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Abstract. The ever-growing evidence of the climate emergency continues to drive the need for innovative solutions to reduce the release of anthropogenic harmful gases. Continuing to heavily rely on energy originating from fossil fuels remains non-sustainable owing to their limited, exhausting supplies, dependence on politically insecure sources and adverse environmental impacts. These considerations, coupled with the current desperate need for energy security, have driven research towards finding cleaner alternatives. Hydrogen (H_2) has the potential to reduce 5Gt of CO_2 emissions annually, create 30 million new jobs and power over 400 million cars by 2050. However, for hydrogen to be justified and to be successful in feeding the world's appetite for energy, its full life cycle, including its production methods, is required to be safe, efficient, affordable and environmentally benign. This paper aims to review the status of the potential hydrogen production methods that have strong eligibility within the UK and facilitate the much-required wider discussion around hydrogen by employing a multi-disciplinary approach. The analytic hierarchy process (AHP) has been employed to allow for pairwise comparisons of decision criteria and ranks decision alternatives using expert knowledge. Six hydrogen production methods (Green Electrolysis, SMR, ATR, POX, Anaerobic Digestion and Gasification) were chosen for review against nine parameters to determine which hydrogen production method(s) present most viable for the UK to aid in decarbonising the energy system. Collating performance scores against relevant parameters from industry experts allowed for a non-bias, holistic review of the production methods. Green electrolysis was found to be the better method (score 131) when assessed against all but one parameter, resulting in the method being considered the most viable option for the UK, however, considerations are to be made for electrolyser longevity and cost. SMR score second most viable (score 125), however, despite presenting as an effective production method for the UK based on the performance scores, this does not reflect the current deployment or construction rate of SMR with CCS projects in the UK. ATR (score 114) and POX (score 116) carry similar characteristics and subsequently scored similarly in performance scores. Anaerobic digestion (score 104) and gasification (score 101) scored amongst the lowest as their challenge is to scale in order to reach government goals as set out in the Government Hydrogen Strategy.

Keywords: Hydrogen, Analytic hierarchy process, Sustainability, Energy

1. Introduction

General background

The welfare and comfort of all life on earth heavily depend on the success in the development of science and technology. Energy production lies at the heart of this development, as it is central to the functioning of our ecosystem and modern human society. However, the demand for energy continues to accelerate due to the ever-growing human population. Global energy demand predictions show an increasing trend with an annual consumption predicted to reach around 778 Zetta Joule by 2035 (Zhang and Yang, 2018). As we witness this surge, the purpose of energy as an essential commodity for promoting productivity in both agriculture and industry is highly recognised.

Conventional fossil fuels continue to dominate the source of energy; currently, 80% of the world's energy demand is met by fossil fuels (Moodley and Trois, 2021). However, despite their widespread availability and convenience of use, fossil fuels are not expected to keep up with the surge in the world's appetite for energy. During the combustion process, large quantities of greenhouse gases (GHGs), such as methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O) are emitted into the atmosphere. Subsequently, these gases are accumulating as an insulating blanket around the earth, trapping the Sun's heat in our atmosphere. This in turn is warming our planet which poses an array of detrimental impacts on the health of our environments, ecosystems and biodiversity. To really highlight the scale of emissions, in 2018, global CO_2 emissions peaked at 408.52ppm, a figure recognised as the highest level recorded in over 800,000 years (Ritchie, Roser and Rosado, 2020). Moreover, global energy-related CO_2 emissions rose by 1.7% to a record high of 33.1 Gt as a result of increased energy demands (IEA, 2019). Without intervention, atmospheric warming attributable to anthropogenic emissions will continue to persist for centuries to millennia and subsequently continue to pose these long-term adverse effects on our climate system. To push the global response to this matter, the Climate Change Act seeks to maintain a global temperature rise of below 2^{0}C with further efforts to limit this to 1.5^{0}C (UNFCCC, 2019). To align with this goal, global emissions must decrease by 7.6% per annum between 2020 and 2030 (UNEP, 2020). With these statistics in mind, significant transitions in our energy systems are required in a rapid time frame.

