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Circular Hydrogen Economy and Its Challenges

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The global climate change has become an inevitable reality of existence, causing a radical destabilisation of life on earth. Swift mitigation measures should be taken to avert the irreversible build-up of greenhouse gas emissions and global warming. A rising coalition of over 70 countries have now enacted climate change legislation and policies to ease the corporations of low-carbon economy transition towards net-zero by 2050. Given hydrogen's appealing diverse applications and its ability to decarbonise, hydrogen is a priority area for a sustainable circular economy, claimed European commissions. Yet, hydrogen production was confronted with numerous profound challenges in circular economy implementation, including waste management issues, infrastructural constraints, cost, safety and environmental concerns and so forth. Upon addressing such challenges, optimisation and tailored impact assessment tool like mathematical programming and life cycle assessment can be employed for feasible and sustainable hydrogen production pathway(s) identification. This paper investigates various hydrogen production pathways, green hydrogen in particular, followed by key challenges identification aforementioned for large-scale implementation and near-term opportunities to accelerate hydrogen deployment. Considering commercial viability of hydrogen generation is crucial for the realisation of a circular economy system and sustainable development, a transition to a hydrogen economy is able to enhance the penetration of variable renewables in grids whilst simultaneously lowering urban pollution emissions as well as the total carbon footprint, driving the hydrogen economy towards a circular economy. Amid increasing world's future demand, hydrogen derived from ever-changing power sources may co-exist for future extension of the current hydrogen rainbow. Integrated or hybrid hydrogen production networks may be identified and optimised via a combination of mathematical programming model and tailored impact assessment tools.

1. Introduction

Fossil fuels have been dominating the world's energy system, accounting for over 80 % of the total primary energy demand and three-quarters of global greenhouse gas (GHG) emissions. This calls for a rapid paradigm shift towards a low-carbon energy system via decarbonisation. To fulfill the Paris Agreement's global climate change commitment of limiting global warming to a maximum of 1.5 °C, new strategic perspectives on novel and inventive alternatives to fossil fuel expansion is necessitated to achieve climate neutrality. Experts believe that green hydrogen production, that is produced in a climate neutral manner, is a promising pathway for a prompt and successful response to climate change (Timperley, 2020). Green hydrogen is a clean fuel produced using renewable energy sources. Blue hydrogen, by contrast, is derived from fossil fuels with carbon capture and storage. Though blue hydrogen may be a critical enabler of the transition, its deployment is not wholly devoid of CO_2 due to its 85 to 95 % CO_2 capture efficiency, implying that 5 to 15 % of total CO_2 is leaked (Gielen et al., 2019). Owing to decades of subsidy-driven technological advancement, solar and wind energies have become cost-effective power generating sources in the majority of the globe. Making renewable (green)

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hydrogen production more viable, with additional cost and emission reductions projected, via good integrated energy planning (Eljack and Kazi, 2021). However, financing the shift from fossil fuels to a hydrogen economy to meet GHG emissions reduction by 40 % by 2030 could be an expensive endeavour, requiring significant technological advances and consumption patterns as part of the new normal adjustment process. This paper aims to explore some major challenges and proposes a multi-aspect consideration approach to those challenges for circular hydrogen economy. This helps to build momentum for establishing a robust circular hydrogen economy with minimal negative emissions, safeguarding against the accelerating climate crisis.

2. Hydrogen in the circular economy

2.1 Hydrogen production pathways

Hydrogen is coloured to grey, brown, blue, green, and occasionally pink according to the different resources and technologies employed in its production. Hydrogen may be synthesised from a variety of resources, from fossil fuels to nuclear energy, and renewable energy sources. Figure 1 gives an overview of the current global hydrogen production pathways from different energy sources. Despite the fact that hydrogen is often regarded as the clean energy of the future, fossil fuels are used for approximately 95 % of global hydrogen production today (Gielen et al., 2019). Most hydrogen produced globally today is either grey or brown, derived from fossil fuels with carbon emissions being released into the atmosphere.

