TRASH TO TREASURE…

The Cleanest Ways to Produce Hydrogen from Municipal Solid Waste

KEY HIGHLIGHTS

- Need for Transforming Waste into Clean Energy
- Technologies
- Technology Developers
- Latest Ventures
- Upcoming Projects
- Factors Influencing Market Demand
- Future Outlook

Introduction

Global economies have shifted their focus towards cleaner fuel alternatives—mainly hydrogen—owing to the ongoing energy crisis, escalating environmental degradation, and mounting pressure due to climate change. Hydrogen emerges as a promising solution to address these pressing concerns. Notably, the zero-emission capability makes hydrogen a versatile option for a wide range of applications and positions it as a prominent player in the future energy market.

Need for Transforming Waste into Clean Energy

As of now, a substantial portion of global hydrogen is produced via coal and natural gas processing, leading to unavoidable GHG emissions. However, there exists a vast reservoir of hydrocarbons in Municipal Solid Waste (MSW), which, unfortunately, reaches the end of its life cycle in landfills, releasing significant pollutants into the environment. Thus, producing hydrogen from MSW can be a promising avenue to deliver clean, safe, cost-effective, and secure energy for the future.

Many nations are adopting waste-to-energy strategies to overcome their waste management-challenges. This approach offers a dual advantage, as it mitigates environmental concerns by significantly reducing the amount of waste, and simultaneously generates renewable energy.

Exhibit 1: Generation of MSW, in billion tonnes per year

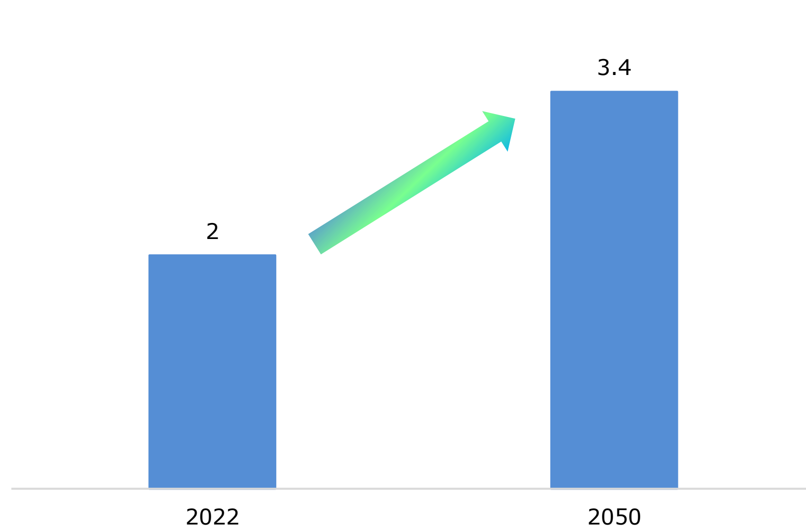
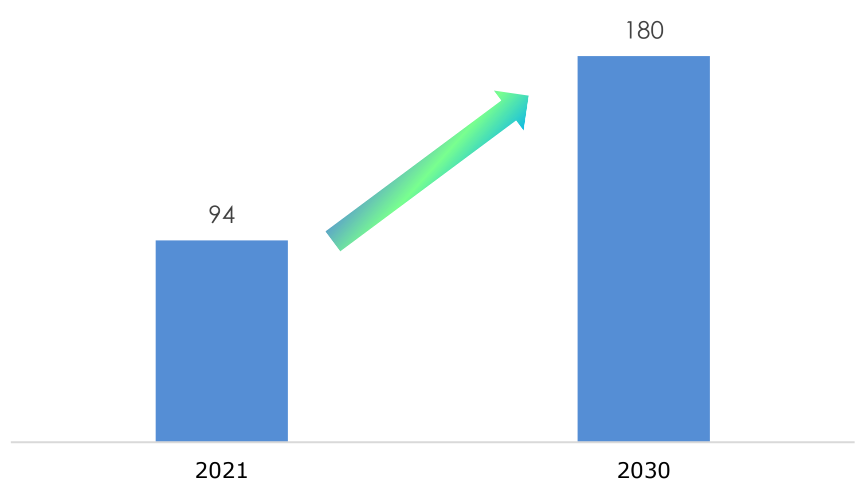


Exhibit 1 shows that the world is facing a significant challenge with municipal solid waste (MSW), which is **expected to double by the year 2050** compared to its current levels [1] [2]. Accordingly, there is a growing urgency to explore alternative methods for managing MSW, thereby driving the advancement of bioenergy projects.

