Energy Proceedings
Vol 41, 2024
ISSN 2004-2965

Assessing the UK's attempt to Establish a Zero-carbon Hydrogen Economy in the Industrial Sector

Oliver Morgan[1], Lucy Elwy[1], Gbemi Oluleye[1,2]*
1 Centre for Environmental Policy, Imperial College London, London, United Kingdom
2 The Sargent Centre for Process Systems Engineering, Imperial College London, London, United Kingdom
(*Corresponding Author: o.oluleye@imperial.ac.uk)

ABSTRACT

This study determines the cost reducing effect of hydrogen supply-push targets, which will indicate the sufficiency of current UK government policy to initiate a hydrogen economy within the industrial sector. This study will also answer the question "What demand-pull policies can support fuel switching to hydrogen in UK industry?" A novel mixed-methods approach is used, in-depth rapid evidence assessment and a macro market penetration assessment to understand how to best establish an industrial hydrogen economy. Our findings show that without demand-pull policies, 65 GW to 350 GW of hydrogen supply is required to achieve price parity with natural gas.

Keywords: Hydrogen for industry uptake modelling, demand pull policy, supply push policy, rapid evidence assessment, market penetration assessment, industrial decarbonisation

1. INTRODUCTION

1.1 Background

Despite decrease in economic output, the volume of greenhouse gases (GHG's) emitted by UK industry constitutes a sizeable 16% of all UK emissions (72 MtCO2e) (HM Government, 2021a). These emissions are primarily produced through the combustion of fossil fuels to produce heat (85% of emissions), whilst 15% are associated with processes in industry (CCC, 2019a). To reach Net Zero, hydrogen is emphasized for use as a fuel or a feedstock in industry. This is primarily due to its similarity to natural gas given its combustibility. In the 'British Energy Security Strategy' the government set a particularly ambitious 5GW electrolytic hydrogen production target by 2030, but it is sufficient to establish a zero-carbon hydrogen economy? For industry to make the switch from fossil fuels to clean hydrogen, it must be both technically feasible and financially viable. The UK has other supply-push policies to demonstrate the technical feasibility of green hydrogen for industry. Examples include a £105 billion funding package as part of its Net-Zero Innovation portfolio which provides £55 million fuel switching competition; where Phase 1 funds feasibility studies, and phase 2 funds demonstrations (BEIS, 2021a). Current barriers to adoption of these green technologies include upfront costs of installation, time and costs associated with technology development, and a lack of demand-pull policy. Demand-pull policies refer to policies which aim to incentivise uptake of technologies through market instruments (Albrecht et al., 2015). This is opposed to supply-push policies which focus on improving technical performance (Ren et al., 2015). At the time of writing, no demand-pull policies specifically for hydrogen use in the UK industry exist. More generally policies for uptake of these technologies, rather than simply making them available, is missing from both domestic and international policy (Nilsson et al., 2021). To assess policy related to the interplay of quantity of supply and the effect this has on price, impacting volume demanded, a novel mixed-methods approach is necessary to answer the research question. Given the novelty of this research area, the complexity of analysing future markets, and the consequent high level of uncertainty, a set of methods has been developed to enrich and advance understanding in this complex area. These stages include rapid evidence assessment, and a macro market penetration assessment that utilizes historic datasets, and future scenarios from the UK TIMES model (UKTM) to determine future prices based on technology experiencial learning.

1.2 Literature Review

Green hydrogen costs rely on a complex combination of the cost of renewable electricity, the CAPEX of the electrolyser and balance of plant, the capacity factor, and

This is a paper for 15th International Conference on Applied Energy (ICAE2023), Dec. 3-7, 2023, Doha, Qatar.

the energy efficiency of the production system (Lambert & Oluleye, 2019). Consequently, hydrogen carries a high price, and some studies have projected it to remain high falling to just 6.4p/kWh compared to 3.5p/kWh for natural gas, and 2.2p/kWh for biomass by 2030 (Element Energy & Jacobs, 2018). For a hydrogen economy to be established, the cost of hydrogen must fall so that it becomes economically competitive with existing fuels like natural gas.

