Hydrogen's potential in accelerating the transition to a circular economy

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Abstract:

Adopting a circular economy approach is a highly effective strategy for achieving sustainable reductions in CO_2 emissions and promoting other sustainable practices. The main objective of a circular economy is to decouple economic growth from the depletion of natural capital. This involves reducing the use of finite resources on one hand, and minimizing negative environmental impacts, such as emissions, waste, and pollution, on the other hand. One way to support this circular economy vision is by embracing green hydrogen. The use of hydrogen produced from renewable sources can help industries to significantly lower their greenhouse gas emissions, promote long-term price stability, and mitigate the negative health effects associated with fossil fuel pollution. By improving energy efficiency and resource management, green hydrogen can contribute to creating a circular economy that is more sustainable and resource efficient.

In the house of circular economy practice, hydrogen finds its place under:

- **Regenerate** – use renewable power to produce hydrogen.
- **Optimize** – continue to develop and refine hydrogen technology.
- **Loop** – recycle materials and use waste products.
- **Exchange** – switch to green instead of blue or grey hydrogen

Due to its complex and energy-intensive production process, as well as limited production capacity, green hydrogen production requires multiple organizations to establish different hydrogen production streams. Nevertheless, some practices can facilitate the transition from the conventional linear energy-and-material flow model to a circular business model. By adopting such practices, companies can find ways to reuse green hydrogen or restructure their material flow to generate hydrogen as a by-product. For instance, hydrogen can be derived from chemical, wood, or plastic waste, where feasible and beneficial. These circular economy practices not only enhance the sustainability of the production process, but also improve the efficient use of resources, helping to build a more sustainable future.

While the use of hydrogen is conceivable across sectors, application areas should be individually assessed to get the most efficient value from hydrogen. Considerations shouldn't simply be limited to technical feasibility, rather should focus on the contribution to long-term sustainability goals based on the following three criteria:

- Potential for decarbonization
- Potential and market readiness to include hydrogen.
- Circular economy potential

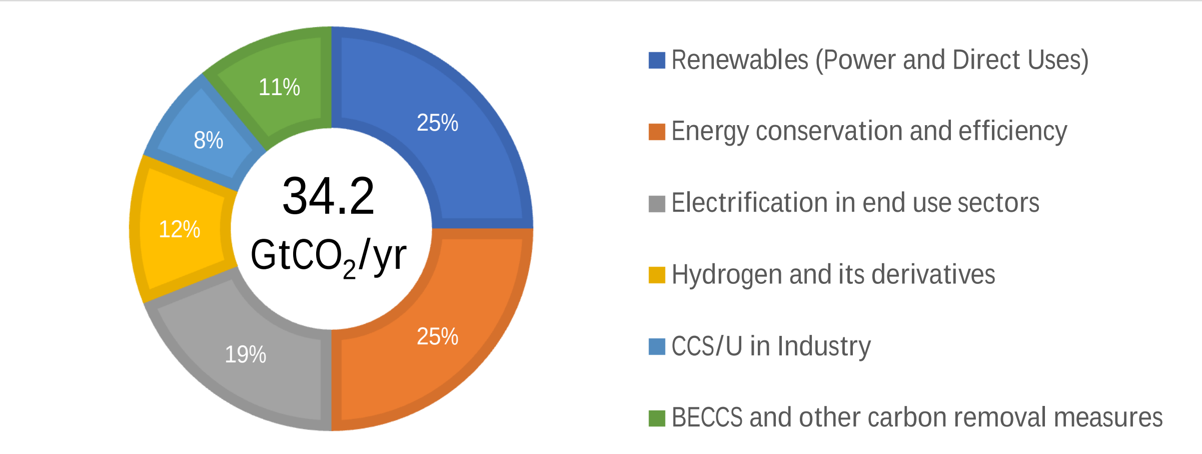
Hydrogen is key to fueling a low-carbon and circular economy particularly for the emission intensive industries. Though not commercially viable till recently, policy interventions and market dynamics have increased cost competitiveness of producing green hydrogen. This paper would analyse the ability of hydrogen to decarbonize the global economy, competitive landscape across major industrial hubs (US and Europe),the challenges faced during the transportation, storage, and use of hydrogen as a fuel, and its ability to close gaps contribute to a circular economy.