The **potential market for such projects counts over 20,000** solely utilizing MSW as a resource in the upcoming years [3].

Waste disposal currently accounts for 3% of global Greenhouse Gas (GHG) emissions, primarily due to unregulated methane emission during the decomposition of organic materials in landfills. **Methane is a highly potent GHG responsible for more than 30% of global warming and possesses a staggering 28 times greater heat-trapping capacity than carbon dioxide** [2]. Consequently, reducing methane emissions has become a paramount global priority in the ongoing battle against climate change, highlighting the urgency to ensure proper waste disposal methods.

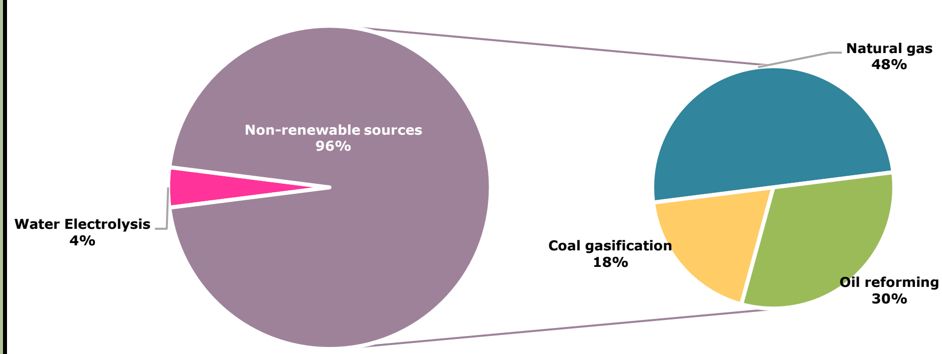
Exhibit 2: Global hydrogen demand, in Million Metric Tonnes (MMT)



Hydrogen is poised to become a key player in shaping a clean, secure, and cost-effective energy landscape in the future. As depicted in **Exhibit 2**, the global demand for hydrogen has been likely to grow substantially, reaching **180 MMT in 2030 compared to 94 MMT in 2021**[4]. This trend emphasizes the increasing acknowledgment and adoption of hydrogen as a crucial component in addressing energy challenges and advancing toward a greener and more sustainable future.

Exhibit 3 reveals a significant trend in which **96% of hydrogen production technologies primarily rely on non-renewable sources** [5]; Therefore, there is an urgent need to focus on developing new and sustainable processes for hydrogen that utilize renewable sources, particularly the organic component of municipal solid waste production.

Exhibit 3: Current technologies used for the production of H_2



Researchers are actively engaged in enhancing the efficiency of several routes for generating hydrogen from MSW. The advancement of these technologies can pave the way for future eco-friendly approaches, aligning with the global goal of transitioning towards more environmentally sustainable energy solutions.

Technologies

Among the waste treatment technologies available, including biological methods and chemical treatments, the thermochemical treatment stands out as the most effective solution for hydrogen production. Below is an overview of the thermochemical treatment process that converts MSW into hydrogen.