In addition to fossil fuels' damaging consequences due to their associated GHGs, there is also evidence of a significant surge in oil and gas prices across the globe. This is a result of the political insecurities of the countries that withhold the supplies. In the current climate (September 2022), European countries are applying sanctions on Russia as a punitive measure and to deprive the country of revenue in response to the invasion of Ukraine. The repercussions of these sanctions are having a detrimental effect on energy availability across Europe as conventionally, ~40% of European gas consumption originates from Russia (IEA, 2022). However, sanctioning Russia's pipeline exports has led to a net loss of gas available to the world's market and has sent utility prices spiking for all customers. As we witness soaring gas and electricity prices (rising by 50% (Zakeri et al., 2022)) across Europe, predictions for intensified inflation and a heightened risk of a recession are being realised. Furthermore, fossil fuels are not expected to keep up with the world's ever-increasing energy demand due to their finite nature and nonhomogeneous distribution (Acar and Dincer, 2019). Despite even the case of fixed damage, current depletion rates evidence that oil reserves are expected to be completely used up in less than 80 years (Acar and Dincer, 2019). These considerations, coupled with the current desperate need for energy security, have driven the necessity toward finding cleaner, more secure, energy source alternatives.

Hydrogen

Hydrogen has been recognised as an emerging, unique and clean alternative energy source as it has many potential energies uses such as powering vehicles (Manoharan et al., 2019), fuelling air crafts (Baroutaji et al., 2019), and heating homes and offices (Scott and Powells, 2020). Furthermore, it is reported that hydrogen could meet 18% of final energy demand, reduce 5 Gt of CO_2 emissions annually by 2050 and create 30 million new jobs (Uyar and Besikci, 2017). According to the UK's Hydrogen Strategy, the government is aiming for 10GW of low carbon hydrogen production capacity by 2030 for use across the economy (GOV, 2021). The strategy looks at methods to capture the economic benefits of growing the UK hydrogen economy, supporting innovation and stimulating investment to develop the supply chains and skills needed, and creating jobs and export opportunities for the UK.

In order to accomplish a fully developed hydrogen economy and to establish hydrogen as a critical component in the energy market, significant research and investment in hydrogen production methods is required. As discussed, hydrogen has been recognised for its environmentally benign characteristics when utilised for energy, however, those advantageous characteristics only benefit the point of use and can be tarnished by hydrogen's complex production methods. Despite methods posing efficient production potential, the challenges of hydrogen production span beyond those of a technical nature. Adopting a production method must ensure compliance with policy and regulatory barriers, whilst also considering all wider parameters, such as social implications. The Department for Business, Energy and Industrial Strategy (BEIS) has released the UK Hydrogen Strategy 2021 which aims to see a deployment of 10GW of low carbon hydrogen production capacity by 2030 (GOV. 2021). However, the industry can be considered in its infancy as we start the transition away from fossil fuels, and thus being paramount, that research is undertaken to support the government in determining which production methods will play a vital part in contributing to this goal and offer guidance when allocating financial subsidies.

Hydrogen Production Methods

There is an array of hydrogen production methods available today due to the advancement in technological abilities. The different types of hydrogen production methods can be broken down into several different subcategories, which differ across the literature. Several papers distinguish between renewable and non-renewable sources (Nikolaidis and Poullikkas, 2017), others prefer to split technologies by primary energies (i.e. thermal, electrical, photonic and biochemical) (Wang et al., 2019). Hydrogen production methods can also be categorised by their cleanliness with three main colours: grey, blue and green. Grey is considered the most polluting type of hydrogen with fossil fuels as the primary source; blue is defined by carbon capture and storage (CSS) inclusive with grey hydrogen; and green refers to 100% renewable energy source (Dawood, Anda and Shafiullah, 2020). However, this colour coding system fails to determine accurately how clean the hydrogen that is produced as it only factors in the energy type rather than the amount of GHGs emitted during the production process. Therefore, comparing methods by their cleanliness via the colour coding method can be limiting when wanting to comparatively assess all areas individually.

Table 1: Description of the six hydrogen production methods chosen for analysis in this study.

Method	*Primary energy*	*Material*	*Brief description*
Green Electrolysis	Electrical	Water	Direct current splits water into O_2 and H_2
Steam Methane Reforming (SMR)	Thermal	Fossil fuels	Thermal heat converts fossil fuels to H_2 and CO_2
Autothermal Reforming (ATR)	Thermal	Fossil fuels	Thermal heat converts fossil fuels to H_2 and CO_2
Partial Oxidation (POX)	Thermal	Fossil fuels	Thermal heat converts fossil fuels to H_2 and CO_2

Anaerobic Digestion	Biochemical	Biomass	Natural break down biomass to create H_2 and CH_4
Gasification	Electrical/ Thermal	Biomass	Heat, steam and oxygen converts biomass to H_2

Collaboration across varying stakeholders and disciplines is crucial in establishing a market for hydrogen. Despite the ever-growing body of literature regarding hydrogen, there are very few publications, if any, that have integrated research from multiple disciplines to address hydrogen in its wider context. Research papers typically focus on hydrogen technologies and their association with only one discipline, such as government (policies) or local communities, rather than gathering data from all affected disciplines to achieve a more holistic result. Furthermore, the available literature assesses hydrogen production methods against only one or limited parameters, such as efficiency or cost; limiting the viability of these papers. Finally, hydrogen production methods that will not be supported by government subsidy, or methods that see no future within the UK hydrogen economy due to their unfavourable nature, have been incorporated within published literature.