Introduction:

Despite the increasing number of policy initiatives and regulatory measures aimed at promoting renewable energy sources and reducing greenhouse gas emissions, the existing policy and regulatory systems continue to be primarily designed for fossil fuels. While it is inevitable that fossil fuels will still play a role in the energy mix for some time, their share must be significantly diminished as we approach the mid-century mark. Consequently, policy frameworks and markets should prioritize expediting the transition and establishing the foundations of a resilient and inclusive system.

The combination of specific technologies within certain country and institutional contexts can drive energy transitions in various sectors of energy consumption. These technology combinations can also induce changes in supply-side processes and transformative practices, depending on factors such as institutional conditions, resource availability, and infrastructure. However, a common imperative for all countries is the imperative to electrify heating and transportation through the utilization of renewable electricity, implementing efficiency measures, and directly harnessing renewable sources such as bioenergy, solar power, and hydrogen.

Figure 1: Carbon dioxide emissions abatement under the 1.5°C Scenario in 2050 (IRENA)

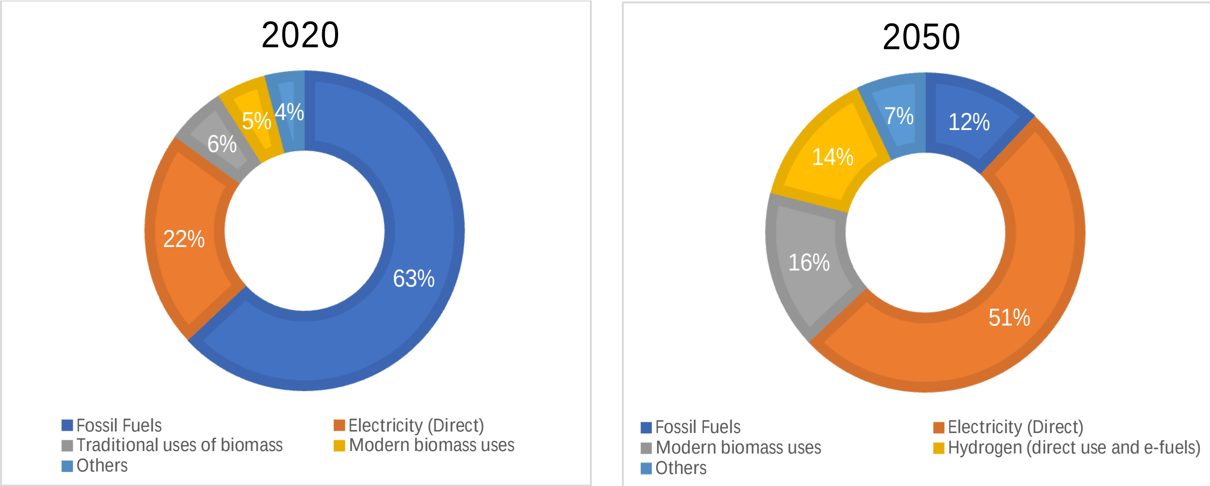


Source: IRENA World Energy Transition Outlook 2023

IRENA's 1.5°C pathway emphasizes the crucial role of energy efficiency and electrification in driving the transition to sustainable energy, supported by renewables, hydrogen, and sustainable biomass. This pathway, which requires a massive change in how societies produce and consume energy, would result in a reduction of nearly **34 gigatons of annual CO_2 emissions by 2050.** These emission cuts can be achieved through the following measures:

- significant expansion of renewable electricity generation and its direct utilization,
- substantial enhancements in energy efficiency,
- the widespread adoption of electric vehicles and heat pumps, leading to the electrification of various sectors,
- the utilization of clean hydrogen and its derivatives,
- the combination of bioenergy with carbon capture and storage, and
- the application of carbon capture and storage technologies in the final stage of emissions reduction.