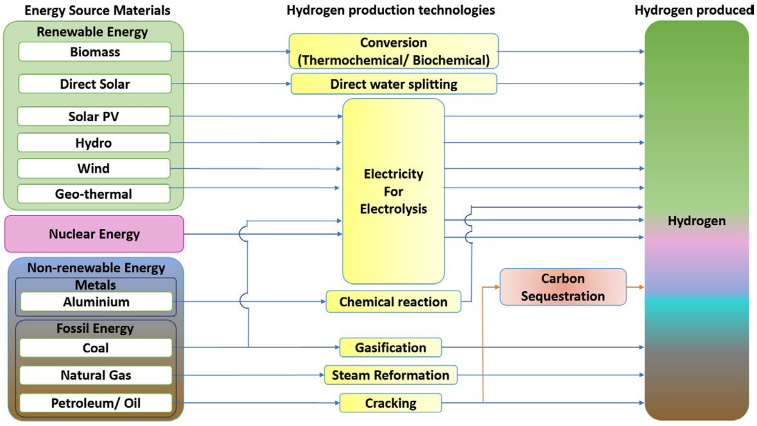

Figure 1: Hydrogen production pathways

The most common grey hydrogen is derived from natural gas, or methane via the steam methane reformation (SMR) technique whilst brown hydrogen is produced from coal via gasification. Another key difference between grey and brown hydrogen is simply the lower emissions generated in creating grey hydrogen. In a similar manner, blue hydrogen is introduced with carbon capture and sequestration. Amid fossil fuels scars, a recent scientific breakthrough of hydrogen-producing from the reaction between aluminium metal with water, serves as a carbon-free alternative to fossil fuels (Bolt et al., 2021). Pink hydrogen is produced via water electrolysis fuelled by nuclear energy instead of renewables (Graaf et al., 2022). Green hydrogen is the only variety that is synthesised in a climate-neutral manner (Marchant, 2021) and it is deemed to be a promising fuel for a low-carbon future. Racing towards net-zero, there has been a resurgence of interest in the creation of green hydrogen from renewable energy. Green hydrogen is generally created via water electrolysis fuelled by renewable energy sources. Water electrolysis is an electrochemical process that separates water into its constituents of oxygen and hydrogen in gaseous form. Green hydrogen may also be produced via direct solar-driven water splitting without the need for an intermediate electrolysis step or through the thermochemical or biochemical conversion of biomass (Megia et al., 2021).

2.2 Circular hydrogen economy

A linear economy is a once-through system in which resources are extracted, processed, exploited, and discarded, that drives a dual crisis of resource scarcity, and waste overload. Engendering ecosystem degradation and global climate change. As a result, a circular economy (CE) which was founded in 2009, has been proffered as a more environmentally friendly alternative to the linear economy (Stahel, 2016). A CE is a model that seeks to bridge the gap between production and ecosystem cycles via waste valorisation. It is introduced to attain higher resource efficiency via recycling whilst achieving green growth, and sustainable development goals. Raw material (waste) cycles are closed in a CE at their highest value, supported by a shift towards renewable energy or materials. Nevertheless, only 8.6 % of the global economy is circular today.

Lately, the resource recovery model which reflects the circular economy's principles of reduce, reuse, and recycle has been focused, with resource recovery from waste streams. Hydrogen-containing industrial waste streams with over 50 % concentration also showed a prospective source for hydrogen recovery via separation processes. Solely in Europe, approximately 10 Gm^3/y of hydrogen is reported to be lost from industrial waste streams (Yáñez et al., 2019). Yáñez et al. (2019) devised a cutting-edge hydrogen CE via a techno-economic model and mixed-integer linear programming (MILP) and revealed that upcycled hydrogen is far less expensive, with optimal levelized cost of hydrogen (LCOH) of 0.35 to 1.09 €/kg hydrogen, 1.5 up to 2 times cheaper than those hydrogen generated via natural gas steam conversion. Their results also revealed that the availability of industrial surplus hydrogen was also a notable factor for optimal configuration of hydrogen production. Gai et al. (2022) presented a novel approach to reduce fresh hydrogen consumption and waste hydrogen discharge via uniting of Pinch Analysis (PA) with waste hydrogen recovery technology. Taking into account the delivery of fresh hydrogen sources of varying qualities, an extended multiple-level resource PA approach for Total Site Hydrogen Integration is devised for further waste hydrogen regeneration. With the goal to minimise further fresh hydrogen consumption, they also optimised the waste hydrogen regeneration via a techno-economic analysis (TEA) for waste hydrogen purification process. This enabled the identification of sustainable waste hydrogen recovery design process which lowers both the waste hydrogen discharge and fresh hydrogen consumption.