To address this existing gap in the literature, this paper aims to review the status of the potential hydrogen production methods that have strong eligibility within the UK and facilitate the much-required wider discussion around hydrogen by employing a multi-disciplinary approach. This study discusses the most UK-adopted production methods and technologies. Details on the research project will subsequently be discussed, including the chosen data collection, analysis and utilisation procedures. Data results have then been interpreted for discussion.

Review of Current Literature

After an extensive review of the current literature, it is evident that research has been undertaken with the same objective as this paper, however, the methodology for the already published research lacks robustness and thus does not provide completely reliable results. Only one or a limited number of parameters are assessed per paper, such as storage (Zhang et al., 2015); cost (Al-Qahtani et al., 2021); and energy and exergy efficiency (Dincer and Acar, 2019). A study by Nikolaidis and Poullikkas (2017) investigated 14 hydrogen production methods in relation to their sustainability, system efficiency, scalability, and investment costs which are among the parameters assessed for both new and conventional hydrogen production methods. The study revealed that thermochemical pyrolysis and gasification were the most economically viable as they provided the most potential for large scalability, whereas, water splitting technologies exhibit low conversion efficiencies with high investment costs. However, considerations for environmental and social impacts lacked, which reduced the value of this paper's research as these two considerations are at the forefront of today's decision-making. This is also reflected in several further studies; Fukuzumi, Lee and Nam (2018) explored thermal and photocatalytic hydrogen production with earth-abundant complexes. Despite demonstrating the possibility of reduced production costs and improved efficiency, the assessment of the environmental impact of this method was neglected.

Contradictions between papers has also been observed during this literature review research. A study on low-cost hydrogen production by anion exchange membrane electrolysis was reviewed (Vincent and Bessarabov, 2018). The authors of this paper identified directions and the need for future research in water electrolysis, specifically highlighting performance and reference to previously conducted research on membranes, electrocatalysts, and ionomers used in electrolysers. By doing this, it was concluded that further investigation and improvements were required in order for this technology to fulfil its optimal potential. Whereas Acar, Dincer and Naterer (2016) discuss that this method is well-established and capable of producing hydrogen at promising rates with high efficiencies and therefore, does not require further investigating as the previous paper stated. However, although the technical, economic and safety aspects have been considered, the environmental and social impacts are again, to have been disregarded, thus questioning the reliability of the results of this study.

A possible reason for the disregard of relevant parameters could be a lack of funding or resourcing available for the reviewed studies. This paper however has conducted essential preliminary research to ensure all relevant parameters are assessed to heighten the reliability and effectiveness of the results.

Review of Current Literature Methodology

There is a diverse range of literature that assesses and compares H_2 production methods against different parameters to aid in determining which would be the preferred method to implement. Although there is diversity in the aims of the studies, common denominators can be seen within the methodological choices. The life cycle assessment (LCA) is a well-developed methodology preference to evaluate the inputs, outputs and impacts of products and systems. The application of the LCA on H_2 production has increased rapidly to support challenging decisions, particularly with the selection of technology pathways. Despite accessibility to LCA guides (Klöpffer and Grahl, 2014; Zampori et al., 2016), along with international standardisation, such as ISO 14040:2006, studies on H_2 production methods follow their own methodological choices within the LCA. This heavily influences final interpretations of results as the discrepancy in methodological choices restricts robust comparisons being made. A study by Mehmeti et al. (2018) looked at a process-based streamlined LCA of several H_2 production methods by combining impacts at the mid-point and end-point with the use of the impact method ReCiPe 2016 - a harmonised life cycle impact assessment. Furthermore, the analysis of water consumption associated with H_2 production to better understand life-cycle water- related impacts on human health and the environment was assessed. This method differentiates from conventional studies where a single approach is applied and only one impact stage is assessed. This study can be considered effective and reliable as not only does it provide a more accurate review of how the process affects human health and the environment, but the impact assessment on water use has become an emerging interest to the LCA community, due to the ever-growing concern of water availability and quality across the globe, and has now been adopted across several studies (Berger and Finkbeiner, 2010; Boulay, Hoekstra and Vionnet, 2013; Hoekstra, 2016; Kounina, 2016).