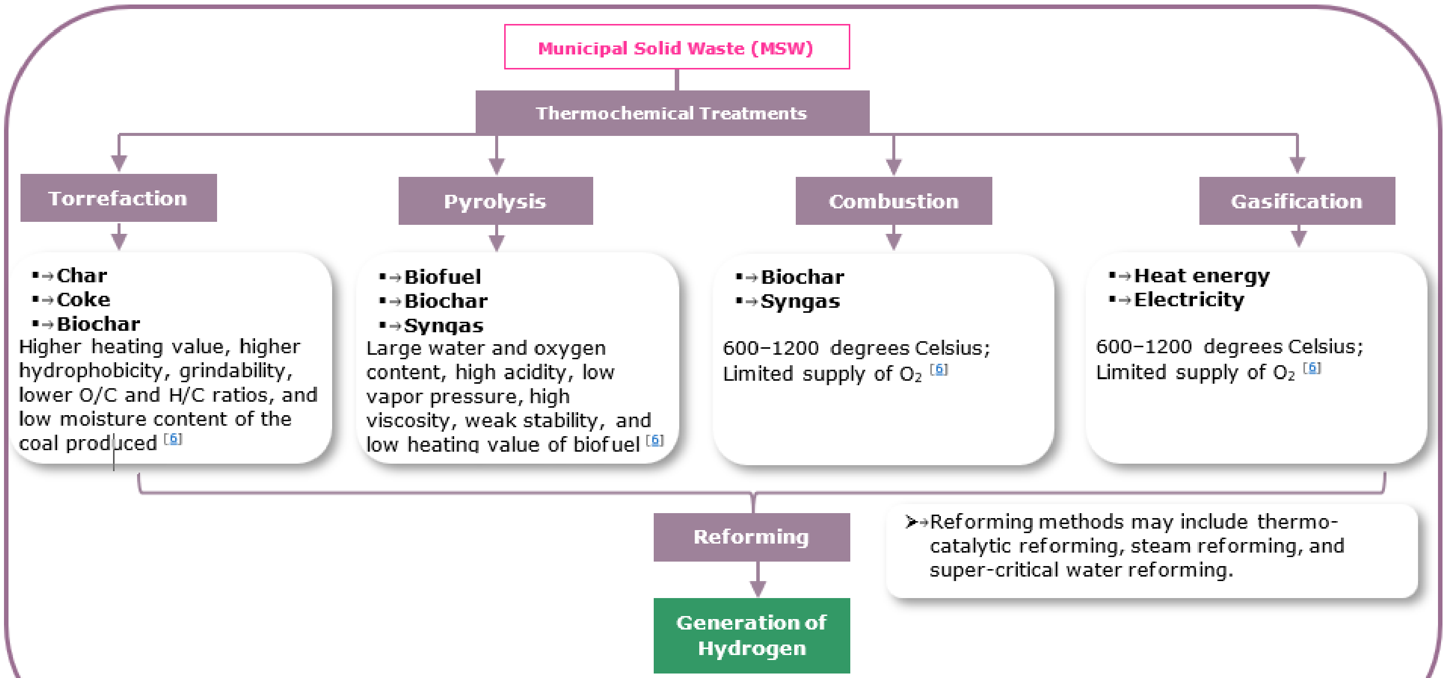


Exhibit 4: Thermochemical treatments for the conversion of MSW to Hydrogen

Approximately 50% of the global MSW encompasses organic materials [5]. The inorganic fraction of MSW is typically recycled or reused. However, managing the organic fraction of MSW (OFMSW) poses both opportunities and risks. Below are some challenges encountered by numerous conversion technologies aiming to transform OFMSW into hydrogen.

- **Anaerobic digestion:** Anaerobic digestion of MSW is a biological process that involves the decomposition of organic waste in the absence of oxygen, producing biogas. During anaerobic digestion, microorganisms break down organic materials, such as food waste, yard trimmings, and other biodegradable waste, to digestate while releasing methane-rich biogas as a byproduct.

This digestate can result in a high level of nitrate content. When this digestate is released into aquatic systems, it can contribute to eutrophication, causing oxygen depletion in the water, harming marine life, and disrupting the ecosystem balance.[5]

- **Gasification:** Gasification of MSW is a thermochemical process that converts organic and non-organic materials into a synthesis gas (syngas), mainly comprising hydrogen, carbon monoxide, and methane. The process occurs in the absence of oxygen at high temperatures, typically ranging from 700°C to 1,200°C. Gasification is a promising waste-to-energy technology that can effectively reduce the volume of MSW while recovering valuable energy resources.

During the gasification process, pyrolysis volatiles' cracking can lead to solid tar formation. This tar can present significant challenges, such as clogging equipment and pipelines, which can severely reduce the system's overall efficiency. The accumulation of solid tar in the processing equipment can hinder the smooth flow of gases and liquids, leading to operational disruptions and increased maintenance requirements. Proper tar management and mitigation strategies are essential to avoid these issues and ensure the efficient operation of the pyrolysis system.[7]

- **Pyrolysis:** The technology of converting organic fractions of OFMSW through pyrolysis holds significant potential for energy recovery. However, to utilize pyrolytic products effectively, additional processes are necessary to refine them for practical applications. For instance, solid tars and other byproducts generated during pyrolysis must be treated and processed to enhance usability. Moreover, the water removed during pyrolysis must be purified to meet quality standards before reusing. This water purification process involves substantial investments in wastewater treatment infrastructure and technologies. The need for such investments may pose economic challenges, especially for smaller-scale pyrolysis facilities.[5] Despite these challenges, the technology's energy recovery potential makes it an attractive avenue for managing organic waste and contributing to sustainable energy solutions. Addressing the purification and refining aspects can further enhance the viability and efficiency of pyrolysis-based systems in the future.

