enough demand for it (Hou et al., 2017). Favourable returns on investment are demonstrated by Hou et al. (2017) and Khosravi et al. (2018). Hydrogen has been proven to be highly profitable in the long term and exceedingly well suited for remote areas that are not connected to the national power grid (Khosravi et al., 2018). Prasanna and Dorer (2017) found similar results and argue that it is more profitable to produce hydrogen from excess RESs and use it within the district of production rather than sell it to the power grid. Yan et al. (2017) proved that hydrogen storage is an efficient, environmentally friendly, and profitable way to solve the issue of energy curtailment for renewables.

Assessing the economic feasibility of hydrogen storage remains complicated because the price range of hydrogen is large, since hydrogen demand profiles vary and storage technologies are not mature (APERC, 2018; Menanteau et al., 2011). Research is ongoing to figure out which storage technology is cheapest and most efficient and has the lowest level of loss (Di Profio et al., 2009; Teichmann et al., 2012; Reuß et al., 2017; Aako-Saksa et al., 2018; Abe et al., 2019). Studies point out that the most viable storage technologies are LOHC (Teichmann et al., 2012; Reuß et al., 2017; Aako-Saksa et al., 2018), circular hydrogen carriers (Aako-Saksa et al., 2018), and metal hydrides (Abe et al., 2019).

2. Hydrogen Use in Remote Island Locations

Here we review the possibilities of developing hydrogen use in remote islands, where, as many authors have shown, energy is a challenge (Young et al., 2007; Groppi et al., 2018; Dorotić et al., 2019). Many islands rely completely on fossil fuels (Dorotić et al., 2019). However, growing climate change concerns and the increasing profitability of renewables has helped increase the share of RESs. Yet, many issues remain, such as the intermittency or seasonality of energy production and demand mismatch in peak hours (Groppi et al., 2018; Cabrera et al., 2018). Several islands have started to see hydrogen as a solution.

One possibility is importing and distributing hydrogen produced from RESs, but several studies show that it is not economically viable. Teichmann et al. (2012) mentioned that, although long-distance liquid hydrogen (LH_2) transport by sea could be important in the future, it is not attractive now because of the low weight percentage and not feasible using existing ships. Because of its diesel-like properties, LOHC could be a storage solution. Whilst LOHC costs decrease spectacularly for short distances, they remain high for distances above 5,000 km, with 1 kg of hydrogen costing about €0.221. More recent studies emphasise that pipelines and short-distance delivery by truck are the preferred transport choices for hydrogen (Singh et al., 2015). Whilst ships allow for international transport of extremely high volumes of hydrogen, the price is prohibitive: US$1.80–US$2.00/kg compared with US$0.10–US$1.00 by pipeline (Singh et al., 2015). Boil-off losses of hydrogen are more significant when LH_2 technology is used (Singh et al., 2015). Overall, electricity transmission is far more efficient and the cheapest option for transporting energy. However, electrical energy is difficult to store and chemical energy such as hydrogen is inevitably the complementary solution (Teichmann et al., 2012).

Another possibility is producing electricity from RESs such as solar photovoltaic or wind, and using hydrogen storage and FCEVs to compensate for seasonality and to match energy demand in peak hours. Many islands have attempted to stop relying on fossil fuels and increase their renewable energy share. Chen et al. (2007) introduced programmes and trials of integrated fuel cells and hydrogen storage in various islands in Europe and concluded that 100% renewable energy penetration was technically and economically feasible for small islands. Ma et al. (2014) presented a feasibility study of a stand-alone hybrid solar–wind system with battery energy storage for a remote island of Hong Kong SAR, and showed that it could fully rely on RESs thanks to 'practical and cost-effective' battery storage. Several recent case studies have demonstrated that Mediterranean islands could use hydrogen storage and FCEVs to decrease their fossil fuel consumption (Groppi et al., 2018; Cabrera et al., 2018). Certain islands, such as Korčula in Croatia, could even rely entirely on RESs thanks to hydrogen storage technology (Dorotić et al., 2019). However, all the studies used examples of remote locations in developed countries that have national and regional energy and environmental legislation favouring hydrogen development (Chen et al., 2007). The feasibility of such trials in developing countries remains to be explored.

3. Hydrogen Produced from Renewable Energy Sources to Supply Fuel Cell Electric Vehicles

This section examines the economic feasibility of using hydrogen produced from RESs to supply FCEVs. Climate change concerns and the willingness to decrease GHG emissions from transport required considering hydrogen as a potential transport fuel. The transition to hydrogen fuel would offer social benefits, including greater energy security, reduced pollution, and a drop in GHG emissions (Southall and Khare, 2016). However, the development of renewables-produced hydrogen for fuel cell applications has been slow.