Currently, the European Commission Hydrogen Strategy has approximated that the cost of green hydrogen is between £56.39 and £124.21 per MWh (European Commission, 2020). A more optimistic KPMG report found that hydrogen prices lie between £47.50 and £114.05 per MWh (KPMG, 2022). By comparison, the most expensive year on record for UK natural gas prices recorded an average price of £25.48 per MWh in 2021. Although the cost of hydrogen is not competitive with natural gas in 2022, given the immaturity of production technology we can expect costs to decrease over time. This is called the learning rate and refers to reducing costs due to accumulated learnings from repeated implementation of a technology. Previous studies have already calculated the learning rate of green hydrogen to be between 19% and 26% (Lambert & Oluleye, 2019). This learning rate is comparable to what has been observed with solar PV throughout the 2010's. Germany targets 5GW of green hydrogen by 2030, 4GW of green hydrogen in Spain, and 2-2.5GW in Portugal (IEA, 2021a; World Energy Council, 2021). The UK's level of ambition aims to establish itself as a world leader in hydrogen production as evidenced by the policy focus on hydrogen supply. However, there is an evident gap in developing demand side policy, encouraging the uptake of new clean hydrogen.

Not only is there a one-sided emphasis when it comes to government policy for production of clean hydrogen, a research gap exists in the academic literature especially in not accounting for the direction of both supply-push and demand-pull policy undercurrents which could inform the choices industrial consumers might make. Recent academic reviews such as (Yaqub Qazi, 2022) also emphasise the future applications of hydrogen whilst avoiding difficult questions around future hydrogen price and the interface with policy in ensuring price parity with natural gas. Meanwhile, there are numerous examples of articles which solely address the technical feasibility of hydrogen technologies in industry (Saif et al., 2020, Davies et al., 2022; Li, Huang & Kobayashi, 2017; Barrett et al., 2018, Song et al., 2020).

For a developing technology to succeed, there must be an incentive for adoption over existing technologies. Although the academic community has thoroughly demonstrated hydrogen's usefulness to industry (Amin et al., 2020), it has neglected the crucial questions of how and when hydrogen costs become competitive. As a result, it is uncertain whether government policy is effective to ensure that future supply and demand of hydrogen will achieve equilibrium.

The novelty of this report and the estimated price scenarios it presents is due to its timing, as it accounts for the updated UK hydrogen production targets, as well as its endogenous use of the learning rate effect. Furthermore, the uniqueness of this research is founded in the mixed-methods assessment using a rapid evidence assessment to identify demand-pull policies and applying a novel macro market penetration assessment of these policies, in conjunction with analysis of the falling cost of hydrogen compared to existing fuels. This is imperative for the future success of this technology (if there is to be any), as the hydrogen economy will not take off without consideration for economic viability. Therefore, this report offers a new and important perspective to the discussion on the clean hydrogen potential in the UK.

2. METHODS

A mixed-methods approach was taken to provide the most thorough response to this policy assessment. Due to the novelty of this research area, observed data, modelled scenarios and literature are used to support one another and the resultant findings.

2.1 Rapid Evidence Assessment (REA)

The first part of the methodology involves a rapid evidence assessment (REA) based on recommendations by Thomas et al., 2013 to identify demand-pull policies. Three electronic databases, Environment Complete and GreenFILE, available through EBSCOhost and OSTI.GOV, were searched using specific key words associated with the review question, "What demand-pull policies can support hydrogen uptake in the UK industry?" Any results from these searches (Table 1) were then screened based on a series of inclusion criteria following a review of their abstracts and titles. Once the relevant articles were gathered (n=25 out of 1425), data was extracted to summarise the characteristics of each policy and whether the policy had been a success. Finally, these findings were analysed for statistical information and learnings from failures. These learnings were then used to inform two policy recommendations to increase the uptake of hydrogen UK industry.