Furthermore, many studies on hydrogen production conduct their work within the frame of Task 36 of the International Energy (IEA) Hydrogen Implementing Agreement (HIA). This document seeks to facilitate decision-making within the hydrogen production section by providing a robust methodological framework based on the life cycle sustainability assessment (LCSA) on hydrogen energy systems (Valente, Iribarren and Dufour, 2017). A study by Dufour et al. (2011) adopted the use of IEA HIA to evaluate the potential evolution of different hydrogen production technologies with fossil fuels at the source. The study proposed future scenarios by the IEA to detect how the technologies could perform differently in relation to the different GHG emission generation rates, including the World Energy Outlook (WEO) analysis which is studied and published by the IEA on an annual basis. In 2011, the WEO baseline case predicted some moderate policies on global warming to be implemented, however, are to be strongly restricted by economic factors. It is evident from the current climate that these predictions lacked accuracy as there has been a significant spike in policies and plans for the future of alternative energy sources. It should, however, be noted that despite the prediction not reflecting entirely on the present condition of laws and legislations, environmental protection policies will always have a battle against economic factors in some way or another.

2. Methodology

Chosen Methodology

Many methods and multi-criteria decision-making appro aches such as the AHP (analytic hierarchy process), A NP (analytic network process) and technique for order preference by similarity to ideal solution (TOPSIS) wer e developed to support researchers in ranking proposed factors that are being assessed. This study will use the benefit of the analytic hierarchy process to rank differe nt hydrogen production methods based on all relevant parameters. Decision makers and stakeholders then have the opportunity to use the outcome of this study to su pport informed decisions about determining the implem entation of a hydrogen production method.

The AHP is a measurement technique that performs pairwise comparisons of decision criteria and ranks decision alternatives using expert knowledge. The AHP links to the research objectives of this study as the method allows for a robust investigation into relevant parameters and a thorough comparison of varying hydrogen production methods via performing pairwise comparisons.

The justification for deciding a hydrogen production method carriers an array of parameters that must be considered to allow the method to be considered viable. Currently, commercial-scale green and blue hydrogen lies within its infancy and therefore, it is paramount we investigate and determine the most viable hydrogen production method for the UK. To determine which hydrogen production method(s) present as the most viable for the UK, a full exploration of all influencing factors needs to be undertaken, including an analysis of feedback submitted by multi-disciplinary industry experts and the determinants of the project parameters. Therefore, the AHP has been allocated for this study as it aligns with the necessary requirements by providing a non-bias review and ensures impartiality in decision-making, reflecting all values and priorities.

Chosen data

In this study, chosen hydrogen production methods underwent a performance assessment against relevant parameters which carry the appropriate weightings. Initially, the hydrogen production methods, discussed in Table 1, were determined with support from the Hydrogen Strategy set out by UK government. The strategy looks to launch a £240 million Net Zero Hydrogen Fund in early 2022 for co-investment in early hydrogen projects. Grey hydrogen is not supported in the business model due to its associated high GHG emissions and subsequently not discussed in this study. All methods discussed in this paper are eligible for government funding, and therefore are considered vital contenders in this comparison assessment.

The chosen parameters, as discussed in table 2, were selected via an intensive literature review (Al-Qahtani et al., 2021; Dincer and Acar, 2019; Nikolaidis and Poullikkas, 2017 Zhang et al., 2015) and interviews with two industry experts; one expert known on a personal level who works in research and withholds strong knowledge of the hydrogen industry and the other who works on the development of a blue hydrogen project, whose details were provided by a family member. The nine chosen parameters are considered to cover all relevance to considerations when determining a hydrogen production method.

Table 2: Chosen parameters for this study.

Parameter	*Description*	*Category*
CAPEX (Capital Expenditure)	○ Construction costs ○ Equipment costs ○ Raw materials ○ Labour costs ○ Legal/financial costs	Economy
OPEX (Operation Expenditure)	○ Production costs ○ Maintenance ○ Employee salaries	Economy

	○ Logistics	
Social	○ Local disruption ○ Noise ○ Pollution ○ Job creation ○ Job security	Society/ Economy
Longevity	○ Long-term stability	Technology
Scalability	○ Can the method scale to meet GOV goals?	Technology
E of O (Ease of Operation)	○ How easy is the method to operate? (equipment, required staff and skills)	Technology
Environmental	○ GHG emissions ○ Landscape disruption ○ Embodied carbon ○ Wildlife disruption	Environment
Efficiency	○ How much energy is converted from source to hydrogen?	Technology
Maturity	○ How established is the technology? ○ Technology Readiness Level	Technology

Data collection procedures

This study utilised three data collection procedures to capture the required information in an appropriate manner, including:

- Survey
- Interview
- Secondary Data

The variety in data collection procedures allowed for a higher influx of responses and were tailored to the parameter's nature of being either measurable and have units which are found as factual data within literature, or subject to variations. The survey requested the participant to rank the parameters in order of importance, from 1 (most important) – 9 (least important), when determining a production method. The average ranking place for each parameter was then determined and a subsequent weighting factor was allocated for each parameter. When determining the performance score for each parameter, CAPEX, OPEX, social, longevity, scalability, ease of operation and environmental were collected via a survey or interview with industry experts who were contacted primarily via LinkedIn after an assessment of expertise background. The efficiency and maturity of each method underwent a performance score based on secondary data via a literature review. The efficiency looks at the energy conversion percentage for each method and is available from studies conducting this research. The assessment of the maturity of technologies used Technology Readiness Level (TRL) – a method employed by researchers to determine the level of maturity for a given technology. A score of 0 implies the method scored poorly against that parameter, whereas 5 would suggest it scored well.

How the data was analysed

The AHP solicits industry experts' assessment and secondary data for the performance of hydrogen production methods against relevant parameters using a scale of 0-5.

Table 3: Performance scores of parameters.

	Scores	
Parameter	**0**	**5**
CAPEX	Most expensive	Least expensive
OPEX	Most expensive	Least expensive
Social	Extremely negative impact on local community	Significantly positive impact on local community
Longevity	Expected short life span	Long-term sustainable life span
Scalability	Very challenging to scale to meet GOV goals	High potential to scale
Ease of operation	Very difficult to operate	Relatively easy to operate
Environmental	Most harmful to the environment	Very little or negligible impact on the environment
Efficiency	Small or negligible energy conversion rates	Very high energy conversion rates
Maturity	New or undeveloped	Well-established

Once all surveys, interviews and secondary data assessments were completed, the data analysis included separating the parameters to see where each method ranked after determining the mean average of all participant's scores for that given parameter. Figure 1 highlights the underlying hierarchical structure of the survey where results subsequently rank hydrogen production methods.

The ranking of hydrogen production methods could be conducted via a variety of methods such as data envelope analysis (DEA) and TOPSIS, however, the AHP has been decided to be the most appropriate method for the analysis of problems with hierarchical structures similar to that in Figure 1. Furthermore, the AHP performs better in regard to obtaining experts' responses and checking the consistencies of the responses than other assessment methods. Figure 2 supports the readers of this paper understand the procedural process chosen for this study from preparation of survey, to interpretation of results.

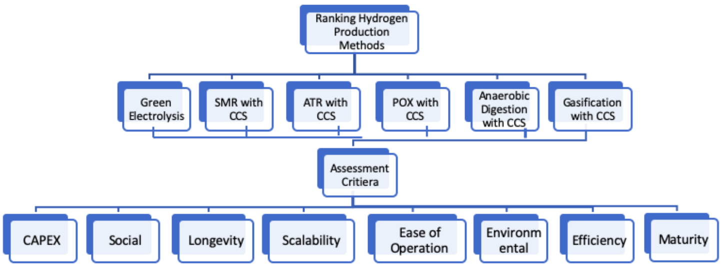

Figure 1: Hierarchy Structure of Ranking and Selection of Hydrogen Production Methods

