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IEAGHG

A Critical Study on Waste to Low Carbon (CCS-abated) Hydrogen

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IEAGHG

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CONTACT DETAILS

Tel:	+44 (0) 1242 802911	Address:	IEAGHG, Pure Offices,
E-mail:	mail@ieaghg.org		Cheltenham Office Park, Hatherley Lane,
Internet:	www.ieaghg.org		Cheltenham, GL51 6SH, UK



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- Prof. Ali Abbas (University of Sydney)
- Prof. Rose Amal (University of New South Wales)
- Dr. Rahman Daiyan (University of New South Wales)
- Dr. Gustavo Fimbres Weihs (University of Sydney)
- Mr. Thomas Gao (University of New South Wales)
- Dr. Denny Gunawan (University of New South Wales)
- Prof. Cameron Holley (University of New South Wales)
- Dr. Eric Sanjaya (University of Sydney)
- Dr. William Hadinata Lie (University of New South Wales)

Supporting Authors:

- Dr. Muhammad Haider Ali Khan (University of New South Wales)
- Dr. Peter Ellersdorfer (University of New South Wales)
- Dr. Mandalena Hermawan (University of New South Wales)

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The IEAGHG manager for this report was: Abdul'Aziz Aliyu.

The expert reviewers for this report were:

- Muhammad Akram, Theme Manager Carbon Capture and Utilisation at The Translational Energy Research Centre (TERC), University of Sheffield
- Brandy Johnson, Chief Technology Officer at Babcock and Wilcox
- Eric Lewis, Research General Engineer at National Energy Technology Laboratory, US Department of Energy (NETL - DOE)
- Kai Lieball, Director Decarbonisation at Kanadevia Inova
- Charoula Melliou, Head of Policy at European Suppliers of Waste to Energy Technology (ESWET)
- Tim Podesta, Independent Consultant at Tim Podesta Consulting
- Federico Vigano, Assistant Professor of Systems for Energy and the Environment at Department of Energy, Polytechnic University of Milan
- Berend Vreugdenhil, Senior Scientist Specialist, Energy & Materials Transition at Dutch Organisation for Applied Scientific Research (TNO)



Report Overview:

A Critical Study on Waste to Low Carbon (CCS-abated) Hydrogen

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Introduction

This study presents a systematic review of waste-to-hydrogen (WtH) technologies and conducts analysis of the technological, economical, and environmental aspects of the most promising waste-to-low carbon hydrogen technologies for near-term commercial deployment. The findings provide valuable insights into the opportunities, challenges, and potential solutions to foster and expedite the global adoption of WtH projects.

Further, the report introduces a modular environmental justice (EJ) framework designed to assess the fairness of WtH projects, enabling a thorough evaluation of their potential environmental and social impacts.

Key Messages

- Following a review of thermochemical, biochemical, electrochemical, and photochemical processes for hydrogen production pathways from municipal solid waste (MSW), gasification, pyrolysis, dark fermentation, and incineration-electrolysis were identified for further study with carbon capture and storage (CCS) retrofit due to their high technology readiness levels (TRLs).

- Thermochemical processes stand out as the most balanced and promising WtH pathways. They offer high hydrogen yields and energy efficiency with relatively lower levelized costs of hydrogen (LCOH) compared to biochemical conversion pathways. Specifically, gasification requires ~23 kg of MSW to produce 1 kg of hydrogen, while pyrolysis uses ~25 kg of MSW to achieve the same hydrogen output.
- Dark fermentation exhibits a markedly lower efficiency, requiring approximately ~143 kg of MSW to generate 1 kg of hydrogen, underscoring its limited effectiveness compared to thermochemical methods. Meanwhile, the incineration-electrolysis process requires ~80 kg of MSW to produce the same amount of hydrogen, reflecting its suboptimal resource utilisation.
- Maintaining an economically viable LCOH in WtH technologies hinges on both the cost and consistent availability and quality of MSW. While the baseline scenario assumes zero-cost MSW, implementing a waste tipping fee can further reduce LCOH. A steady supply of MSW is essential; fluctuations in availability, reflected in the capacity factor, can lead to increased costs due to lower operational efficiency.
- Variability in the quality of waste feedstock presents a significant obstacle for WtH projects, when waste quality fluctuates, operational efficiency is compromised, and the LCOH increases to address this, pre-treatment methods such as torrefaction (as used in the RWE Fuse Reuse Recycle (FUREC) project) are increasingly implemented to standardise feedstock and reduce variability, ensuring more reliable hydrogen production.
- Economically, WtH-CCS processes are currently not viable, as indicated by the significantly high LCOH (US\$5.15/kg-US\$14.91/kg across the pathways examined in this study) compared to the costs of hydrogen from coal (US\$1.20-2.21/kg without CCS or US\$2.10-2.62/kg with CCS) and natural gas (US\$0.91-1.79/kg without CCS or US\$1.21-2.11/kg with CCS). The high LCOH for WtH-CCS is primarily driven by high CAPEX and OPEX due to the complexity and/or currently limited efficiency of the process.
- The cost feasibility improvement analysis suggests that a combination of efficiency improvements, byproduct recovery, CAPEX reduction, effective waste management and carbon incentives are required to lower the LCOH for CCS-abated gasification, pyrolysis, incineration-electrolysis, and dark fermentation pathways. In addition, economies of scale are essential to establish a cost-effective waste-to-low-carbon-hydrogen conversion.

- Hydrogen production via pyrolysis and gasification are the most environmentally favourable processes across most impact categories¹. However, their reliance on natural gas leads to higher ozone depletion potential (ODP) compared to dark fermentation and incineration. Dark fermentation has the highest overall environmental impact due to significant chemical usage, high power demands from fossil-fuel grids, and complex wastewater treatment. Incineration, on the other hand, has the greatest impact on terrestrial ecotoxicity, primarily due to the disposal of char and ash from high MSW consumption.
- Substituting energy inputs with renewable energy generally reduces environmental impacts across most categories. However, it also introduces new challenges, such as heightened water consumption, increased land use, and the depletion of metals. Electrifying the heating system within the process could further mitigate environmental impacts, but doing so would necessitate expanding the lifecycle assessment (LCA) boundary to encompass the generation, manufacturing, and recycling of renewable energy technologies.
- Deploying WtH-CCS to produce clean hydrogen faces notable logistical and economic hurdles, particularly due to the complexities of coordinating transport, storage of feedstock, the CO₂ captured, and the hydrogen produced. Small-scale, geographically dispersed projects may struggle with economic feasibility, especially given the potential for fluctuating waste availability and quality.
- This report develops a modular EJ framework to assess the fairness of WtH projects by evaluating six EJ dimensions² across five critical aspects³. Applied to the FUREC (FUse REuse ReCycle) project in the Netherlands, the EJ fairness evaluation showed strong performance in environmental & economic opportunities. However, the FUREC WtH site location choice in Chemelot scores very poorly in terms of fairness, which can be attributed to its proximity to residential areas and the current uncertainty of the FUREC funding status.

¹ Agricultural land occupation (ALOP), climate change (GWP100), fossil depletion (FDP), freshwater ecotoxicity (FETPinf), freshwater eutrophication (FEP), human toxicity (HTPinf), ionising radiation (IRP_HE), marine ecotoxicity (METPinf), marine eutrophication (MEP), metal depletion (MDP), natural land transformation (NLTP), ozone depletion (ODPinf), particulate matter formation (PMFP), photochemical oxidant formation (POFP), terrestrial acidification (TAP100), terrestrial ecotoxicity (TETPinf), urban land occupation (ULOP), water depletion (WDP)

² F. Müller et al.'s six environmental justice dimensions: Procedural, relational, recognitional, distributive, restorative, & epistemic justice.

³ Site location, economic opportunities, environmental impact, health impact, and community engagement

Background of study

Generating hydrogen from waste streams offers significant potential for the realisation of a sustainable hydrogen economy. In particular, MSW is one of potential waste feedstock for hydrogen production. Utilising global MSW as feedstock (approximately 2 billion tonnes per year) has the potential to generate 60 million tonnes of hydrogen annually.

Currently, waste management predominantly follows a linear “take-make-dispose” economy paradigm. 70% of global MSW is currently either sent to landfill or openly dumped each year (see Figure 1). By incorporating waste prevention strategies and promoting recovery and recycling, the world could potentially reduce GHG emissions by 15-20%.

The aim of a circular economy approach is to close the material loop by treating waste as a resource. Therefore, it is critical to develop sustainable waste treatment methods that focus on reclamation and valorisation, eliminating, or at least reducing, the discarding of waste into the environment.

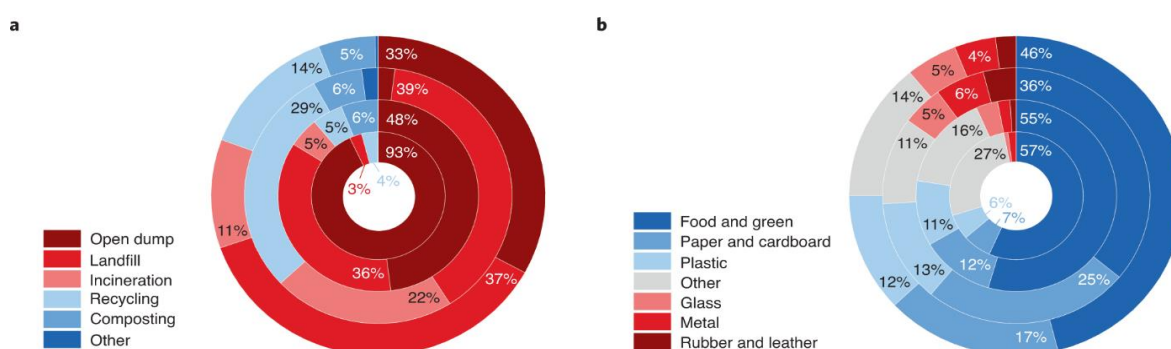


Figure 1. Municipal waste (a) disposal methods and (b) composition.⁽¹³⁾ Outer rings are world averages, second rings upper-income countries, third rings middle-income countries, and inner rings low-income countries. Copyright © 2021 Springer Nature.

Scope

The Netherlands was selected as the reference plant location, in line with the IEAGHG techno-economic assessment criteria. The plant was designed to convert 2,000 tonnes of MSW per day (tpd) into hydrogen via four different WtH pathways. These include gasification, pyrolysis, dark fermentation, and incineration-electrolysis, which were selected from a broad spectrum of hydrogen production technologies from MSW through a rigorous multi-criteria assessment (MCA) approach. Gasification, pyrolysis, and incineration-electrolysis were designed to process unsorted MSW, while dark fermentation was designed to handle the organic fraction of MSW (OFMSW). The plant capacity of 2,000 tpd MSW is adopted based on the planned capacity of FUREC gasification project that aims to process ~700,000 tonnes of MSW per annum (equivalent to ~2,000 tpd). Where carbon capture is modelled in this study, a high CO₂ capture efficiency of 95%

is employed. The CO₂ is conditioned at a pressure of 11 bar and a temperature of 30 °C, suitable for pipeline transport to storage site e.g., in offshore gas fields in the North Sea, which are the closest existing CO₂ storage projects identified in the case studies. In the first year of operation, the plant capacity factor is set to 60% to allow for start-up and debugging. Subsequently, the plant operates at base load, at a capacity factor of 85%. Cost analysis is carried out in US\$ throughout this study because most of the process equipment capital costs have been obtained from literature or commercial vendors in that currency. The discount rate, construction time, and plant lifetime are assumed to be 8%, 3 years, and 25 years, respectively.

The techno-economic analysis is based on models developed from literature and vendor data, tailored to generic designs with assumptions relevant to a base case scenario situated at the Chemelot Industrial Park, in the Netherlands. The system was costed using the open-source HySupply⁴ cost analysis tool. The time value of money was then applied to generate a levelised cost of hydrogen (LCOH) for each process.

The LCA, conducted using OpenLCA with the Ecoinvent 3.6 database, adheres to a cradle-to-gate scope, evaluating the environmental impacts from resource extraction to hydrogen production, using one kilogram of hydrogen (H₂) as the functional unit.

For the WtH study within the context of EJ, the research adapts insights from F. Müller et al.'s six-element justice framework.² This framework, initially developed for hydrogen projects, is adapted to assess the equitable distribution of benefits and burdens in WtH projects, acknowledging the added complexity of municipal waste management and its associated social and EJ concerns. The adaptation ensures that the unique challenges and nuances of the WtH technologies in this study are effectively captured, given their differences from conventional hydrogen production processes.

Further, to evaluate the fairness and equity of WtH projects within the context of the 6-dimension EJ framework, a 5-step process was proposed:

1. Gather Information:
2. Identify Key EJ Concerns:
3. Assess Impacts:
4. Develop and Implement Mitigation Strategies:
5. Monitor and Evaluate:

⁴ HySupply is an open-source cost analysis tool developed to model the costs involved in the production of green hydrogen. The cost model is then used to estimate the levelised cost of hydrogen through a discounted net present value analysis.

Depending on the project's goals and aims, step 4 may be revisited until all EJ concerns have been satisfactorily addressed.

Findings

Techno-economic analysis: CCS-abated hydrogen production via MSW gasification

A discounted cash flow analysis based on the CAPEX and OPEX estimations was performed to obtain the LCOH. The LCOH for a gasification process, with a capacity of 2,000 tpd MSW and generating 89 tpd hydrogen, is estimated to be US\$5.15/kg, which is more expensive than the current market price range of unabated hydrogen from coal gasification and steam methane reforming (US\$0.91-2.21/kg). The contributors to this LCOH are shown in Figure 2.

The major components are the capital investment, which contributes 52% of the LCOH, followed by fixed O&M (20%) and energy costs for heating and electricity (15%).

The LCOH of MSW gasification process is highly influenced by the plant scale. For example, a small 100 tpd MSW gasification plant is estimated to have a LCOH of US\$13.3/kg which represents an increase of almost 160% from the base case capacity of 2,000 tpd MSW. Thus, economies of scale play a prominent role in determining the economic feasibility of the MSW gasification process. However, designing the suitable plant capacity for a high-risk MSW gasification project requires careful assessment of the availability of waste feedstock to ensure continuous operation. The fluctuation in the supply of waste feedstock, represented by the capacity factor, also substantially impacts the LCOH. For instance, a decrease in the capacity factor to 60% leads to an increase in LCOH of nearly 30%.

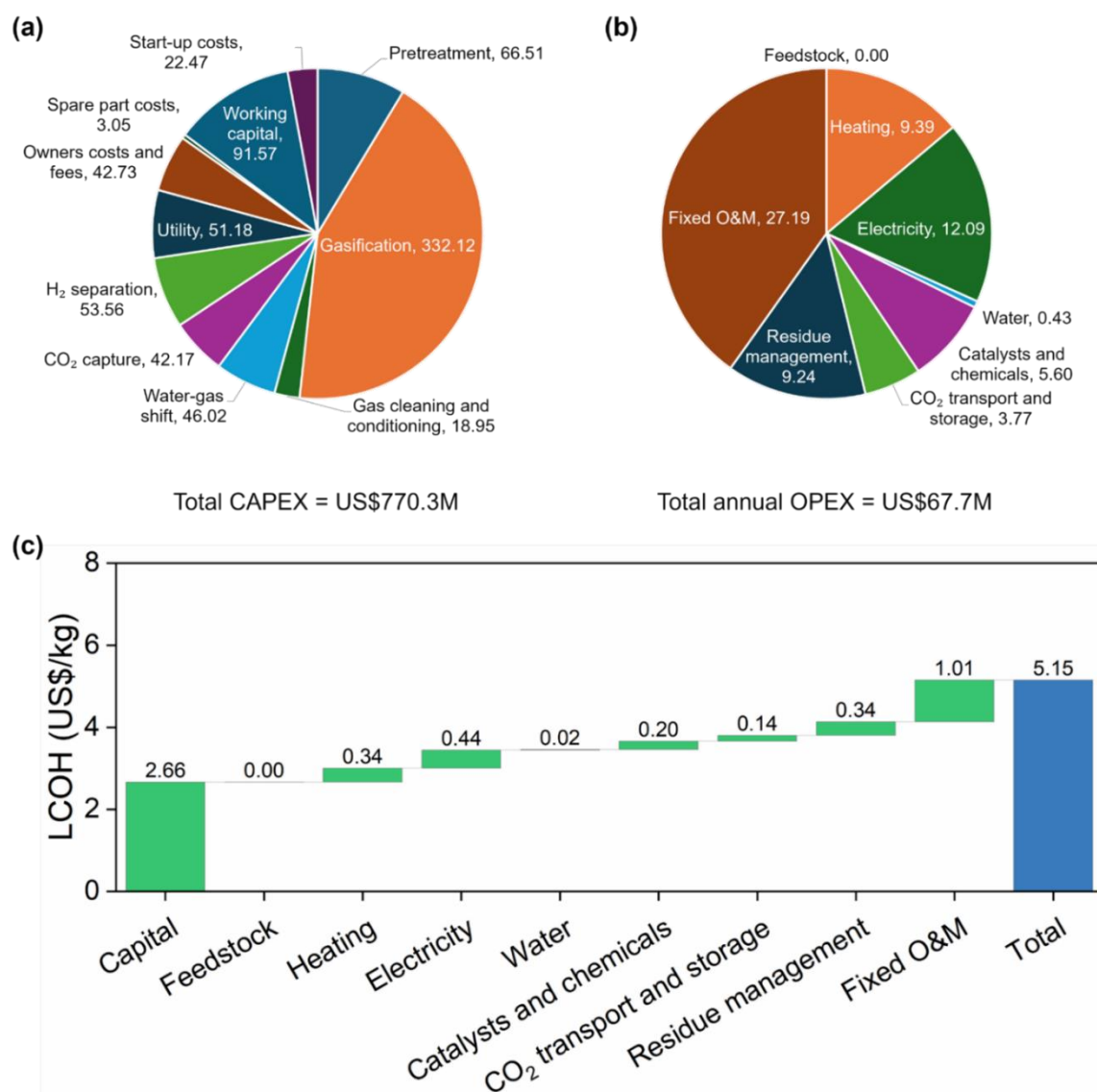


Figure 2. (a) Indicative CAPEX and (b) OPEX breakdown for MSW gasification process with a MSW processing capacity of 2,000 tpd generating 89 tpd hydrogen. © Indicative current LCOH breakdown for MSW gasification process under base case scenario with a MSW processing capacity of 2,000 tpd generating 89 tpd hydrogen.

Besides scale and capacity factor, several technical and economic parameters were also varied in sensitivity analysis to evaluate the impact on the LCOH. The lower heating value (LHV) efficiency of MSW to hydrogen conversion has a prominent effect on the LCOH and may be affected by the gasifier efficiency, catalytic performance, feedstock quality, and operating conditions such as temperature, pressure, and steam/O₂ ratio. Improving the LHV efficiency from 49.4% (base case scenario) to 60% would significantly reduce the LCOH by 16%.

Techno-economic analysis: CCS-abated hydrogen production via MSW pyrolysis

The LCOH for pyrolysis process, with a capacity of 2,000 tpd MSW generating 80 tpd hydrogen, is estimated to be US\$6.00/kg, which remains higher than the market price range of unabated hydrogen from coal gasification and steam methane reforming (US\$0.91-2.21/kg). The contributions to the LCOH for pyrolysis route are shown in Figure 3.

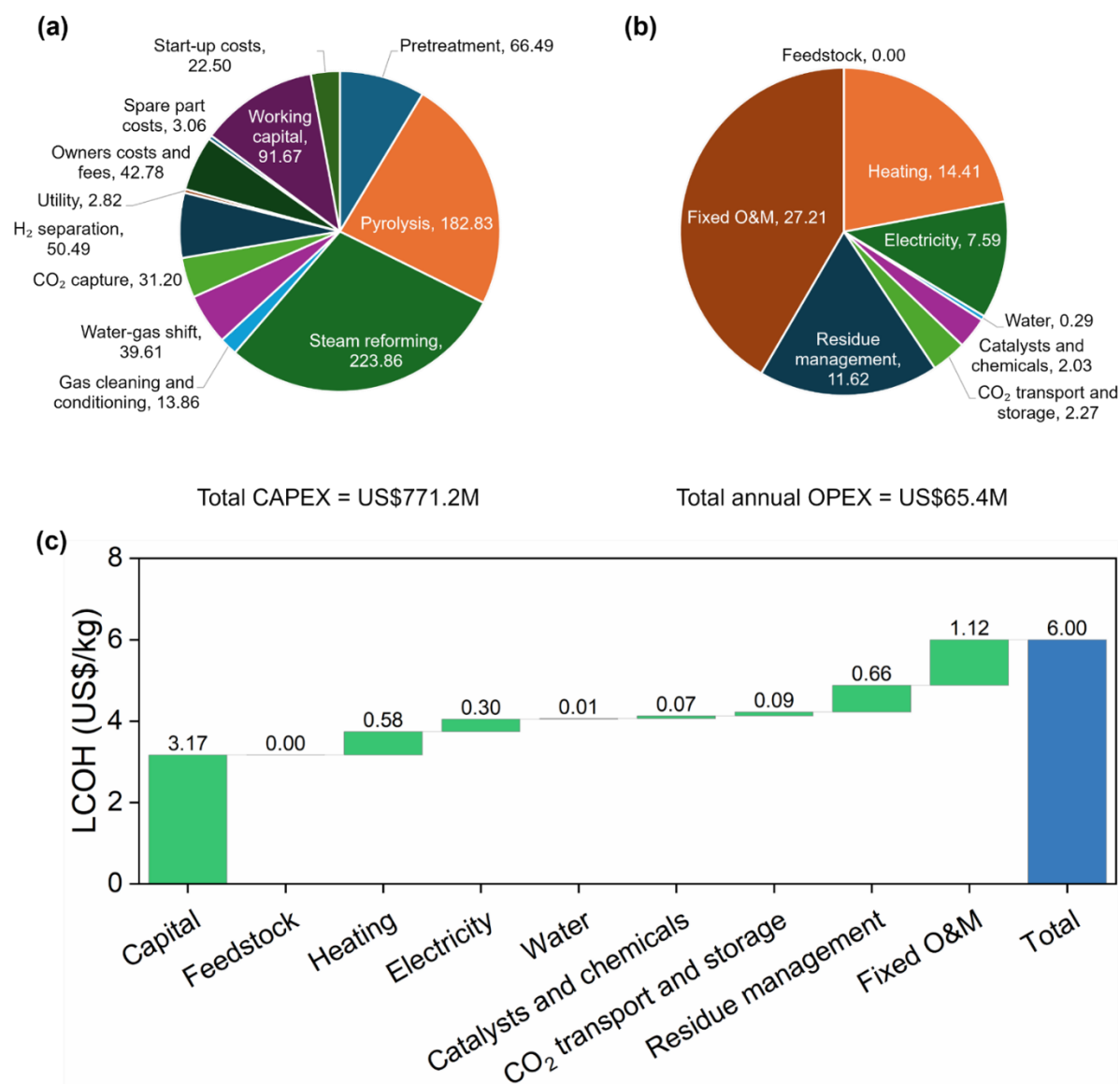


Figure 3. (a) Indicative CAPEX and (b) OPEX breakdown for MSW pyrolysis process with a MSW processing capacity of 2,000 tpd generating 80 tpd hydrogen. © Indicative current LCOH breakdown for MSW pyrolysis process under base case scenario with a MSW processing capacity of 2,000 tpd generating 80 tpd hydrogen.

The main cost component is the capital investment, which contributes 53% followed by the fixed O&M costs (19%) and energy costs (15%).

The economic feasibility of the MSW pyrolysis process is strongly influenced by the economies of scale. A small 100 tpd MSW pyrolysis plant has a LCOH of US\$16.67/kg, representing an increase of 177.83% from the base case capacity of 2,000 tpd. Nevertheless, setting the designed plant capacity for a pyrolysis project must consider the availability of waste feedstock to ensure continuous operation.

Sensitivity analysis reveals that fluctuations in MSW supply, as indicated by the capacity factor, affect the LCOH. A reduction in the capacity factor to 60% would result in a 27% increase in the LCOH. Further analysis revealed that the LHV efficiency plays a significant role in driving the LCOH, with improvements to 60% potentially reducing LCOH by 15%. This efficiency may be influenced by factors such as catalytic efficiency of the pyrolyser, steam reformer, and water-gas shift reactor, as well as the type and quality of feedstock and operating conditions.

Sensitivities also highlighted the capital-intensive nature of waste pyrolysis, where CAPEX reductions are critical; a 15% decrease in CAPEX could lower LCOH by 10%, particularly in the pyrolyser and steam reformer. Additionally, the cost of waste feedstock has a significant impact on LCOH. A waste tipping fee of US\$46/t could reduce LCOH to US\$5.34/kg, whereas an increase in MSW cost to US\$33/t would raise it to US\$6.47/kg. Furthermore, integrating CCS into MSW pyrolysis could unlock carbon credits, which would significantly lower LCOH by 14% at the average carbon price under the European Union Emissions Trading System (EU ETS) in 2023, set at US\$90/t.

Techno-economic analysis: CCS-abated hydrogen production via dark fermentation of OFMSW

The LCOH for the fermentation process, with a capacity of 2,000 tpd OFMSW generating 14 tpd hydrogen, is estimated to be US\$13.70/kg, which is significantly higher than the market price range of unabated hydrogen from coal gasification and steam methane reforming (US\$0.91-2.21/kg).

The contributions to the LCOH are shown in Figure 4. The main contributor is capital investment, which contributes 35% to the LCOH. The next most significant costs are for residue management, fixed O&M, and catalysts and chemicals which account for 22%, 22%, and 12% of the total LCOH, respectively.

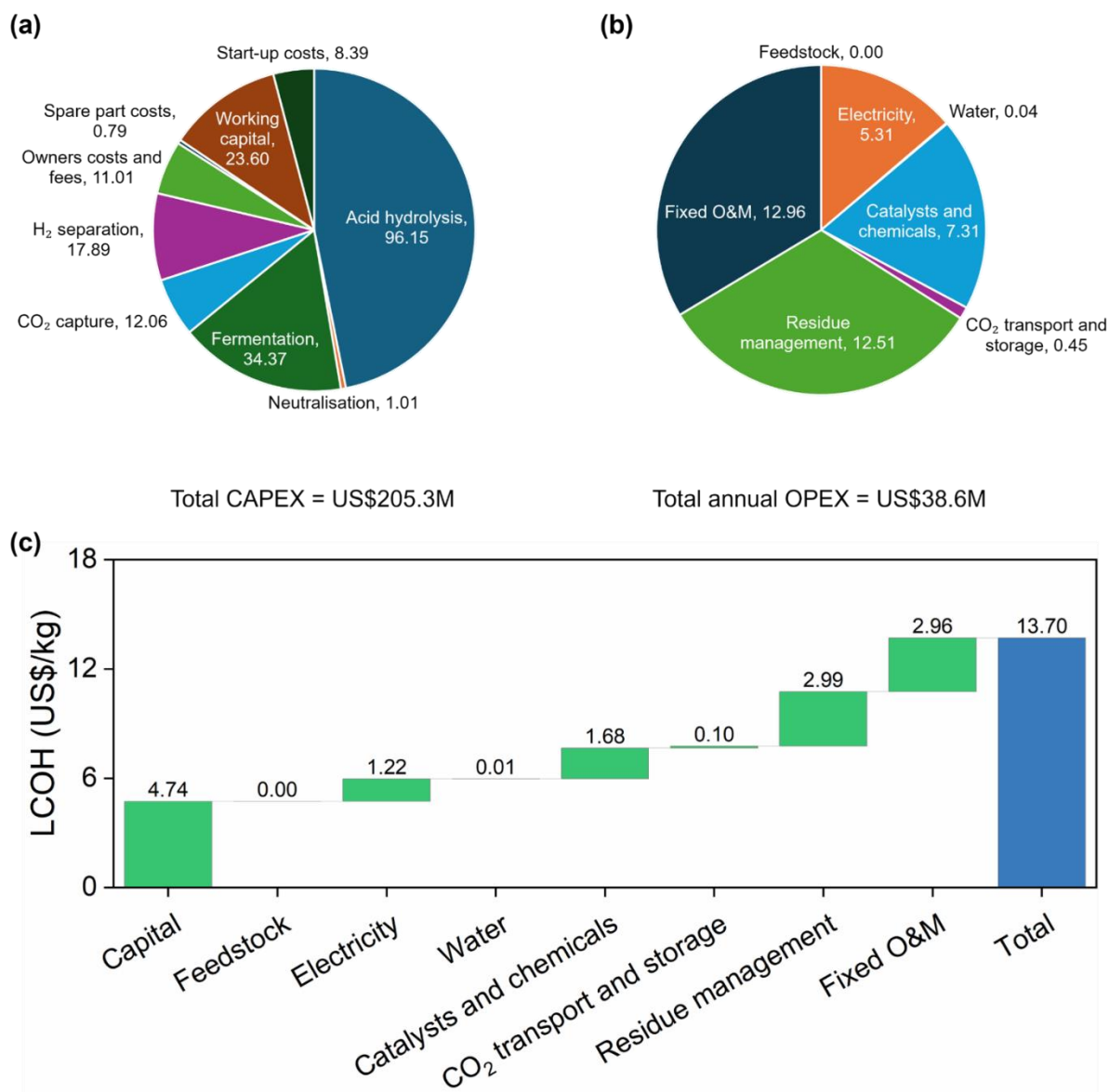


Figure 4. (a) Indicative CAPEX and (b) OPEX breakdown for OFMSW dark fermentation process with a OFMSW processing capacity of 2,000 tpd generating 14 tpd hydrogen. © Indicative current LCOH breakdown for OFMSW dark fermentation process under base case scenario with a OFMSW processing capacity of 2,000 tpd generating 14 tpd hydrogen.