Further, the evaporated water from the pyrolysis process can be strategically utilized as a reactant in the reforming process, particularly when catalytic reforming and pyrolysis are combined. This innovative approach enables the integration of the two processes, creating a synergy that offers multiple benefits.[5] By using the evaporated water as a reactant in the reforming stage, the combined process can substantially reduce the costs associated with cleaning the wastewater generated during the drying process. This integration optimizes resource utilization and minimizes waste generation, making it an environmentally and economically attractive solution. The combination of catalytic reforming with pyrolysis represents one of the most promising and emergent technologies in waste-to-energy conversion. By harnessing the potential of both processes, this integrated approach not only maximizes energy recovery from organic waste but also addresses wastewater management effectively, contributing to a more sustainable and efficient waste treatment solution.

- **Pyrolysis + Catalytic Reforming:** As depicted in Exhibit 5, the MSW undergoes a series of well-coordinated steps to maximize energy recovery and hydrogen production. First, the MSW is directed to an anaerobic digestion facility, where it undergoes decomposition to produce biogas. The biogas is then fed into a catalytic steam reforming reactor. Simultaneously, the digestate from the anaerobic digester undergoes a mechanical dewatering process and is subsequently subjected to pyrolysis. The resulting pyrolytic vapor is combined with the biogas in the reactor.

One of the main advantages of this process lies in its resource efficiency. The steam required for the reforming reactor is supplied by the water content in the digestate, eliminating the need for additional steam. This integrated approach optimizes the use of available resources, making it an environmentally friendly option.

The reformed gas from the reactor is then passed through a cooling tower, followed by a water-gas shift reactor and pressure-swing adsorption unit. These steps are crucial for further purification and separation of the gases. During this process, CO_2 is captured and subsequently compressed, resulting in the production of hydrogen gas. This hydrogen production has the potential to be a frontrunner in the future energy system due to its clean and renewable nature.[5]

Overall, this comprehensive waste-to-energy process effectively utilizes MSW and biogas resources while minimizing waste and greenhouse gas emissions. It showcases the potential of hydrogen as a promising alternative in the global energy transition towards a sustainable and cleaner energy future.