Aside from waste recovery, waste valorisation schemes pertaining to diverse biomass, byproducts, and waste materials are also being emphasised for the development of value-added hydrogen. ZEPPELIN project, which sought to discover novel, effective, and circular technology roadmap for green hydrogen generation and storage with modelling tools, focuses on the development of novel technologies for green hydrogen generation alternative to conventional water electrolysis. The idea of promoting CE via by-product or waste valorisation is propounded from various industries including wastewater treatment facilities and agri-food, serving as the raw material for energy industry (CETIM, 2021). Dark fermentation, for example, a technique of producing biohydrogen from organic waste without any need for anaerobic microorganisms or light, is explored alongside hydrogen purification technology to obtain its hydrogen and waste revaluation. A mathematical energy optimisation tool via digital twins is developed in aiding the hydrogen generation via ideal waste recovery, in which 135,000 t/y of circular green hydrogen are produced with 99 and 50 Mt of rubbish and municipal wastewater recovered, boosting the CE (Dokso, 2022).

On the other hand, Rumayor et al. (2022) claimed that photo-reforming is a potential technology for recycling and converting biomass-derived waste such as crude glycerol, the main byproduct of biodiesel production, into renewable hydrogen production. Photo-reforming is in the limelight given its flexibility, simple, low-energy consumption, and low cost due to its mild temperature demand at ambient temperature. However, the technology is at low technology readiness level of 3 to 4, owing to its comparably poor hydrogen generation rates and limited catalyst lifespan. To evaluate the waste photo-reforming hydrogen manufacturing, they used life cycle assessment (LCA) to evaluate the major environmental consequences. The hotspot performance parameters for potential trade-off for sustainable photo-reforming operation was also identified, which the key hotspots are identified to be glycerol purification, electricity consumption, and catalyst lifespan. Decision-making is further aided by technological resource savings realised from enhanced waste glycerol recycling in the context of a CE. A comparative analysis of environmental indicators to benchmark datasets of the commercially available water electrolysis and SMR, in terms of the desired hydrogen generation rates and sustainable operations was performed. The findings revealed that biowaste photo-reforming is comparable to other prospective renewable technologies like water electrolysis (Rumayor et al., 2022). Whilst hydrogen plays a pivotal role in a decarbonized economy, the notion of a CE takes on greater significance, advocating for an alternative model that incorporates circular routes for sustainable hydrogen production. However, there are inherent hurdles that must be overcome to avoid potential disruptive hydrogen applications.

3. Challenges and gaps towards circular hydrogen economy

Hydrogen's feasibility as a viable alternative to fossil fuels is currently hampered by a number of barriers and constraints which can be generally grouped into few categories, including, but not limited to, waste and cost management challenges, hydrogen transport and storage infrastructure requirements as well as the environmental safety concerns.

3.1 Waste management challenges

One of the biggest global challenges is the ever-growing mounds of garbage, with approximately 2.01 Gt of waste accumulating annually across the globe, eventually ending up in landfills and water resources, posing severe environmental concerns (Koh and Raghu, 2019). As a result of such prevalent waste mismanagement, the growth of a circular hydrogen economy is retarded. In 2020, barely 8.6 % (dropped from 9.1 % since 2018) of all fossil fuels, biomass, minerals and metals entering the system are recycled annually (Wit et al., 2020).