Table 1. The number of search results, relevant articles, and included studies from the REA

Source of Article Identification	Search Terms	Number of Articles Identified	Number of Articles Meeting Initial Inclusion Criteria	Number of Articles Included in the REA
EBSCO*host* (Environment Complete and GreenFILE databases)	Case Study AND Technology AND Policy; Case Study AND Technology AND Energy Policy	17	11	8
U.S. Department of Energy, Office of Scientific and Technical Information (OSTI.GOV)	Economic Policy AND Technology, limited to Journal Article AND Published Article	1,378	11	6
Hand Searches				
Of Articles from EBSCO*host* and OSTI.GOV database	Hand searched references of 12 included articles	15	2	0
***Energy Policy* journal**	Hand searched 2022 table of contents	12	12	9
***Energy and Environmental Science* journal**	Hand searched 2022 table of contents	3	2	2
Total Articles included in REA				**25**

2.2 Macro Market Penetration Assessment (MMPA)

The objective of the MMPA is to determine the future price of hydrogen based on the UK government supply push (2030 production target) based on the learning rate effect. Given that the government target for clean hydrogen production in 2030 is significantly higher than production levels today, and that electrolytic hydrogen production is an immature technology, the learning rate effect implies that the more hydrogen is produced the lower its price will be. The learning rate used was based on a range of 19% to 26%. Using this information, together with the hydrogen flow, and the current price of hydrogen, a pessimistic and optimistic hydrogen price scenario was produced. The current hydrogen price was also based on two separate price ranges given the volatility of markets, and the poorly recorded data on hydrogen price. The pessimistic and optimistic future hydrogen price range was compared to the estimated future price range of natural gas, based on price data from the 'Non-Domestic Energy Prices' published by BEIS. Calculations identifying the price disparity between hydrogen and natural gas in 2030 were conducted. the MMPA was also used to explore the impact of increasing the supply push to allow competitive prices or utilise the demand-pull instrument from the REA. This enabled an optimisation model to be produced which identified the lowest absolute cost for government and industry to enable green hydrogen to be competitive with natural gas. The combination of both supply push and demand pull may reduce the price disparity sufficiently with the aim to incentivise industry to replace fossil fuel consumption with clean electrolytic hydrogen.

Data from the 'Energy Consumption in the UK' dataset, published by BEIS, provided background on current industrial fuel use, whilst data collated from a range of literature sources provided an impression of current UK hydrogen consumption. The UK Times Model (UKTM) was used to extract central Net Zero scenarios for industrial natural gas and hydrogen consumption until 2050. Using the hydrogen production capacity target for 2030, the consequent hydrogen flow was calculated to aid comparison and later use in calculations. For this, the normalised volumetric flow conversion (166.67 Nm^3), the higher heating value conversion factor of hydrogen (142 MJ/kg), and a standard assumed electrolyser operation time of 6000 hours per year, were used to calculate the annual flow of green hydrogen in TWh (Eq. (1)).

Table 2. Estimating the supply-push hydrogen flow

Production capacity	5GW green hydrogen in 2030
Normalised Volumetric Flow Conversion	166.67 Nm^3
HHV Conversion Factor	142 MJ/kg
Production operating hours	6000 hours/year

The consequent calculation for the hydrogen flow in TWh from 5GW of electrolytic production is:

$$\left((5GW * 166.67Nm^3) * 142\ MJ/kg\right) * 6000\frac{hours}{yr} * TWh\ conversion = Hydrogen\ flow$$

Equation 1

Therefore, the future hydrogen price can be calculated using the equation below:

$$(1 - Learning\ Rate\ (\%))^{Number\ of\ times\ production\ volume\ doubles} * Hydrogen\ Price = New\ Hydrogen\ Price\ (\frac{£}{MWh})$$

Equation 2

The resultant prices are compared to the price of natural gas in 2030. The natural gas price was approximated from data published by BEIS as part of the 'Non-Domestic Energy Price' releases (BEIS, 2022a). This 2030 estimated price range is based on the most recent average annual prices paid by industry for the last three years. Despite natural gas being a mature, typically stable commodity, the average cost in 2020 was the lowest in 15 years, and the 2023 average cost was the highest ever. Thus, it is assumed highly unlikely that the price will deviate from these extremes in 2030.