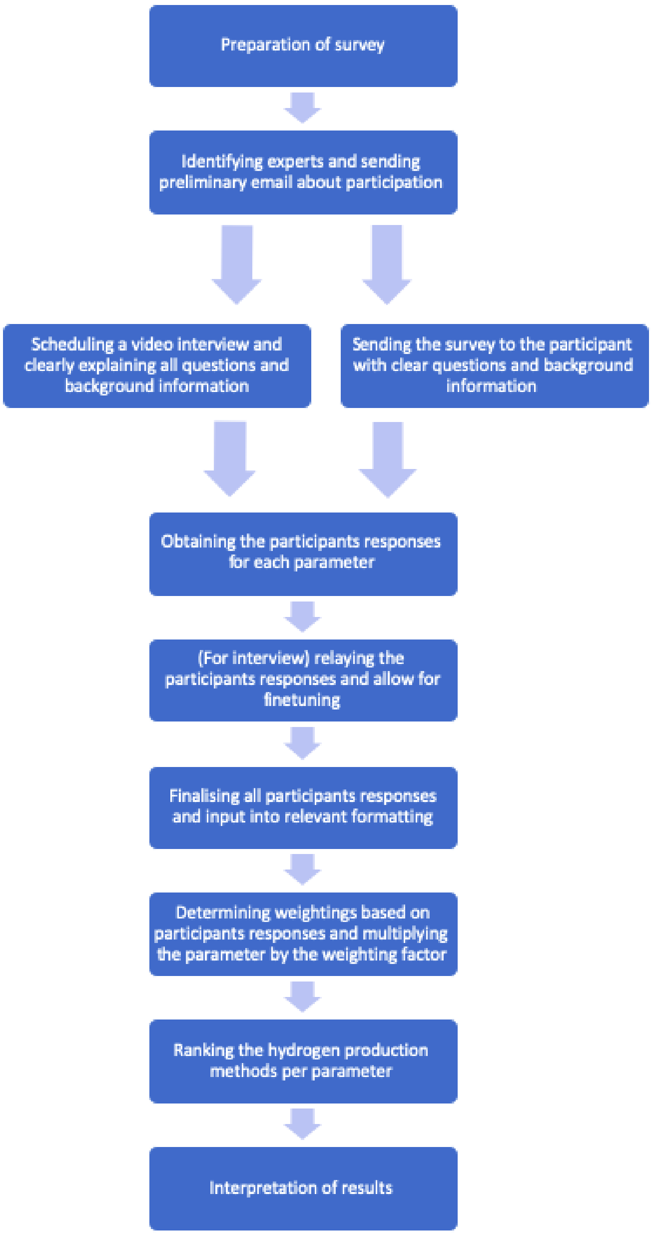

Figure 2: Flowchart of the AHP process used in this study.

3. Results

The research survey was sent to 87 industry experts via LinkedIn with 22 respondents. Justification for survey scores were provided by the industry experts and are discussed later within this section of the paper.

Weightings

As part of the survey, participants were asked to rank the nine parameters in order of importance. Figure 3 provides the mean average ranking number for each parameter based on industry expert feedback.

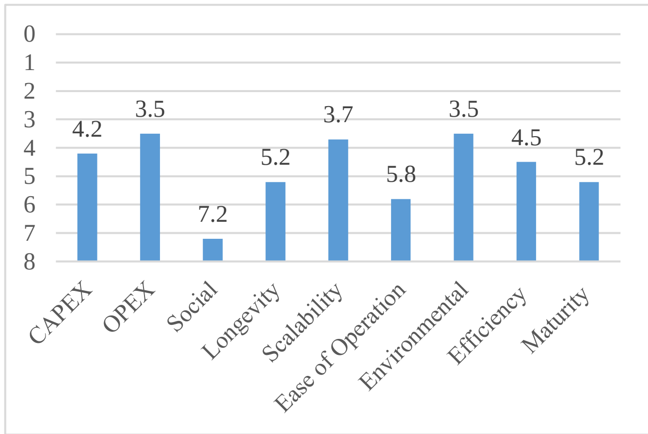

Figure 3: Mean average ranking number for each parameter based on industry expert feedback.

Figure 3 demonstrates social and ease of operation are the least important to industry experts, with OPEX and environmental ranking the highest importance. An observation can be seen within the longevity score as it sits within the parameters of lesser importance to industry experts. With the global agenda to find a sustainable alternative energy source, longevity would have been expected to have been ranked higher.

Based on the mean average scores highlights in figure 3, weightings have been determined and displayed in table 4. As the rankings ranged from 1 (most important) – 9 (least important), subsequent calculations allowed for accurate weightings for each parameter.

Table 4: Weightings for each parameter based on industry expert's' importance rankings.

Parameter	Weighting
CAPEX	5.8
OPEX	6.5
Social	2.8
Longevity	4.8
Scalability	6.3
E of O	4.2
Environmental	6.5
Efficiency	5.5
Maturity	4.8

Performance Scores

The total performance scores of all nine parameters for each production methods are displayed in table 5 and figure 4. All assessed methods that emit GHGs as a by-product during production have only been considered with the integration of carbon capture and storage (CCS) to ensure alignment with The Hydrogen Strategy.

Table 5: Total performance scores.

	Method					
Parameter	Green Electrolysis	SMR (with CCS)	ATR (with CCS)	POX (with CCS)	Anaerobic digestion (with CCS)	Gasification (with CCS)
CAPEX	12.8	11.6	8.7	12.8	10.4	9.3
OPEX	15.0	11.1	13.0	13.0	13.7	15.0
Social	7.8	7.6	6.7	6.7	6.4	6.7
Longevity	13.4	13.0	11.5	11.5	11.0	11.5
Scalability	17.6	17.0	15.1	15.1	14.5	15.1
E of O	11.8	11.3	10.1	10.1	9.7	10.1
Environmental	18.2	17.6	15.6	15.6	15.0	15.6
Efficiency	16.5	22	16.5	16.5	16.5	8.3
Maturity	18.2	13.4	16.8	14.4	7.2	9.6
Total	**131**	**125**	**114**	**116**	**104**	**101**