A dark fermentation process does not produce significant amounts of CO₂ as most of the carbon remains as an acetic acid byproduct in the solution. This renders the impact of CCS credit on the LCOH for dark fermentation process relatively small. The base case assumes that the liquid fermentation product containing acetic acid is sent to external anaerobic digestion wastewater treatment facility at US\$2/m³ cost. However, recovering the acetic acid product by retrofitting an extractive distillation unit (which significantly adds the CAPEX and annual OPEX by US\$34.4M and US\$13.6M, respectively at the base case capacity) and selling it at US\$500/t shows a prominent LCOH reduction to US\$10.15/kg.

The LCOH for OFMSW dark fermentation is primarily driven by the hydrogen yield, acetic acid revenue, and feedstock cost. To identify cost reduction opportunity for dark fermentation process, a cost feasibility improvement analysis was conducted. Enhancing the hydrogen yield from 2.5 mol H₂/mol glucose to 3.2 mol H₂/mol glucose, which can be done by optimising the dark fermentation process conditions, would significantly lower the LCOH by US\$1.96/kg. In addition, there is an opportunity for the co-production of acetic acid byproduct by installing extractive distillation unit. Taking into account additional CAPEX and OPEX for acetic acid separation and purification unit, the LCOH could be reduced by US\$3.97/kg. Decreasing the plant CAPEX combined with imposing CCS credit and waste tipping fee would further bring down the LCOH to a projected value of US\$3.80/kg. These cost reduction opportunities offer future directions for the development of WtH conversion via dark fermentation process.

Techno-economic analysis: CCS-abated incineration of MSW coupled with water electrolysis to produce hydrogen

The LCOH for the incineration-electrolysis process, with a capacity of 2,000 tpd MSW generating 25 tpd hydrogen, was estimated to be US\$14.91/kg (Figure 5), which is higher than the market price range of unabated hydrogen from coal gasification and steam methane reforming (US\$0.91-2.21/kg).

In addition, CAPEX reduction for both WtE and water electrolysis sections are crucial. Decreasing the WtE CAPEX by 15%, for instance, would lead to a nearly 10% LCOH reduction. The anticipated proton exchange membrane (PEM) electrolyser capital cost reduction from US\$1,700/kW to US\$700/kW by 2030 could also lower the LCOH by approximately 10%. The waste feedstock cost plays a significant role in determining the LCOH. In the event that a waste tipping fee of US\$46/t is imposed, the LCOH may decrease substantially by 21%. Imposing a carbon credit would help to significantly lower the LCOH. At an average CO₂ price of US\$90/t in 2023, the LCOH can be reduced to US\$9.71/kg.

The primary driving factors of LCOH for MSW incineration-electrolysis process, which have been identified through the sensitivity analysis, include WtE and electrolyser efficiencies, equipment CAPEX, CCS credit, and feedstock cost. The LCOH can be substantially lowered by improving the efficiency of the WtE plant to 35% and decreasing the PEM electrolyser specific energy consumption to 42 kWh/kg H₂. Additionally, imposing a CCS credit of US\$90/t CO₂ and a waste tipping fee at the current average waste disposal cost in the Netherlands (US\$46/t MSW) has substantial impacts in reducing the LCOH for incineration-electrolysis. This projected LCOH provides future directions for developing more cost-effective waste incineration-electrolysis process for hydrogen production.

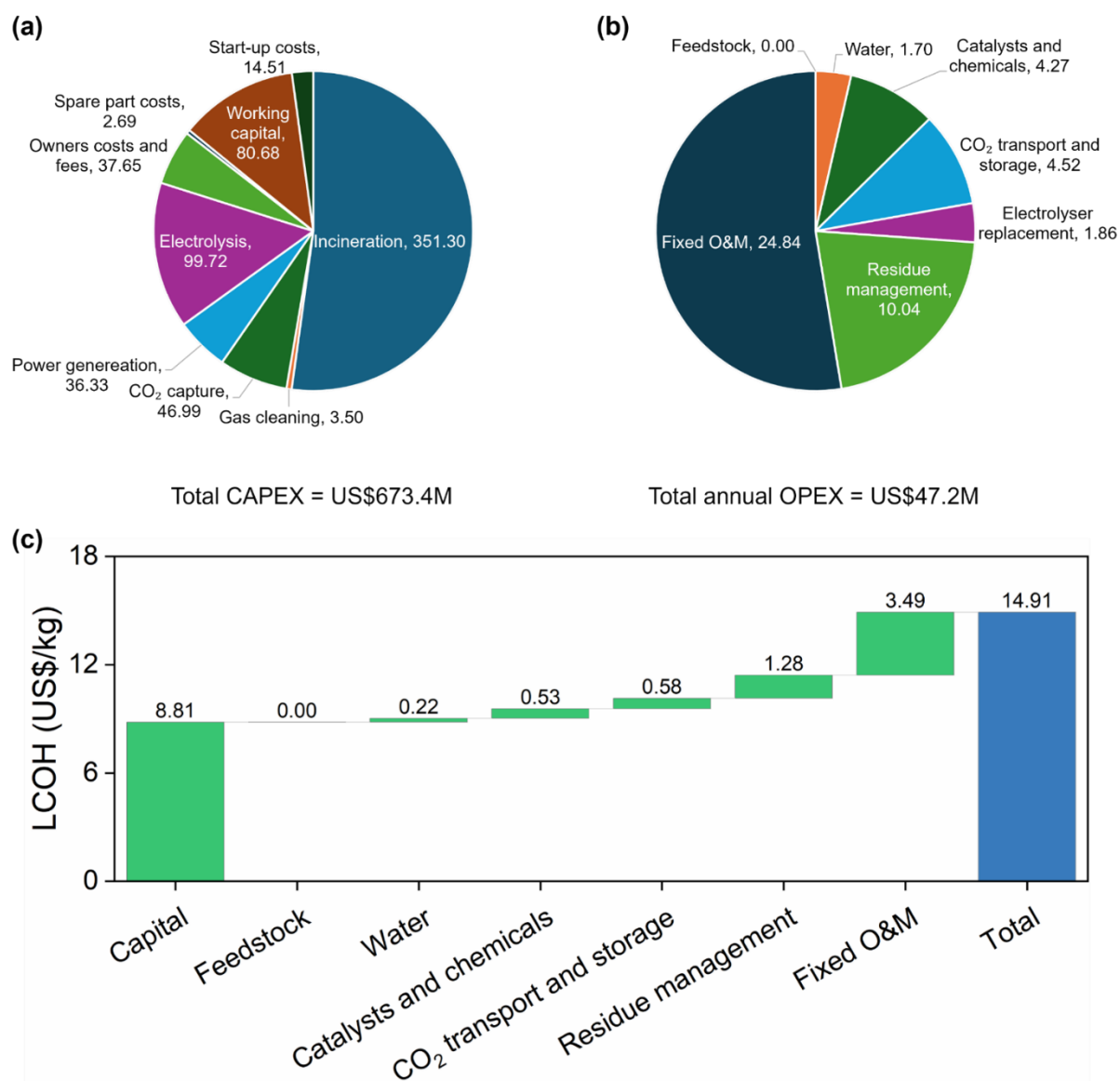


Figure 5. (a) Indicative CAPEX and (b) OPEX breakdown for MSW incineration-electrolysis process with a MSW processing capacity of 2,000 tpd generating 25 tpd hydrogen. All values are in million US\$. © Indicative current LCOH breakdown for MSW incineration-electrolysis under base case scenario with a MSW processing capacity of 2,000 tpd generating 25 tpd hydrogen.

Summary of LCA of Waste to Hydrogen

To produce 1 kg of hydrogen, pyrolysis and gasification stand out as the most environmentally beneficial processes across all impact categories¹ (see figure 6), except in the categories of terrestrial ecotoxicity, photochemical oxidation formation, and ozone depletion. The environmental benefit of these processes is due to their higher reliance on heating as an energy source than power (under the business-as-usual scenario). The effect is that this scenario predominantly uses energy generated from natural gas

combustion (as opposed to the fossil fuel mix from the power grid), which leads to cleaner energy generation and a reduced environmental impact.

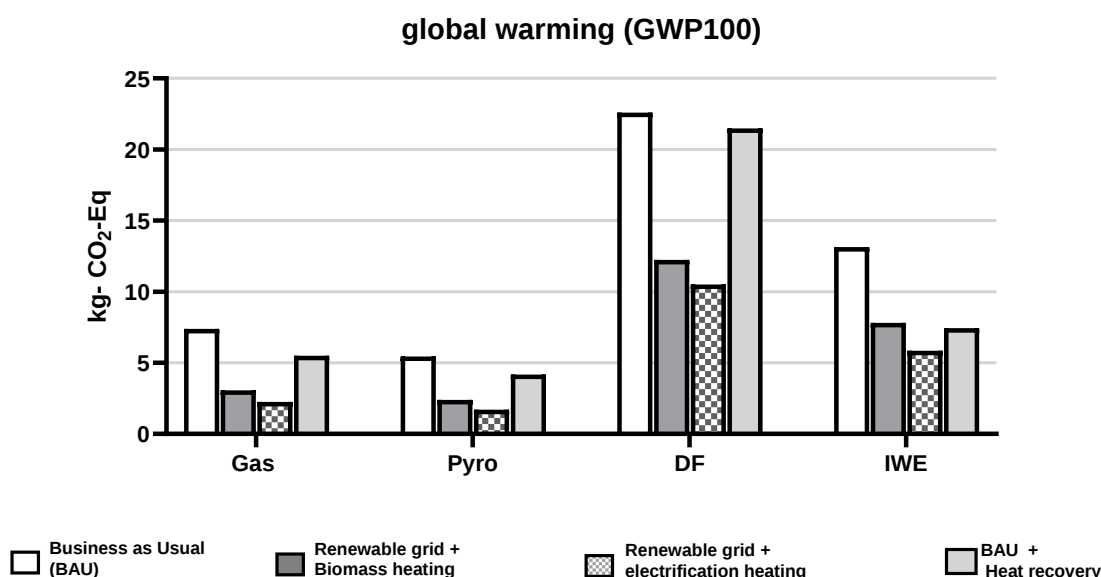


Figure 6. GWP comparison between BAU, Renewable energy, process electrification, and BAU with heat recovery for four WtH processes.

However, this heightened dependence on natural gas means pyrolysis and gasification exhibit a higher ozone depletion potential (ODP), compared to dark fermentation or incineration, because on-site natural gas combustion for energy emits less emissions than the electricity network, consequently resulting in higher ODP.

In contrast, dark fermentation displays the highest environmental impact in most categories. This can be attributed to factors such as (1) the significant additional chemicals required for the process, (2) high power demands, which are sourced from a fossil-fuel dependent power grid, and (3) more complex wastewater treatment.

In dark fermentation, auxiliary processes add to the environmental impact caused by the high-power requirement. Moreover, as a result of the assumption that it requires more advanced wastewater treatment (WWT), dark fermentation registers a high environmental impact in the categories of marine eutrophication and metal depletion. This may be caused by the high nutrient content and additional resources required.

Incineration consumes the most MSW (80 kg) to produce 1 kg of hydrogen and serves as an example that high waste processing does not necessarily equate to greater environmental benefit. Incineration with electrolysis shows that utilising energy to produce hydrogen rather than generating it directly from waste material can be ineffective, especially when compared to a thermochemical process that synthesises hydrogen directly from waste material, e.g. pyrolysis and gasification.

The environmental impacts of gasification and pyrolysis are relatively similar across a range of categories, as both processes consume a similar amount of power and heat. Interestingly, direct emissions play an insignificant role for the two processes, possibly due to CO₂ capture and air pollution control (APC). Direct emissions have a significant role in terrestrial ecotoxicity potential and freshwater ecotoxicity due to char and ash landfilling, and acid emissions (Sulphur and HCl), respectively. Pyrolysis has the lowest environmental impact in all categories apart than photochemical oxidant formation (POFP), and slightly lower than gasification. This is because pyrolysis utilises more heating than grid power, which produces less environmental impact.

However, gasification and pyrolysis have a higher POFP than other processes. This is because both processes employ a partial oxidation process that produces carbon monoxide. For contrast, incineration causes a minimal POFP as complete combustion eliminates it.

In summary, the primary contributors to environmental impact across the processes are fossil-fuel-mix power generation, followed by auxiliary processes, such as chemical production and associated wastewater treatment. Although less impactful, direct emissions from the process can produce significant impact in certain categories, such as eco-toxicity and photochemical formation. Direct emissions low impact on global warming potential (GWP) is due to the installed CO₂ carbon capture.

Note: it is important to acknowledge when the functional unit is standardised into 1 kg of MSW, shifting the perspective of the technology from hydrogen production into a waste treatment technology. Overall, CCS-enabled incineration has the lowest environmental impact for most categories. This can be attributed to the high MSW capacity while producing low emissions. This means that a highly efficient process like incineration may be more desirable when the main objective is to process waste instead of producing hydrogen.

Waste-to-Hydrogen in the Context of Environmental Justice

A 5-step methodology framework was proposed to perform a quantitative and qualitative assessment of the 'fairness' of existing WtH projects through the lens of EJ. Fairness in this context covers both the equitable access to information, resources, and benefits related to WtH to disadvantaged and historically marginalised communities, as well as acknowledging and addressing the environmental and socio-economic burdens that are often overlooked when planning WtH infrastructure projects.

Leveraging the overlap between conventional hydrogen and WtH projects, a well-established hydrogen justice framework was adapted to evaluate fairness in WtH

implementation. This framework assessed six key justice dimensions². For each aspect, a subjective scoring system that considered the specific context of the WtH project was employed. This scoring system integrated project data, local demographics, existing legislation, and industry initiatives.

The decision to implement a WtH facility hinges on a careful evaluation of its impact on EJ principles. The perceived benefits against the potential burden on the local community was weighted, while considering the specific geographical and socio-economic context.

- **Environmental impact:** This focused on potential greenhouse gas emissions from the WtH plant, considering existing emission controls and relevant environmental regulations.
- **Health impact:** Changes in community health outcomes before and after the project's implementation was assessed. This evaluation considered factors like local healthcare infrastructure, social programs, and existing health concerns.
- **Socio-economic impact:** This analysis had two key aspects: site location and economic opportunities. Site location examined disruptions to daily life, such as housing prices, job displacement, and construction noise. Economic opportunities focused on job creation (direct and indirect) and potential tax revenue to support public works.
- **Community engagement:** This assessed how the public perceived the project. It considered transparency in information dissemination, inclusion of community voices in decision-making, and acknowledgement of past injustices, if any.

To demonstrate its applicability, we apply the framework to a real-world case study, the FUREC project, established in 2021. It is crucial to recognise that assigning weight scores to any decision matrix is inherently subjective and risks oversimplifying the nuances of each project aspect or concern. Prioritising an individual EJ concern without considering its broader effects may result in a biased outcome.

Based on positive scores across each dimension, the FUREC project is considered to be reasonably fair, given the available context of the Chemelot facility in Limburg, Netherlands. Analysing each aspect individually, the initiative scores high in environmental and economic opportunity. The Netherlands' strong environmental protection laws and robust circular economy industry effectively mitigate the potential burdens associated with the collection, transport, and processing of MSW for hydrogen production. However, the FUREC WtH site location at Chemelot scores poorly in terms of fairness, primarily due to its proximity to residential areas and the current uncertainty regarding its funding status.

Conclusions

Technological viability:

The study identified that thermochemical processes, such as gasification and pyrolysis with in-line reforming, are currently the most promising WtH pathways due to their higher hydrogen yields compared to other methods like biochemical or electrochemical processes. However, these technologies still face significant challenges, including high capital costs and the need for commercial upscaling, which have yet to be fully demonstrated. Coupling WtH with CCS offers additional environmental benefits by reducing greenhouse gas emissions, but the logistical complexity and high upfront costs of integrating CCS remain major barriers.

Economic considerations:

The techno-economic analysis revealed that the LCOH for WtH-CCS processes is currently not competitive with hydrogen production from fossil fuels, primarily due to high CAPEX and OPEX. Efficiency improvements, cost reductions, and incentives such as carbon credits are essential to improving the economic feasibility of these technologies. Moreover, WtH technologies, while potentially more expensive than traditional waste management methods like landfilling, offer opportunities for revenue generation through hydrogen and CCS credits, as well as waste tipping fees.

Environmental impact:

The LCA showed that gasification and pyrolysis are the most environmentally friendly WtH options compared to other methods like biochemical or electrochemical processes under a business-as-usual scenario, largely due to their efficient hydrogen production processes. However, challenges such as water consumption, land use, and metal depletion arise when substituting fossil fuels with renewable energy. The LCA also highlighted that secondary products from processes like dark fermentation and incineration can significantly offset emissions. Interestingly, when the focus shifts from hydrogen production to waste management, incineration-water electrolysis emerges as a more favourable option due to its high capacity and efficiency.

Positioning within the Waste-to-Energy Landscape:

When compared to other waste-to-energy technologies, such as waste-to-sustainable aviation fuel (WtSAF) and waste-to-electricity (WtE), WtH technologies exhibit subdued viability. While they offer competitive advantages in reducing climate impact, they face shared technical and cost challenges. The overall viability of WtH applications is likely to be

constrained by the niche nature of hydrogen applications and the lack of existing infrastructure for hydrogen transport, storage, and utilisation.

Evaluation of Environmental Justice in the FUREC Project:

This report's proposed framework considers six social justice dimensions for WtH projects as follows

- Procedural Justice: Fair and inclusive decision-making
- Relational Justice: Respectful and trusting relationships
- Restorative Justice: Addressing past environmental injustices
- Distributive Justice: Fair distribution of benefits and burdens
- Cosmopolitan Justice: Global implications of local projects
- Epistemic Justice: Recognising diverse forms of knowledge

The EJ study framework was applied to the FUREC project, which is deemed reasonably fair overall, with high scores in environmental and economic opportunities. Strong environmental laws in the Netherlands and a robust circular economy help mitigate the burdens of MSW-to-hydrogen processes. However, the project scores poorly in terms of fairness due to its proximity to residential areas and uncertainty surrounding its funding.

Expert Review

Seven expert reviewers from across the industry and research organisations participated in the review process of this study. The reviewers provided valuable feedback on several key aspects, which were addressed to further enhance the rigour of the report.

While some reviewers offered positive feedback, describing the study as robust techno-economic analysis of WtH, they also suggested a few improvements. One reviewer recommended creating a more concise and business-oriented Executive Summary to improve clarity and relevance for industry stakeholders. Additionally, they highlighted the potential to focus more on small-scale WtH plants, suggesting that emerging technologies such as plasma pyrolysis, currently being developed in Europe, could be particularly beneficial in rural and remote locations.

An IEAGHG member inquired if comparison between hydrogen production in this study and other CCS-abated hydrogen production routes, such as the IEAGHG studies on natural gas and oil-based hydrogen, had been considered. However, a direct comparison is likely to be misplaced and offer limited value in the context of reporting. This is based on significant project distinctions that include but not limited to hydrogen compression

requirements, capacity factor, production scale, carbon credit and CO₂ transport costs, and hydrogen distribution.

These differences underscore the challenges of comparing technologies developed across different years, geographies, feedstocks, and authors, each with its own inherent assumptions. Therefore, aligning such varied parameters may not yield meaningful insights or contribute value to objective reporting.

Recommendations

To advance WtH technologies, it is recommended to conduct demonstration trials to identify and address operational challenges to enhance commercial viability. Strategies to reduce upfront capital expenditure, such as improving energy efficiency, exploring modular designs, and retrofitting existing infrastructure, should be pursued. Additionally, alternative financing models, including public-private partnerships and carbon-credit trading mechanisms, should be investigated to attract investment. Policy support is important to incentivise WtH development, with a focus on feedstock availability, carbon pricing, and streamlined permitting processes.

Further regional assessments using the developed techno-economic and life-cycle frameworks are recommended, particularly in regions like Asia with high waste-to-energy potential. To refine the EJ framework, pilot tests on existing WtH projects are suggested, alongside the exploration of online surveys and community forums to enhance data collection. Conducting cost-benefit analyses will help assess the long-term gains from robust EJ processes.

Lastly, recognising the challenges of hydrogen use in sectors like aviation, Sustainable Aviation Fuel (SAF) and MSW conversion into chemicals should be explored as viable alternatives. Comprehensive assessments of waste-to-SAF and waste-to-chemicals will provide a deeper understanding of their cost and environmental impacts.



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IEAGHG R&D Study - A Critical Study on Waste to Low Carbon (CCS-abated) Hydrogen (IEA/CON/23/299)

Disclaimer

This report is prepared by the University of New South Wales and the University of Sydney for the IEAGHG in accordance with the scope in the Terms of Reference (IEA/CON/23/299). We do not take the responsibility arising in any way from reliance placed in this report. Any reliance placed is that party's sole responsibility. We shall not be liable to any losses, claims, expenses, demands, damages, liability, or any other proceedings out of reliance by any third party on this report.

Note that this report provides indicative costs and environmental impacts for waste-to-hydrogen, and we acknowledge that detailed analysis on a case-by-case basis is required.

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List of Abbreviations

1,4-DCB	1,4-Dichlorobenzene
ALOP	Agricultural land occupation
APC	Air pollution control
ASU	Air separation unit
AtJ	Alcohol-to-jet
BAU	Business as usual
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CCUS	Carbon capture, storage and utilisation
CFC₁₁	Chlorofluorocarbon
CHJ	Catalytic hydrothermolysis jet fuel
DF	Dark fermentation
DSHC	Direct fermentation of sugar to hydrocarbon
EJ	Environmental justice
EOL	End-of-life
ETS	Emissions Trading System
EU	European Union
FDP	Fossil depletion
FETPinf	Freshwater ecotoxicity
FEP	Freshwater eutrophication
Gas	Gasification
GFT	Gasification and Fischer-Tropsch
GHG	Greenhouse gas
GWP100	Climate change
HEFA	Hydrotreated esters and fatty acids
HTPinf	Human toxicity
IRP_HE	Ionising radiation
IS	Iceland
IWE	Incineration-water electrolysis
LCA	Life cycle assessment
LCOH	Levelised cost of hydrogen
LHV	Lower heating value
MCA	Multi-criteria assessment
MDP	Metal depletion
MEA	Monoethanolamine
MEC	Microbial electrolysis cell
MFC	Microbial fuel cell
MEP	Marine eutrophication
METPinf	Marine ecotoxicity
MSW	Municipal solid waste
NLTP	Natural land transformation
O&M	Operation & maintenance
ODPinf	Ozone depletion
OFMSW	Organic fraction of municipal solid waste
OPEX	Operational expenditure
PM	Particulate matter
PMFP	Particulate matter formation
POFP	Photochemical oxidant formation
PSA	Pressure swing adsorption
Pyro	Pyrolysis
SAF	Sustainable aviation fuel

SMR	Steam methane reforming
TAP100	Terrestrial acidification
TCR	Total capital requirement
TPC	Total plant cost
TRL	Technology readiness level
ULOP	Urban land occupation
US	United States
VOC	Volatile organic compounds
WDP	Water depletion
WGS	Water-gas shift
WtE	Waste-to-electricity
WtH	Waste-to-hydrogen
WtSAF	Waste-to-sustainable aviation fuel
WWT	Wastewater treatment

Executive Summary

When it comes to addressing climate change and advancing a circular economy, waste-to-hydrogen technologies are a promising solution. Integrating carbon capture and storage into waste-to-hydrogen conversion provides a potential way of producing low-carbon hydrogen.

Several waste-to-hydrogen processes—such as thermochemical, biochemical, electrochemical, and photochemical methods—have already been developed. Thermochemical processes like gasification and pyrolysis with in-line reforming are considered likely to be technically feasible waste-to-hydrogen pathways, although their economic viability remains uncertain. Additionally, dark fermentation has emerged as an alternative method that operates under milder conditions. Another potential approach is water electrolysis powered by electricity generated from waste incineration, which leverages existing waste-to-electricity infrastructure as an indirect waste-to-hydrogen process.

Case studies, including REVIVE and FUREC projects in Europe, Chevron’s Waste-to-Hydrogen project in the US, and the Sunamachi Wastewater Reclamation Centre in Japan, demonstrate the technical attractiveness of waste-to-hydrogen for generating low-carbon hydrogen. However, commercial viability is yet to be proven, as fully integrated waste-to-hydrogen demonstration projects are currently limited and at a relatively small scale.

The report sought to analyse the economics of producing low-carbon hydrogen from municipal solid waste by integrating carbon capture and storage into different waste-to-hydrogen technologies. These included gasification, pyrolysis with in-line reforming, dark fermentation, and incineration-water electrolysis. The findings revealed that gasification and pyrolysis with in-line reforming produce hydrogen at lower costs compared to dark fermentation and incineration-water electrolysis, mainly due to their higher efficiencies. However, these processes are currently not economically viable, as their costs remain significantly higher compared to hydrogen produced from coal and natural gas. Future cost feasibility could be achieved through a combination of efficiency improvements, reductions in capital costs, and the implementation of waste management and carbon incentives.

Apart from the technical and economic aspects, the report evaluated the environmental impacts of these processes using a life cycle assessment. In general, waste-to-hydrogen technologies, particularly gasification and pyrolysis with in-line reforming, offer a significant opportunity to produce low-carbon hydrogen. The integration of renewable energy to supply electricity and heating for the processes, along with heat recovery, has a substantial effect on further reduction of greenhouse gas emissions. While waste-to-hydrogen processes have a lower global warming impact compared to unabated fossil hydrogen production, they may result in higher impacts on other environmental factors, such as increased metal and water depletion.

This report then contextualised waste-to-hydrogen within the waste-to-energy landscape by comparing its cost and environmental impacts to alternative processes like waste-to-sustainable aviation fuel and waste-to-electricity. Despite the competitive advantage of waste-to-hydrogen, waste-to-sustainable aviation fuel, and waste-to-electricity in lowering climate change impact compared to existing fossil fuel-based processes, substantial technical and cost challenges exist across these waste-to-energy solutions. In particular, the overall viability of waste-to-hydrogen applications is likely to be constrained due to the niche applications of hydrogen and the relatively lower infrastructure readiness compared to waste-to-electricity and waste-to-sustainable aviation fuel.

This report also develops a modular environmental justice framework to assess the fairness of waste-to-hydrogen projects. The approach provides a structured method for evaluating the potential environmental and social impacts, which empowers stakeholders to actively participate in shaping the project design. This framework assesses six key justice dimensions: procedural, distributive, relational, restorative, cosmopolitan, and epistemic. These dimensions encompass the distribution of benefits and burdens across five crucial aspects of waste-to-hydrogen: site location, economic opportunities, environmental impact, health impact, and community engagement. The framework also incorporates a step to identify the root causes of the burdens associated with waste-to-hydrogen projects, and this is critical to proposing steps to mitigate them.

Finally, this report advocates for further actions to consolidate waste-to-hydrogen's standing within the range of waste-to-energy solutions. It identifies the following actions to consider in further development:

1. Development of waste-to-hydrogen demonstration trials to identify potential operational challenges and improve the commercial viability.
2. Additional research on strategies to reduce upfront capital costs through technological enhancements needs to be conducted.
3. Further techno-economic-environmental assessments should be conducted internationally, using the frameworks outlined in this report.
4. The environmental justice framework could be enhanced and refined by testing it on existing waste-to-hydrogen projects. The modular environmental justice framework could be applied in developing countries under a variety of regulations and socio-economic conditions.
5. The study should be extended to include other emerging waste valorisation solutions, such as waste-to-sustainable aviation fuel and waste-to-chemicals, to understand the opportunity costs for these technologies. This would allow the assessment to leverage the current techno-economic, life cycle, and environmental justice frameworks for waste-to-sustainable aviation fuel and chemicals, using municipal solid waste.