3. RESULTS AND DISCUSSION

Of the 25 articles, 26 demand-pull policies were included in the analysis (Table 3). It was found that policies had varying rates of success depending on region, sector, aspect of ecosystem or policy instrument. These rates provide information on the effectiveness of individual policy characteristics. The success rate of policies varied regionally from 0-100%, by aspect of ecosystem 68-100%, and by policy instrument 50-100%. Based on these findings, two policies are recommended. First, a tax incentive for fuel switching installations. Second, a subsidy to buy hydrogen fuel was suggested, since hydrogen is at present more expensive than traditional natural gas. Subsidies and tax incentives were successful 88% of the time.

Table 3. The number of specific policy instruments in the policies studied. For policies that contained more than one aspect, each aspect was counted

Policy Type	Number of Occurrences	Number of Successes	Percentage of Successes
Carbon Tax / sequestration credit	9	6	67%
Grants or funding	3	2	67%
Tax Incentive	8	7	88%
Subsidy	8	7	88%
Cap and Trade	2	1	50%
Rebates	1	1	100%
Certification scheme	2	1	50%
Price fixing	1	1	100%

The REA findings show that failures of specific policy instruments occurred because of a policy system, rather than a singular policy. The calculations carried out using the learning rate and current hydrogen price have resulted in a unique hydrogen price range based on the 2030 5GW production capacity target (a supply push policy). Table 4 contains the results of these calculations compared with the expected price of natural gas in 2030. Both learning rates (26% and 19%), and both the current price range estimates, demonstrate that the green hydrogen price does not fall below the expected price of natural gas in 2030. The lower bound of the range for both learning rates falls within the expected natural gas price range in 2030, however neither falls below the lower bound of the expected natural gas price. Figures 1 and 2 show industrial fuel demand, and expected hydrogen consumption to support the UK net zero ambition. The study finds that 5GW electrolytic production capacity yields 16.45 TWh of hydrogen. The UKTM demonstrates that it is expected that natural gas consumption from industry will experience a significant decline, whilst hydrogen fuel consumption will experience significant growth (Figure 2). By 2030, natural gas consumption is likely to decrease by 37 TWh whilst hydrogen consumption is likely to increase to 25.22 TWh. Meanwhile, Figure 3 shows that the future hydrogen price at 16.45 TWh of production, lies between £14.66 and £54.56/MWh, providing an optimistic and a pessimistic scenario for the future price of hydrogen.

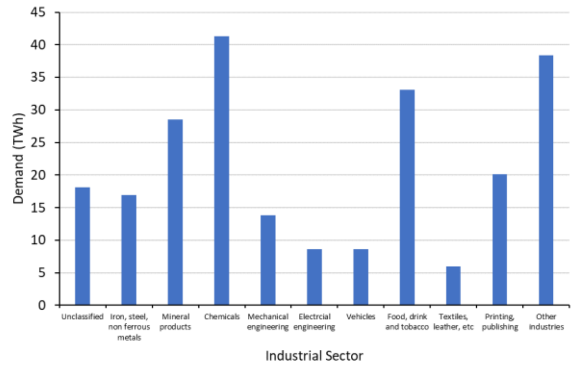

Fig. 1. Total industrial fuel demand by sector in 2020 (Total: 233 TWh) (Sources: BEIS, 2021b)

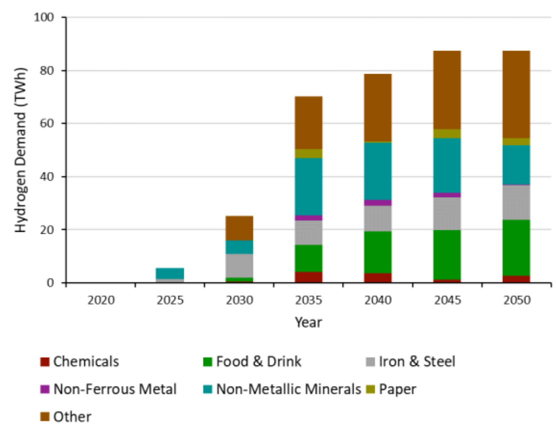

Fig. 2. Future industrial hydrogen fuel consumption by sector (Source: UKTM central Net Zero scenario)

This is comparable to an estimated natural gas price expected to be between £14.64 and £25.48/MWh. Meanwhile, other studies have determined that the price would be £63/MWh (Element Energy & Jacobs, 2018), whilst another provided a range of between £22.86 - £53.59/MWh. Compared with Table 4 these estimates seem aligned with a learning rate of 19%.