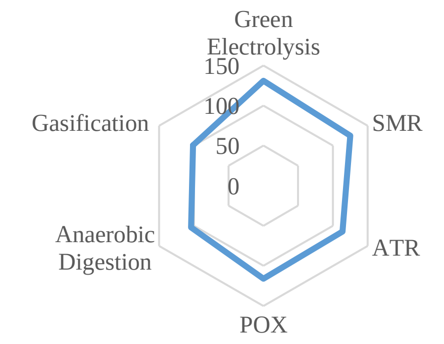

Fig. 4 Radar chart of total performance scores.

Green Electrolysis

As presented in table 3 and figure 4, green electrolysis displayed the highest overall score when all performance scores for each parameter are combined. This suggests that green electrolysis presents as the most viable hydrogen production method for the UK, as decided by industry experts, followed by SMR, POX, ATR, Anaerobic Digestion and Gasification respectively. Aside from efficiency, green electrolysis scored highest in all performance scores for each parameter. However, research and development are required in electrolyser production, costs and longevity, although evidence now demonstrations a decrease in electrolyser costs via the development of Gigafactories. The method offers positive social impacts as strong job creation and security are associated with its infinite nature which further supports the methods longevity potential. However, considerations are to be made for the vast land use requirements for the renewable power generation. Due to the method acquiring no associated pollutants or upstream footprints, it is considered the method with the highest scalability potential. This can be supported by projects such as the Whitelee project, HyGreen and Protium which are all aiming for to supply green hydrogen on the commercial market by mid-2020s. Green electrolysis plants are also being designed to work autonomously to aid in ease of operation, although this contradicts the methods attribute of offering promising job availability and security. Moreover, as the method is still within nascent development, future issues for autonomous production have not been fully discovered. Despite the method sourcing renewable power for production, and is the cleanest method of hydrogen production, attention should be made to the rare earth mineral mining which retrieves the rare elements and precious materials that are required in electrolysers. The efficiency of green electrolysis depends on whether the method is employing Polymer electrolyte membrane (PEM), Alkaline or Solid oxide (SOSE) electrolysis. PEM electrolysis carries the highest efficiency of ~81% whereas SOSE obtains an efficiency of ~56%. The maturity also depended on the specific electrolysis method adopted, however, as there are currently three utility scale green hydrogen plants under construction for predicted operation by mid-2020s, green electrolysis again scored the highest for this criterion.

SMR with CCS

SMR with CCS scored as the second most viable with a total score of 125. Despite presenting as an effective production method for the UK based on the performance scores, this does not reflect the current deployment or construction rate of SMR with CCS projects in the UK. SMR provides the UK with the majority (>80%) of its hydrogen and is therefore considered a well-established, proven technology. However, without the integration of CCS, the method would not be eligible for government incentives. Furthermore, as gas prices continue to surge, the OPEX for SMR, along with all other fossil-fuelled production methods, will increase, however, feedback highlighted that CCS plants are relatively easy to operate. The requirement of CO_2 pipelines can cause local disruption to local and environments and efforts must be made to reduce the negative social impacts produced through the large infrastructure requirements and significant landscape disruption. With regular maintenance, a long life in service is achievable and commitments today could mean operation to still be active in 2050. However, considerations are to be made for the ongoing rise in gas prices and the finite nature of CCS facilities. In terms of scalability, the technology today can be deployed at GW scale, however, CCS plants must meet this capacity. Despite the challenges of heat provision, the maturity of the method has resulted in reasonably simple operation. Whilst the method continues to rely on fossil fuels, the encouragement of harmful gas extraction will persist, resulting in adverse environmental impacts. SMR can exhibit high efficiencies, although alternative methods are considered better. Finally, the maturity of the method is among the highest, however, this is without the integration of CCS facilities and the small number of current utility-scale plants evidence the lack of recognition for the method.