Chapter 1. Review of Waste-to-Hydrogen Technology

1.1. Background

Climate change has emerged as a pressing global concern that exerts profound impacts across a diverse range of sectors. In 2018, a report by the Intergovernmental Panel on Climate Change (IPCC) highlighted the alarming and continuous rate at which the Earth's surface temperature has been rising by 0.2°C per decade.⁽¹⁾ The primary drivers of this crisis are greenhouse gas (GHG) emissions, particularly carbon dioxide (CO₂) and methane (CH₄). These gases trap heat in the atmosphere and the impacts of the resulting temperature increase can be seen in phenomena such as sea ice loss, rising sea levels, and extreme weather events.

The burgeoning global population and the resulting intensification of human activities has escalated the problem of greenhouse gas emissions. In 2022, global anthropogenic GHG emissions hit a new record high of 50.6 billion tonnes of CO₂-eq as the world's economy rebounded from the COVID-19 crisis.⁽²⁾ In an attempt to avert the catastrophic consequences of climate change, as of November 2023, around 145 countries have announced, or are considering adopting, net zero targets that cover nearly 90% of global emissions.⁽³⁾

In the energy sector, which accounts for 55% of global anthropogenic GHG emissions,⁽⁴⁾ renewables, such as solar and wind, have a vital role to play in electricity generation. However, several heavy sectors, including chemical manufacturing and long-haul transportation, are difficult to decarbonise through direct electrification due to their high energy demands. Hydrogen (H₂) has emerged as a promising alternative. It can serve as an energy carrier thanks to its lightweight, storable, and high energy density properties. However, the way H₂ is currently produced—96% is derived through the steam reforming of fossil fuels—results in substantial emissions. Therefore, if H₂ is to become a significant contributor to a sustainable energy system, a shift to low-carbon production methods is imperative.

The remaining 45% of anthropogenic GHG emissions are linked to the production of industrial goods and agriculture.⁽⁴⁾ Waste is a significant contributor to these emissions—around 21 billion tonnes of material is lost during industrial processes,⁽⁵⁾ and an additional 2 billion tonnes of municipal solid waste (MSW) are generated annually by consumers.⁽⁶⁾ This issue is exacerbated by the direct disposal of 60-80% of all waste without recycling, composting, or reuse, which means that while improvements in industrial processes, product redesign, and changes in consumer behaviour can aid in reducing waste in the future, addressing waste that has already been produced or cannot be reused is equally crucial.

When it comes to eliminating the risks that emanate from waste, developing proper approaches to waste management is of utmost importance. Currently, waste management is predominantly focused on a linear “take-make-dispose” economy paradigm. This approach involves a sequence of stages, from resource extraction to production, consumption and waste disposal. Unfortunately, this traditional approach not only generates a substantial amount of harmful waste, but it also exacerbates the shortage of finite resources. In contrast, the aim of a circular economy approach is to close the material loop by treating waste as resources. Therefore, it is critical to conceive methods of sustainable waste treatment that focus on reclamation and valorisation to eliminate the discarding of waste into the environment.

Waste-to-hydrogen (WtH) conversion is a promising approach for addressing contemporary energy and waste challenges. The technology not only offers a sustainable solution for waste management, but also contributes to the realisation of a circular economy while generating low carbon energy carrier.

1.2. Overview of Waste-to-Hydrogen Conversion

1.2.1. Waste Feedstocks

A wide range of feedstocks, which span from edible crops and non-edible energy crops to waste and residues, can serve as substrates for the production of H₂ to substitute fossil fuels. Among these potential feedstocks, waste streams—especially agricultural and forestry residues, wood-processing waste, and municipal solid waste—are regarded as suitable candidates for sustainable H₂ production. They offer a substantial reduction in GHG emissions reduction while also minimising the sustainability constraints associated with direct competition with food, land use change, and water use (Table 1).

Table 1. Sustainability constraints of various biomass feedstocks for H₂ generation.^(7, 8)

Feedstock type	Feedstock category	Feedstock	Sustainability constraints		
			Direct competition with food	Land use change	Water use
Crop-based	Edible oil crops	Palm, soybean, sunflower, rapeseed, canola	High constraint	High constraint	Medium constraint
	Edible sugars	Sugar cane, maize, other	High constraint	High constraint	Medium constraint
Advanced and waste	Waste and residue lipids	Used cooking oil, tallow, palm oil mill effluent	Low constraint	Medium constraint	Low constraint
	Purposely grown energy plants	Jatropha, pongamia, camelina, switchgrass	Low constraint	Medium constraint	Low constraint
	Agricultural residues	Rice straw, bagasse, corn stover	Low constraint	Low constraint	Low constraint
	Forestry residues	Branches and other unmerchantable leftovers	Low constraint	Low constraint	Low constraint
	Wood-processing waste	Sawmill slabs, sawdust, wood chips	Low constraint	Low constraint	Low constraint
	Municipal solid waste	Food and garden waste, non-reusable plastic waste	Low constraint	Low constraint	Low constraint

High constraint	Medium constraint	Low constraint
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Generating H₂ from waste streams offers significant potential for the realisation of a sustainable hydrogen economy. In particular, municipal solid waste (MSW) is one of potential waste feedstock for H₂ production. Utilising global MSW as feedstock (approximately 2 billion tonnes per year) has the potential to generate 60 million tonnes of H₂ annually,⁽⁹⁾ which can be used to produce 340 million tonnes NH₃ for fertiliser manufacturing.⁽¹⁰⁾ However, utilising MSW as feedstock poses challenges. MSW typically contains harmful contaminants like heavy metals, pesticides, sulphur compounds, and toxic chemicals. These contaminants pose environmental and health risks during the initial collection and pre-treatment stages of the process. Additionally, the variable composition of MSW from different sources may impact the process efficiency and output. Mitigating the two challenges above would require the integration of advanced sorting facilities and adaptive management strategies.

As illustrated in **Figure 1a**, seventy percent of global MSW is currently either sent to landfill or openly dumped each year. Although MSW management strategies vary by economic status, recycling rates are noticeably different. In 2024, high-income countries such as those in the European Union only reach a maximum 49%.⁽¹¹⁾ Conversely lower-income countries like India is significantly lower at 8%.⁽¹²⁾ Inadequate management like this significantly affects public health and the environment. By incorporating waste prevention strategies and promoting recovery and recycling, the world could potentially reduce GHG emissions by 15-20%.

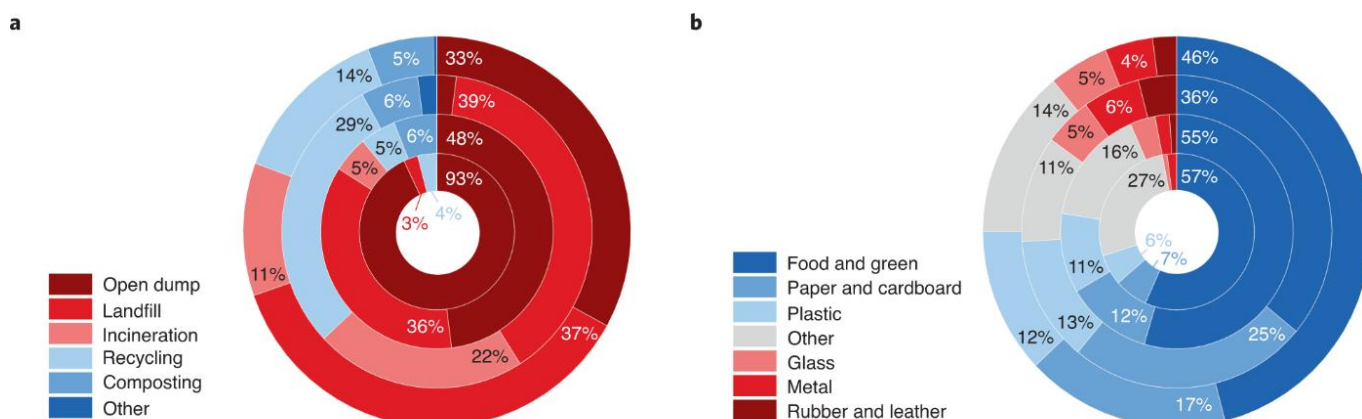


Figure 1. Municipal waste (a) disposal methods and (b) composition.⁽¹³⁾ Outer rings are world averages, second rings upper-income countries, third rings middle-income countries, and inner rings low-income countries. Copyright © 2021 Springer Nature.

Typically, MSW is primarily composed of food and biomass (46%), paper and cardboard (17%), and plastic (12%), while glass, metal, rubber, and other waste make up the remaining 25% (**Figure 1b**). In high-income countries, there is a higher proportion of paper and cardboard (25%) and plastic (13%), whereas low-income countries generate more waste from food and biomass (57%). Of all these components, some—types of biomass, food, plastic, as well as paper and cardboard—which make up between 69% and 77% of MSW, have high potential for H₂ production (**Table 2**).

Table 2. Global quantity and composition of waste streams for H₂ production.⁽¹³⁾

Waste type	Total mass generated (million tonnes per year)	Chemical composition
TOTAL BIOMASS	3977	
Agricultural residues	2900	30-60% cellulose 10-60% hemicellulose 2-40% lignin
Wood residues	923	40-50% cellulose 25-40% hemicellulose 20-35% lignin
Paper	154	55-60% cellulose 5-15% hemicellulose 1-15% lignin
TOTAL PLASTIC	302	
Low density polyethylene	57	(C ₂ H ₄) _n
High density polyethylene	40	(C ₂ H ₄) _n
Polypropylene	55	(C ₃ H ₆) _n
Polystyrene	17	(C ₈ H ₈) _n
Polyvinyl chloride	15	(C ₂ H ₃ Cl) _n
Polyethylene terephthalate	32	(C ₁₀ H ₈ O ₄) _n
Polyurethane	16	(C ₁₂ H ₁₄ N ₂ O ₄) _n

Nylon fibres	42	$(C_{12}H_{22}N_2O_2)_n$
Other	11	-
Additives	17	-
TOTAL FOOD	1300	
Cereals	310	70-80% carbohydrate 5-10% protein 1-5% fat 10-15% water
Vegetables	330	5-20% carbohydrate 1-10% protein 0-1% fat 75-95% water
Meat	50	0-2% carbohydrate 10-20% protein 2-50% fat
Milk & eggs	90	0-5% carbohydrate 2-20% protein 2-12% fat 70-90% water
Fruits	200	10-30% carbohydrate 1-2% protein 0-1% fat 70-80% water
Starchy roots	230	20-30% carbohydrate 1-2% protein 0-1% fat 70-80% water
Fish & seafood	40	0-2% carbohydrate 15-20% protein 1-20% fat 60-80% water
Oil crops & pulses	50	0-60% carbohydrate 20-30% protein 1-50% fat 0-10% water

1.2.2. Waste-to-Hydrogen Conversion Pathways

Waste-to-hydrogen (WtH) conversion can be achieved through various pathways, including thermochemical, biochemical, electrochemical, and photochemical processes (**Figure 2**), each of which has a different technology maturity level¹, energy requirement, operating conditions, efficiency, yield, and byproducts.

¹ Technology maturity level is evaluated based on technology readiness level (TRL). The evaluation of TRL follows the international guidelines from NASA (see **Appendix 1**).

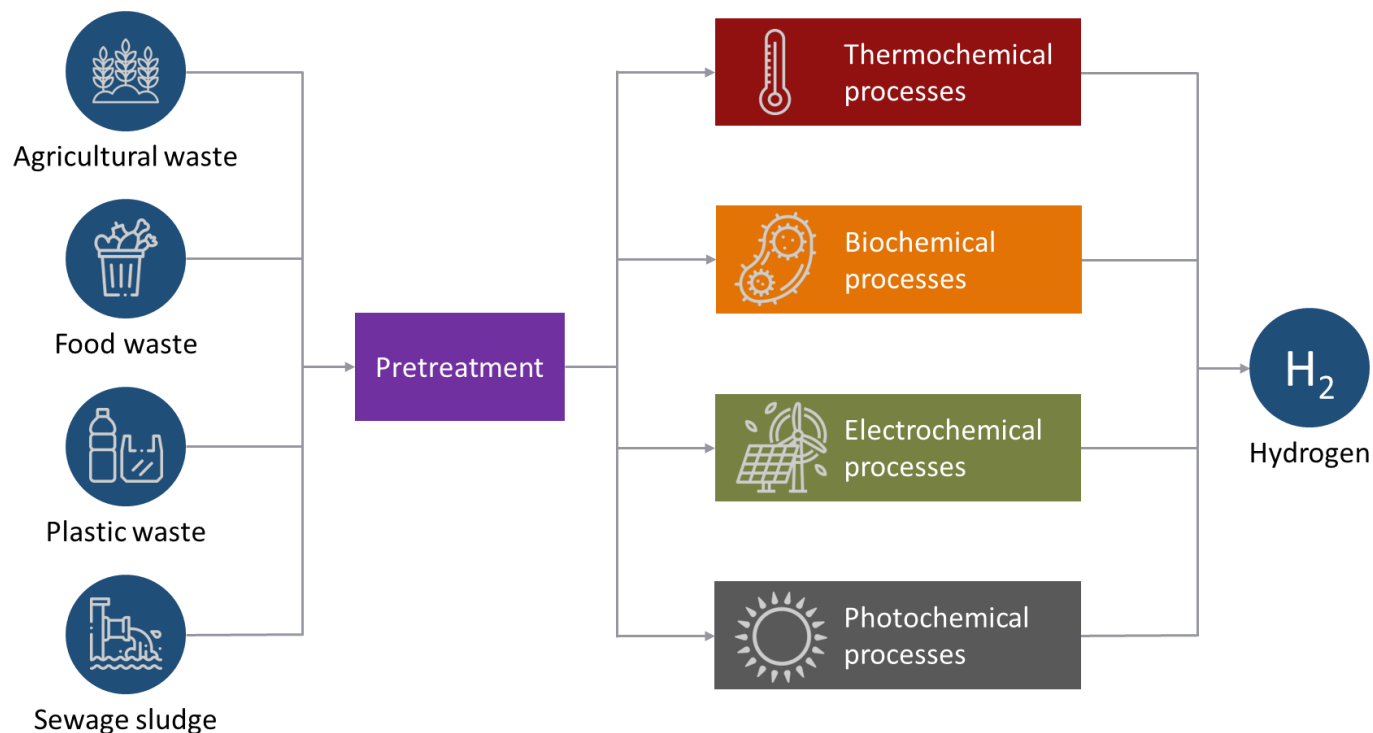


Figure 2. Potential WtH technological pathways including thermochemical, biochemical, electrochemical, and photochemical processes. Source: Author.

1.2.2.1. Thermochemical Conversion

In a thermochemical conversion pathway,⁽¹⁴⁾ waste feedstock undergoes elevated temperatures, and transforms into gaseous products, tar, char, and ash. The advantages of thermochemical processes include the reduction of landfill gas emissions and the destruction of organic contaminants—such as halogenated hydrocarbons—which ultimately ensures safe disposal. In addition, this pathway has been deemed feasible for use at various scales and can encompass a broad range of waste feedstock. Despite the potential technical feasibility, this pathway has not been widely adopted. Compared to the more commonly adopted practice of waste incineration, the implementation of thermochemical WtH conversion is relatively limited. The two primary thermochemical routes are gasification and pyrolysis. Furthermore, chemical looping hydrogen has emerged as an alternative process, where a solid oxygen carrier is used to separate the CO₂ when it is already in the combustion stage.⁽¹⁵⁾

Gasification

Gasification (TRL 6-9)⁽¹⁶⁾ is a thermochemical WtH process in which combustible gaseous fuels are produced from waste feedstock in the presence of a specific gasification agent.⁽¹⁷⁾ A simplified schematic representation of the gasification process is shown in **Figure 3**.

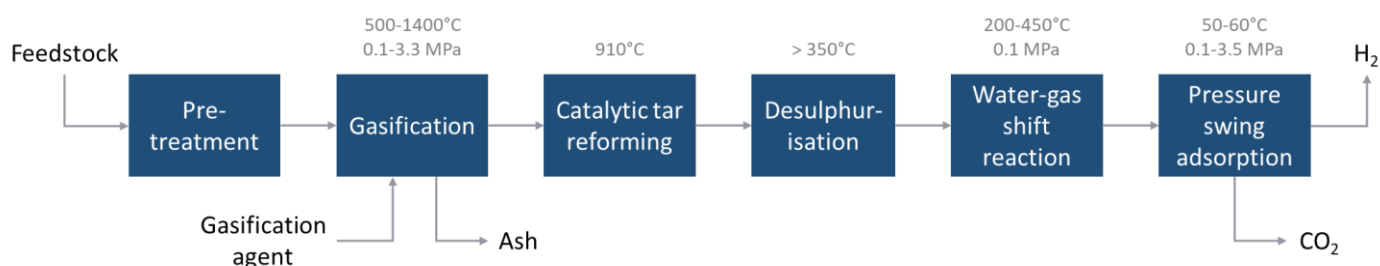


Figure 3. A simplified schematic overview of gasification to produce H₂. Note: detailed process units for the pre-treatment and gas cleaning as well as byproducts may differ according to the feedstock type as well as gasification temperature and pressure. Source: Author.

Gasification can handle a wide variety of waste feedstock—including lignocellulosic biomass residues from agriculture and forestry, residues from the pulp and paper industry, the organic fraction of MSW, and plastic waste—but the characteristics of the feedstock have been found to significantly impact H₂ yield and gasification efficiency. MSW, for instance, often has relatively high nitrogen contents, ash fractions, low ash melting temperatures, high moisture content, excessive particle size, and/or contain unwanted components such as heavy metals. These undesirable properties may create operational problems in feeding the material into the gasification process. Therefore, pre-treatment is necessary to adjust the physical and/or chemical properties of waste feedstock, before it is used for in the gasification process. Waste pre-treatment can include sorting, separation, mechanical size reduction, drying, and biological treatment.⁽¹⁸⁾

After the pre-treatment, waste feedstock undergoes gasification step. Depending on the gasification agent used and the method of heat supply, various gasification processes exist. In general, based on the type of gasification agents, gasification can be classified into air gasification (where air serves as the primary gasification agent), oxygen gasification (involving the use of pure O₂ as the primary gasification agent), and steam gasification (where steam is introduced as a gasification agent to enhance hydrogen production and reduce tar formation). According to the method of heat supply, gasification can be grouped into direct gasification and indirect gasification.⁽¹⁹⁾ In direct gasification, heat necessary for the gasification reactions is produced in the reactor by the combustion of a fraction of the feedstock. In the case of indirect gasification, heat production takes place outside the reactor and transferred to the reactor using a circulating sand medium or via heatpipes.

Gasification is comprised of several steps: (i) evaporation of moisture at temperatures up to 150°C; (ii) pyrolysis, thus releasing volatiles (H₂, CO, CO₂, CH₄, tar, etc.) between 200 and 650°C; (iii) reaction of volatiles in the gas phase between 700 and 1000°C; and (iv) heterogeneous reaction of char between 700 and 1000°C. The main product is syngas, a mixture of primarily H₂ and carbon monoxide (CO) with small volumes of CO₂ and CH₄. The reactions occurring in the gasifier are presented in **Equations 1-2**.



Gasifiers come in various designs, each tailored to specific needs and considerations. Several common types of gasifiers include fixed bed, fluidised bed, and entrained flow gasifiers.⁽²⁰⁾ Fixed bed gasifiers involve a stationary bed of feedstock, and the reaction takes place as gasification agents pass through the bed. There are three types of fixed bed gasifiers: updraft, downdraft, and cross-draft gasifiers. In updraft gasifiers, the feedstock is supplied at the top and the gas at the bottom so that feedstock moves against the gas flow. The downdraft design is essentially the same as the updraft design, except that feedstock and gas move concurrently from the top to the bottom of the gasifier. On the other hand, cross-draft design is an intermediate between updraft and downdraft designs. This design works on the principle that feedstock moves downward however the produced syngas is taken out laterally from the gasifiers. Fluidised bed gasifiers fluidise a bed of small feedstock particles using an upward-flowing gas stream. The gasifiers normally operate at moderately high temperature to achieve an acceptable carbon conversion rate and at the same time to prevent agglomeration. This design allows for better mixing and efficient heat transfer and is known for its ability to handle a wide range of fuel feedstock. Based on the variation in design and operation, fluidised bed gasifiers can be further subdivided into (i) bubbling bed, (ii) circulating bed, and (iii) dual bed gasifiers. In entrained flow gasifiers, the feedstock and gasification agent are fed simultaneously into the gasifier. This design is known for its ability to operate at a higher temperature usually >1200°C compared to fixed bed and fluidised bed gasifiers.⁽²¹⁾ As a result, entrained flow gasifiers exhibit high carbon conversion efficiency and the resulting syngas produces lower methane and tar content.

The syngas product from the gasification process is subsequently subjected to the water-gas shift reaction (WGSR), as shown in **Equation 3**, to increase the H₂ yield.



Prior to WGSR, it is often necessary to remove tar and sulphur from syngas. Tar removal can be done through scrubbing systems or catalytic thermal conversion at high temperatures. Sulphur removal is typically achieved via dry or wet processes.⁽²²⁾ An example of dry process is ZnO adsorption, which has been extensively demonstrated in coal gasification process. However, the applicability to the somewhat more complex waste gasification gas remains to be demonstrated. An alternative sulphur removal process is liquid chemical oxidation process, such as LO-CAT® technology (by Gas Technology Products LLC, a unit of Merichem). LO-CAT® is an oxidation process that uses chelated Fe(III) catalyst to oxidise H₂S to elemental sulphur, while converting Fe(III) to Fe(II). The solution is then brought to a sparger vessel where air is used to re-oxidise Fe(II) to Fe(III) and to separate the sulphur formed by flotation. After WGSR, CO₂ is captured typically using amine absorption technique, followed by H₂ purification through pressure swing adsorption (PSA).

Nevertheless, the process faces certain limitations. These include tar and char formations, which lead to catalyst deactivation, product variation due to feedstock complexity and composition variations, high operating temperatures, the need for a catalyst, regeneration, and the relatively high upfront capital cost for a gasifier. In addition, the operation of biomass/waste gasification remains complex, with challenges such as temporal and geographical variability of biomass resources and supply chains. In addition, gasification also faces challenges in terms of the complex syngas cleaning process from biomass/waste gasification and issues associated with the handling of high temperature flammable, explosive, and toxic syngas.

Economically, the H₂ production cost via waste gasification is significantly affected by the scale as well as the feedstock. It has been estimated that a small gasification plant produces H₂ for US\$10/kg, while a larger plant has a lower H₂ production cost of US\$1.21-3.5/kg.⁽²³⁾ In a separate study, the levelised cost of H₂ production from bioamss gasification ranges from US\$2.8-3.4/kg, while residual waste gasification yields a H₂ production cost of US\$1.4-4.8/kg at feedstock processing scales of 75-150 MW_{th}.⁽²⁴⁾

Nonetheless, waste gasification to H₂ projects have been limited thus far, with most current projects are on the paper under feasibility studies, and only few projects have been demonstrated in a relatively smaller scale compared to H₂ production via steam methane reforming and coal gasification (**Table 3**). For instance, Ways2H has demonstrated the gasification of solid waste in Joso, Japan, with a capacity of 6 tonnes of solid waste per day to produce 300 kg H₂ per year. In addition, Ways2H has operated a Tokyo Sewage-to-H₂ plant in Tokyo, Japan. The facility is located at the Sunamachi Water Reclamation Centre, near Tokyo Bay. This gasification demonstration plant processes 1 tpd dried sewage sludge to generate 40 to 50 kg per day of H₂, to fuel 10 passenger vehicles or 25 fuel cell e-bikes. Efforts in upscaling waste gasification have been devoted. However, challenges around technical, operational, and financial aspects have led to several project failures and/or delays. For instance, the US gas producer, Air Products has quitted two gasification projects in the Tees Valley.⁽²⁵⁾ The company said that testing and analysis at the Tees Valley Project had concluded that additional design and operational challenges would require significant time and cost to rectify. This highlights the importance of proper process design, implementation, and management to avoid failed high-risk waste gasification projects. Further discussions on lessons learned from several failed commercial waste gasification projects and potential strategies to overcome the challenges are presented in **Section 1.4.2**.

Table 3. Non-exhaustive list of waste gasification demonstration projects.

Project	Location	Technology	Product	Status	Capacity	Brief description	Ref.
Ways2H Joso	Joso, Japan	Gasification	H ₂	Operational	300 kg H ₂ per year by processing 6 tpd waste	The plant in Joso can handle 6 tonnes of solid waste per day and produce 300 kg of H ₂ using a gasification technology developed by Japan Blue Energy Co. (JBEC).	⁽²⁶⁾
Tokyo Sewage-to- H ₂ plant (Ways2H)	Tokyo, Japan	Gasification	H ₂	Operational	40-50 kg H ₂ /day, 1 tpd sewage sludge	The facility, located at the Sunamachi Water Reclamation Centre, near Tokyo Bay, processes 1 tpd dried sewage sludge, to generate 40 to 50 kg per day of H ₂ , enough to fuel 10 passenger vehicles or 25 fuel cell e-bikes.	⁽²⁷⁾

Advanced Biofuel Solutions (ABSL)	Swindon, UK	Gasification	Synthetic natural gas, H ₂	In operation for synthetic natural gas production	8,000 tpa waste	The facility, located in Swindon, UK, converts 8,000 tonnes of household waste into 22 GWh or 2.2 million cubic metres of bio-substitute natural gas (BioSNG) each year. ABSL will also demonstrate the production of bio-H ₂ at the Swindon plant. The facility can switch between bio-H ₂ and BioSNG production on demand. This flexibility will allow the plant to supply H ₂ projects as the market develops.	(28)
Güssing Renewable Energy	Güssing, Austria	Dual fluid bed (DFB) gasification	Thermal, electricity, liquid fuel, syngas, H ₂	Successfully operated from 2001-2015	8 MW fuel, 2.4 MW electricity, and 4.5 MW thermal	The plant can convert wood chips to fuel, electricity, and heat with 8 MW fuel power capacity, 2.4 MW electric power capacity, and 4.5 MW thermal power capacity.	(29)
Raven SR, Chevron, and Hyzon Motors	Richmond, California	Non-combustion reforming	H ₂	Commercial operation is targeted in Q1 2024	99 wet tpd waste	The plant will produce up to 2,400 metric tonnes of renewable H ₂ from green waste and food waste with non-combustion reforming process.	(30)
Project NextChem	Rome, Italy	Gasification, Chemical looping, and syngas fermentation	H ₂ and ethanol	Under construction, planned operation in 2027	20,000 tpa H ₂ by processing 200,000 tpa non-recyclable waste	Project NextChem uses several conversion technologies to convert non-recyclable waste material into hydrogen and ethanol. The project recently secured €194 million funding from the EU to build a facility slated to be operational by first half of 2027.	(31)
Fuse, Reuse, Recycle (FUREC)	Netherlands	Entrained flow gasification	H ₂	Final investment decision in 2024	54,000 tpa H ₂ by processing 700,000 tpa waste	FUREC aims to use non-recyclable MSW to produce H ₂ . RWE Generation has designed the WtH plant on the Chemelot Industrial Park, targeting 54,000 tonnes/year H ₂ production. The H ₂ is supplied for demands in the industrial park, such as OCI N.V.'s ammonia production. FUREC also produces pure CO ₂ , ready for utilisation/storage.	(32)
Riverbend Energy Hub (Greenhill Energy)	South Australia	Gasification	H ₂ , synthetic fuels, urea fertilisers	AU\$425 million investment and construction is expected in 2025	60,000 tpa waste	The plant will upcycle biomass and landfill waste into low-cost clean H ₂ , producing energy and high value industrial products, including synthetic fuels and up to 100,000 tonnes a year of urea fertilisers. The plant will be able to process up to 60,000 tonnes of dry biomass or waste per year.	(33)
Ways2H and H2E Power	Pune, India	Gasification	H ₂	The project agreement was signed on July 6th, 2023, and preliminary	10 tpd waste	In the first phase, the facility, which will be deployed near Pune, Maharashtra, will divert 10 tonnes of waste from landfills per day, permanently sequester 11 tonnes of CO ₂ and produce 1 tonne of	(34)

				work has already started		fuel cell grade carbon negative H ₂ . The partnership envisages deploying systems with a processing capacity up to 100 tonnes per day each, throughout India,	
Wildfire Energy	Queensland, Australia	Moving injection horizontal gasification	H ₂	Awarded AU\$200,000 to commercialise Australia's first Waste-to-hydrogen process	1 tpd waste	The project aims to develop small-scale distributed waste-to-energy and waste-to-hydrogen projects using moving injection horizontal gasification (MIHG) to produce hydrogen for domestic use and to power fuel cell vehicles while reducing GHG emissions from waste management	(35)

Pyrolysis with In-Line Reforming

Pyrolysis with in-line reforming (TRL 4-7)^(23, 36) is another thermochemical WtH pathway where feedstock is transformed into char, pyrolysis oil, and syngas, followed by steam reforming of the pyrolysis oil to increase the overall H₂ yield. Finally, H₂ product can then be separated via PSA. A simplified schematic diagram of pyrolysis with in-line reforming is shown in **Figure 4**.