Figure 2: Breakdown of total final energy consumption by energy carrier between 2020 and 2050 under the 1.5°C Scenario



Source: IRENA World Energy Transition Outlook 2023

Note: The figures above include only energy consumption, excluding non-energy uses. For electricity use, 28% in 2020 and 91% in 2050 are sourced from renewable sources; for hydrogen (direct use and e-fuels), the renewable energy share (i.e., green hydrogen) would reach 94% by 2050. The category Hydrogen (direct use and e-fuels) accounts for total hydrogen consumption (green and blue) and other e-fuels (e-ammonia and e-methanol). Electricity (direct) includes the consumption of electricity that is provided by all sources of generation: renewable, nuclear and fossil fuel based. Traditional uses of biomass refer to the solid biofuels in non-OECD countries. Modern bioenergy uses include solid biomass, biogas and biomethane used in buildings and industry; and liquid biofuels used mainly in transport, but also in buildings, industry and other final consumption

OECD = Organisation for Economic Co-operation and Development

Overview of types of hydrogen:

Table 1: Different colours of hydrogen and their sources

Colour of Hydrogen	Technology	Feedstock/Electricity Source	GHG Footprint
Green	Water Electrolysis	Wind, solar, small hydro, geothermal, tidal	Minimal
Purple/Pink		Nuclear	
Yellow		Mixed-origin grid electricity	Medium
Blue	SMR/Coal Gasification with CCS	Natural gas, coal	Low
Turquoise	Pyrolysis	Natural gas	Low
Grey	SMR		Medium
Brown	Coal Gasification	Brown coal (lignite)	High
Black		Black coal	

Source: Council for Energy, Environment and Water

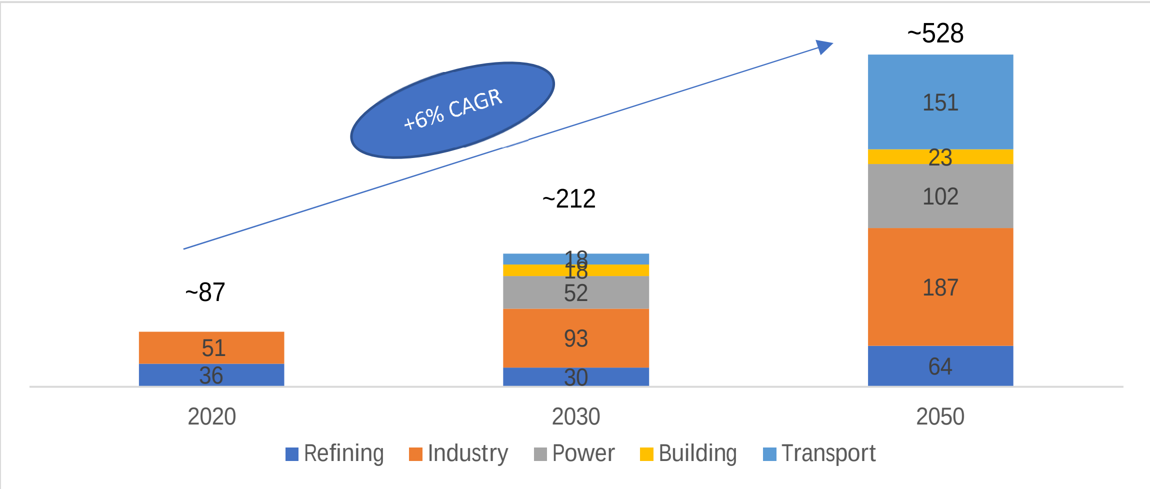
Hydrogen will play a unique role in the energy transition, especially for industrial processes and certain transport modes. By 2050, total hydrogen demand would need to be met entirely with clean hydrogen, the majority of which is green hydrogen. This would require rapid expansion of both renewable power and electrolyser capacity. If we calculate the kg of emissions generated for each kg of hydrogen produced, then green hydrogen would be the lowest with 0.3, followed by blue hydrogen at 1.5 and grey hydrogen would be the highest with 9.2 (Hydrogen Insights 2023).