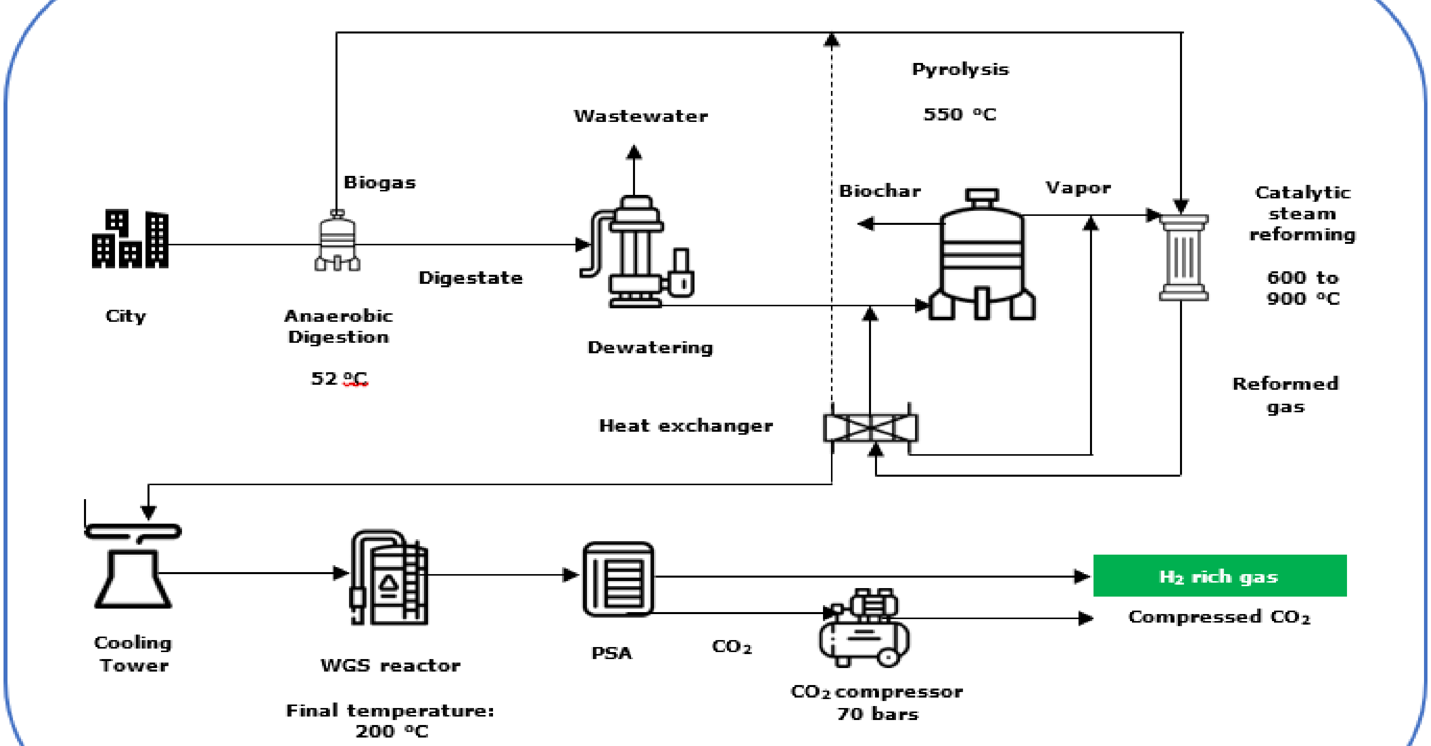


Exhibit 5: Overview of pyrolysis combined with catalytic reforming technology

Exhibit 6 below illustrates the diverse conversion pathways of MSW into hydrogen, along with the respective temperature conditions required for each process.

Treatment method	Temperature conditions	Process yields
Pyrolysis [8]	600 to 900 °C	18.3 to 22.4% H_2 content and 22–26.5% CO content
Torrefaction [8]	1200 °C	Mass residual rate equivalent to 48.71% and lower heating value at 13,000 kJ/kg
Gasification [9]	850 °C	14% of total syngas yield
Gasification [9]	500 to 900 °C	84% of total syngas yield
In-situ steam gasification [10]	750 °C	49.42 vol% H_2 conc. H_2 yield: 277.67 mL/g MSW
Steam Gasification [10]	800 °C	H_2 yield: 34.34 gH_2/kg MSW
Torrefaction [10]	350 °C	-
Plasma Gasification [10]	-	43.3% efficient process

Exhibit 6: Different conversion routes of MSW into hydrogen with their temperature conditions

Technology Developers

Several companies are actively engaged in developing cleaner and more efficient processes for converting MSW into hydrogen while lowering the need for landfill disposal. These industry leaders focus on extracting pure and usable hydrogen from the organic materials in MSW while capturing and managing their carbon content. Simultaneously, they are recycling or reusing the inorganic components of MSW.

These companies are pioneering low-cost, direct conversion solutions that have the added benefit of not generating greenhouse gas emissions. The clean hydrogen produced through these advanced processes holds vast potential for various applications. It can serve as a clean fuel or industrial feedstock, finding use across a broad spectrum of industries, from transportation and industrial applications to power generation.

These technology developers' collective efforts drive innovation in waste-to-hydrogen conversion, revolutionize waste management practices, and contribute to a more sustainable and environmentally friendly energy land.