The first obstacle to its development is what many authors call the 'chicken and egg dilemma' (Southall and Khare, 2016; Campinez-Romero et al., 2018). Campínez-Romero et al. (2018) argued that the main reason for the lack of FCEV adoption is the lack of a hydrogen refuelling network, contributing to low demand for FCEVs. However, to develop hydrogen refuelling stations (HRSs), they must be fundable and economically viable, which they are not because of low demand. Southall and Khare (2016) argued that, despite the existence of commercial-scale hydrogen production, the distribution network depends on the sale of hydrogen-fuelled vehicles.

Another obstacle is the high costs of HRSs, as highlighted by several studies (Frank et al. 2019; Apostolou and Xydis, 2019; Bai and Zhang, 2020). Inadequate deployment of HRSs is a major barrier to the commercial introduction of FCEVs. Investments in HRSs would be profitable if FCEV numbers grew, but the FCEV market would be hindered if hydrogen infrastructure development were inadequate (Apostolou and Xydis, 2019).

Xu et al. (2020) recognised six barriers to developing HRSs in China, where HRS construction is lagging behind expectations: high initial capital cost (B11), limited financing channels (B13), immature hydrogen storage technology (B22), incomplete hydrogen transportation technology (B23), lack of standards (B42), and an imperfect subsidy mechanism (B43). A ranking of the relative importance of these barriers is concluded in the case of China.

How can HRSs be financed and operated? Bai and Zhang (2020) introduced four business models for financing and operating HRSs (build-operate-transfer, transfer-operate-transfer, public–private partnership, and asset-backed securitisation) and identified six criteria for prioritising them.

Taghizadeh-Hesary and Yoshino (2019, 2020) found that lack of long-term financing, low rate of return, existence of various risks, and market players' lack of capacity are major challenges to developing green energy projects, including hydrogen projects. The authors provide practical solutions for filling the green financing gap, including increasing the role of public financial institutions and non-banking financial institutions (pension funds and insurance companies) in green investments, utilising the spillover tax to increase the rate of return of green projects, developing green credit guarantee schemes to reduce credit risk, establishing community-based trust funds, and mitigating green investment risks via financial and policy de-risking.

Another reason for the lack of HRS infrastructure is the high upfront investment needed to build it. Nagashima (2018) argued that, particularly in Japan, despite heavy subsidies to develop FCEVs, tight regulations and technical constraints raise infrastructure costs: an HRS costs two or three times more than in Europe. However, some authors argue that lack of infrastructure and financial resources used to be an issue at the beginning of the commercialisation of fossil fuels, as well (Singh et al., 2015). Therefore, it can be overcome with support from government and state subsidies (Campinez-Romero et al., 2018). Subsidies would significantly reduce the costs of hydrogen technologies (Nistor et al., 2016) and increase the share of RES-produced hydrogen (Southall and Khare, 2016).

Most studies that assess the economic feasibility of hydrogen use for FCEVs conclude that costs could be brought down through subsidies and economies of scale of electrolysers and hydrogen storage equipment (Southall and Khare, 2016; Kan and Shibata, 2018). Nistor et al. (2016) argued that the hydrogen unit cost could be below that of petrol if the expected return on investment period were over 10 years for proton exchange membrane (PEM) and electrolysers and 5 years for alkaline electrolysers. Whilst hydrogen technologies seem to be profitable in the long term, Southall and Khare (2016) argued that, in the short term, hydrogen production infrastructure, coupled with renewable energy tariffs, would be financially viable under certain configurations.[1]

4. Summary of the Literature Review

We reviewed the academic literature to analyse the economic feasibility of RES-produced hydrogen storage for power generation and FCEVs and for remote locations. It appears that hydrogen produced from RESs is not competitive with that produced from fossil fuels. However, hydrogen storage proves to be a desirable way to increase electricity produced from RESs and solve curtailment issues. Uncertainty remains, however, over economic feasibility as the price range for hydrogen is large and technology is still not mature.

The cost of hydrogen transport and distribution proves to be a substantial portion of the overall supply cost of hydrogen. The literature shows that long-distance transport of hydrogen to remote locations is not economically feasible now. However, hydrogen is an economically feasible solution for remote islands to store RES-produced electricity and, in certain cases, can meet all energy demand. In both cases, state subsidies would not only help overcome issues of high upfront investment in infrastructure development but also resolve the chicken-and-egg dilemma.

Incentivising projects for private investors through green credit guarantee schemes, utilising the spillover effect of power supply, and mitigating green investment risks via financial and policy de-risking are recommended.

[1] The authors used average wind speeds in the United Kingdom for their calculations. Varying wind speed might affect the results of the study.