Green hydrogen is still in its infancy, and policy support is needed to scale it from a niche to a mainstream energy source. Policy support could include proactive planning, target setting, financial and fiscal support, green hydrogen quotas, etc.

Hydrogen demand, cost and policy incentives:

Hydrogen demand is expected to grow by a **CAGR of 6%,** driven by transport and industry. Driven by demand in hard-to-abate sectors, the hydrogen economy will scale up in the coming decade(s), making hydrogen a non-niche market. By 2050, in a mature hydrogen economy, the demand will spread to other end uses (not convenient today) due to the convenience of specific supply centers/clusters (IEA 2022).

Figure 3: Global hydrogen demand by sector (Mt)



Source: IEA

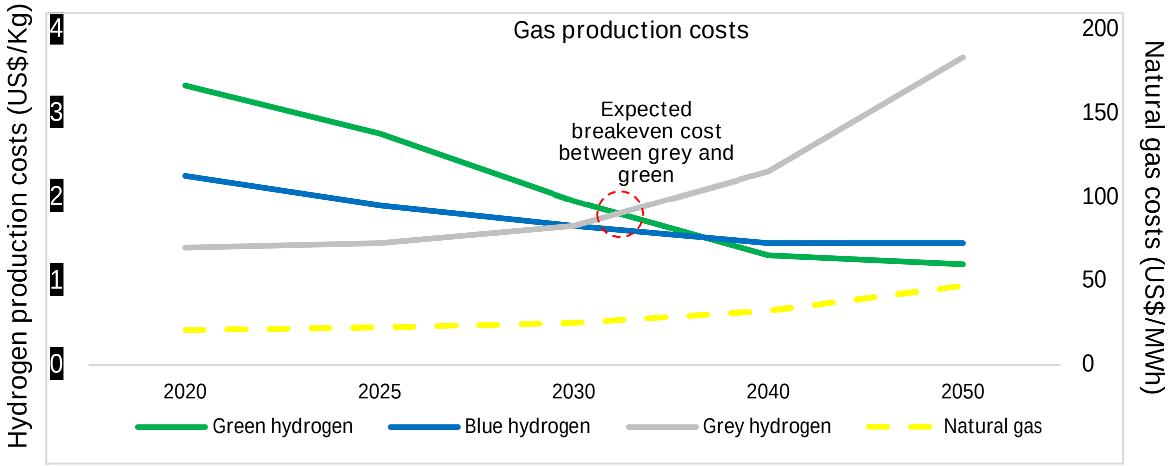
A major driving force behind the rise of green hydrogen has been the decreasing costs of renewable energy, a critical input in the production process. In 2023, as renewable energy penetration on the grid increases, green hydrogen development is also expected to grow, owing to its potential to act as long-duration and seasonal storage of fuel available on demand to generate power. The recently approved IIJA and IRA allocates US$9.5 billion for clean hydrogen projects and proposes regional clean hydrogen hubs to expand hydrogen infrastructure. The BBB Reconciliation Act includes a hydrogen tax credit and would likely encourage the technology's growth if passed. Launched recently, the US Department of Energy's (DOE) "Energy Earth shots" initiative aims to reduce the costs of green hydrogen and long-duration energy storage by 80% and 90%, respectively, by 2030 (EY 2022).