Table 4. Green hydrogen 2030 price (£/MWh) range based on learning rates and two different price estimates compared with expected 2030 price range of natural gas

Green Hydrogen (£/MWh)				
	26% Learning Rate		19% Learning Rate	
	Lower	Upper	Lower	Upper
European Commission	**£17.41**	**£38.34**	**£24.77**	**£54.56**
KPMG	**£14.66**	**£35.20**	**£20.87**	**£50.10**
Natural Gas (£/MWh)				
	Lower	Upper		
	£14.64	**£25.48**		

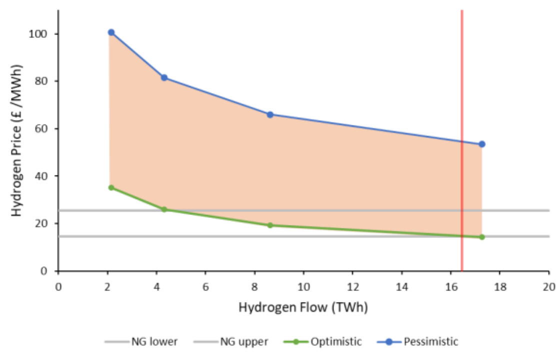

Fig. 3. Pessimistic and Optimistic hydrogen price scenarios compared to the volume of hydrogen produced using learning rates. The expected natural gas price range is indicated in grey, and the 2030 production volume is indicated by the red line

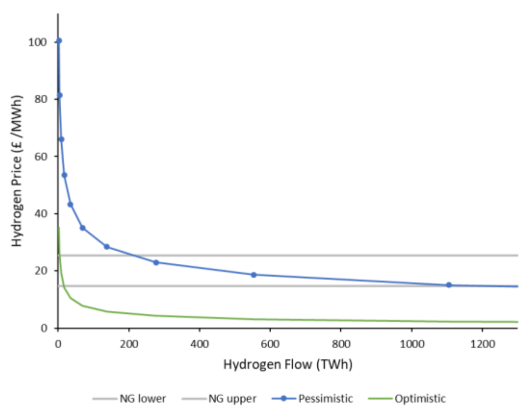

Fig. 4. The hydrogen price scenarios extrapolated over a larger hydrogen production volume

The curve demonstrates the price reducing effect of learning rates as more hydrogen is produced. This curve can be extrapolated to demonstrate that in the pessimistic hydrogen price scenario, competitiveness will be achieved at a 65 GW to 350 GW production capacity if supply policies are used alone (Figure 4). Hence, the two demand-pull policies (natural gas tax and clean hydrogen subsidy) from the REA will be implemented. The study has demonstrated that in 2030, supply can be sufficient to meet demand, but the hydrogen price will not be competitive. Therefore, demand-pull policy must bridge the price gap between natural gas and electrolytic hydrogen. The four price difference scenarios from Figure 3 are coded below:

Pessimistic Hydrogen Scenario – Natural Gas Lower (PsH-NgL)

Pessimistic Hydrogen Scenario – Natural Gas Upper (PsH-NgU)

Optimistic Hydrogen Scenario – Natural Gas Lower (OpH-NgL)

Optimistic Hydrogen Scenario – Natural Gas Upper (OpH-NgU)

These price differences are displayed in **Error! Reference source not found.**ure 5, and represent which scenarios would require the most policy intervention for hydrogen to be competitive with natural gas.