ATR and POX with CCS

ATR and POX overall scored very similarly (114 and 166 respectively), and the feedback from industry experts often coincides for the two methods. The main discrepancies between the two methods lie with the CAPEX and OPEX. ATR exhibits a 17% lower CAPEX due to the accompanying smaller H_2 compressor, whereas POX demonstrates a lower efficiency rate than that of ATR resulting in a higher OPEX. ATR is currently the most accepted technology to create low-carbon H_2 given that CO_2 facilities are in place as it maximises the amount of H_2 produced per unit of hydrocarbons used as feedstock. Both methods also incorporate the need for natural gas for production where there is a coupled requirement of CO_2 pipelines which cause disruption to local landscapes. Furthermore, as these methods fall under blue hydrogen, job security is not considered sustainable. As with SMR, the longevity of these plants heavily depends on gas availability and cost. There is also the potential impact of future government regulations causing a restriction on hydrogen production entailing natural gas, particularly if the carbon net-zero goal is struggling to be met. Despite being less mature than SMR, both methods have been recognised by successful construction and production companies (Cadent and Shell) and utility-scale projects are currently under development. As a whole, the two methods carry very similar performance scores for the assessed criteria and whilst the methods withhold some appealing characteristics, such as high-efficiency rates, the elephant in the room is to be addressed that whilst natural gas is still heavily relied upon, the future of blue hydrogen is questionable.

Anaerobic Digestion and Gasification with CCS

Anaerobic digestion and gasification sit at the bottom of the total performance scores with 104 and 101 respectively, and therefore, are considered the least viable options for the UK out of the 6 methods in this study. The CAPEX for both methods includes the sourcing of digestive material which can be costly. The CAPEX for gasification also includes an acid removal plant, sludge treatment and a Sulphur recovery unit, depending on the material being gasified. The OPEX for the two methods is heavily influenced by the feed choice, however, the need for significant maintenance for the generator engines increases the cost, with the addition of frequent cleaning. Both methods can be seen as efficient use of waste, however, significant volumes of feedstock require large truck and rail movements. Only small-scale facilities are currently active for the two methods. A significant spike in facilities would promote job availability, but conflictingly would contribute to landscape disruption. As the two methods are unique in their ability to tackle two major global issues: energy and waste, further research and development are expected to grow to support these methods, owing to their longevity potential. Gasification is considered easier to scale than that of anaerobic digestion, however, there is no evidence of either method reaching the required scale to meet government goals. Biomass feeds are difficult to manage due to feedstock composition and other irregularities, whilst the biological process in anaerobic digestion further reduces the ease of operation. Whilst independent from fossil fuels and relying fully on renewable sources with no environmental impact when burnt, considerations are to be made for: land use, transportation, volume availability and biodiversity issues. Moreover, the manufacturing of vessels and pipework made up of stainless steel and plastic, increases the method's environmental impact. The largest difference between the two methods is the efficiency. Anaerobic digestion is significantly more energy efficient than gasification which explains the small difference in overall scores. Finally, whilst neither methods are deployed at large-scale today, they are eligible for government funding to support the development to reach to that level.

4. Conclusions

This paper has made use of the AHP to assess the six hydrogen production methods that have the potential to contribute to the hydrogen strategy goals. By utilising the feedback from industry experts, a systematic and holistic review of relevant hydrogen production methods has been effective to determine which hydrogen production method(s) present most viable for the UK. Results from this study show:

- Green electrolysis can be considered the most viable hydrogen production method when considering all relevant parameters which are reviewed when determining a hydrogen production method. However, research and development are required for electrolyser cost and longevity. Efficiency is the only parameter in which green electrolysis did not score the highest and therefore efforts are to be made to improve the efficiency to strengthen the viability of the method.

- SMR with CCS scored as the next best method, although this is not a reflection on current deployment or planned future facilities. SMR without CCS is the most mature technology with the highest production rates in the UK and therefore, integration of CCS facilities onto already constructed SMR plants is considered the easiest out of all other methods that require CCS. Challenges include: the reliance on ever-fluctuating, finite natural gas; landscape disruption; and social impacts.

- ATR and POX with CCS are similar in their suitability for implementation in the UK. It would depend on a case-by-case basis on which method would be preferred as the main discrepancy is the opposing CAPEX and OPEX for the two. Therefore, it would depend on the budget of the project to determine which would be the most suitable of the two. Both carry high-efficiency rates, although challenges mirror that of SMR.

- Anaerobic digestion and gasification have been considered the lesser viable options for the UK out of the 6 methods. Whilst an efficient use of waste and avoiding the need for natural gas for production, the methods entail a high CAPEX due to the multiple stages of production. The government is offering funding to support lesser developed methods, and although may not compete directly with methods such as green electrolysis, they can complement utility-scale projects and play a vital part in developing a hydrogen economy, despite that meaning at a smaller scale.

It is crucial that imminent action to the continuing release of damaging anthropogenic gases because of burning fossil fuels for energy is required, and hydrogen being recognised to play a vital part in this transition. Due to the nascent nature of green and blue hydrogen production, a pragmatic approach for further research and funding that required to support the development and operation of hydrogen production methods is required to help tackle against climate change and support the growth of a cleaner, more sustainable future.

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