Regulations and Policies:

While there has been significant progress made in terms of standardizing definitions and de-risking investments over the last 18 months, hydrogen transition still needs to resolve significant challenges near term, before greater investment can be unlocked. With more lights turning green, greater regulatory clarity and further public fiscal support could offer positive flashpoints over second half of 2023 and early 2024.

In the US, clarity around the US Treasury's guidance for the IRA Production Tax Credit (PTC), which could hypothetically amount to US$3/kg for production that meets all the required criteria and achieves the lowest CO_2 intensity could help advance green hydrogen projects over the second half of 2023 (JP Morgan 2023).

Figure 4: Green hydrogen will become economically competitive with other hydrogen production methods by the early 30s



Source: IRENA, Hydrogen Council

Countries have made progress on “guarantee of origin” schemes, inc. a clarification of emissions assessment methodology for clean hydrogen. While a cross-regional or global standard has yet to emerge, the EU may have set the path for global harmonization with the release of its long-awaited EU Delegated Acts on Renewable Hydrogen in February 2023, which is expected to be adopted soon.

Table 2: Hydrogen tax credit mechanism under the IRA, 2022

Hydrogen Type	**H_2 Source**	**Carbon intensity level**	**Tax credit amount**		**Wage/other benefits**	**% Credit received**
		Kg-CO_2e/kg-H_2	PTC Value (per kg of H2)	ITC Value (% of facility cost)	5x multiplier	
Green	RE Electrolysis	0 – 0.45	$0.60	6%	$3.00	100%
Pink	Nuclear + Electrolysis	0.45 – 1.5	$0.20	2%	$1.00	33.4%
Blue *	SMR +CCUS	1.5 – 2.5	$0.15	1.5%	$0.75	25%
Blue	SMR+CCUS	2.5 - 4	$0.12	1.2%	$0.60	20%

Source: US Department of Energy, IEA

Note: PTC – Production Tax Credit; ITC – Investment Tax credit. Multiplier mechanism would be triggered if producers build new facilities within a certain time and if they meet certain wage and Labor requirements for the project.

42 countries have adopted a hydrogen strategy as of February 2023, a significant increase from 27 in January 2022. Among these countries, 20 have set targets for electrolyzer capacity, aiming for a total of 90GW by 2030, up from 69GW in January 2022. Governments worldwide are implementing various policies, such as grants, loans, tax incentives, to mitigate risks and attract private investment for hydrogen projects. These measures facilitate better financing conditions and enhance the feasibility of capital-intensive hydrogen initiatives. In 2022, hydrogen subsidies experienced a substantial surge, reaching US$146

billion by 2030. This includes US$76.4 billion in targeted support for hydrogen projects and US$69.4 billion in technology-neutral funds that can be accessed by hydrogen projects (JP Morgan 2023).

Circularity and Hydrogen:

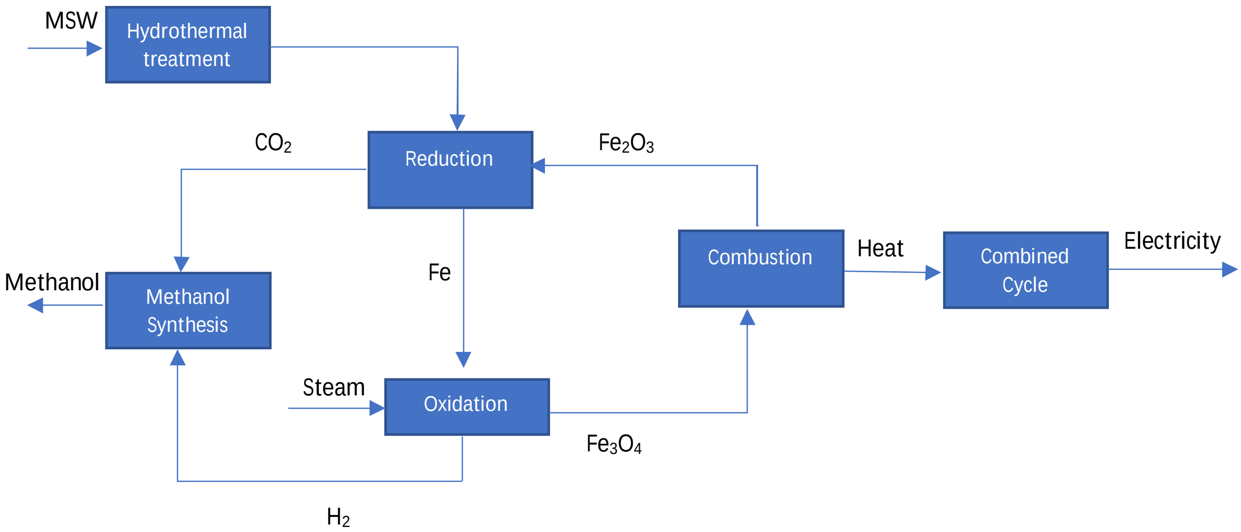
The circular economy has three key principles: eliminating waste and pollution, circulating products and materials at their highest value, and regenerating nature. It entails decoupling economic activity from the consumption of finite resources. To support industrial decarbonisation, these principles can be applied to close energy and material loops; promote more efficient consumption of energy, water and materials; and minimise waste in the environment.

The production of green hydrogen is complex, requiring significant energy input and limited production capacity. To meet demand, several organizations may need to contribute to hydrogen production. Transitioning from a linear energy-and-material flow model to a circular business model can support this shift. Companies can explore practices such as reusing green hydrogen and restructuring material flow to obtain hydrogen as a by-product from waste sources like chemicals, wood, or plastics. Several case studies demonstrate the potential for hydrogen production from waste, contributing to the development of a circular ecosystem.

Case 1: Conversion of municipal solid waste to hydrogen and its storage to methanol

Municipal solid waste (MSW) has become a challenging issue for many decades, especially in developing countries, leading to several social and environmental problems. Appropriate treatment and conversion of this MSW are urgently demanded. A 2022 study by Hakandai e.al., proposed an efficient conversion of MSW to methanol. The developed system consists of simultaneous processes, integrating hydrothermal treatment (HTT), direct chemical looping, methanol synthesis, and combined cycle for power generation. HTT is conducted to increase the carbon content and caloric value of the MSW, as well as to physically uniform the material. The treated MSW flows to direct chemical looping for conversion to hydrogen while separating CO_2. The produced hydrogen and CO_2 are then used as feeds for methanol synthesis. Finally, the heat involved in the system is recovered by gas and steam turbines for power generation (Hakandai 2022).