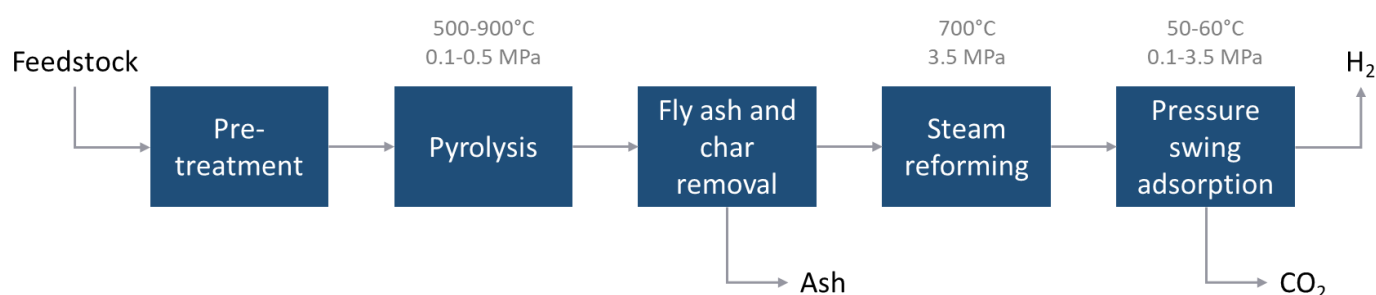


Figure 4. A simplified schematic overview of pyrolysis to produce H₂. Note: detailed process units for the pre-treatment and gas cleaning as well as byproducts may differ according to the feedstock type as well as pyrolysis temperature and pressure. Source: Author.

Various types of waste feedstocks, such as forestry waste (e.g., pinewood sawdust and beech wood) and agricultural waste (e.g., rice straw, tea waste, wheat straw, and corn straw), are suitable for pyrolysis.⁽¹⁷⁾ Typically, the gaseous product yields for these feedstocks range between 25% and 40% in weight, which can be further increased by the in-line steam reforming process that converts the bio-oil fraction to syngas. In addition, waste rubber tyres,⁽³⁷⁾ carton packages,⁽³⁸⁾ and unsorted MSW⁽¹⁴⁾ have been demonstrated for pyrolysis based H₂ production. Similar to gasification, feedstock pre-treatment is often required to modify the physical and chemical properties of the feedstock prior to the pyrolysis process. This pre-treatment can include waste sorting, separation, mechanical size reduction, drying, and biological treatment.⁽¹⁸⁾

Figure 5 shows the two-step process of waste pyrolysis and in-line steam reforming.⁽³⁹⁾ Initially, waste undergoes pyrolysis at temperatures around 500°C, with the option of using either an N₂ atmosphere or, more commonly, steam as a fluidising agent. In the case of rotary kiln pyrolysis reactor, fluidising agents are not required. Subsequently, steam reforming of the resulting pyrolysis products, including syngas and pyrolysis oil, occurs rapidly in the presence of a metal-based catalyst, at temperatures ranging from 600-800°C under atmospheric or higher pressures. This reaction (R1) is highly endothermic and strongly favoured at elevated temperatures. Concurrently, secondary reactions, including the cracking of oxygenated compounds (R4), generate oxygenates, light hydrocarbons (such as methane), CO, and CO₂. The products obtained from both reforming and cracking reactions (R1 and R4) promote the moderately exothermic WGS (R2) and the steam methane reforming reaction (R3). These reactions are essentially equilibrium

reactions, which enable the achievement of high H₂ yields through effective catalysts and optimum operating conditions, such as temperature, pressure, and the steam/carbon (S/C) ratio.

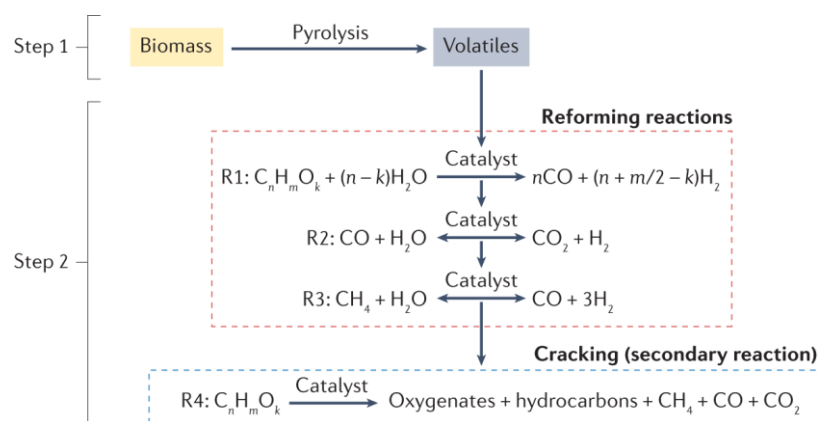


Figure 5. Key equations for biomass pyrolysis and in-line steam reforming process.⁽³⁹⁾ Copyright © 2022 Springer Nature.

Waste pyrolysis and in-line steam reforming technology is available in various process configurations, as depicted in **Figure 6**. Fixed-bed reactors are the most frequently used at the laboratory scale due to their simplicity and ease of control. **Figure 6a** illustrates a two-stage fixed-bed reactor with a broad range of applications, integrating the pyrolysis reactor and reforming reactor. In this setup, the feedstock is typically loaded into the upper stage and the pyrolysis volatiles are transported by the carrier gas. Fluidised-bed reactors (**Figure 6b-c**) offer superior performance for industrial applications owing to their excellent gas-solid contact, which improves the heat transfer and conversion rates. Fluidised-bed reactors are often employed for the pyrolysis of a single feedstock, where the pyrolysis efficiency is closely related to the particle size of the feedstock. In a fluidised-bed reactor, gas is passed through a distributor to suspend the solid particles in the gas stream and achieve a uniform temperature within the reactor.

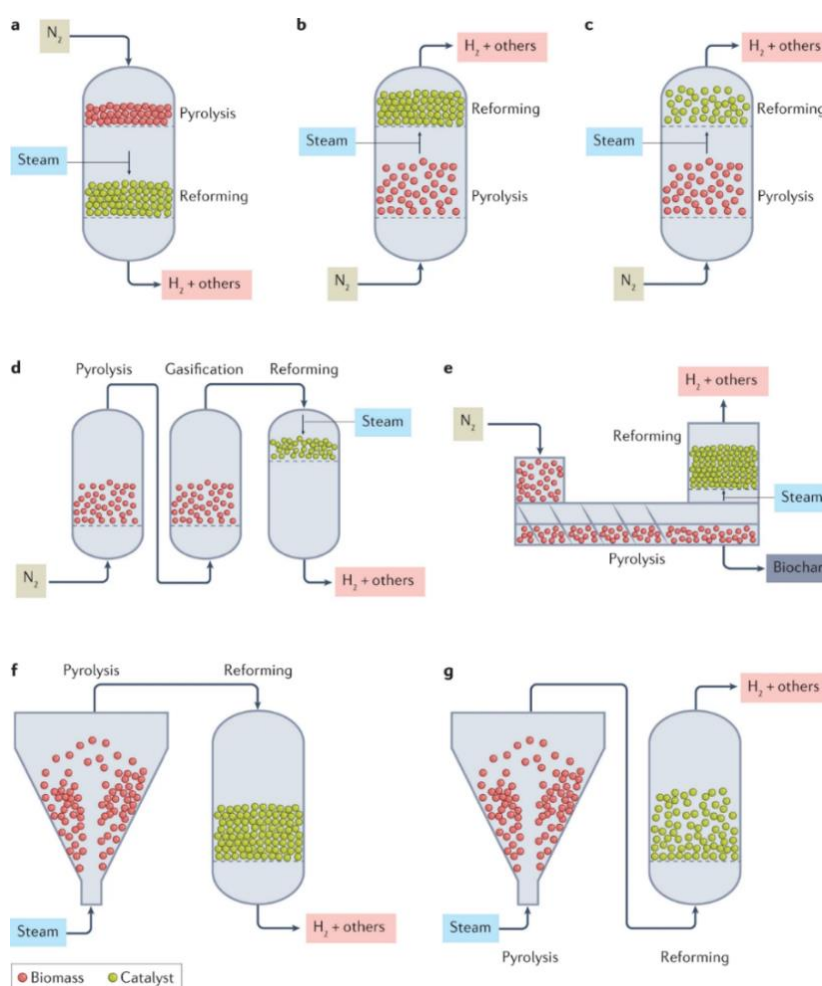


Figure 6. Reactor configurations for pyrolysis and in-line reforming of biomass.⁽³⁹⁾ Copyright © 2022 Springer Nature.

Figure 6d depicts an integrated system with three reaction stages, which involves an intermediate stage for the joint gasification of the entrained gas and solid flow. However, this setup faces challenges due to inadequate heat transfer between the hot gas and solid particles. The entrained flow reactor requires a high gas flow rate to achieve sufficient heat transfer and a low partial pressure of steam for collecting the liquid-phase product for further reforming. An alternative gas-contact method, shown in **Figure 6e**, utilises a screw-kiln reactor as the pyrolysis reactor, and this allows continuous production with suitable heat and mass transfer rates. This setup is particularly well-suited for challenging or heterogeneous feedstocks. Waste pyrolysis can also take place in conical spouted-bed reactors, and the resulting volatile gas flow can be introduced into a fixed-/fluidised-bed reforming reactor (**Figure 6f-g**). The suitability of the spouted bed for pyrolysis opens numerous possibilities for industrial implementation (e.g., a scale-up has been demonstrated with a continuous pyrolysis of 25 kg/h biomass (TRL 6)).⁽⁴⁰⁾

Like gasification, waste pyrolysis is often combined with Cl, S, and N emissions due to the volatility of those elements. Numerous measures have been reported to alleviate the environmental effects associated with pyrolysis, including the interception of HCl, SO₂, and NH₃ from the gaseous phase, the use of catalysts to upgrade the quality of the products and the avoidance of certain special components in the feedstock.⁽⁴¹⁾ Pyrolysis is typically equipped with gas improving and scrubbing devices. The syngas exits the in-line reforming flows into a water jet quench for a rapid cooling to prevent the formation of dioxins and furans. At the same time, entrained particles, heavy metals, HCl, and HF are also abated in the quench. Following the quench process, the gas passes through a desulphurisation scrubber for the removal of hydrogen sulphide using ZnO bed and/or LO-CAT® process. Overall, the gas cleaning processes for pyrolysis and in-line reforming is similar to those used for waste gasification.

The economics of pyrolysis with in-line reforming process currently remains unfeasible due to the high capital costs required for the pyrolysis reactor and bio-oil steam reformer. While cost estimation for this integrated process has been limited due to the lack of widespread demonstration projects for this technology, the cost for H₂ production via bio-oil steam reforming, which can serve as an indicative cost for pyrolysis and in-line reforming, is estimated to be approximately US\$3.8-4.6/kg H₂ on a relatively large-scale H₂ production capacity of 10,000 to 100,000 Nm³/h of H₂.⁽⁴²⁾

The integrated pyrolysis and steam reforming for waste-to-hydrogen conversion has only been demonstrated in a small pilot scale in Germany.⁽⁴³⁾ The Thermo-Catalytic Reforming (TCR®) technology, located in Fraunhofer UMSICHT site, has successfully converted the organic fraction of MSW into fuels and chemicals (H₂ and bio-oil) in a 2 kg/h continuous pilot scale reactor. While the demonstration of the pyrolysis with in-line reforming process has been limited thus far, there are numerous existing and planned demonstration projects using waste pyrolysis to produce pyrolysis oil and fuels. The Empyro Fast Pyrolysis Bio Oil plant in Hengelo, Netherlands has been in operation to convert 5 tonnes per hour of wood residue into pyrolysis oil, process steam, and electricity. In Boardman, Oregon USA, Canadian-based Klean Industries has developed and successfully demonstrated a pyrolysis technology capable of processing plastics, tyres, and MSW. The company is also collaborating with the remediation and recycling provider, City Circle Group, to construct an integrated continuous tyre pyrolysis plant in Melbourne, Australia. The plant aims to recover carbon black and biofuels from waste tyres.⁽⁴⁴⁾ Western Australia bioenergy company, Renergi, recently installed its innovative biomass pyrolysis technology in the Shire of Collie, Western Australia.⁽⁴⁵⁾ The plant will process MSW and other biomass, such as forestry waste, to generate bio-oil, biochar, and wood vinegar, with a capacity of 100 kg/h (TRL 7-8).

Table 4. Non-exhaustive list of waste pyrolysis demonstration projects.

Project	Location	Technology	Product	Status	Capacity	Brief description	Ref.
Thermo-Catalytic Reforming (TCR®)	Fraunhofer UMSICHT site, Germany	Pyrolysis with in-line reforming	H ₂ , bio-oil	Demonstrated	2 kg/h MSW	TCR® has been demonstrated to convert the organic fraction of MSW into fuels and chemicals (H ₂ and bio-oil) in a 2 kg/h continuous pilot scale reactor.	⁽⁴³⁾
Empyro Biomass Pyrolysis plant	Hengelo, Netherlands	Pyrolysis	Bio-oil, process steam, electricity	Operational	5 tph wood residues	The Empyro plant converts 5 tonnes per hour of wood residues into pyrolysis oil, process steam, and electricity. Start-up of the installation commenced in early	⁽⁴⁶⁾

						2015 and production has gradually increase since.	
Klean Industries and City Circle Group	Melbourne, Australia	Pyrolysis	Carbon black, biofuel	Planning	12 tpd tyre waste	Klean Industries has partnered with City Circle Group (CCG) to build a fully integrated, continuous tyre pyrolysis plant to recover carbon black and biofuel in Melbourne, Australia. The planned initial capacity is up to 120 tpd tyre waste.	(44)
Renergi Grinding Pyrolysis	Western Australia	Pyrolysis	Bio-oil, biochar, and wood vinegar	Under construction	100 kg/h of waste	A 100 kg/h demonstration plant has been designed, build and commissioned. The grinding pyrolysis technology can convert municipal solid waste and forestry waste into crude bio-oil and bio-char.	(47)

Chemical Looping Hydrogen

Chemical looping hydrogen (TRL 3-4)⁽¹⁶⁾ is a novel technology to convert biomass/waste into H₂. The configuration mainly consists of a fuel reactor (FR), an air reactor (AR), and a steam reactor (SR) (Figure 7).⁽⁴⁸⁾ In the FR, biomass/waste is oxidised by a solid oxygen carrier, forming CO₂ and H₂O while reducing the solid oxygen carrier. The reduced solid material is then transported to the SR where it reacts with steam to partially oxidise the solid material and generate pure H₂. The solid material is further oxidised with air in the AR to regenerate the depleted oxygen. The fully regenerated solid material is subsequently returned to the FR to continue the “loop” process. This configuration enables the biomass/waste conversion to a pure stream of CO₂ and H₂O, which can be easily separated by condensation, thereby reducing the costs associated with CO₂ separation. Furthermore, chemical looping water splitting generates pure H₂ stream in the SR, eliminating the need for H₂ separation processes.

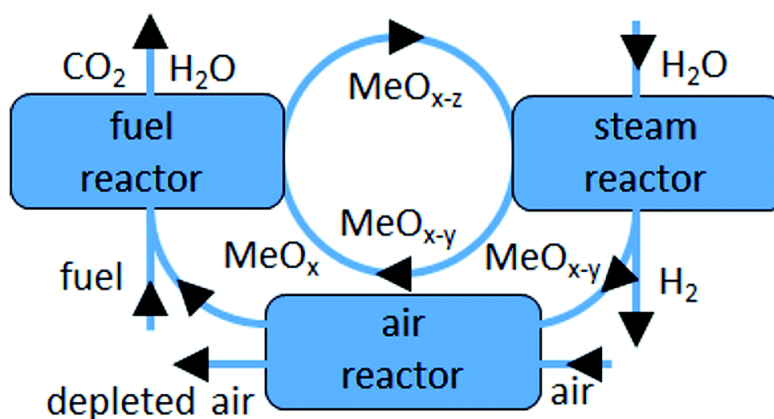


Figure 7. Process schematic of the chemical looping hydrogen process with an alternative air oxidation.⁽⁴⁸⁾ Copyright © 2016 Royal Society of Chemistry.

Despite its promises, chemical looping water splitting requires solid oxygen carriers that can maintain their reactivity and mechanical strength as they undergo multiple redox cycles at high temperatures to improve the overall process economics for commercial viability. In addition, the solid oxygen carriers should exhibit a high oxygen exchange capacity as well as high conversion and selectivity to CO₂ and H₂O. Various natural minerals and synthetic metal oxides have been tested, with a lot of work investigated iron-based oxygen carrier. Natural ilmenite (Fe₂TiO₅), for example, is considered as an inexpensive and abundant oxygen carrier. This mineral can be gradually reduced to Fe₂TiO₄ and FeTiO₃ and finally Fe and TiO₂. The consecutive air oxidation led to the formation of a sample containing only Fe₂O₃ and TiO₂. Hydrogen generation by steam oxidation was feasible at 900°C and Fe₃O₄ and FeTiO₃ are formed in the oxidised solid.⁽⁴⁸⁾

Babcock & Wilcox (B&W) has developed a BrightLoop™ low-carbon hydrogen technology based on chemical looping process.⁽⁴⁹⁾ Under the U.S. Department of Energy-sponsored project, B&W demonstrated a continuous low-carbon hydrogen generation at the 250 kW_{th} pilot unit constructed and tested at the National Carbon Capture Centre in Alabama. There is also the use of chemical looping to produce H₂ from waste to support refining by the Northern Oil & AFC Energy in Gladstone Advanced Biofuels Plant, Queensland, Australia.⁽⁵⁰⁾ The surplus H₂ will be used to power a 200-400 kW fuel cell.

Table 5. Non-exhaustive list of waste chemical looping hydrogen demonstration projects.

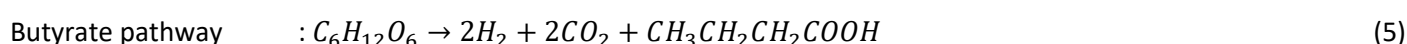
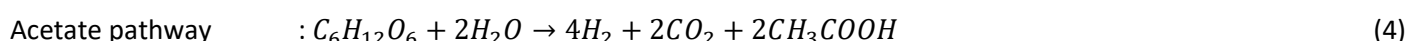
Project	Location	Technology	Product	Status	Capacity	Brief description	Ref.
Project Brightloop	Louisiana, USA	Chemical looping	H ₂	Planned operation in 2026	15-20 tpd of H ₂	Project Brightloop will utilise biomass material from forestry trimmings and agricultural waste to generate ~ 7000 tpa of negative carbon intensity H ₂ . The CO ₂ produced from the process will be sequestered in a local CO ₂ well.	⁽⁵¹⁾
Southern Oil Refinery Pty Ltd Bio-Hydrogen	Northern Oil Refinery at Yarwun, near Gladstone, Queensland	Chemical looping	H ₂	Technical and engineering redesign	20 kg H ₂ /h	Southern Oil Refining is investigating the application of steam-over-iron with chemical looping combustion (SOI-CLC) as a process for H ₂ production – using waste gas as feedstock.	⁽⁵²⁾

1.2.2.2. Biochemical Conversion

In the biochemical conversion pathway, waste feedstock undergoes microbial treatment, which breaks down the waste into gaseous products. This route is gaining prominence due to its competitive advantages, such as lower energy intensity and operability under ambient temperature and pressure conditions. However, biochemical conversion often faces challenges like low yields and a slow conversion rate. In addition, when complex biomass is employed as the substrate, significant pretreatment is necessary, which thereby hinders the commercialisation of biochemical processes. Dark fermentation and photo fermentation are two primary WtH biochemical routes that have been extensively studied.

Dark Fermentation

Dark fermentation (TRL 5-6)⁽²³⁾ involves the use of microorganisms to convert organic substrates into H₂ in a dark, anaerobic environment. The microorganisms deployed are generally facultative or obligate anaerobic bacteria, including *Enterobacter*, *Citrobacter*, *Clostridium*, *Sporolactobacillus*, *Ruminococcus*, and *Escherichia coli* bacteria. These microorganisms consume long-chain polymer molecules in substrates such as carbohydrates, proteins, and lipids to fuel their metabolism. Hydrogenase enzymes facilitate H₂ production via two different metabolic pathways: the acetate pathway and the butyrate pathway. Theoretically, these pathways can yield 4 mol and 2 mol of H₂ per mol of glucose digested, respectively. The main overall chemical reactions involved in these two pathways are shown in **Equations 4-5**. **Figure 8** illustrates a schematic diagram of a dark fermenter for H₂ production.



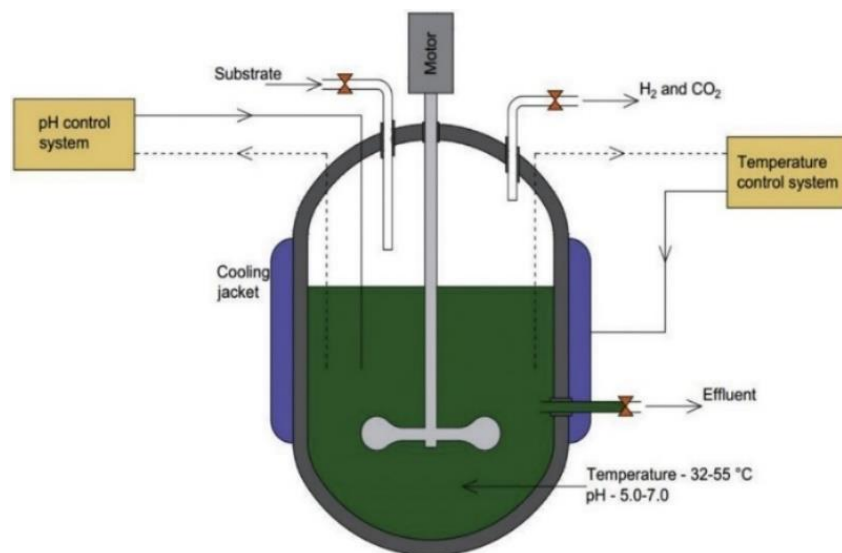


Figure 8. Representation of a typical dark fermenter setup.⁽¹⁷⁾ Copyright © 2021 Elsevier Ltd.

As is evident from the equations, glucose-rich substrates are highly desirable as feedstock for dark fermentation. They have 20 times higher potential for H_2 synthesis than protein- or lipid-based substrates. Lignocellulosic materials, food waste, and agricultural residues form a promising feedstock for dark fermentation. In addition, the most studied bacterial substrate for dark fermentation is industrial wastewater. Different wastewater sources include starch processing, the beverage industry, waste activated sludge, and pig farming. However, palm oil mill effluent (POME) and sewage sludge fermentation have resulted in lower performance due to their high lipid and protein content. Generally, substrate is pretreated before fermentation to activate H_2 -producing bacteria while inhibiting H_2 -consuming microorganisms. Common pretreatment methods include thermal pretreatment such as steam explosion, thermochemical pretreatment with alkalis and dilute acids, and physical pretreatment such as ultrasound, freezing, and the use of UV radiation.

The presence of contaminants from the waste feedstock is another challenge in dark fermentation process. For example, the use of manure substrates which may contain methanogenic microorganisms can potentially consume H_2 , thus lowering the H_2 yield.⁽⁵³⁾ Manure substrates, therefore, need physical and chemical treatment to inhibit the methanogenic activity. Another contaminant is ammonia in swine, poultry, and dairy manure that have a low C/N ratio and high levels of ammoniacal nitrogen, which can inhibit H_2 production.⁽⁵⁴⁾ In addition, high sulphate concentrations in swine manure can inhibit the H_2 production due to the presence of H_2 consuming sulphate reducers.⁽⁵⁵⁾

From economic perspective, dark fermentation process stands at an estimated higher levelised cost of H_2 production due to the lower H_2 yield compared to thermochemical processes (4-44 kg H_2 /tonne feedstock).⁽²³⁾ The treatment of food waste via dark fermentation with a capacity of 3 tpd food waste was estimated to produce H_2 at a levelised cost of US\$12.2/kg.⁽⁵⁶⁾

While dark fermentation for biohydrogen production has not been available in commercial scale to date, this process has been demonstrated and/or planned on a pilot scale. For example, the pilot-scale operation of the fermentation of cane molasses substrate in 10 m³ bioreactors was able to achieve 76.2 m³ H_2 yield with an energy conversion efficiency of 38%.⁽⁵⁷⁾

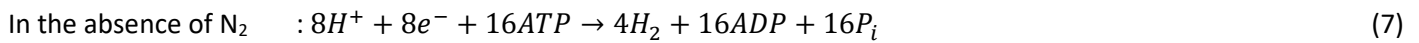
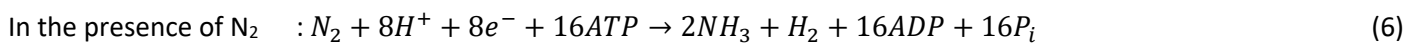
Table 6. Non-exhaustive list of dark fermentation demonstration projects.

Project	Location	Technology	Product	Status	Capacity	Brief description	Ref.
IIT Kharagpur Dark Fermentation	India	Dark fermentation	H_2	Demonstration	10 m ³ bioreactors, 76.2 m ³ H_2 /day	The pilot scale study achieved 76.2 m ³ hydrogen with a COD removal and energy conversion efficiency of 18.1 kg m ⁻³ and 37.9%, respectively.	⁽⁵⁷⁾

HydGene Renewables	Australia	Dark fermentation	H ₂	HydGene has raised US\$4 million in Seed Funding to build pilot testing	1 kg H ₂ /day	HydGene, an Australia-based start-up, utilises synthetic biology to engineer microorganisms to act as a proprietary biocatalyst to produce green H ₂ from waste biomass via fermentation.	(58)
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Photo Fermentation

In photo fermentation (TRL 3-4)⁽²³⁾, photosynthetic microbes digest carbon-based substrates using light energy and produce H₂ in an anoxic environment. Microbes commonly employed for photo fermentation are purple non-sulphur bacteria, such as Rhodobacter, Rhodospirillum, and Rhodopseudomonas species. Light illumination can be provided through solar energy or artificial light sources. In contrast to dark fermentation, metabolic reactions occur through nitrogenase enzymes in photo fermentation, and it is highly dependent on the presence of N₂. The metabolic activities can follow two distinct pathways based on N₂ availability ([Equations 6-7](#)). [Figure 9](#) depicts a schematic diagram of an illuminated photo fermenter.



where ATP is adenosine triphosphate and ADP is adenosine diphosphate, respectively.