Recycling, an essential component of the CE, should be undertaken to repurpose waste into forms that retain as much value as possible, like hydrogen, while enhancing waste minimisation and energy conservation. For instance, Solo Resource Recover, an organisation dedicated to delivering cost-effective technology with an emphasis on diverting residual waste from landfills via maximum recycling potential, proposed investigating the CE prospects of exploiting municipal solid waste (MSW) for hydrogen generation through steam gasification (Keys, 2021). In addition, steam gasification, a low-cost chemical recycling process, is deemed to be best suited for converting mixed or contaminated waste which are difficult to be recycled or reused, into hydrogen along with some other high-value green products. It is however noted that there are indeed a few waste-to-hydrogen initiatives, but majority of which are in early stages and on a modest scale. An integrated process is expected to have a low 40-50 % and 60-70 % efficiency for MSW and fossil fuels feedstocks (Wallman et al., 1998). Still, energy experts predict that clean, low- to zero-carbon hydrogen has the potential to become a mainstream owing to its higher energy efficiency, widespread availability, and environmental friendliness compared to fossil fuels (Karidis, 2020). To address growing waste build-up problems, inventive and effective waste conversion technologies are crucial for sustainable waste management, as they are an integral part of future urban growth and economic development in CE (Sharma et al., 2020).

3.2 Cost management challenges

The biggest barrier to the uptake and utilisation of green hydrogen is its high cost, due to its energy-intensive production processes. Green hydrogen presently only accounts for 0.1 % of global hydrogen generation. However, green hydrogen contribution is likely to surge as the cost of renewables continues to plummet given the growing scale and markdowns of renewables such as solar and wind energy taking over the proportion of grey, brown, and blue hydrogen production (Petrova, 2020). Hydrogen’s average market price is hovering around 2.5 to over 6 USD/kg, and it is likely to remain expensive in the absence of subsidies and other policy supports (KPMG, 2018). Even in areas with ample renewable energy, zero-carbon electricity remains the principal cost element in hydrogen manufacturing, accounting for about 50-70 % of the total cost (Fan et al., 2021). Though the cost of green hydrogen has fallen due to rising demand for hydrogen and technological advancements, this cost-cutting trend for hydrogen may differ from renewables cost. Renewable power costs for green hydrogen production via electrolysis, for example, might cut LCOH in half (Taibi et al., 2020). Given that technological advancements are just part of the solution, raising end-user demand will also lower the hydrogen manufacturing costs via economies of scale, resulting in LCOH reductions. In short, scale-up of existing hydrogen technologies may enable low-carbon hydrogen supply alternatives over a broad range of applications prior to net-zero over conventional fossil fuels. In order to attain such a scale, expenditures, alignment of policy frameworks, as well as the creation of end-user demand are necessary. According to Fan (2021), nations and regions should ratify market-aligned policies and manufacturing standards to close the significant price gap between green and grey hydrogen, cutting emissions rapidly via green hydrogen deployment. This includes zero-carbon energy subsidies and public incentives toward internationalisation, encouraging the development of sustainable hydrogen technology.

3.3 Hydrogen transport and storage infrastructure requirements

Notwithstanding both the technological innovations and emerging market development initiatives, one of the most significant hurdles towards the development of a hydrogen economy is the infrastructure necessary to construct it (Fan et al., 2021). Today, vast hydrogen infrastructure initiatives for the energy industry are still predominantly in the research and development stage. Considering that the hydrogen infrastructure has not yet advanced to the extent where hydrogen fuel cell systems can be utilised in a decentralised way, hydrogen transportation and storage of hydrogen are two issues that must be addressed to accelerate both the commercialisation of hydrogen and fuel cell technologies. As such, on-site hydrogen manufacturing technologies are deployed for fuel cell supply. Today, though a hydrogen infrastructure has been envisaged to consist of industrial-sized subterranean pipelines and fuelling stations distributed throughout the user-country, establishing a “Hydrogen Highway”, stations that are not situated close to the pipelines would have to rely on conveyance trucks and trailers (Dell et al., 2014). Otherwise, on-site hydrogen production is needed. Despite the existing well-established network of natural gas pipelines, costly treatments would be expected to retrofit them for hydrogen, making it unfeasible (Eberle et al., 2012). Hydrogen refuelling station (HRS) network density, should be raised steadily to bridge the gap between isolated demonstration fields and the pre-commercial phase. A successful HRS deployment would provide safe and low-cost hydrogen delivery and also allow faster deployment and commercialisation of hydrogen. Gas pipelines and infrastructure may be reconfigured for hydrogen transport and storage. It was however discovered that the techno-economic feasibility of hydrogen storage systems has yet to be acknowledged as none of the current conventional liquid, gaseous, and metal hydrides satisfy every essential criteria for a realistic hydrogen economy. This is primarily due to safety concerns, low hydrogen storage capacity, high cost, and so forth (Abe et al., 2019).