Exhibit 7: Key technology developers and their recent innovations

Steam/CO_2 Reforming process

The company's patented process transforms all waste, including municipal solid waste into renewable energy products including hydrogen, fuels, additives, and solvents. The hydrogen produced is 99.99% pure and can be used in fuel cells. This technology is unique to Raven as it requires minimal waste sorting before processing waste methane.[11]

RAVEN

Bio-reformation technology

The technique harnesses the organic components of municipal solid waste (MSW) to obtain clean and usable hydrogen while effectively capturing their carbon content. By directly converting MSW, this technology achieves the production of pure hydrogen at an economical cost, all without emitting greenhouse gases. [12]

ECO ENERGY INTERNATIONAL

Waste-to-Hydrogen Technology

The approach employs high-temperature conversion to convert waste into pure hydrogen. The method involves two stages: steam reforming and a water-gas shift reaction, followed by gas separation to isolate H_2 and CO_2. The resulting hydrogen undergoes further refinement at the process's conclusion, while the captured CO_2 can be commercialized for other purposes. [13]

H_2 | Enterprises

Waste-to-Hydrogen Technology

H2e is an innovative company that pioneers cleaner technology, significantly reducing landfill requirements. Their cutting-edge conversion system allows to produce 50 kg of H_2 per day from one ton of biomass feedstock. This eco-friendly solution directly addresses the growing worldwide demand for a source of green, renewable hydrogen for clean mobility applications. [14]

h2e POWER
GOODENERGYSOLUTIONS

Latest Ventures

The success of the hydrogen economy is strongly reliant on global collaboration. International and multilateral cooperation is essential for achieving an economy powered by clean hydrogen and effective waste management. In this complex ecosystem, it is crucial for the entire supply chain to band together and act as one. A cleaner future is attainable through collective effort and unwavering commitment.

Hydrogen has the potential to be a significant energy source in the coming years if a strong waste-management plan is implemented and value-based collaborations are fostered. Its widespread political, technological, and investment interest comes as no surprise. The prospects for widespread adoption of hydrogen are encouraging, as it holds the potential for a sustainable and prosperous future. By joining forces and collaborating, stakeholders can unlock the full potential of hydrogen as a transformative energy solution. Exhibit 8 provides an overview of recent collaboration activities among key stakeholders in the hydrogen industry, highlighting the joint efforts and partnerships aimed at advancing hydrogen technology, infrastructure, and market adoption.

Activity	Intent of the Activity
European Commission RWE	**JANUARY 2023 | INVESTMENT | RWE's waste-to-hydrogen project FUREC receives an EU Innovation Fund of around €108 million.** The project aims to produce 54.000 tonnes of hydrogen per year from about 700,000 tonnes of MSW, of which about 50% will be of biogenic origin. **The final investment decision is anticipated in 2024.** [15]
WAYS2H FROM WASTE TO HYDROGEN ELEMENT 2	**JUNE 2021 | PARTNERSHIP | Ways2H and Element 2 entered a strategic partnership** for producing and distributing renewable hydrogen fuel for transport in the UK, Ireland, and Europe. Under the partnership, **Ways2H will provide facilities that will convert municipal solid waste into hydrogen gas to supply hydrogen to the refuelling stations network of Element 2.** [16]
	JANUARY 2023 | PARTNERSHIP | The Green Billions Limited (TGBL) joins hands with Pune Municipal Corporation (PMC) to set up the first plant in India to extract clean hydrogen from municipal solid waste. [17]
AUBURN UNIVERSITY	**JANUARY 2023 | INVESTMENT | Department of Energy grants $2 million to the researchers of Auburn University** to produce hydrogen from mixed feedstock, including municipal solid waste. The Administration is focused on delivering clean hydrogen at $1/kg. [18]
	AUGUST 2022 | INVESTMENT | Department of Energy planned a new $32 million funding opportunity for research to produce advanced clean hydrogen technology solutions from waste including municipal solid wastes. The funding will support clean hydrogen uses for a more available and affordable fuel for electricity generation. [19]
H2 INDUSTRIES مدائن madayn	**APRIL 2022 | COLLABORATION | H_2-Industries and Madayan have signed a memorandum of understanding** (MOU) to develop a waste-to-hydrogen plant that will initially convert up to **one million tons of municipal solid waste each year into 67,000 tons of green hydrogen** and one million tons of CO_2. [20]

Exhibit 8: Overview of recent Waste-to-Hydrogen conversion activities undertaken by various players

Upcoming Projects

Hydrogen production from waste materials offers a sustainable alternative to landfilling and incineration and serves as a clean fuel option. As depicted in Exhibit 9, the advancement and current development of upcoming technologies in this domain coincides with the growing popularity of hydrogen as a fuel source.