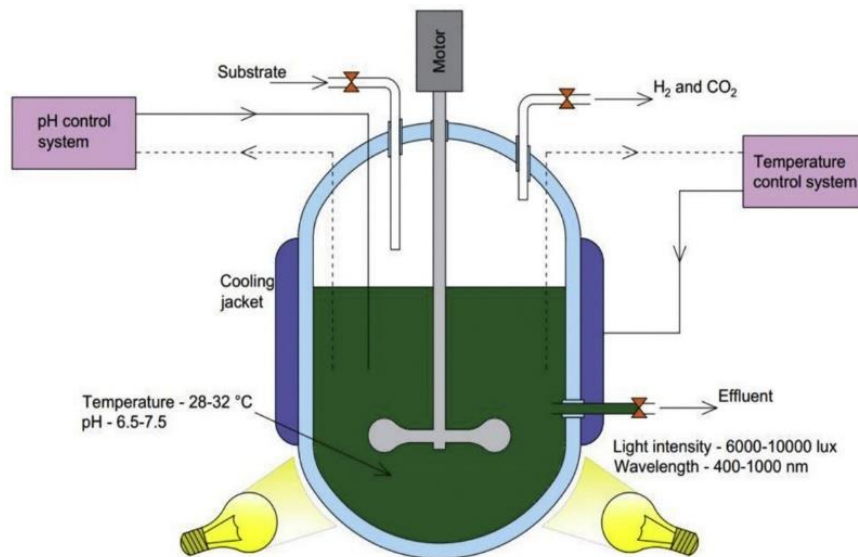
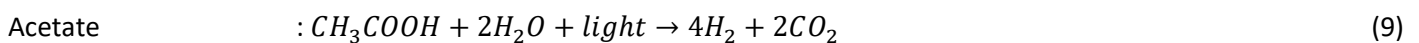
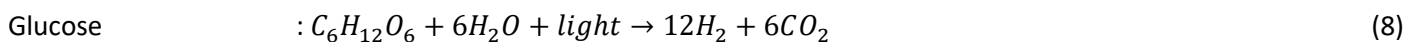


Figure 9. Representation of a typical photo fermenter setup.⁽¹⁷⁾ Copyright © 2021 Elsevier Ltd.

As evident, all protons would be converted into H₂ in an N₂-limited environment. Furthermore, formation of NH₃ in the presence of N₂ has been discovered to have an inhibitory effect on enzymes as well as H₂ generation. Nevertheless, nitrogen is an essential macronutrient for cell growth. H₂ production utilising different substrates can be demonstrated through [Equations 8-10](#), which display the differences of H₂ outputs based on the carbon source.



Feedstock with high volatile fatty acids (VFA) content are desirable for photo fermentation. As with dark fermentation, the most investigated feedstock for use in different industries is wastewater, including wastewater from industries such as sugar refining, dairy, brewing, and various other food industries, as well as sugar beet molasses and POME. In addition, solid food waste streams such as sugarcane bagasse, vegetable waste, and waste barley have also been used.

Photo fermentation is a relatively novel process and currently lacks the competitiveness that more mature pathways have. Two process configurations have been suggested: a single step and a two-step approach. A single photo fermentation reactor has a low specific investment cost but suffers from low efficiencies. In the two-step approach, dark fermentation stage is added before photo fermentation, where the organic acids formed in the previous dark fermentation step are further degraded in the subsequent step, increasing the overall H₂ yield. However, this process is challenging to operate and control due to the different bacteria and parameters between the separate stages.

1.2.2.3. Electrochemical Conversion

Electrochemical water splitting using renewable electricity is considered a promising technology to produce renewable H₂. In general, water electrolysis (TRL 8-9)⁽¹⁶⁾ involves H₂ evolution reaction (HER) at the cathode and O₂ evolution reaction (OER) at the anode (**Figure 10a**), with the requirement for a theoretical energy input of 1.23 eV. In addition to electricity sourced from solar and wind energy, water electrolysis can also utilise power generated from waste-to-electricity (WtE) conversion. Waste incineration (TRL 9) is an example of WtE, where the hot flue gas emanating from incinerators is utilised to produce steam in a boiler, and the steam subsequently powers an electric generator turbine to produce electricity. A key advantage of coupling water electrolysis with waste incineration is that the electricity source is not intermittent like solar and wind energy and thereby enables continuous H₂ production. This integrated WtE and water electrolysis pathway has been demonstrated in Europe under the Waste-to-Wheels study, such as for powering fuel cell trucks in the REVIVE project in the Netherlands, and for powering fuel cell buses in Germany's Wuppertal project and in Walloon region, Belgium.

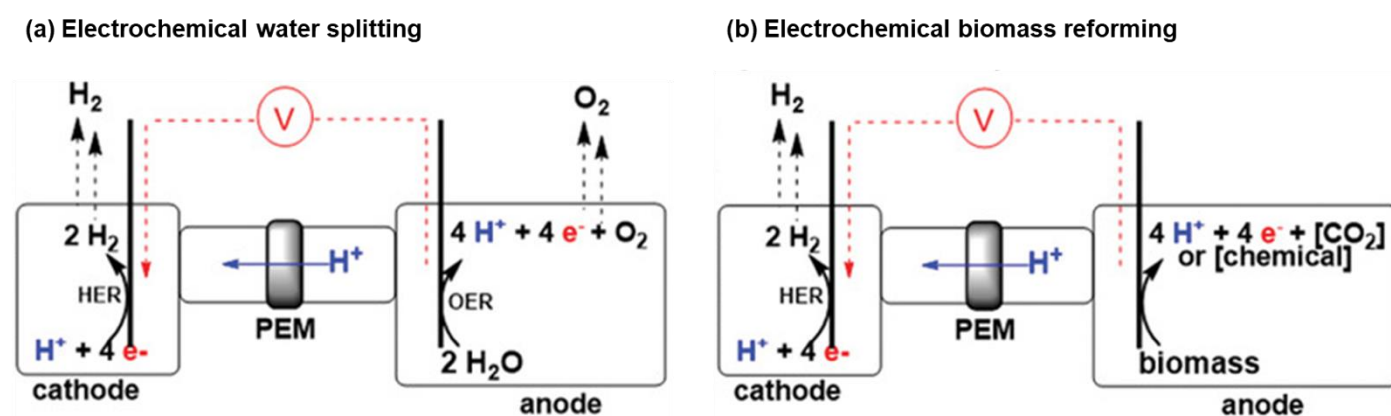


Figure 10. Schematic diagram of (a) electrochemical water splitting and (b) electrochemical biomass reforming.⁽⁵⁹⁾ Copyright © 2021 Wiley-VCH GmbH.

Table 7. Selected water electrolysis demonstration projects.

Project	Location	Technology	Product	Status	Capacity	Brief description	Ref.
Waste-to-Wheels Wallonia	Walloon region, Belgium	Water electrolysis (coupled to incineration)	H ₂	Planning	1 MW electrolyser	1 MW electrolyser is planned to be installed at incinerator site in Walloon region, Belgium to supply hydrogen for a bus fleet.	⁽⁶⁰⁾
REVIVE	Netherlands	Water electrolysis (coupled to incineration)	H ₂	Planning	N/A	The REVIVE project is aiming to build the largest demonstration network of hydrogen fuel cell refuse trucks. It has 15 heavy-duty vehicles across 8 sites in Europe. Part of the project involves trucks fuelled by Waste-to-hydrogen. The first one was deployed in 2020 in Breda (the Netherlands).	⁽⁶¹⁾

Wuppertal Waste-to-Hydrogen	Germany	Water electrolysis (coupled to incineration)	H ₂	Planning	2 MW electrolyser (limited to 1 MW in the first step)	Ten buses are using H ₂ generated by the WtE plant in Wuppertal, Germany. Half of the bus fleet of Wuppertal should run on H ₂ by 2025. The project is likely to be replicated in other cities and expand to the local taxi fleet and Dusseldorf airport's utility vehicles.	(62)
Sinopec's Kuqa project	Xinjiang, China	Water electrolysis (powered by solar PV)	H ₂	Operational	260 MW, 20 ktpa H ₂	The Kuqa project in Xinjiang province has been completed and put into operation in 2023. The facility has transmitted 2,000 tonnes of green H ₂ to Sinopec's Tahe Refining & Chemical Company. The production will gradually increase, reaching 20,000 tonnes per year by the fourth quarter of 2025.	(63)

Water electrolysis requires a substantial energy input, primarily due to the sluggish kinetics of the OER. As a result, a significant amount of energy needs to be spent on a product with very low market value—something that hinders the deployment of this pathway in which the cost is a major drawback. As an alternative to electrochemical water splitting, electroreforming (TRL 4-5) utilises organic substrates (C_xH_yO_z) to replace the challenging OER (Figure 10b). The oxidation of organic molecules during electroreforming could lower the energy input required to drive H₂ production since these oxidation reactions are thermodynamically more favourable compared to OER. In addition, electroreforming could potentially enable the conversion of waste organics into value-added products.

Wastewater that contains organic compounds generated as byproducts in the biofuel industry is among the potential substrates for electroreforming. As an illustration, glycerol, a major byproduct of biodiesel production, can undergo electroreforming to simultaneously produce H₂ and value-added chemicals, such as 2,5-dihydroxyacetone (DHA). Notably, the DHA product, which is a crucial building block for functional food, holds a significantly higher value of US\$150 per kg than the glycerol substrate (US\$0.11 per kg). When solid waste is utilised as a feedstock, a substantial pre-treatment step may be necessary to break down complex structures into simpler constituents that can be readily reformed into H₂. For instance, lignocellulosic waste requires thermal pretreatment via acid hydrolysis to generate 5-(hydroxymethyl)furfural (HMF), which is a key biomass platform intermediate. The HMF produced can subsequently act as a substrate for the electroreforming step, which results in the production of H₂ and 2,5-furandicarboxylic acid (FDCA)—a precursor for bioplastic manufacturing.

While electrochemical water splitting has been demonstrated on a pilot to commercial scale (based on IEA database last updated 17 November 2023, there are 756 water electrolysis demonstration/operational projects)⁽⁶⁴⁾, studies on biomass electroreforming have predominantly remained confined to the lab or to prototype demonstration. A recent development by a group from the University of New South Wales presented an integrated solar-driven conversion of waste biomass. This involved a waste biomass concentrator (WBC), a PV-thermal biomass preconditioning reactor (BPR) and a flow electrolysis cell (FEC). The aim was to show the feasibility of scaling up the process under real conditions (Figure 11). The BPR was designed to transform recovered waste biomass into bio-alcohol (HMF) with a yield of 25 mol%. Subsequently, the transformed biomass was then utilised to feed the anodic side of the FEC. This system achieved an overall solar-to-H₂ efficiency of 7.5%, with additional revenue generated from clean water production and a value-added chemical byproduct (FDCA). Cost analysis suggests that this integrated system can effectively treat 5 m³/day of sugar-containing wastewater, with a projected payback period ranging from 3 to 14 years. However, this projection assumes an H₂ price of US\$2.68-3.35/kg, which remains higher than the costs of H₂ from coal (US\$1.20-2.21/kg) and natural gas (US\$0.91-1.79/kg).⁽⁶⁵⁾

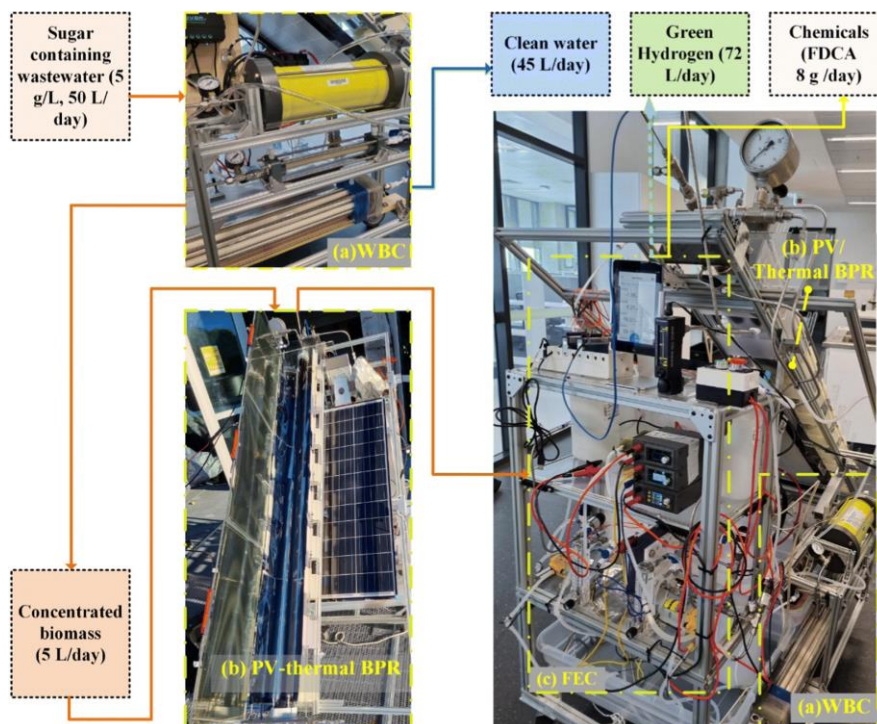


Figure 11. The rooftop integrated prototype: (a) waste biomass concentrator (WBC), (b) PV-thermal biomass preconditioning reactor (BPR), (c) flow electrolysis cell (FEC) and overall arrangement.⁽⁶⁶⁾ Copyright © 2023 Royal Society of Chemistry.

Microbial electrolysis (TRL 2-4)⁽²³⁾ represents a combined biological and electrochemical pathway. In a microbial electrolysis cell (MEC), exoelectrogenic microorganisms are employed for H_2 evolution. **Figure 12** depicts a schematic representation of a typical MEC, which features two electrodes installed in separate compartments. The organic substrate is introduced into the anode compartment, where the anode is coated with a biofilm of exoelectrogenic microorganisms. The substrate undergoes oxidation, producing CO_2 , protons, and electrons. The electrodes are connected through an external voltage source, thus enabling the flow of electrons to the cathode. The generated protons in the anode compartment migrate to the cathode compartment through a membrane. Subsequently, the protons undergo reduction by electrons, and this results in the production of H_2 . The reactions in the two compartments are shown in **Equations 11-12**, with acetic acid serving as the substrate.

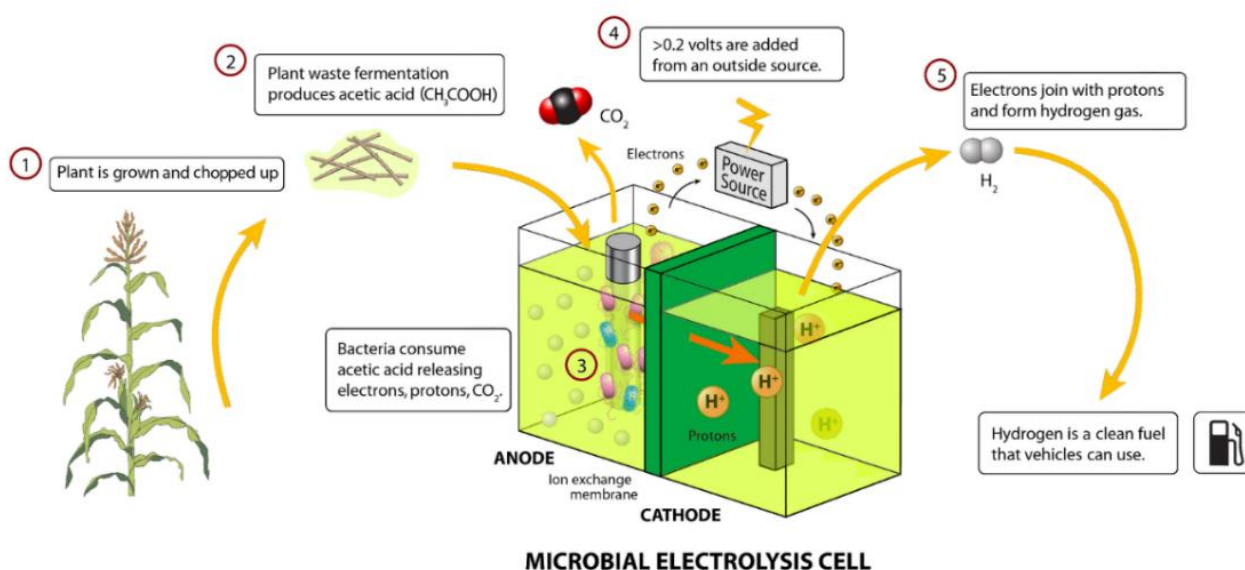
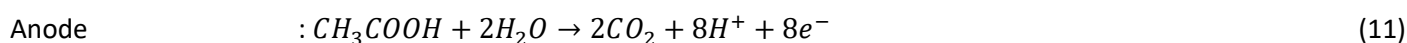


Figure 12. Schematic representation of a microbial electrolysis cell.

Organic compounds, such as acetic acid, butyric acid, and glucose, which can be derived from lignocellulose waste, serve as potential substrates for microbial electrolysis. In addition, wastewater streams, including urban, swine and winery wastewater, primary sludge, and sugar industry effluents are also applicable substrates for this process. Microbial electrolysis offers a significant COD removal efficiency for wastewater substrates, ranging from 73% to 98%.^(67, 68) This suggests that the system can achieve simultaneous wastewater treatment and H₂ production.

Like electroreforming, microbial electrolysis has primarily operated on a relatively small scale so far. A demonstration project undertaken by a group from Pennsylvania State University involved the development of a 1 m³ continuous flow MEC to treat winery wastewater in Oakville, Canada, as depicted in **Figure 13**.⁽⁶⁹⁾ The wastewater was introduced to the reactor with a retention time of 1 day, and the system exhibited a COD removal efficiency of 62% and a biogas generation rate of 0.28 L/L/day. Significant challenges arising from this test included: (1) a considerable time of over 20 days required for reactor startup before wastewater could be fed to the MEC, (2) 86% of the generated gas was methane, (3) H₂ gas separation difficulties, and (4) a lower relative current density compared to laboratory setups, primarily attributed to the scaled-up electrode configuration.⁽⁷⁰⁾

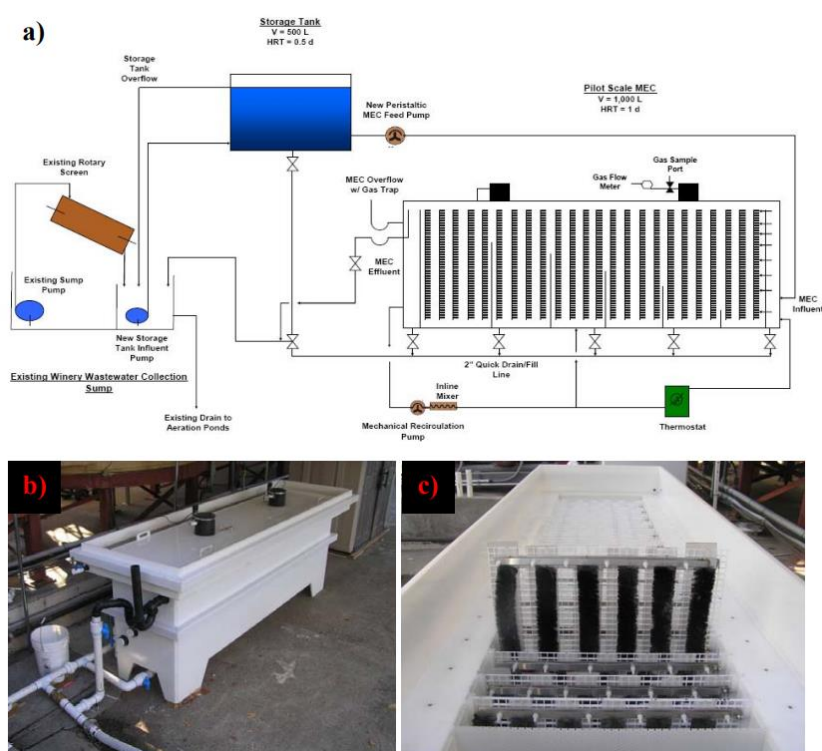


Figure 13. (a) Schematic of pilot-scale microbial electrolysis plant. (b) Overview of the reactor, and (c) module orientation within reactor.⁽⁶⁹⁾

1.2.2.4. Photochemical Conversion

Photoreforming (TRL 2-3) is an emerging WtH technology that harnesses the redox capability of a photocatalyst under sunlight irradiation to drive simultaneous H₂ evolution and organic oxidation reactions. In this process, the photocatalyst absorbs sunlight energy to break down organic waste in water into simpler organic molecules or CO₂ and H₂.⁽¹³⁾ Similarly to electroreforming, photoreforming serves as an alternative to overall water splitting. It overcomes the limitations imposed by an energetically and kinetically demanding O₂ evolution reaction (OER).

Photoreforming combines H₂ evolution reaction (HER) with the organic oxidation reaction on a semiconductor. When illuminated, electrons in the photocatalyst are excited to the conduction band (CB), which facilitates the reduction of protons to H₂. Simultaneously, the holes left in the valence band (VB) oxidise the organic substrate (C_xH_yO_z) to either CO₂ or intermediate products (**Figure 14**). The overall photoreforming process is nearly energetically neutral for many common organic waste substrates. For instance, the photoreforming of glucose (a biomass component) or ethylene glycol (a component of the plastic polyethylene terephthalate) has $\Delta G^0 = -84.7$ kJ/mol or $\Delta G^0 = +9.2$ kJ/mol, respectively, both of which compare favourably to water splitting.

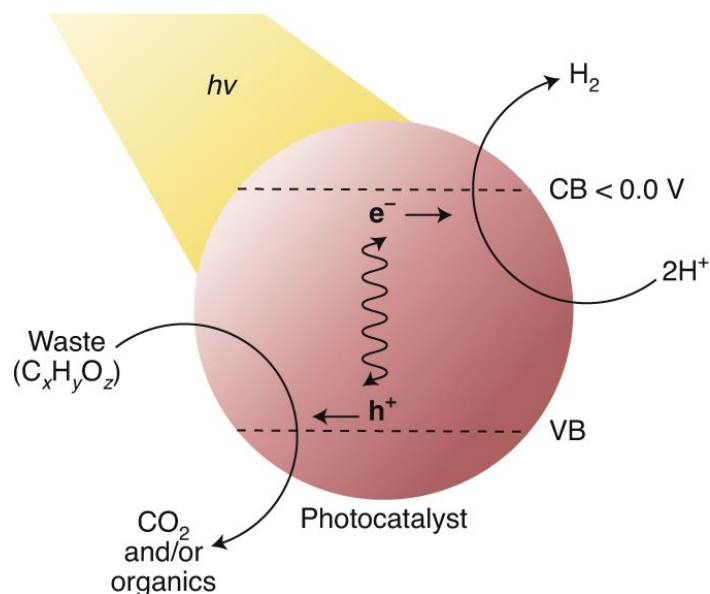


Figure 14. Diagram of the waste photoreforming process.⁽¹³⁾ Copyright © 2021 Springer Nature.

Typical substrates for photoreforming are oxygenated compounds with the formula $C_xH_yO_z$. In general, photoreforming favours substrates characterised by low complexity, high hydrophilicity, water solubility, and functional groups that readily adsorb to the photocatalyst surface. An ideal feedstock for photoreforming should possess as many of these attributes as possible while simultaneously being sourced from waste streams. Photoreforming has been demonstrated to be able to transform components derived from various waste streams, especially biomass, food, and plastic, into H_2 fuel and organic chemicals utilising sunlight as the energy input. Preliminary techno-economic and life cycle assessments have indicated that the carbon footprint of photoreforming is lower than or comparable to existing waste-to-fuel conversion methods, although improvements in production cost and energy efficiency are necessary before its commercial applications can be envisioned (**Figure 15**). Key factors influencing the economic and environmental feasibility of photoreforming include substrate pretreatment, photocatalyst efficiency and durability, water usage, and the production of valuable organics.

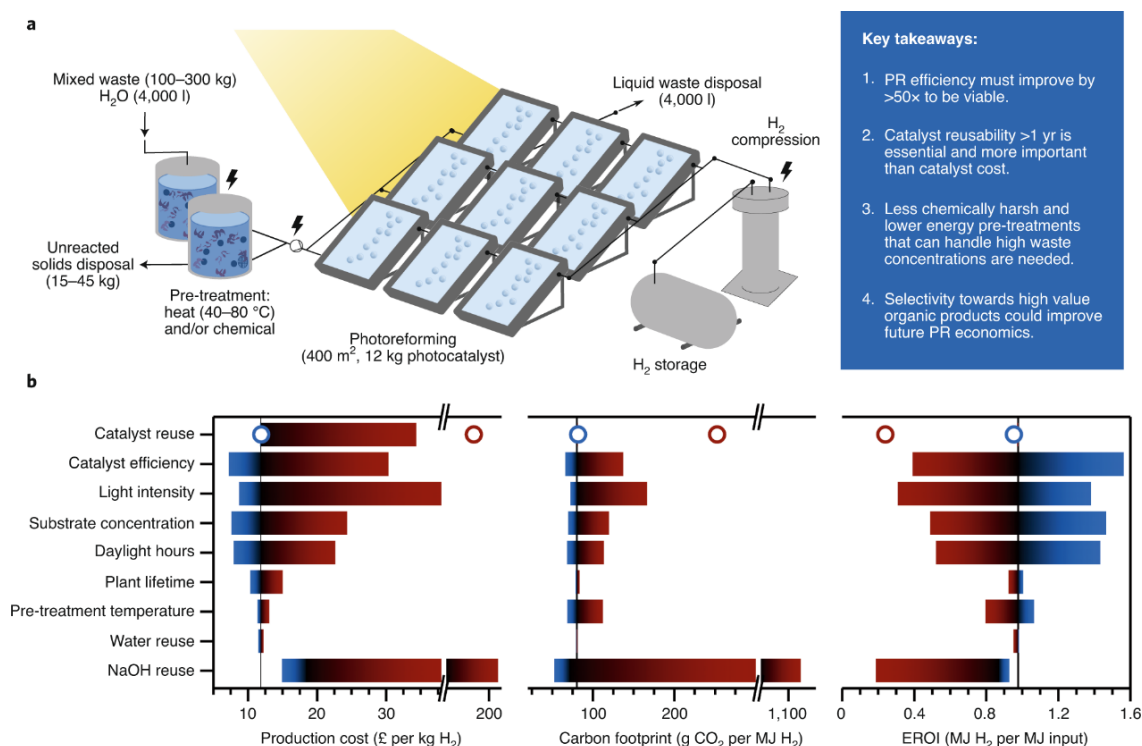


Figure 15. Feasibility of pilot-scale photoreforming.⁽¹³⁾ **(a)** Model photoreforming pilot plant capable of processing 4,000 L of solution and 300 kg of waste per day. **(b)** Sensitivity analysis of H_2 production cost, carbon footprint and EROI upon variation of individual parameters. EROI: Energy Return on Investment. Copyright © 2021 Springer Nature.

1.2.3. Comparative Assessment of Waste-to-Hydrogen Technology

A multi-criteria assessment (MCA) approach has been developed to evaluate the overall performance of each WtH process. The MCA involves comparing and assessing the potential WtH technologies across the following metric:

Commercial Performance: This includes assessing the technology maturity indicated by technology readiness level (TRL) and scale of the technology currently demonstrated.

Technological Performance: This includes assessing the H₂ yield, energy efficiency, feedstock flexibility, and process complexity considering the upstream, main, and downstream units (e.g, substrate pretreatment, main reactor design and control product separation, and flue gas cleaning).

Economic Performance: This includes assessing the upfront capital cost of the technology and the estimated price disparity with fossil based H₂ production technology (coal gasification and steam methane reforming).

Environmental Performance: This includes assessing the GHG emissions intensity compared to fossil based H₂ produced via coal gasification or steam methane reforming.

The MCA framework (**Table 8**) is subsequently applied to determine the overall performance rating of each WtH technology pathway, particularly to treat MSW. The rating ranges from 1 to 5, with 1 representing least favourable performance and 5 representing most favourable performance. The rating for each category is assigned based on literature data, which may have variations in assumptions. A balanced approach is taken in the MCA framework by putting equal weights for each metric and sub-metric. It is also important to note that the assessment conducted in this study illustrates the performance of each WtH pathway relative to each other. In other words, a higher rating does not necessarily mean a higher absolute viability of the technology.

Table 8. Multi criteria analysis framework for various pathways.

Metric	Sub-metric	Rating				
		1	2	3	4	5
Commercial (25%)	TRL (50%)	1-2	3-4	5-6	7-8	9
	Scale (50%)	Lab (g to kg scale)	Small (>1 tpa H ₂ / >10 tpa feedstock)	Medium (>100 tpa H ₂ / >1 ktpa feedstock)	Large (>1 ktpa H ₂ / >10 ktpa feedstock)	Commercial (>10 ktpa H ₂ / >100 ktpa feedstock)
Technological (25%)	H ₂ yield (kg _{H2} /t _{feedstock}) (16.7%)	<20	20-40	40-60	60-80	>80
	Energy efficiency (%) (16.7%)	<10%	10-30%	30-50%	50-70%	70-90%
	Feedstock flexibility (16.7%)	Simple molecules with high sensitivity to contaminants	-	Intermediate molecules with intermediate sensitivity to contaminants	-	Able to handle complex feedstock with high tolerance to contaminants
	Pretreatment complexity (16.7%)	Very complex	Complex	Moderate	Simple	Very simple
	Main treatment complexity (16.7%)	Very complex	Complex	Moderate	Simple	Very simple
	Downstream complexity (16.7%)	Very complex	Complex	Moderate	Simple	Very simple
Economic (25%)	CAPEX (US\$/kg H ₂ pa) (50%)	>US\$50	US\$30-50	US\$10-30	US\$5-10	<US\$5
	LCOH (US\$/kg H ₂) (50%)	>US\$10	US\$5-10	US\$3-5	US\$2-3	<US\$2
Environmental (25%)	GHG emissions (kg CO ₂ -eq/kg H ₂) (100%)	>4	3-4	2-3	1-2	<1

Table 9. Assessment of the commercial performances of WtH technological pathways.