Fig 5: Graphical representation of the conversion of MSW to Hydrogen



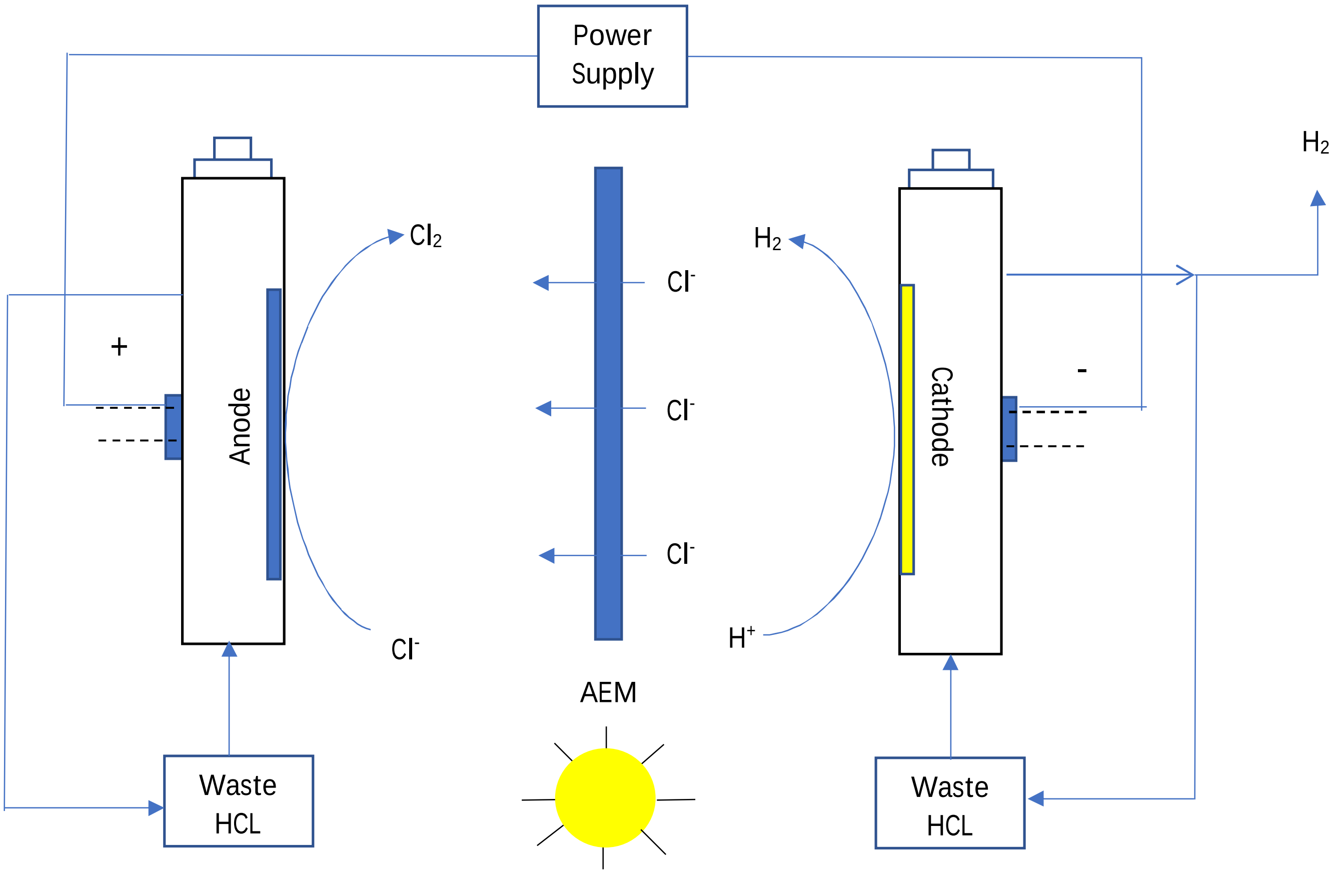
Source: Conversion of municipal solid waste to hydrogen and its storage to methanol,

Hakandai et.al

Case 2: Waste acid to useful hydrogen

The galvanizing industry uses concentrated hydrochloric acid in metal surface treatment processes, known as ‘pickling’. At the end of the “pickling” process, waste acid solutions polluted with metal ions are typically discharged to the environment. A 2020 study by Chehade et al. reported on a novel photo-electrochemical reactor that was designed and developed to enable production of hydrogen and chlorine gas from spent hydrochloric acid, generated in the galvanizing industry. Using waste acid as the electrolyte in a photo-electrochemical reactor in this way avoids environmental pollution and allows chemical components to re-enter the ecosystem as valuable resources (Chehade 2020).

Fig 6: Design of the photoelectrochemical reactor proposed for efficient hydrogen and chlorine gas production.