3.4 Safety and environmental concerns

Another major impediment to the hydrogen economy is environmental safety concerns. Due to hydrogen's low density and broad flammability range relative to other fuels, ranging from 4 % to 75 % by volume in air and up to 95 % in oxygen at atmospheric condition (Schmidtchen, 2009), a hydrogen leak will result in an explosion when ignited or sparked. As a result, hydrogen is highly dangerous in confined spaces. The odourless and almost invisible flame of hydrogen further poses security and detection challenges. For hydrogen safety prediction and analysis of HRS leakage incidents, Han et al. (2018) proposed the application of computational fluid dynamics for extensive analysis and numerical modelling of gas discharge and mixing. Also, owing to the current hydrogen production from fossil fuels, environmental concerns like resource depletion and climate change have grown as a result of the increased carbon emissions into the atmosphere. On the other hand, establishing hydrogen blending standards is a logical way to address the technical barriers such as hydrogen embrittlement at the transition stage. Modernisation and harmonisation of regulatory standards governing hydrogen blending, the injection of clean (green) hydrogen into natural gas grids at optimal concentrations compatible with existing infrastructure, is necessitated for a dedicated hydrogen network and market.

4. Transiting towards circular hydrogen economy

The prospect of utilising hydrogen as a fuel source to minimise GHG emissions is a lofty and noble goal. According to the literature findings, the efficiency of recycling-based waste conversion technology is comparably low. Green hydrogen production presents a comparably lower capacity factor to other sources such as biomass energy. For low-cost realisation of green hydrogen production, a combination of low-cost zero-carbon electricity and large capacity factors are necessitated. To achieve such goal, amid the increasing world's future energy demand and a budding market, hydrogen produced from the ever-changing power sources in the energy transition to net-zero may co-exist for further expansion of the current hydrogen rainbow. Extending integrated or hybrid production networks, boosting hydrogen production demand. To maximise resource efficiency and allocation, a combination of mathematical optimisation tool, such as MILP modelling, and customised environmental and economic impact tools, like LCA and TEA, could be employed in identifying the most practical and sustainable hydrogen production pathway(s). MILP has the capability to address a broad range of optimisation problems involving both continuous and discrete variables, whilst the incorporation of LCA and TEA allows for a critical assessment of the viability of hydrogen technologies and serves as a guide for effective decision-making. This guides the creation of a publicly accessible model that is capable of defining the risks, prospects, and costs of blending, overcoming the technical impediments to hydrogen blending and providing clean hydrogen utilisation across sectors. Current low allocational efficiency could also be enhanced with effective modelling of the HRS infrastructure network via TEA.

5. Conclusions

With peak oil demand, there has been a greater market and a surge of interest in alternative, economical, and safer methods for hydrogen synthesis. Upscaling the existing hydrogen production technologies will enable hydrogen to compete with conventional fossil fuels as a potential low-carbon alternative. To accomplish such a scale, policy frameworks, investment, and growing end-user demand will be necessitated. Research studies have been undertaken worldwide in response to the challenges in the pursuit of developing low-cost, safe hydrogen production processes, realising the ideal hydrogen economy. The major challenges to scaling of circular hydrogen economy include waste and cost management challenges, hydrogen transport and storage infrastructure requirements as well as environmental safety concerns. This study proposed a coherent approach integrating both tailored economic and environmental impact assessment tools into the mathematical optimisation tool for the analysis of hybrid hydrogen production system to proffer sustainable and commercially viable hydrogen production pathway(s). Hydrogen rainbow will play a big part in attaining net-zero by transitioning away from our reliance on fossil fuels and toward greener technologies to power human activities.

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