Technology	TRL ^{a)}	Scale ^{b)}
Gasification	6-9 ⁽¹⁶⁾	Demonstrated at medium scale (100 tpa H ₂ /2 ktpa waste). ⁽²⁶⁾ Planned to upscale to large scale (54k tpa H ₂ /700 ktpa waste). ⁽⁷¹⁾
Pyrolysis with in-line reforming	4-7 ^(23, 36)	Pyrolysis with in-line reforming demonstrated at small pilot scale. ⁽⁴³⁾
Chemical looping hydrogen	3-4 ⁽¹⁶⁾	Demonstrated at small scale for coal.
Dark fermentation	5-6 ⁽²³⁾	Demonstrated at small pilot scale (2.5 tpa H ₂ /10 m ³ reactor). ⁽⁵⁷⁾
Photo fermentation	3-4 ⁽²³⁾	Mostly conducted in lab scale under research.
Incineration-water electrolysis	8-9 ⁽¹⁶⁾	Incineration demonstrated at large scale (300 ktpa waste) coupled to small pilot 2 MW electrolyser (146 tpa H ₂). ⁽⁶⁰⁾ PV-electrolysis demonstrated at large scale (260 MW, 20 ktpa H ₂). ⁽⁶³⁾
Electroreforming	3-4	Mostly conducted in lab scale under research.
Microbial electrolysis	2-4	Mostly conducted in lab scale under research.
Photoreforming	2-3	Mostly conducted in lab scale under research.

^{a)} TRL assessment is based on international guidelines released by NASA (see [Appendix 1](#)).⁽⁷²⁾

^{b)} Scale is assessed based on operational projects. In the case of no operational projects, the scale is assessed based on any planned/under construction projects.



Note: 1 represents the least favourable performance, 5 represents the most favourable performance. The rating is relative among WtH technologies and does not represent the absolute viability of the technology.

Table 10. Assessment of the technical performances of WtH technological pathways.

WtH process	Yield (kg H ₂ /t feedstock)	Energy efficiency (%)	Feedstock flexibility	Pretreatment complexity	Main treatment complexity	Downstream complexity
Gasification	40-190 ⁽²³⁾	35-50%	Able to handle various complex waste: biowaste, MSW, MPW.	Relatively simple pretreatment such as drying, torrefaction and grinding.	Moderate complexity with requirements for temperature and pressure control.	Complex gas cleaning process due to presence of waste contamination and possible tar formation.
Pyrolysis with in-line reforming	Pyrolysis: 25-65 ⁽²³⁾ Reforming: 40-130 ⁽²³⁾	35-50%	Able to handle various complex waste: biowaste, MSW, MPW.	Relatively simple pretreatment such as drying, torrefaction and grinding.	Moderate complexity with requirements for temperature and pressure control.	Complex gas cleaning process due to presence of waste contamination and possible tar formation.
Chemical looping hydrogen	143.5 ⁽⁷³⁾	61.6% ⁽⁷⁴⁾	Able to handle various complex waste: biowaste, MSW, MPW.	Relatively simple pretreatment such as drying, torrefaction and grinding.	Complex due to challenges of the solid oxygen carriers.	Simple gas cleaning process without the need for CO ₂ capture and PSA H ₂ separation. ⁽⁷⁵⁾
Dark fermentation	4-44 ⁽²³⁾	2.6-13.3% ⁽⁷⁶⁾	Only suitable for sugar-rich solid waste or wastewater. Sensitive to contamination such as ammonia and sulphate.	Complex pretreatment to break down lignocellulose via acid or enzymatic hydrolysis.	Complex control of seed reactor and fermenter due to high sensitivity to environment (e.g., pH, temperature, product accumulation). ⁽⁷⁷⁾	Requires post-treatment to handle organic acid byproducts and undigested solid residue.
Photo fermentation	9-49 ⁽²³⁾	10-16% ^(76, 78)	Only suitable for sugar-rich solid waste or wastewater. Sensitive to contamination such as ammonia and sulphate.	Complex pretreatment to break down lignocellulose via acid or enzymatic hydrolysis.	Complex control of seed reactor and fermenter due to high sensitivity to environment (e.g., pH, temperature, product accumulation). ⁽⁷⁷⁾	Requires post-treatment to handle organic acid byproducts and undigested solid residue.
Incineration-water electrolysis	11.3-18.9	12-21%	Able to handle various solid waste feedstock: biowaste, MSW, MPW.	Simple to no feedstock pretreatment.	Operation of combustion reactor is simple but the flue gas cleaning is complex.	Complex flue gas treatment to remove harmful substances.
Electroreforming	PET: 16.9, ⁽⁷⁹⁾ 47.4 ⁽⁸⁰⁾	Sugar (7.5%), ⁽⁶⁶⁾ PET (16%) ⁽⁸¹⁾	More suitable for simple organic molecules.	Solid feedstock: complex pretreatment to break down waste into simple molecules, wastewater: pH adjustment, undesired ion removal.	Electrolyser is quite complex with the need for electrical auxiliary system.	H ₂ separation is not needed. Organic byproducts recovery can be complex if selective oxidation is targeted.
Microbial electrolysis	Food waste: 46 (combined with AD) ⁽⁸²⁾	62-78% ⁽⁸³⁾	More suitable for simple organic molecules, such as organic acids.	Solid feedstock: complex pretreatment to break down waste into simple molecules, wastewater: pH adjustment, undesired ion removal.	Relatively complex setup and operation, requires electrical auxiliary system, control of pH, temperature, ions.	Post-treatment of product and flue gas is simple. H ₂ is formed in cathode chamber, while CO ₂ is formed in anode chamber.
Photoreforming	PET: 0.2 ⁽⁸⁴⁾ Polyester: 2-20 ⁽⁸⁵⁾	2-6% ⁽⁸³⁾	More suitable for simple organic molecules.	Solid feedstock: complex pretreatment to break down waste into simple molecules, wastewater: pH adjustment, undesired ion removal.	Relatively simple with less complex balance of plant but operational can be challenging.	H ₂ separation may be required. Organic byproducts recovery can be complex if selective oxidation is targeted.

1	2	3	4	5
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Note: 1 represents the least favourable performance, 5 represents the most favourable performance. The rating is relative among WtH technologies and does not represent the absolute viability of the technology.

Table 11. Assessment of the economic and environmental performances of WtH technological pathways.

Technology	Indicative initial CAPEX ^{a)} (US\$/kg H ₂ pa)	Indicative LCOH ^{a)} (US\$/kg H ₂)	GHG emissions ^{b)} (kg CO ₂ -eq/kg H ₂)
Gasification	US\$11.2/kg H ₂ pa (240 tpd MSW) ⁽⁸⁶⁾ US\$13.9/kg H ₂ pa (700 ktpa MSW, 54 ktpa H ₂) ⁽⁷¹⁾	US\$3.41/kg (240 tpd MSW) ⁽⁸⁶⁾ US\$2.6-4.8/kg (500 tpd MSW) ⁽²⁴⁾ US\$1.4-3.5/kg (1,000 tpd MSW) ⁽²⁴⁾	MSW: 4-5 (w/o CCS), -13.3 (w/ CCS) ⁽⁸⁷⁾ MPW: 16-21 (w/o CCS), 5.1-6.2 (w/ CCS) ⁽⁶⁵⁾
Pyrolysis and in-line reforming	US\$38.2/kg H ₂ pa (8.5 ktpa H ₂) ⁽⁸⁸⁾	Pyrolysis: US\$1.21-2.57/kg ⁽²³⁾ Steam reforming: US\$3.8-4.6/kg ⁽⁴²⁾ , US\$3-4.6/kg ⁽⁸⁹⁾	Wood waste: 6.5 (w/o CCS) ⁽⁹⁰⁾ Biomass: 1.15-2.4 (w/o CCS) ⁽⁸⁹⁾ , -9.5 (w/ CCS) ⁽⁴²⁾
Chemical looping hydrogen	US\$4.2/kg H ₂ pa (46 ktpa H ₂) ⁽⁹¹⁾ US\$8.6/kg H ₂ pa (90 ktpa H ₂) ⁽⁹²⁾ US\$27.1/kg H ₂ pa (175 tpa H ₂) ⁽⁹³⁾	US\$1.21-1.47/kg (46 ktpa H ₂) ⁽⁹¹⁾ US\$3.37/kg ⁽⁹⁴⁾	Biomass: -14.58 (w/ CCS) ⁽⁹⁴⁾
Dark fermentation	Food waste: US\$162.5/kg H ₂ pa (3.6 tpd H ₂) ⁽⁵⁶⁾ Barley straw: US\$475/kg H ₂ pa (1.3 tpd H ₂)	Food waste: US\$12.2/kg (3.6 tpd H ₂) ⁽⁵⁶⁾ Barley straw: US\$58.5/kg (1.3 tpd H ₂) ⁽⁹⁵⁾ Wheatstraw: US\$26.7/kg (42.6 tpd H ₂) ⁽⁹⁶⁾ Wastewater: US\$2.5-3.2/kg ⁽⁸³⁾	MSW: 6-7 ⁽⁹⁷⁾ Food waste: 3.4-5.4 ⁽¹³⁾ Starch wastewater: 0.49 ⁽⁹⁸⁾ Wastewater: 0.7-1.11 ⁽⁸³⁾
Photo fermentation	US\$205/kg H ₂ pa (480 tpa H ₂) ⁽⁹⁹⁾	US\$60-65/kg (480 tpa H ₂) ⁽⁹⁹⁾ US\$8.15-13.0/kg (400 tpa H ₂) ⁽⁷⁶⁾	Starch wastewater: 0.21 ⁽⁹⁸⁾ Wastewater: 0.55-0.8 ⁽⁸³⁾
Incineration-water electrolysis	US\$620-700/tpa MSW (incineration) ⁽¹⁰⁰⁾ US\$1,700/kW (PEM electrolyser) ⁽¹⁰¹⁾ US\$43.1-74/kg H ₂ pa (estimated)	US\$120-170/MWh (LCOE incineration) US\$13-15.7/kg (estimated)	GHG emissions depend on incineration MSW: 13.1 (w/o CCS), -147 (w/ CCS) ⁽⁸⁷⁾
Electroreforming	PET: US\$95/kg H ₂ pa ⁽⁷⁹⁾	Wastewater: US\$7.59/kg ⁽⁸³⁾ MSW, PET: Data is not available but it can be estimated to be similar to photoreforming (US\$0.3-53/kg) ^(13, 85)	GHG emissions depend on the electricity source, estimated to be 2.4 (renewable) ⁽⁸³⁾
Microbial electrolysis	US\$48.2-94.8/kg H ₂ pa (30-60 tpa H ₂) ⁽¹⁰²⁾	Wastewater: US\$2.6-4.51/kg, ⁽⁸³⁾ US\$6.54/kg, ⁽¹⁰³⁾ US\$12.43/kg ⁽⁷⁶⁾	GHG emissions depend on the electricity source 11.5-18 (current grid), ⁽¹⁰⁴⁾ 0.17-2.17 (renewable) ⁽⁸³⁾
Photoreforming	MSW: US\$58/kg H ₂ pa (14.36 kg H ₂ /day) ⁽¹³⁾ PET: US\$147/kg H ₂ pa (55.9 kg H ₂ /day) (alkaline pretreatment), US\$46/kg H ₂ pa (190 kg H ₂ /day) ⁽⁸⁵⁾ (enzymatic treatment)	MSW: US\$15.3/kg (alkaline treatment) ⁽¹³⁾ PET: US\$53/kg (alkaline treatment), US\$0.3/kg (enzymatic treatment) ⁽⁸⁵⁾ Wastewater: US\$3.36-4.98/kg ⁽⁸³⁾	MSW: 9.7 (alkaline treatment) ⁽¹³⁾ PET: 9, (alkaline treatment), 3.8 (enzymatic treatment) ⁽⁸⁵⁾ Wastewater: 0.48-0.51 ⁽⁸³⁾

^{a)} Initial CAPEX and LCOH are dependent on the scale of the plant and efficiency. Data for initial CAPEX and LCOH are obtained from literature on techno-economic studies with varying assumptions and predominantly conducted on hypothetical scale and/or efficiency that have not been demonstrated yet.

^{b)} GHG emissions vary between different feedstock and process design in which whether CCS is integrated or not and additional energy (electricity/heat) input source. GHG emissions metric is evaluated by compare emissions reduction relative to coal gasification and steam methane reforming by considering different types of waste feedstock and optimum process configurations.

1	2	3	4	5
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Note: 1 represents the least favourable performance, 5 represents the most favourable performance. The rating is relative among WtH technologies and does not represent the absolute viability of the technology.

Table 12. Overall comparative analysis of WtH technological pathways.

Criteria	Sub-criteria	Gasification	Pyrolysis with in-line reforming	Chemical looping hydrogen	Dark fermentation	Photo fermentation	Incineration-water electrolysis	Electroreforming	Microbial electrolysis	Photoreforming
Commercial (25%)	TRL (50%)	4	3	2	3	2	5	2	2	1
	Scale (50%)	3	2	2	2	1	3	1	1	1
	Sub-rating	3.5	2.5	2	2.5	1.5	4	1.5	1.5	1
Technological (25%)	Yield (16.7%)	4	4	5	2	2	1	2	3	1
	Energy efficiency (16.7%)	3	3	4	2	2	2	2	4	1
	Feedstock flexibility (16.7%)	5	5	5	3	3	5	1	1	1
	Pretreatment complexity (16.7%)	4	4	4	1	1	5	1	1	1
	Main process complexity (16.7%)	3	3	2	2	2	4	2	2	4
	Downstream complexity (16.7%)	1	1	5	2	2	1	4	4	4
	Sub-rating	3.3	3.3	4.2	2	2	3	2	2.5	2
Economic (25%)	CAPEX (50%)	3	2	3	1	1	1	1	1	1
	LCOH (50%)	3	3	3	1	1	1	1	1	1
	Sub rating	3	2.5	3	1	1	1	1	1	1
Environmental (25%)	GHG emissions (100%)	5	5	5	4	4	5	4	4	4
Overall rating		3.7	3.3	3.6	2.4	2.1	3.3	2.1	2.3	2



Note: 1 represents the least favourable performance, 5 represents the most favourable performance. The rating is relative among WtH technologies and does not represent the absolute viability of the technology.

The MCA reveals that thermochemical WtH processes, particularly gasification, pyrolysis with in-line reforming, and chemical looping hydrogen, outperform other WtH pathways for the conversion of MSW to hydrogen. These thermal processes benefit from the relatively higher H₂ yield compared to other pathways. From economic perspective, waste gasification, pyrolysis with in-line reforming, and chemical looping hydrogen exhibit relatively lower H₂ production costs compared to other pathways but remain higher compared to the costs of H₂ from coal (US\$1.20-2.21/kg) and natural gas (US\$0.91-1.79/kg).⁽⁶⁵⁾ It is important to note, however, that the indicative costs provided here are primarily estimated based on large scale that currently does not exist. This is reflected by the relatively low commercial performance for these thermochemical processes as there are only a handful of successful demonstration projects taking off at a relatively small scale (currently WtH demonstration project is only around 100 tpa H₂, substantially lower than coal gasification and steam methane reforming that typically produces >100 ktpa H₂)^(26, 105). The commercial upscaling of these thermochemical processes has remained to be demonstrated. In addition, indirect WtH through incineration-water electrolysis appears to be a potential pathway, primarily due to the feedstock flexibility and possibility to capitalise on existing waste incineration facilities. Additionally, water electrolysis processes, particularly alkaline and PEM electrolyzers, are deemed as H₂ production technologies at relatively high TRL. Nonetheless, the process suffers from low efficiency due to limited power generation efficiency and currently high specific energy consumption of water electrolyzers, resulting in high hydrogen production cost.

Other WtH processes that employ milder reaction conditions exhibit lower rating compared to the thermal processes for the conversion of MSW to H₂. This is primarily due to the limitations of these processes in directly handling complex MSW solid feedstock. As a result, significant waste pre-treatment processes are often required, leading to low overall efficiency and high costs. Nevertheless, these low-temperature processes, such as fermentation, electroreforming, and photoreforming, offer the additional benefits of mild reaction conditions and opportunities for generating value-added byproducts when product recovery processes are integrated. For instance, dark fermentation typically produces organic acids such as acetic acid and butyric acid, which can be recovered via additional distillation unit.

While the MCA results indicate that thermochemical conversion pathways stand out as potential technologies for MSW conversion to H₂, the role of other alternative technologies should not be overlooked. Currently, there is no viable technology yet to effectively transform waste to H₂ on a commercial scale as evidenced by limited numbers of successful WtH projects and some failed commercial waste-to-energy projects, which are further discussed in [Section 1.4.2](#). This underscores the importance of further development of WtH technologies to achieve pathways towards commercial feasibility in the future.

1.3. Carbon Capture and Storage Integration

Coupling WtH with carbon capture and storage (CCS) has the potential to cut greenhouse gas emissions associated with waste. By diverting waste from landfilling or incineration through an integrated WtH and CCS technology (WtH-CCS), the greenhouse gas emissions from waste generation can be significantly reduced. In addition, WtH-CCS has the potential to sequester carbon from the atmosphere depending on the biogenic carbon content in waste. CCS encompasses methods to capture and store CO₂ emitted from typically large point sources associated with fossil fuel-based power plants, industrial activities, and waste-to-energy systems. The captured CO₂ is transported and injected into suitable underground geological formations for permanent storage or utilised as feedstock for materials, fuels, and chemicals production.

1.3.1. CO₂ Capture

1.3.1.1. Absorption

CO₂ can be captured via absorption, a process that typically uses a liquid-based solvent to separate a specific component of gas from a gas mixture. Absorption can be grouped into physical and chemical absorption, depending on the interaction between the gas and the solvent. Physical absorption relies on the solubility of the gas in the solvent while chemical absorption involves a chemical reaction between the gas and the solvent. In a typical CO₂ absorption process as illustrated in [Figure 16](#), liquid-based solvents contact with the flue gas stream counter-currently in the

absorber unit and absorb CO₂ either physically or chemically. The CO₂ removal efficiency could reach 99%.⁽¹⁰⁶⁾ Then, the captured CO₂ is released from the solution by applying heat and/or varying pressure in the stripper unit.⁽¹⁰⁷⁾

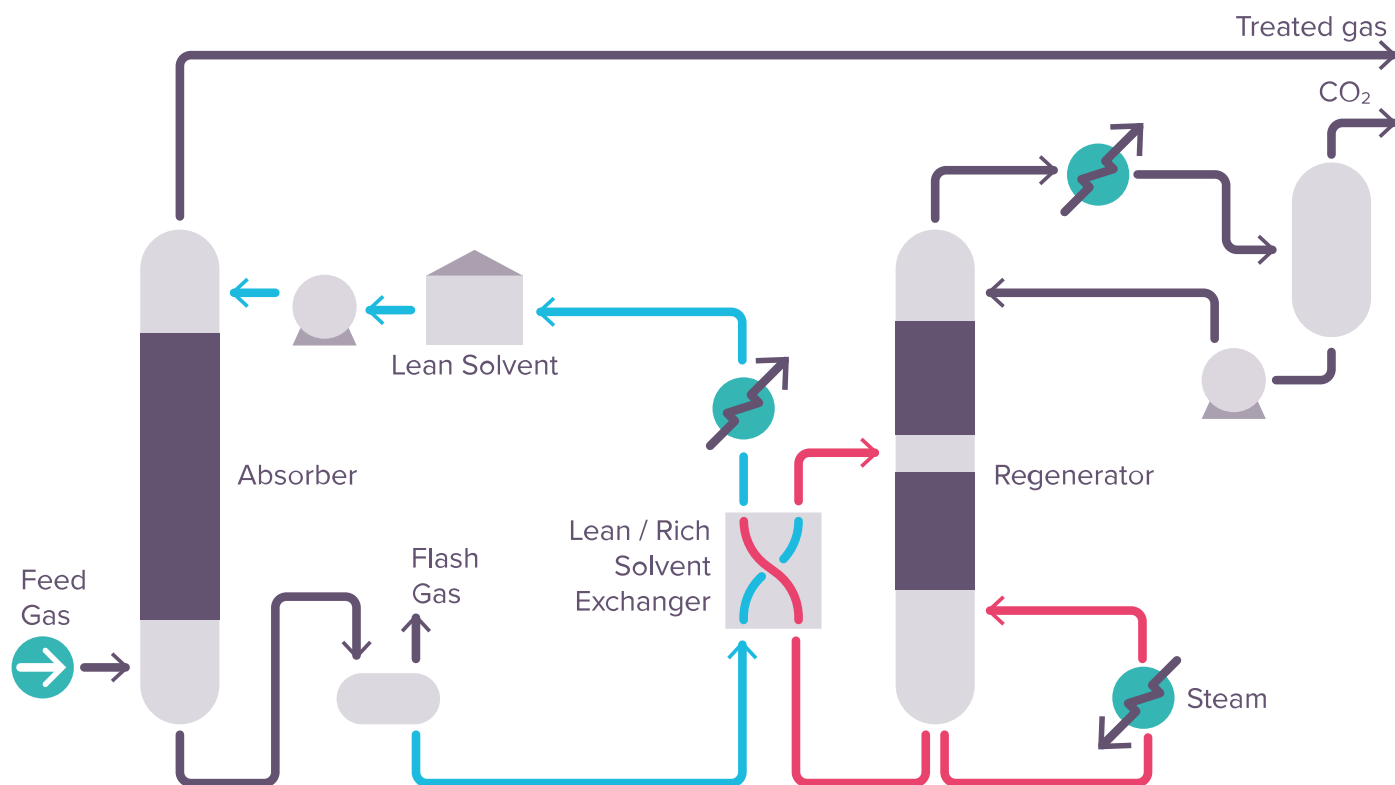


Figure 16. Simplified process flow diagram of chemical CO₂ absorption.⁽¹⁰⁸⁾

Amine-based solvents, such as monoethanolamine (MEA), diethanolamine (DEA), methyldiethanolamine (MDEA), and triethanolamine (TEA), are mature solvents for CO₂ capture due to their high CO₂ absorption rate, large CO₂ capacity, and low viscosity. In addition, their high reactivity towards chemical absorption makes them attractive in capturing CO₂ from dilute and low-pressure flue gas streams. This renders amine-based liquid absorption suitable for a wide variety of point emissions sources. Further, amine-based liquid absorption has high TRL of 9.⁽¹⁰⁹⁾ However, CO₂ absorption by amine-based solvents suffers from several limitations, including high regeneration energy, equipment corrosion, and amine degradation during operation. In amine-based chemical absorption, MEA is the most popular solvent due to its high CO₂ absorption capacity (0.5 mol CO₂/mol MEA, equivalent to 360 g CO₂/kg MEA),⁽¹¹⁰⁾ high CO₂ recovery (>90%) and CO₂ purity (>99%), low cost, and high availability. Typically, dilute MEA solutions are used in the process with concentration around 20-30 wt%.⁽¹¹¹⁾ The operating temperature of the absorber is 20-50°C while the stripping process is carried out at 110-130°C.

In general, the cost of CO₂ capture varies with CO₂ concentration and partial pressure in the gas stream as well as the targeted capture rate. The lower concentration and pressure would lead to an increase in the cost of capture. The higher targeted capture rate will also lead to an increase in the costs. The levelised cost of CO₂ capture using the absorption method with different CO₂ partial pressures can be seen in [Table 13](#).⁽¹¹²⁾ Examples of low partial pressure point sources include natural gas turbines (3-4 kPa, 3-4 vol%). Medium partial pressure point sources include coal power plants (12-14 kPa, 12-15 vol%), cement factories (14-33 kPa, 14-33 vol%), and steelmaking plants (15 kPa, 15 vol%). In contrast, ethanol fermentation plants (100 kPa, 100 vol%) and ammonia production facilities (500 kPa, 18 vol%) are considered high partial pressure point sources.⁽¹¹²⁾

Table 13. Cost comparison of CO₂ absorption with different CO₂ partial pressure levels. MEA is monoethanolamine, FG+ is Econamine FG Plus solvent formulation developed by Fluor, and Selexol utilises dimethyl ether of polyethylene glycol innovated by Union Carbide as a physical absorbent.⁽¹¹²⁾

Variable	Low partial pressure		Medium partial pressure		High partial pressure	
	Base case	Best case	Base case	Best case	Base case	Best case
Plant capacity (t _{CO2} /day)	1000	5000	1000	5000	1000	5000
Absorbent	MEA	FG+	MEA	FG+	Selexol	Selexol
Capture rate (%)	90	90	90	90	90	90
Capital costs (US\$/t _{CO2})*	32.46	14.50	14.50	6.91	26.93	11.74
Variable OPEX (US\$/t _{CO2})	43.51	24.86	37.98	28.32	6.91	5.53
Fixed OPEX (US\$/t _{CO2})*	10.36	6.22	4.14	2.07	8.98	4.14
Levelised cost of CO ₂ capture (US\$/t _{CO2})	85.63	46.27	56.63	37.29	45.58	22.79

*) CAPEX and fixed OPEX are referred to the nominal capacity of the plant.

1.3.1.2. Adsorption

CO₂ can also be captured via adsorption, which works based on the condensation of gases on the solid adsorbent surface and the differences in sorption capacity of particular gas components in a gas mixture stream. As in absorption, adsorption can occur physically or chemically (physisorption or chemisorption). Adsorption is considered as a promising CO₂ separation method, despite its appreciably lower TRL compared to absorption, due to several factors: (i) easy retrofitting to various existing plants; (ii) high CO₂ capacity and selectivity; and (iii) low energy requirements for regeneration.

A number of solid adsorbent materials are widely available for CO₂ capture. Zeolites are commonly used in refinery and gas separation industry. Although zeolites have quite high CO₂ uptake, it is highly sensitive to moisture, leading to a significant decrease in CO₂ uptake. As an alternative to zeolites, carbon materials such as activated carbons, carbon nanotubes, and graphene have also been demonstrated as CO₂ adsorbents. Carbon materials exhibit better stability in the presence of water than zeolites. However, the CO₂ capacities of carbon materials typically decrease at low pressure.

After CO₂ is adsorbed and separated from other gas components, CO₂ can be released from the adsorbent surface using numerous regeneration methods ([Figure 17](#)). Basically, the regeneration methods can be done by either varying pressure or temperature. Several methods for CO₂ regeneration in a fixed bed system that have been developed include vacuum swing adsorption (VSA) and pressure swing adsorption (PSA), temperature swing adsorption (TSA) and electric swing adsorption (ESA). The PSA method involves pressure change from high to atmospheric pressure, while VSA works based on the same principle as PSA, but with a final pressure below atmospheric pressure. In TSA, the temperature is increased to desorb the CO₂ from the surface. The temperature increase can be achieved through electric heating or a stream of hot fluid. In the case of hot fluid heating, there could be a combined effect of increasing temperature and lowering the partial pressure of CO₂. An ESA system also requires temperature rise but the system is heated using a Joule effect.