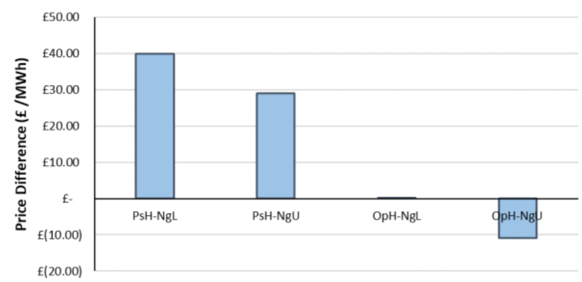

Fig. 5. Four scenarios of price difference between electrolytic hydrogen and natural gas in 2030

To suggest a best-case policy intervention using taxes and subsidies, the four price difference scenarios have been used to model four different optimised tax/subsidy policy scenarios. A combination of natural gas tax and clean hydrogen subsidy worked together at an optimised level to create price parity, meanwhile reducing the absolute cost to both government and industry. However, despite a high level of uncertainty, by optimising the balance between a tax and subsidy working in tandem, the price of hydrogen should be competitive with natural gas in 2030. An example of this is represented in Figure 6. Understanding future fuel consumption dynamics is based on data from the UKTM central Net Zero scenario which itself is based on a multitude of assumptions that enable an impression of what future consumption could look like. It is important to consider these findings as providing, within the mixedmethod context, an informed interpretation of the future.

Table 5. Optimised tax and subsidy values (£/MWh) and associated cost to government and industry (£/MWh)

	Tax (Ng+ £/MWh)	Subsidy (H- £/MWh)	Cost to Government (£/MWh)	Cost to Industry (£/MWh)
PsH-NgL	£13.30	£26.62	£13.32	£13.30
PsH-NgU	£9.69	£19.39	£9.70	£9.69
OpH-NgL	£0.0065	£0.0135	£0.007	£0.0065
OpH-NgU	0	0	0	0

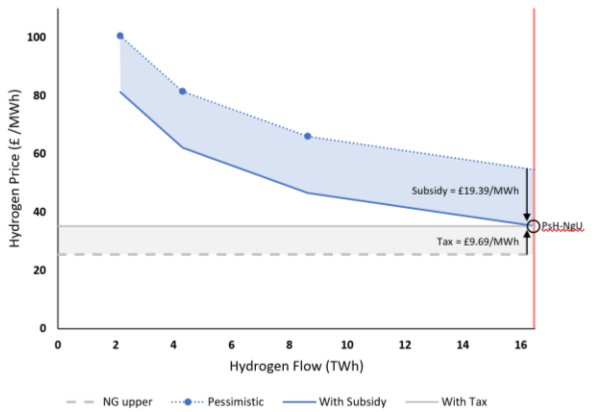

Fig. 6. Optimised supply and demand policy impact curve for PsH-NgU

4. CONCLUSIONS

This study has assessed the UK government's attempt to establish an industrial hydrogen economy, through investigating how the new 5GW electrolytic hydrogen production target in 2030 will change the dynamics of industrial fuel and feedstock consumption. A mixed-methods approach was selected to optimise the validity of the findings given the high levels of uncertainty associated with this subject. A key finding of the study is that UK hydrogen policy is heavily skewed to the supply side. Therefore, a research gap exists, whereby an investigation into the optimal balance of supply and demand policy to initiate an industrial hydrogen economy was determined. This would be useful to inform future policy makers in different economies about the 'least cost' approach for initiating competitive hydrogen markets. Unique to this study is the calculation of the 2030 electrolytic hydrogen price using expected capacity and the learning rate effect. The study finds it is unlikely that hydrogen will be economically competitive with natural gas based on supply-push policy alone – It is calculated that under the current supply-push approach, a target of 65-350GW of electrolytic production capacity is required to render price parity with natural gas. Therefore, the study emphasises that demand-pull policy must be implemented in tandem. Incentivising demand will drive innovation, reduce cost further and engender the growth of the market more effectively. An optimised combination of a natural gas tax and a clean hydrogen subsidy is suggested to distribute the absolute cost of incentivising hydrogen consumption between government and industry. Therefore, supply-push and demand-pull policies working in tandem are necessary for a competitive hydrogen market. Since Individual policies do not exist in a vacuum—policy makers must fully understand the interactions between new and existing policies to make sure that they complement rather than inhibit each other.

DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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