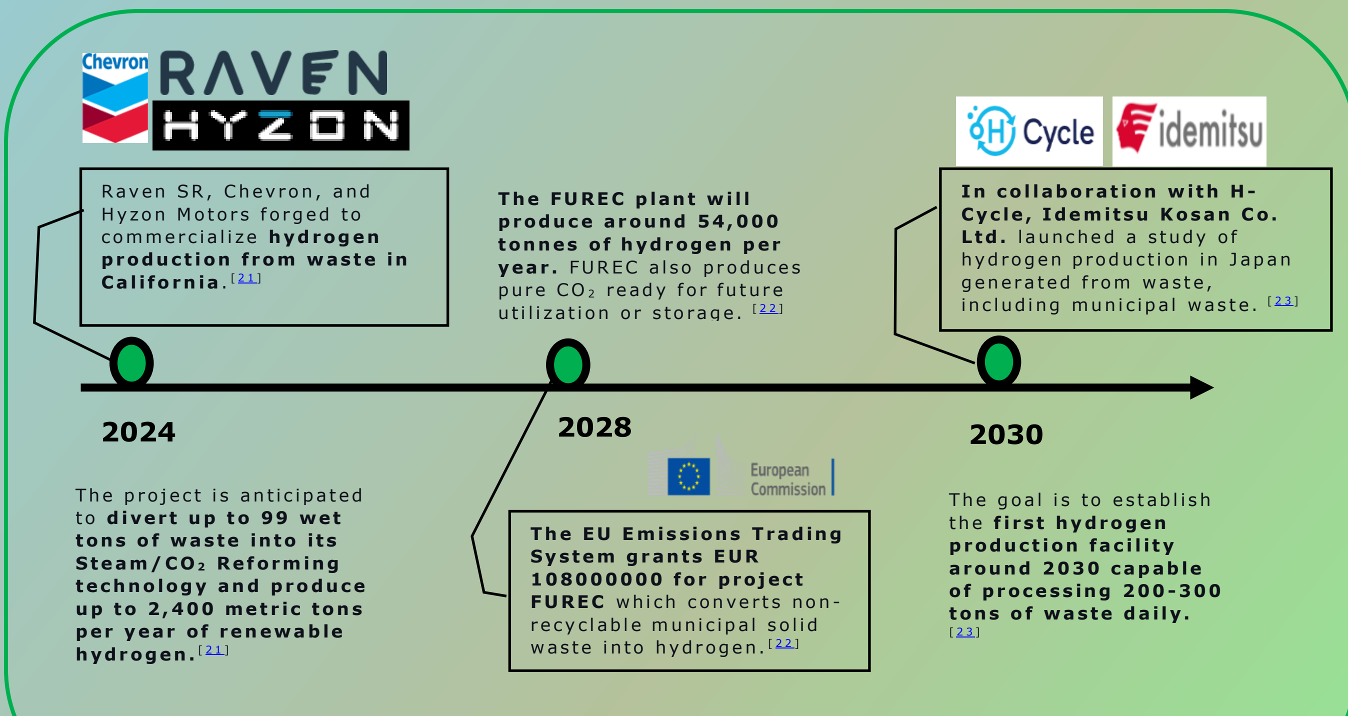


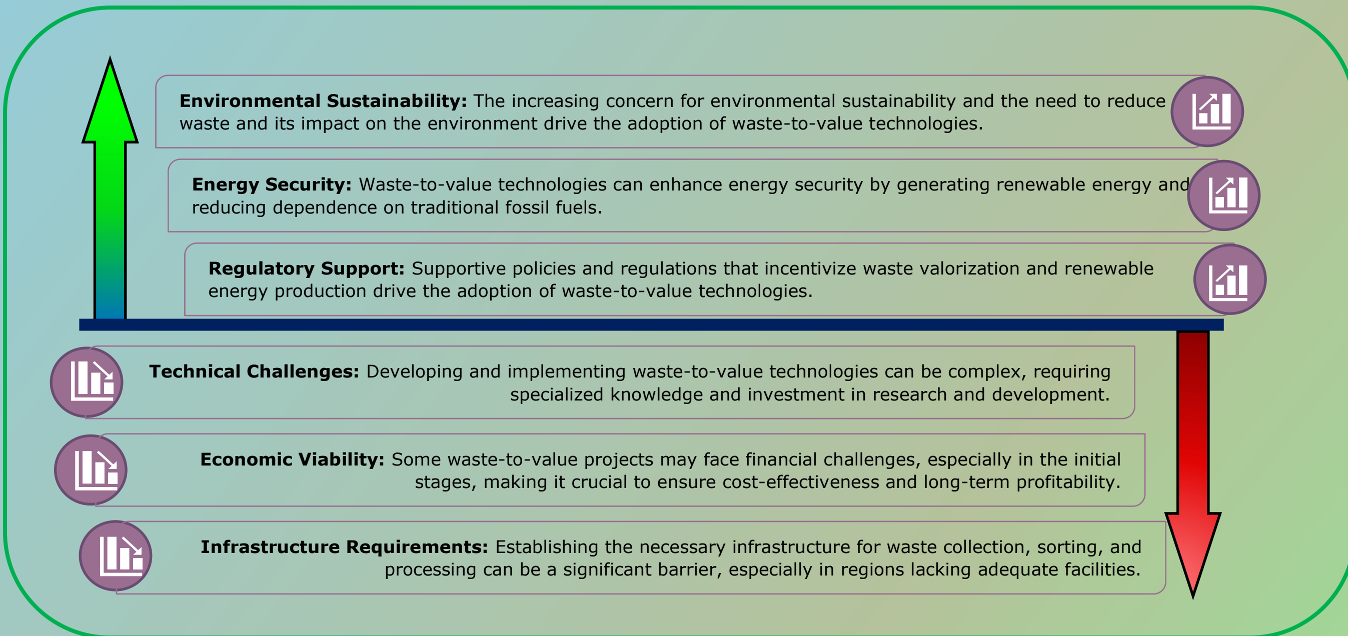
Exhibit 9: Some of the major upcoming projects for Waste-to-Hydrogen conversion

Factors Influencing Market Demand

Hydrogen assumes a critical role in sectors where emission reduction is challenging or alternative mitigation measures are not feasible. Additionally, its overall impact becomes more pronounced in the long run as hydrogen-based technologies mature. As of 2021, global hydrogen demand reached 94 MMT, with a 5% rise compared to the previous year [4]. Hydrogen's contribution to getting the world on track with the net zero scenario will increase demand for hydrogen in almost every sector.

Creating value from waste is influenced by several driving factors and challenges impacting technology. Here are some of the key factors discussed below.

Exhibit 10: Key Drivers & Inhibitors for the Waste-to-Hydrogen conversion



With growing net-zero emission targets of different countries, the potential demand for hydrogen has risen remarkably. The current and target hydrogen demand for different regions [24] is shown below:

Region	Current Hydrogen Demand	Policy Target Demand
Germany 	1.65 MMTPA	2.7 to 3.3 MMTPA by 2030
Hungary 	160 KTPA	36 KTPA (low carbon) + 138 KTPA (grey) by 2030
Japan 	2 MMTPA	3 MMTPA by 2030 | 20 MMTPA by 2050
South Korea 	220 KTPA	3.9 MMTPA by 2030 | 27 MMTPA by 2050
Canada 	3 MMTPA	20 MMTPA
Chile 	58.5 KTPA	5 GW/a (2025) | 25 GW/a (2030)
China 	22 MMTPA	35 MMTPA (by 2030) | 160 MMTPA (by 2050)
Russia 	2-3.5 MMTPA	7 MMTPA by 2035 | 33 MMTPA by 2050

Exhibit 11: Potential hydrogen demand projections in various regions

Future Outlook

According to the International Energy Agency, global hydrogen demand could exceed 200 million tons annually by 2030 in order to meet Net Zero emission targets [13]. Concurrently, the World Bank highlights that approximately 2 billion tons of MSW is generated worldwide each year, demanding environmentally and safely managed practices [13]. To address waste disposal challenges and overcome the hydrogen supply gap, there is a pressing need to develop waste-to-hydrogen conversion technologies.

Advancements in waste-to-hydrogen technologies, coupled with increasing awareness of environmental sustainability, are expected to drive significant investment and innovation in this field. Governments, industries, and research institutions worldwide are likely to collaborate further to develop efficient and economically viable processes that maximize the value of waste materials while lowering greenhouse gas emissions.

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