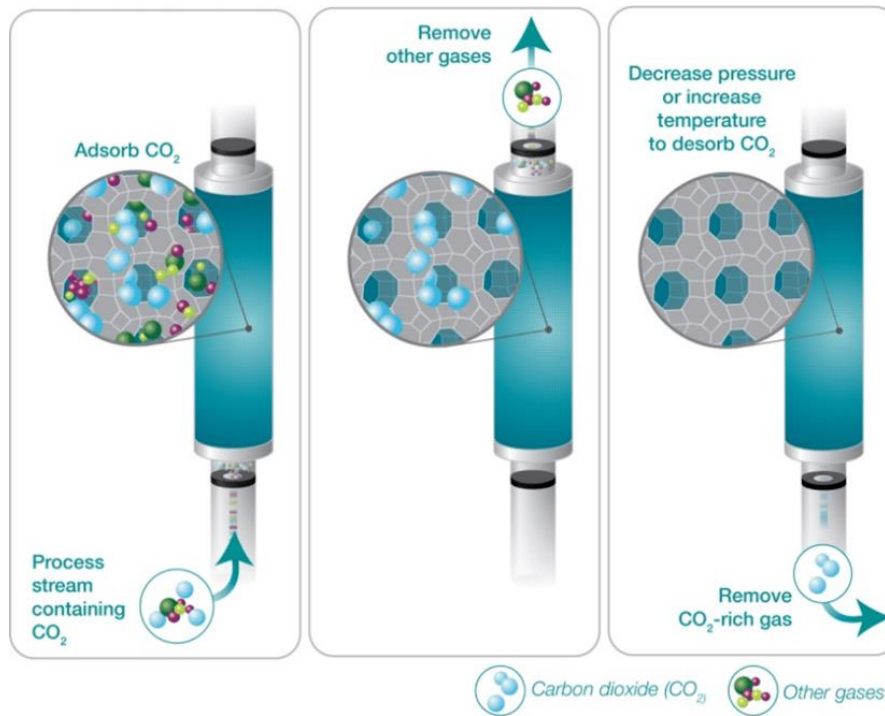


Figure 17. CO₂ separation by adsorption.⁽¹¹³⁾

In terms of economic consideration, cost assessment for CO₂ adsorption using Zeolite-13X as the adsorbent shows that the optimum capture cost is found at US\$87.35 per t_{CO2}.⁽¹¹⁴⁾ The annualised capital and operational costs are estimated to be about US\$51.52 per t_{CO2} and US\$33.6 per t_{CO2}, respectively. The assumptions made include 5000 tonnes of flue gas (12 vol%) processed per day reaching 90% CO₂ recovery.

1.3.1.3. Membrane

Membrane separation offers a simple and compact option for CO₂ capture (**Figure 18**). The driving force for membrane separation is pressure and/or concentration gradient. As a result, the membrane process is more suitable for CO₂ capture from concentrated streams at high pressure. When membrane is applied for CO₂ capture from dilute low-pressure flue gas, it requires more energy input and hence is deemed not viable for post-combustion CO₂ removal. An effective membrane for CO₂ capture must exhibit a number of properties, including high CO₂ permeability, high CO₂ selectivity, as well as high thermal, mechanical, and chemical stability.

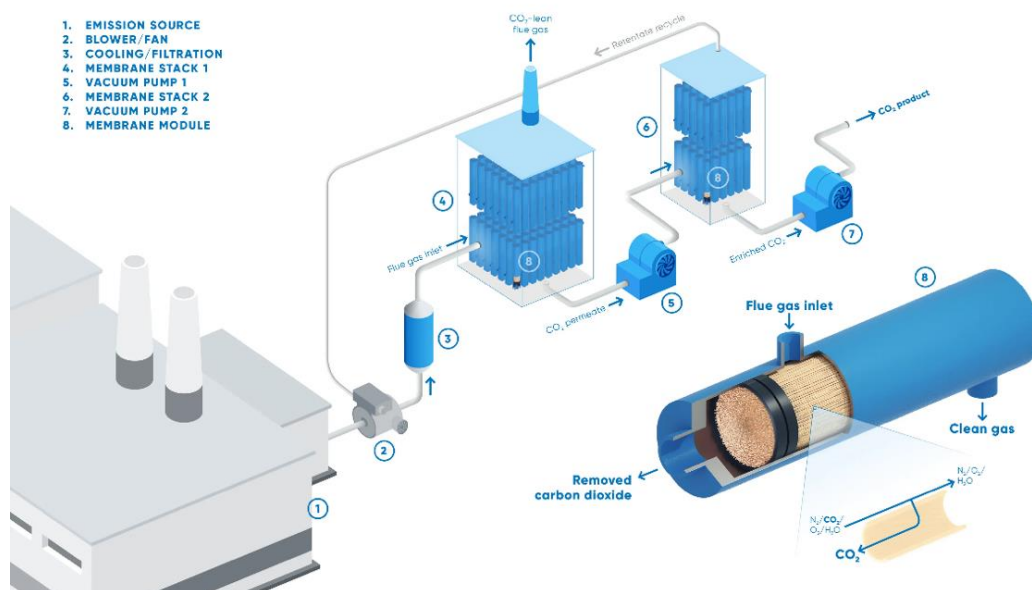


Figure 18. Schematic of CO₂ separation by membrane.⁽¹¹⁵⁾

Several types of membrane have been developed for CO₂ separation. Polymeric and inorganic membranes are among the predominant types being investigated, but each have their own merits and demerits. Polymeric membranes are appealing due to their low fabrication costs, but they typically suffer from lower selectivity compared to inorganic membranes. On the other hand, inorganic membranes are useful for CO₂ separation at high operational temperatures thanks to the robust thermal, chemical, and mechanical stability. However, to make inorganic membrane contactors commercially viable, improvements in reproducibility, reliability, as well as a reduction in manufacturing cost are needed.

Economically, the annualised capital expenditure for a membrane process is around US\$39.2 per t_{CO2}, and the annualised operational cost is US\$39.2 per t_{CO2}.⁽¹¹⁴⁾ Overall, this means the CO₂ capture cost via a membrane process is calculated to be US\$78.39 per t_{CO2} with 5000 tonnes/day flue gas being processed and 50-95% CO₂ recovery.

1.3.2. CO₂ Transport

After the CO₂ is captured, it is transported to a storage site or a facility for utilisation. In some cases, CO₂ is used on-site, reducing or eliminating the need for transport infrastructure. To transport CO₂ economically, the gas must be compressed or liquefied to achieve a reasonable volumetric density. In addition, any water or impurities present in the captured CO₂ must be removed prior to transport to prevent damage that could compromise the integrity of pipelines and other equipment.

Generally, CO₂ may be moved at low cost in small quantities and over short distances using truck and rail transport. To enable this, CO₂ is liquefied in a pressurised vessel prior to transportation. The estimated CO₂ transport cost by truck is US\$0.111/tonne/km.⁽¹¹⁶⁾ CO₂ transport by rail is typically similar to other tanker-shipped commodities, with the exception that staging and loading facilities must be built at the origin station, and unloading and reconditioning facilities must be constructed at the destination station. A pipeline spur is likely also needed at the destination. The cost for CO₂ transport via rail is US\$0.044/tonne/km, with the staging and loading operation adding about US\$2/tonne CO₂.⁽¹¹⁶⁾

For large quantities of CO₂, a pipeline is the most common method of transport involved in CCUS. However, transport via a pipeline is complex and requires investment to build suitable infrastructure. Prior to pipeline transport, CO₂ is compressed until it reaches a supercritical phase. The cost of transportation by pipeline is more variable compared to other modes, as it depends on local construction costs and securing rights of way. The expenses associated with pipeline transport are influenced significantly by economies of scale, making it highly preferred choice for handling large volumes of CO₂. At a flowrate of about 1 million tonnes per annum and above, a pipeline clearly becomes the preferred option over rail.⁽¹¹⁶⁾ Conversely, for quantities below 0.3 million tonnes/year, rail stands out as the more cost-effective alternative.⁽¹¹⁶⁾ For amounts between these values, the optimal transport method will depend on the specifics of the project.

1.3.3. CO₂ Storage and Utilisation

Captured CO₂ can be injected into geological formations for permanent storage. Generally, sedimentary basins—including depleted oil and gas fields, deep coal seams, and deep saline aquifers—are suitable CO₂ underground storage sites. The injected CO₂ is stored as a dense-phase supercritical fluid and immobilised via a number of mechanisms such as structural and stratigraphic, residual CO₂ solubility, mineral, and hydrodynamic trapping. After storing CO₂ underground, monitoring, measurement, and verification are vital to identify and quantify the position of the CO₂ plume and check for any signs of leakage from the storage site. This monitoring should be done at various depths in the geologic column, including at the surface, the biosphere beneath the surface, and the reservoir. This level of monitoring gives assurance to regulators and the public that the CO₂ has been safely stored, and this could be a metric for issuing certification in relation with climate change mitigation protocols.

In addition to underground permanent storage, the opportunities to use captured CO₂ for various purposes have received plenty of attention for their potential to mitigate climate change and contribute to a circular economy. CO₂ utilisation is often claimed to cut the overall costs or increase the financial gain of reducing emissions or removing CO₂ from ambient air. CO₂ is widely used for various direct applications in the food, beverage, and agricultural industries

that usually requires high purity levels. Indirect use of CO₂ involves the utilisation of CO₂ as a feedstock for the manufacture of useful products such as carbonates, building materials, chemicals, and fuels.

1.4. Opportunities and Challenges

1.4.1. Opportunities for Waste-to-Low-Carbon Hydrogen

WtH-CCS represents an opportunity for avoiding emissions from waste generation. Moreover, WtH-CCS may facilitate access to beneficial credits, such as the 45Q tax credit for carbon sequestration (up to US\$50/ton CO₂ stored)⁽¹¹⁷⁾ and the 45V tax credit for the production of clean hydrogen (up to US\$3/kg H₂)⁽¹¹⁸⁾ through the Inflation Reduction Act (IRA) in the United States. In the European Union (EU), through the EU Emissions Trading System (EU ETS), the CO₂ savings from WtH-CCS can potentially create new revenue streams for industries. While this additional revenue from carbon market is possible under EU ETS, proper regulations are not yet issued. In addition to access to carbon credit mechanism, WtH-CCS has potential income from the management of waste.

WtH-CCS has the potential to generate value-added byproducts beyond H₂. For instance, thermochemical WtH pathways often result in the generation of excess heat and tail gas byproducts that contain some combustible gases like methane. These can be effectively harnessed to provide additional value by supporting heat or power generation which, in turn, enhance the overall efficiency. As a waste management technology, WtH-CCS also offers additional revenues from the waste management fees.

In alternative WtH conversion routes that employ milder conditions, such as fermentation, electroreforming, microbial electrolysis, and photoreforming, the organic substrates may not undergo oxidation into gaseous products. The selective oxidation of these organic substrates presents an opportunity for simultaneous production of H₂ and value-added organic chemicals, thus reducing the overall H₂ production cost. For instance, fermentation allows the production of H₂ along with organic acids like acetic acid, butyric acid, and propionic acid. Another example is the electrochemical reforming of HMF derived from lignocellulosic waste, which can lead to the selective coproduction of H₂ and FDCA, a significant bioplastic precursor. The additional revenues generated from these byproducts in addition to the income from waste tipping fees have the potential to cut H₂ production costs.

Finally, the integration of CCS or CCU into WtH, which requires additional costs, can enable the production of other byproducts. For example, the captured CO₂ serves as a valuable feedstock for manufacturing a diverse range of products, including carbonates, building materials, chemicals, and fuels.

1.4.2. Challenges for Waste-to-Low-Carbon Hydrogen

The deployment of WtH-CCS for low-carbon hydrogen production is likely to encounter a range of technical, economic, political, and social hurdles.

Waste, CO₂, and H₂ logistics

One key challenge of WtH-CCS is addressing the transport and logistics issues that connect four elements: (1) the supply of sustainable waste feedstock, (2) the WtH conversion facility, (3) the CO₂ storage site, and (4) the end users of the H₂. This could entail deploying small-scale decentralised WtH facilities near the waste source and transporting CO₂ to the storage site or deploying a large-scale centralised WtH facility near the CO₂ storage site and transporting the waste feedstock from different locations. Additionally, the transport of the H₂ product can be costly if it involves large volumes and long distances. Therefore, locating WtH in close proximity to end users makes it a viable option.

Technology risks and operational challenges

WtH conversion is considered as a high-risk technology with several operational challenges. Decades of attempts to build waste gasification and pyrolysis on a commercial scale have exposed the underlying complications. Many commercial-scale facilities that have been established in Europe, UK, Canada, and US have had trouble maintaining regular operations and producing sufficient energy to remain in business. The complex large-scale gasification projects and the variability of waste feedstock availability and quality have remained the main technical and operational problems. From these failed projects, there are several lessons learned to realise a viable WtH conversion. Further

technology improvements and developments are necessary to address operational challenges with WtH technology. In addition, proper process design in the feasibility stage, implementation, and management are also essential. It is imperative that careful initial assessment on the waste feedstock variability is conducted prior to project execution. Early deployment of WtH process should also focus on small demonstration projects rather than significant large scale.⁽¹¹⁹⁾ This approach allows flexibility in troubleshooting and reduces operational complexity. To overcome challenges with WtH, further research and development is required. There is a significant need for improved simple process designs and process control systems.

Economic feasibility

In terms of economic feasibility, building the necessary infrastructures, particularly for CO₂ transport and storage, means WtH-CCS currently requires a relatively high capital investment. While economies of scale in infrastructure costs have been observed, these seem unfavourable for small-scale WtH-CCS as they are likely to be geographically scattered and use regionally sourced biomass. While the capital cost of WtH and CCS could decrease with learning, variations in waste feedstock quantity and quality may make operations more challenging, thereby increasing operational costs. Key economic challenges facing WtH-CCS also include the potential increase in waste feedstock cost due to higher demand and there could also be a future scenario in which behavioural changes reduce the amount of waste produced.

Many waste gasification projects have failed because of financial non-viability. Examples include: (i) In 2016, two Tees Valley gasification projects in the UK resulted in losses between US\$900 million and US\$1 billion for US company Air Products, (ii) the Thermoselect gasification facility in Karlsruhe, Germany lost over US\$500 million in 5 years of operations, and (iii) Interserve left the “energy-from-waste” field in the UK after losing £70 million on gasification projects.⁽¹²⁰⁾

In general, costs are higher and more uncertain than the project proponents foresee, and revenues are lower and more uncertain. Many facilities have failed due to economic problems, citing inadequate revenues and costs from preparing feedstock. In addition, when the facility does not operate as intended or shuts down for repair, companies with contracts to treat waste must cover the added costs of sending that waste elsewhere. These failed projects indicate that high capital costs, feedstock quantity and quality consistency, system complexity, and unclear business models are primary causes for less successful waste gasification projects.

Learning from these failures, the deployment of WtH technology in its early stage development should focus on small scale distributed demonstration projects first.⁽¹¹⁹⁾ This approach is important to reduce the initial capital cost burdens, minimise system complexity, allow process troubleshooting, thereby de-risking WtH projects.

Policy and regulatory uncertainties

Policy and regulatory uncertainties expose WtH-CCS to an unattractive environment for funding and investment in commercial applications. Economic and fiscal incentives are crucial for commercialisation, and greater transparency and clarity are required over clear carbon accounting and pricing guidelines. Uncertainties in policy and regulations could impede the implementation of WtH-CCS projects, something exemplified by the withdrawal of support for a WtH project plan in Scotland.⁽¹²¹⁾ The project, developed by Peel NRE, faced challenges related to Scotland’s waste incinerator moratorium, policy requirements for H₂ plants to include carbon capture, and concerns about the claimed GHG benefits. Additionally, clear waste management and carbon crediting mechanisms, which play an important role in the economics of WtH-CCS projects, are required.

Social barriers

Social acceptance and public perception issues persist around the deployment of WtH-CCS. Addressing these will be vital to gain local acceptance. Strong policies are needed to implement regulatory frameworks for WtH-CCS that include social justice safeguards. A social reluctance, driven by fears of practices such as land grabbing and compromised food and water security, could shift investors away from financing the implementation of WtH-CCS. For instance, the Peel NRE’s WtH project in Scotland faced opposition from local residents concerned about the lack of public consultation and the risk of turning the town into a dumping ground for plastic waste.

1.5. Case Studies

Waste-to-low-carbon-hydrogen is gaining traction worldwide. Most projects are currently under feasibility study, with only a few projects have been demonstrated. In addition, the currently operating waste gasification projects have remained in a relatively small scale, especially when compared to the scale of fossil fuel-derived hydrogen. To evaluate the market opportunity and feasibility of WtH-CCS, case studies on several projects in the European Union (EU), United States (US), and Japan have been developed.

1.5.1. European Union

The EU has several active WtH projects across the continent that support its ambitions to deploy H₂. The emphasis on these projects has been placed on a decentralised business model.

REVIVE Project

The Refuse Vehicle Innovation and Validation in Europe (REVIVE) project aims to produce H₂ via water electrolysis using electricity sourced from WtE plants to power fuel cell waste collection vehicles across Europe. This Waste-to-Wheels model is expected to be a solution for zero-emission urban waste transport and the transformation of waste into renewable fuel. REVIVE has deployed 15 fuel cell trucks across 8 sites in Europe, including Breda, Helmond, Groningen, Amsterdam, Antwerp, South Tyrol, and Roosendaal (Figure 19).⁽⁶¹⁾

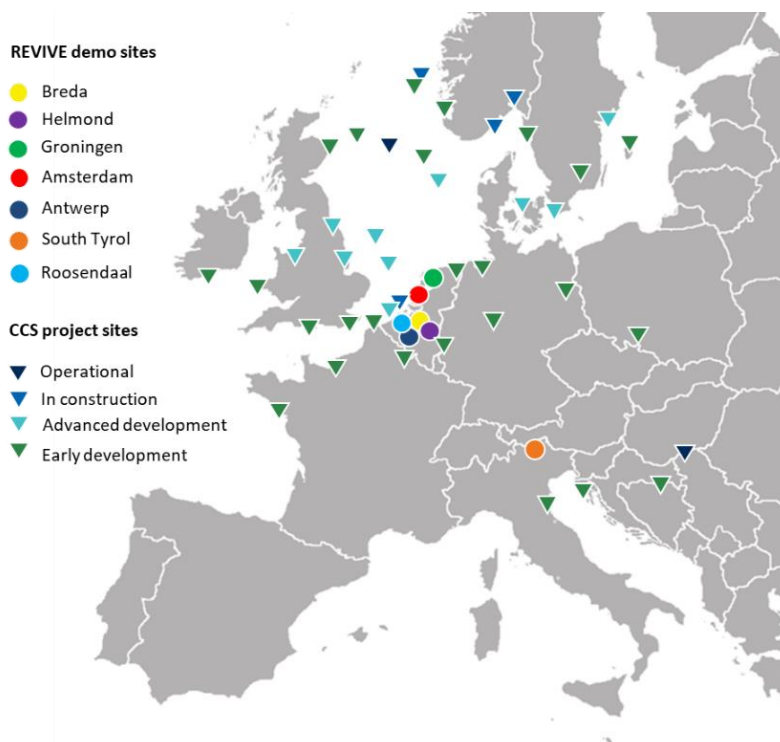


Figure 19. REVIVE demo sites and CCS project locations across Europe. Source: Author.

In Europe, the Waste-to-Wheels business model is considered to have high potential, particularly in Benelux (Belgium-Netherlands-Luxembourg), where there are already several waste incinerators in place (18 in Belgium and 12 in the Netherlands). The electricity can be used for powering decentralised electrolyzers to generate H₂ as fuel for captive fleets, including 5,500 refuse trucks and 2,250 buses in Benelux.⁽⁶⁰⁾ Engie, for example, is planning to instal a 1 MW electrolyser at an incinerator site in the Walloon region, Belgium to supply H₂ for a bus fleet. Additionally, the O₂ generated as a byproduct of water electrolysis can be collected and used for the incinerator, improving its efficiency.

The Waste-to-Wheels projects in Europe offer a pathway to divert non-recyclable waste to H₂, thereby avoiding high GHG emissions from landfilling. Without CCS, it is estimated that the GHG emissions are around 117 kg CO₂-eq/tonne waste,⁽⁸⁷⁾ significantly lower than GHG emissions from landfilling (nearly 400 kg CO₂-eq/tonne waste).⁽¹²²⁾ The next

development for the Waste-to-Wheels projects should focus on the integration of CCS. Integrating CCS with the existing waste incineration has been estimated to enable negative emissions (depending on the biogenic content of the waste) of around -556 kg CO₂-eq/tonne waste.⁽⁸⁷⁾ In this instance, there are opportunities for cross-border transport and underground storage of CO₂ in different regions across Europe with high storage potential. The Federal Government of Belgium, the Walloon region, and the Flemish region, for example, have started formal negotiations with Norway for a bilateral agreement on the cross-border transport and storage of CO₂ on the Norwegian Continental Shelf, under the London Protocol.⁽¹²³⁾ Several ongoing CCS projects in Europe, either operational, in construction, or under development, have been mapped in **Figure 19**.

FUREC Project

Another notable WtH initiative in Europe is the German company RWE's Fuse, Reuse, Recycle (FUREC) project. FUREC aims to produce H₂ from non-recyclable MSW in Limburg, Netherlands (**Figure 20**).⁽³²⁾ RWE is building a pretreatment plant in Zevenellen, Limburg, to convert MSW into solid recovered fuel pellets, via a torrefaction process. This pretreatment is a method that has been implemented to overcome quality variations in the biomass. At the heart of the pretreatment process is the Multi-Hearth Furnace (MHF), where waste pellets will be torrefied in such a way that they can be ground into dust and converted into H₂ and CO₂ later in the process. The plant will process about 700,000 tonnes of MSW per year, of which about 50% will be of biogenic origin. From there, the feedstock pellets will then be converted into H₂ in a second RWE's plant at the Chemelot Industrial Park in Limburg, via entrained flow gasification process.



Figure 20. FUREC project sites and potential CC(U)S applications. Source: Author.

The expected H₂ production capacity at this site is 54,000 tonnes per year, which will be used to supply local H₂ demand in the Chemelot Industrial Park. For instance, the H₂ can be used for OCI N.V.'s ammonia production and other chemical manufacturing processes involving H₂. This has the potential to reduce natural gas consumption by more than 280 million cubic metres per year, which corresponds to half of the annual domestic gas consumption in Limburg. The expectation is that this will save around 400,000 tonnes of CO₂ per year. In addition, the CO₂ released during gasification is planned to either be captured and stored or used as raw material by industry. The CO₂ can be transported via pipelines under the Delta Rhine Corridor route to Rotterdam for offshore CO₂ storage, which is located around 200 km from the Port of Rotterdam. Alternatively, the CO₂ can be marketed as a valuable feedstock for CCU, producing materials, chemicals, and fuels. For example, the growing number of power-to-liquid initiatives in Europe—mapped in **Figure 20**—will need substantial amounts of low-cost sustainable CO₂ feedstock.

1.5.2. United States

The US is actively developing WtH systems throughout the country, as evidenced by the recent Government's funding support (up to US\$19 million) to advance H₂ production technologies from various waste materials, such as biomass, plastics, common household garbage, and other wastes. In particular, there are several planned WtH projects in California as part of efforts to develop a California Hydrogen Hub.

Chevron's Waste-to-Hydrogen project in Richmond, Northern California is a notable example of a WtH project in the US.⁽³⁰⁾ The US oil giant has pledged to invest US\$25 million in this project, in collaboration with Raven SR and Hyzon Motors to build an end-to-end waste derived H₂ system. The project aims to divert up to 99 wet tonnes of green and food waste per day from Republic Services West Contra Costa Sanitary Landfill into H₂ via non-combustion steam/CO₂ reforming process. In the first phase, the target annual H₂ production capacity is 1,825 tonnes, with the potential to scale up to 4,500 tonnes. The H₂ generated will be marketed in the Bay Area and Northern California H₂ refuelling stations, and collaborations with Hyzon Motors are underway to deploy refuelling stations close to customer demand and to transport H₂ from production to refuelling stations using Hyzon hydrogen fuel cell trucks.

Raven SR's innovative steam/CO₂ reforming process in this project allows waste to be converted efficiently into synthetic gas, and subsequent separation of H₂ from the carbon. The remaining gas is then further reformed by steam into H₂, and the excess carbon is sequestered as a valuable bio-carbon byproduct.⁽¹²⁴⁾ Consequently, the project can have significantly lower GHG emissions (-15 to 4 g_{CO2}/MJ_e)⁽¹²⁵⁾ without the need for retrofitting the process with additional CO₂ capture unit as the carbon is sequestered during the reaction as bio-carbon. The project also has the potential to deliver additional revenues from bio-carbon production. More importantly, this technology does not require freshwater input, which is particularly critical given the high drought risks in California. Another key merit of the technology is that it requires less electricity to power the units than other competing technologies. By upgrading the landfill gas electric generators at the landfill, the project is also expected to produce at least 60% of its own electricity demand—further reducing the GHG emissions and the need for grid power.

As a demonstration of WtH, this project lays the important groundwork needed to enable a commercially viable decentralised hydrogen hub that provides affordable, low-to-negative carbon intensity H₂ for fuel cell vehicles. This technology has high potential for deployment in decentralised hubs in other cities or regions throughout California, for example, to support the California Hydrogen Highway Network. The possibility of developing hubs that are economically viable even at low volume is an important component in building highly utilised infrastructure that can scale up to accommodate new customers as the market evolves. In this instance, the deployment of hydrogen hubs in California can be implemented in phases as described in **Figure 21**.

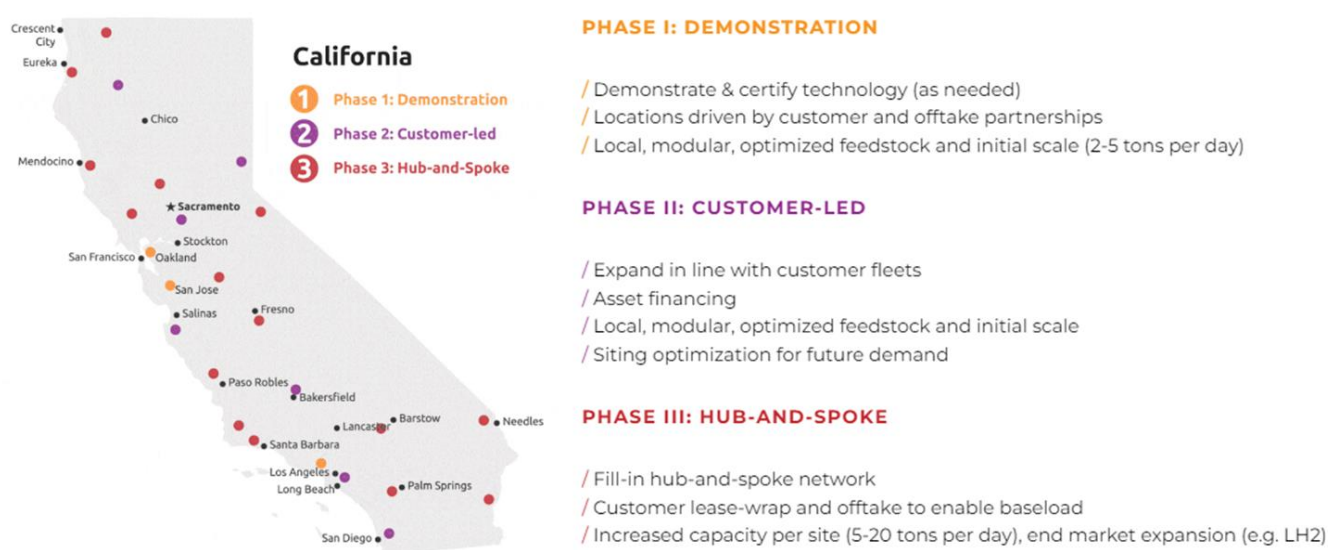


Figure 21. Decentralised hydrogen hubs in California for refuelling network.⁽¹²⁵⁾

1.5.3. Japan

Japan provides an example of a local WtH facility that collects waste materials from the surrounding community and supplies H₂ to fulfill energy demand in the community. Japan Blue Energy Co. (JBEC), for instance, has focused on developing a “local production and consumption” business model that allows the treatment of local waste, such as plastic and sewage sludge, which can be implemented with H₂ supply services for mobility.⁽¹²⁶⁾

In early 2021, JBEC and Ways2H collaborated with the Tokyo Metropolitan Government, TODA Corporation, TOKYU Construction, CHIYODA Kenko, and Tokyo University of Science to complete a WtH plant in the Sunamachi Wastewater Reclamation Centre near Tokyo Bay.⁽²⁷⁾ This demonstration facility (TRL 8) processes 1 tonne of dried sewage sludge per day to generate 40 to 50 kg H₂ per day. This is enough to fuel 10 passenger fuel cell vehicles or 25 fuel cell e-bikes. In addition to wastewater sludge, plastic, paper, municipal solid waste, and other refuse will be processed. This demonstrates the flexibility of the plant’s operation in regard to feedstock input. The waste is heated to a high temperature using alumina balls as a heating carrier and converted into a gas, from which pure H₂ is extracted. The facility is designed to be carbon-neutral and generate its own fuel in a closed-loop process.