Source: A photoelectrochemical system for hydrogen and chlorine production from industrial waste acids, Chehade et. al

Priority application areas for green hydrogen:

While the use of hydrogen is conceivable across sectors, application areas should be individually assessed to get the most efficient value from hydrogen. Considerations shouldn’t simply be limited to technical feasibility, rather should focus on the contribution to long-term sustainability goals based on the following three criteria:

- Potential for decarbonization
- Potential and market readiness to include hydrogen.
- Circular economy potential

Keeping the above things in mind, three priority areas emerge: fuel for transport and power, heat for industry and buildings, and feedstock for chemicals and products.

1. **Fuel for power and transport:**

   Electricity is the preferred fuel for cars due to industry investment, infrastructure, and proven efficacy of batteries. However, as vehicle size or distance increases, hydrogen fuel cells become more advantageous. Hydrogen requires fewer raw materials than batteries or combustion engines, making it appealing for logistics and shipping industries. Additionally, larger transportation can accommodate hydrogen fuel cells.

2. **Heat for buildings and industry:**

   The raw materials industry must reduce its emissions by 25% by 2030 and nearly eliminate them by 2050. The industry has faced stagnation in emissions reduction over the past decade, making these goals challenging. Achieving climate-neutral steel production requires significant innovation beyond incremental efficiency improvements. Green hydrogen offers a promising alternative to coal and fossil fuels due to its high energy content and combustion point, potentially revolutionizing the steel industry and reducing emissions.

   Heat pumps have gained popularity for heating buildings, both in new constructions and renovations. However, adequate insulation is crucial for effective heat pump usage. In cases where insulation is expensive or complicated, alternatives may be explored. Synthetic fuels, which combine hydrogen with carbon monoxide, can be used as a primary energy source or in hybrid systems alongside heat pumps. While prioritizing insulation and heat pumps is preferable, green hydrogen can complement existing solutions and fill important gaps.

3. **Feedback for products and chemicals:**

   The chemical industry has used hydrogen as a raw material for many years, primarily in applications such as ammonia and methanol production. Switching from grey to green hydrogen in existing infrastructure is feasible and can be accomplished relatively quickly compared to other industries. However, the availability of affordable green hydrogen at a large scale is still necessary to accelerate the transition.

   Steel and metallurgy applications are well-suited for green hydrogen adoption. Although hydrogen supply for metallurgy is currently limited, steel production has the potential to become a significant sector for green hydrogen usage once the supply meets the demand. This shift requires long-term investments and funding priorities should be established to facilitate the transition during plant and infrastructure renewal cycles, rather than investing in high-emission technologies. It is important to focus on areas where alternatives like electrification are not feasible, creating a steady demand for hydrogen in the most appropriate areas.

Way Forward:

The potential of circular economy solutions remains largely unexplored due to various challenges. These include high costs, barriers related to technology and infrastructure, limited capacity to implement circular solutions in production and processes, and a lack of access to information about the benefits, solutions, and products associated with the circular economy. To overcome these hurdles and facilitate industrial transformation, collaboration among governments, institutes, and industrial stakeholders is crucial. They need to work together to bridge information gaps, share knowledge, stimulate market demand, and enhance cost competitiveness.

In addition, financial and fiscal measures play a vital role in supporting research, development, and demonstration of innovative technologies. By implementing national and regional circular economy strategies and plans, long-term signals can be sent to investors, encouraging their involvement in circular initiatives. Countries like China, the EU, Italy, Japan, and the United Kingdom have taken steps towards circular economy planning. However, it is essential for more countries to adopt circularity-based measures in their industrial plans and practices to effectively contribute to multiple Sustainable Development Goals.

Green hydrogen can serve as a fuel for transport and power, as heat for industrial use and buildings, as well as a feedstock for chemicals and products. But it shouldn’t be competing in applications where electrification is already doing the job perfectly. At the same time, shifting toward a circular economy (CE) will be key in making decarbonization a success – and use of green hydrogen is essential.

Overall, by addressing these challenges and embracing circular economy principles, we can unlock the untapped potential of circular solutions, foster sustainable development, and create a more resource-efficient and resilient future.

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