This WtH project can provide environmental and economical competitive advantages over the current waste management system in the Sunamachi Wastewater Reclamation Centre. Currently, this facility treats the sewage generated from various zones such as Sumida Ward, most of Koto Ward, a part of Minato Ward. The facility discharges the treated water to Tokyo Bay, and a part of the treated water is further processed, through sand filtration, for use within the facility itself, cooling machines, and flushing toilets. Meanwhile, the sludge generated is carbonised and incinerated at the Tobu Sludge Plant in the Centre. Retrofitting WtH into the facility as an alternative to the current sludge treatment can reduce the GHG emissions and supply H₂ fuel for local mobility uses in Tokyo, which is close to the reclamation centre. Furthermore, there is high potential to build an H₂ value chain for industrial uses around the Sunamachi region, given the area is surrounded by numerous industrial activities (**Figure 22**).

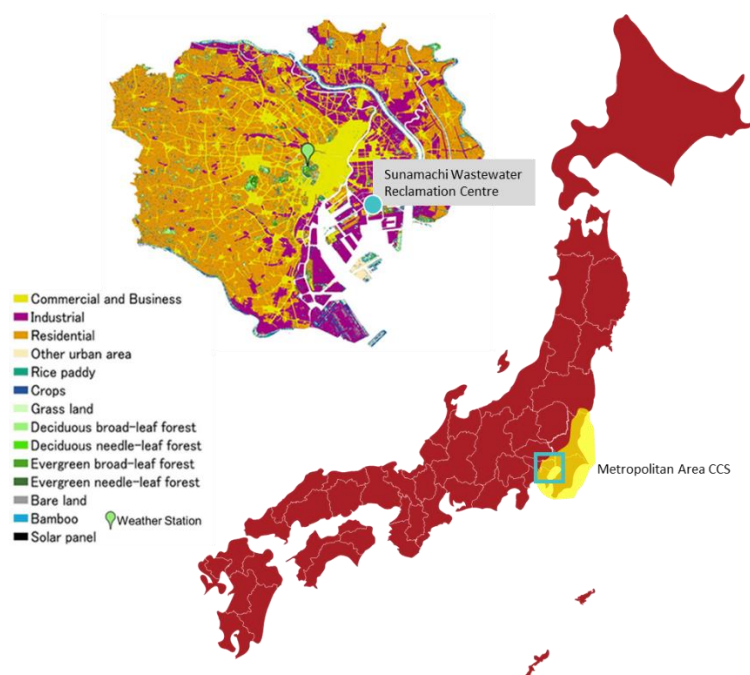


Figure 22. Value chain mapping for WtH-CCS in Sunamachi Wastewater Reclamation Centre.⁽¹²⁷⁾

There is also potential for Japan to integrate CCS into the WtH plans to achieve low-carbon H₂ production. In fact, Sunamachi Wastewater Reclamation Centre benefits from being in close proximity to one of Japan’s major CCS projects, the Metropolitan Area CCS (**Figure 22**), which is a collaboration between INPEX Corporation, Nippon Steel Corporation, and Kanto Natural Gas Development.⁽¹²⁸⁾ The CO₂ storage volume is estimated to be around 1 million tonnes per annum, and the aim is to permanently store CO₂ emissions from major coastal industrial complexes in metropolitan areas.

Chapter 2. Techno-Economic Analysis of Waste-to-Hydrogen Technology

2.1. Introduction

The multi-criteria analysis in [Chapter 1](#) identified thermochemical conversion, such as gasification and pyrolysis with in-line reforming, as WtH conversion options that are likely to be technically feasible. The dark fermentation process has also emerged as a promising pathway operating at milder conditions. In addition, water electrolysis—powered by electricity generated from waste incineration—has shown some appeal as an indirect waste-to-hydrogen pathway, leveraging existing waste-to-electricity facilities. Although the various pathways have had individual techno-economic assessments conducted and reported in literature, a comparative assessment and the economics of integrating CCS with WtH conversion have not yet been widely documented.

This study seeks to address this gap by investigating the economics of producing low-carbon H₂ from waste feedstock by integrating CCS into different potential WtH technologies within current energy markets. The cost drivers of each process have been determined to understand the potential mechanisms that can reduce cost. The cost trajectories of each process have also been developed to provide insight into the opportunity for low-cost H₂ production from waste in the future. In addition, the competitive benefits of WtH processes have been evaluated against existing conventional waste management processes.

Finally, Netherlands was selected as the reference plant location, in line with the IEAGHG techno-economic assessment criteria.⁽¹²⁹⁾ In addition, given the Netherlands' ongoing projects on hydrogen value chain such as REVIVE and FUREC projects, the country provides an interesting case study into the development of a sustainable WtH-CCS process. The Dutch Government has also set a target to deploy H₂ for use across different sectors such as transport, agriculture and urban sectors within Netherlands and European Union.⁽¹³⁰⁾ As such, this study specifically investigates the indicative costs for developing a waste-to-hydrogen facility using the selected promising technology options.

2.2. Methodology

The approach that was used in the development of the techno-economic analysis in this study is shown in [Figure 23](#). Process flow diagrams and models were developed based on information from literature and vendors for mature and similar technologies. The processes developed in this study are generic designs, and more detailed site-specific analysis is required in real cases. Process simulation was performed for different WtH processes (i.e., gasification, pyrolysis with in-line reforming, dark fermentation, and incineration-electrolysis) to define the mass flows, temperature, pressure, and energy demand using open-source DWSIM chemical process simulator.

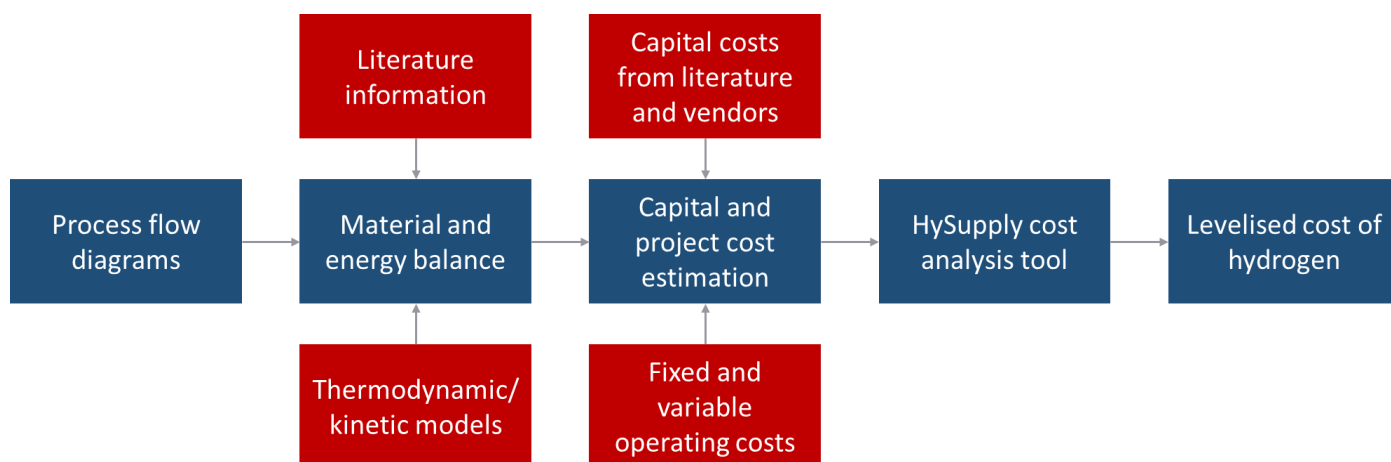


Figure 23. Techno-economic analysis approach adopted in this study.

Once the process was simulated, the entire system was costed using the open-source HySupply² cost analysis tool. The time value of money was then applied to generate a levelised cost of hydrogen (LCOH) for each process, using [Equation 13](#), where t is the year, r is the discount rate, and P_{H_2} is the total annual production of H_2 . It is important to note that the LCOH calculated here represent cradle-to-gate³ hydrogen production costs.

$$LCOH = \frac{\sum_{t=0}^T \frac{Cost_t}{(1+r)^t}}{\sum_{t=0}^T \frac{P_{H_2}}{(1+r)^t}} \quad (13)$$

The general assumptions for the base case shown in [Table 14](#) below were used to define the technical and economic parameters of the system.⁽¹³¹⁾

Table 14. Overall assumptions used in the base case model.⁽¹³¹⁾

Parameter	Value
Plant location	Chemelot Industrial Park, Netherlands
Plant capacity	2,000 tpd MSW (or OFMSW for dark fermentation)
H ₂ outlet condition	20 bar, 30 °C (excluding compression, storage and transport)
CO ₂ capture efficiency	95%
CO ₂ condition	110 bar, 30 °C
Capacity factor	60% for year 1 and 85% for the subsequent years
Currency basis	United States Dollar (US\$)
Discount rate	8%
Construction time	3 years
Plant lifetime	25 years

Chemelot Industrial Park, Netherlands was selected as the location due to its proximity to an existing H_2 market. The plant was designed to convert 2,000 tonnes of municipal solid waste (MSW) per day (tpd) into H_2 via four different WtH-CCS pathways. These were CCS-abated gasification, pyrolysis, dark fermentation, and incineration-electrolysis. CCS-abated gasification, pyrolysis, and incineration-electrolysis were designed to process unsorted MSW, while dark fermentation was designed to handle the organic fraction of MSW (OFMSW). The plant capacity of 2,000 tpd MSW is adopted based on the planned capacity of FUREC gasification project that aims to process ~700,000 tonnes of MSW per annum (equivalent to ~2,000 tpd) (TRL 9 plant).⁽⁷¹⁾ The same capacity was employed for other pathways assessed in this report (pyrolysis, dark fermentation, and incineration-electrolysis) to ensure coherent assumptions, allowing for a comparative techno-economic analysis between different pathways. [Table 15](#) summarises the typical properties of MSW that is used for gasification, pyrolysis, and incineration-electrolysis process simulation, while [Table 16](#) summarises the properties of the OFMSW for dark fermentation process simulation. The MSW is assumed to consist of 60% biogenic material and 40% fossil fuel-derived material. However, it is important to note that the biogenic fraction of MSW may vary due to differences and/or changes in waste management practices and waste composition.

For all the pathways described in this report, once generated, the H_2 outlet condition is 20 bar, 30 °C. The H_2 compression, storage and transport are not included as the study focuses on the cradle-to-gate H_2 production cost. Where carbon capture is modelled in this study, a high CO₂ capture efficiency of 95% is employed.⁽¹³¹⁾ The CO₂ is conditioned at a pressure of 110 bar and a temperature of 30 °C, suitable for pipeline transport to storage site—e.g., in offshore gas fields in the North Sea, which are the closest existing CO₂ storage projects identified in [Chapter 1](#). Note

² HySupply is an open-source cost analysis tool developed to model the costs involved in the production of green hydrogen. The cost model is then used to estimate the levelised cost of hydrogen through a discounted net present value analysis.

³ The cradle-to-gate boundary covers the process from raw material extraction to hydrogen production, up to the point where the hydrogen exits the factory gate, excluding the costs related to hydrogen compression, storage, and transport.

that this study does not account for the cost of CO₂ purification to meet the strict specifications set by transport and storage projects. In the first year of operation, the plant capacity factor is set to 60% to allow for start-up and debugging. Subsequently, the plant operates at base load, at a capacity factor of 85%. Cost analysis is carried out in US Dollars (US\$) throughout this study because most of the process equipment capital costs have been obtained from literature or commercial vendors in that currency. The discount rate, construction time, and plant lifetime are assumed to be 8%, 3 years, and 25 years, respectively.⁽¹³¹⁾ Further technical and financial assumptions are listed in [Appendix 2](#).

Table 15. Typical properties of unsorted MSW feedstock.^(129, 132, 133)

Parameter	Unit	Value
Proximate analysis		
Moisture (wet basis)	wt%	44
Fixed carbon (dry basis)	wt%	6.13
Volatile matter (dry basis)	wt%	63.05
Ash (dry basis)	wt%	30.82
Ultimate analysis		
C	wt%	37.36
H	wt%	5.21
O	wt%	25.27
N	wt%	0.95
S	wt%	0.18
Cl	wt%	0.21
Ash	wt%	30.82
Lower heating value (LHV)	MJ/kg	10.6

Table 16. Typical properties of OFMSW.

Parameter	Unit	Value
Moisture	wt%	60
Cellulose (dry basis)	wt%	50
Hemicellulose (dry basis)	wt%	13
Lignin (dry basis)	wt%	15
Others (dry basis)	wt%	22
Lower heating value (LHV)	MJ/kg	4.5

2.3. Techno-Economic Analysis

2.3.1. CCS-abated Gasification

2.3.1.1. Process Design and Modelling

A block flow diagram of MSW gasification with CCS and the summary of mass and energy flows are illustrated in [Figure 24](#). The process flow diagram and detailed mass and energy flows for the process design are included in [Appendix 2](#). The feedstock used for gasification is unsorted MSW. In general, the MSW gasification process involves MSW

2.3.1.2. Cost Analysis

The CAPEX and annual OPEX for a CCS-abated gasification process with a capacity of 2,000 tpd MSW and generating 89 tpd H₂, are summarised in **Figure 25a-b**. The CAPEX has been estimated in line with similar equipment from literature reports (**Appendix 2**). The OPEX data used is shown in **Appendix 2**. Overall, the total CAPEX is estimated to be around US\$770.3M, nearly similar to the reported CAPEX for FUREC project (~US\$750M) at the same plant capacity.⁽⁷¹⁾ At over 40%, the gasification section is the major contributor to the plant's CAPEX primarily due to the high costs for the gasifier and tar reformer.⁽¹³⁷⁾ This study considers a fluidised bed gasifier, as its design enables better mixing, efficient heat transfer, and the flexibility to process a wide range of feedstocks. Note that using different types of gasifiers may impact performance, which in turn affects cost and environmental outcomes. The annual OPEX is US\$67.7M, driven mainly by fixed O&M costs (40%) and the energy costs for heating and electricity (32%). In the base case scenario, the waste feedstock cost is assumed to be zero.⁴

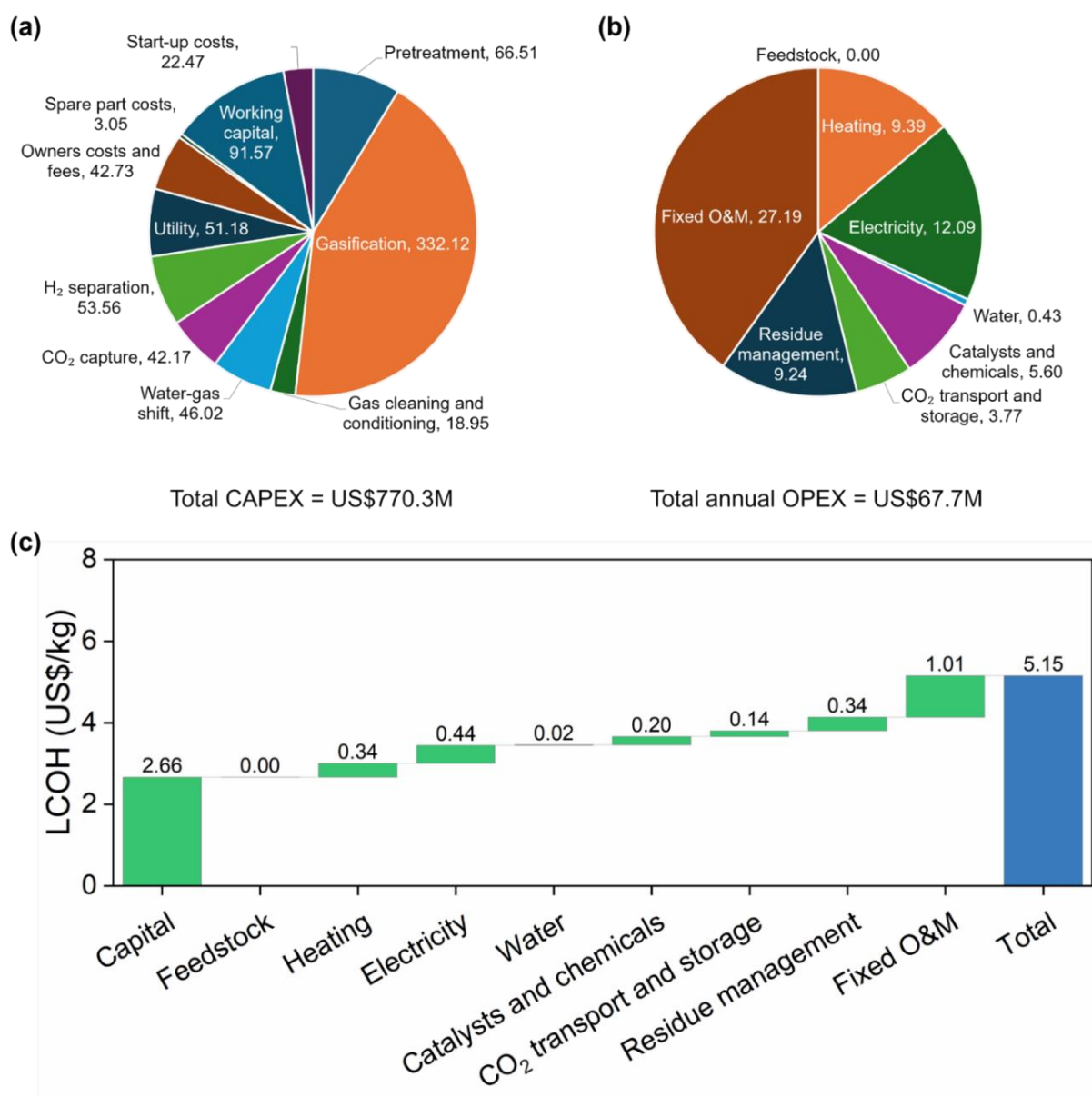


Figure 25. (a) Indicative CAPEX and (b) OPEX breakdown for CCS-abated MSW gasification process with a MSW processing capacity of 2,000 tpd generating 89 tpd hydrogen. All values are in million US\$. (c) Indicative current LCOH breakdown for CCS-abated MSW gasification process under base case scenario with a MSW processing capacity of 2,000 tpd generating 89 tpd hydrogen.

⁴ In some analysis, the cost of obtaining waste feedstock might be negligible, especially if the alternative is to pay for its disposal. Therefore, for the purpose of simplifying economic models, it might be assumed to have no cost under the base case scenario.

A discounted cash flow analysis based on the CAPEX and OPEX estimations was performed to obtain the levelised cost of H_2 (LCOH). The LCOH for a gasification process, with a capacity of 2,000 tpd biomass and generating 89 tpd H_2 , is estimated to be US\$5.15/kg, which is more expensive than the current market price range of unabated H_2 from coal gasification and steam methane reforming (US\$0.91-2.21/kg).⁽¹³⁸⁾ The contributors to this LCOH are shown in **Figure 25c**, and the major components are the capital investment, which contributes 52% of the LCOH, followed by fixed O&M (20%) and energy costs for heating and electricity (15%).

The LCOH of CCS-abated MSW gasification process is highly influenced by the plant scale. The base case capacity of 2,000 tpd MSW is considered a large facility. Smaller CCS-abated MSW gasification plants exhibit higher LCOH, as illustrated in **Figure 26a**. For example, a small 100 tpd MSW gasification plant with CCS is estimated to have a LCOH of US\$13.3/kg, while a medium 500 tpd MSW gasification plant with CCS has a significantly reduced LCOH of US\$7.70/kg. Hence, economies of scale play a prominent role in determining the economic feasibility of the CCS-abated MSW gasification process. However, designing the suitable plant capacity for a high-risk gasification project requires careful assessment of the availability of waste feedstock to ensure continuous operation. As shown in **Figure 26b**, the fluctuation in the supply of waste feedstock, represented by the capacity factor, also substantially impacts the LCOH. For instance, a decrease in the capacity factor to 60% leads to an increase in LCOH of nearly 30%.

Apart from scale and capacity factor, several technical and economic parameters were also varied to evaluate their impact on the LCOH, as shown in **Figure 26b**. The LHV efficiency of MSW to hydrogen conversion has a prominent effect on the LCOH and may be affected by the gasifier efficiency, catalytic performance, feedstock quality, and operating conditions such as temperature, pressure, and steam/ O_2 ratio. Improving the LHV efficiency from 49.4% (base case scenario) to 60% would significantly reduce the LCOH by 16%. In this case, further development on the gasifier is needed. For instance, modifying single-stage gasifier into a multistage gasifier has been demonstrated to improve the efficiency of waste gasification.⁽¹³⁹⁾ The CAPEX cost for process equipment, especially the gasifier, also plays a role in driving the LCOH, as gasification process is considered capital intensive. Decreasing the plant CAPEX by 15%, for example, would lead to a 10% LCOH reduction. In particular, there is a significant opportunity for cost reduction in the gasifier equipment through efficiency improvement.

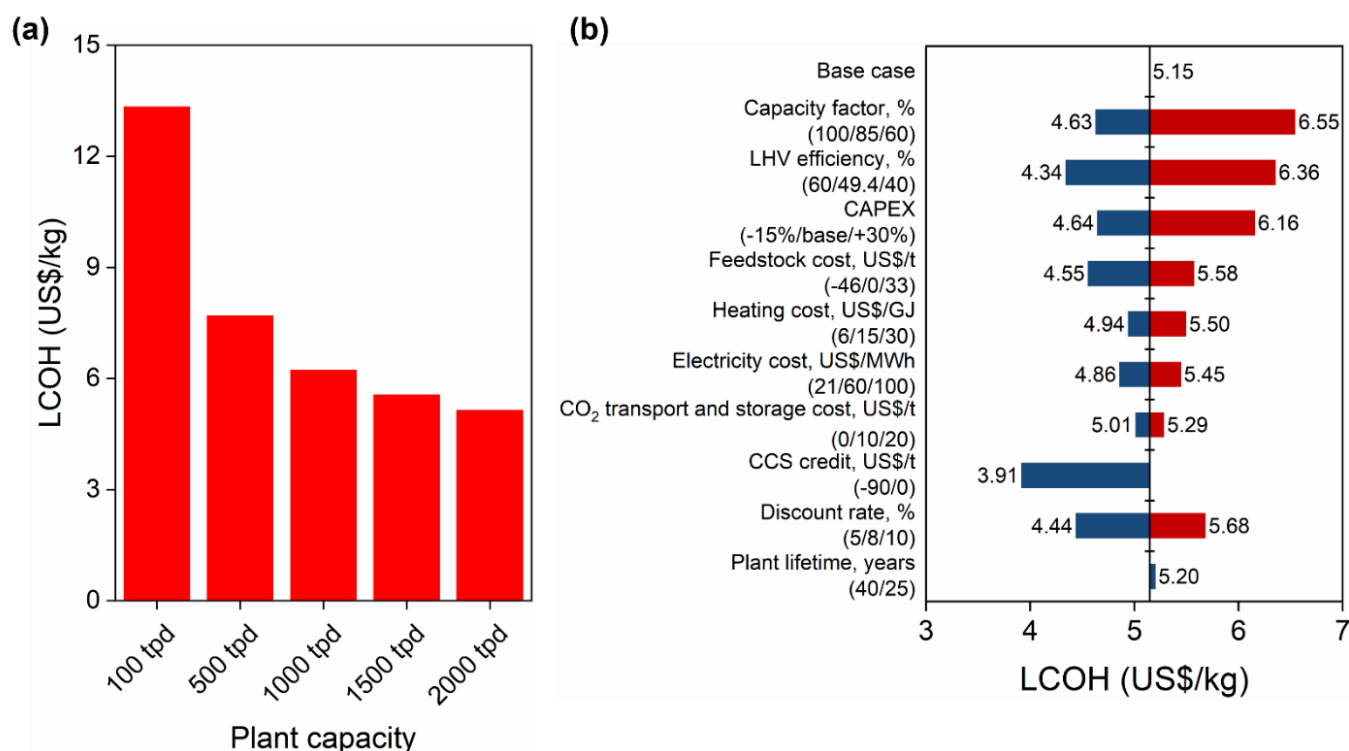


Figure 26. (a) Economies of scale for CCS-abated MSW gasification process. (b) Cost sensitivity analysis for CCS-abated MSW gasification process. Negative costs indicate revenue streams.

The waste feedstock cost has a considerable impact on the LCOH. The base case assumes zero cost MSW. However, if waste tipping fee is imposed, it could become an additional revenue stream to offset the LCOH. The typical waste

disposal cost in the Netherlands is US\$46/t, which comprises US\$13/t in landfill tax and a US\$33/t gate fee.⁽¹⁴⁰⁾ In this case, the LCOH may decrease substantially to US\$4.55/kg. Nevertheless, over time, demand for MSW in fuel production and other industrial sectors may rise, which could give it more value and increase costs, possibly in line with competing feedstocks. Moreover, some countries impose low waste tipping fees. An increase in MSW cost to US\$33/t, which is the typical cost of MSW collection and transport, could significantly increase the resulting LCOH to US\$5.58/kg. The integration of CCS into MSW gasification would allow access to carbon credits, either through tax credits or a cap-and-trade mechanism, lowering the LCOH. For example, using the average carbon price under the European Union Emissions Trading System (EU ETS) in 2023 (US\$90/t),⁽¹³⁸⁾ the LCOH reduces by 24%.

The sensitivity analysis identifies the driving factors of LCOH for CCS-abated MSW gasification process, such as LHV efficiency, equipment CAPEX, CCS credit, and feedstock cost. Based on the sensitivity analysis results, this study subsequently conducted improvement analysis to exhibit a potential roadmap for the future development of waste gasification technology (Figure 27). The LCOH for CCS-abated gasification can be substantially reduced by improving the MSW-to-H₂ conversion efficiency to 60%. The H₂ yield can be increased by enhancing the gasifier technology and improving the catalytic performance for tar reforming and water-gas shift reactions. In addition, a 15% reduction in the overall plant CAPEX plays a significant role. A CAPEX reduction can be attained through increasing the process equipment efficiency and process optimisation. From a policy perspective, low-interest loans from the government may help in reducing the high upfront CAPEX burden. Moreover, imposing a CCS credit of US\$90/t CO₂ (average carbon price under EU ETS in 2023)⁽¹³⁸⁾ combined with a waste tipping fee at the current average waste disposal cost in the Netherlands (US\$46/t waste)⁽¹⁴⁰⁾ has prominent effects in reducing the LCOH for CCS-abated gasification. These cost reduction opportunities shed light on future directions for more cost-effective waste gasification into low-carbon hydrogen.

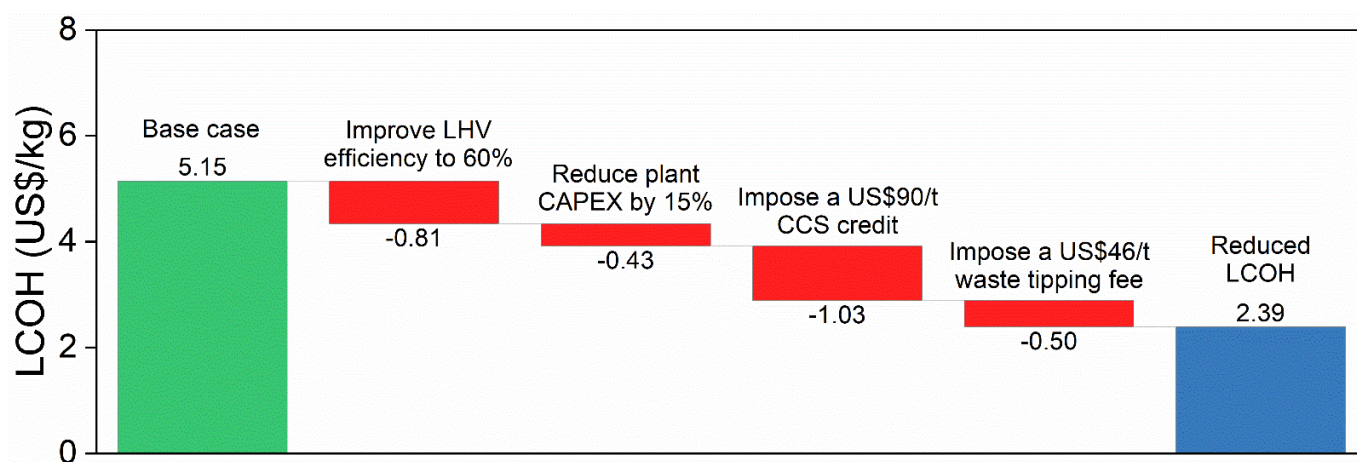


Figure 27. Economic feasibility improvement analysis of CCS-abated MSW gasification process with a MSW processing capacity of 2,000 tpd.

2.3.2. CCS-abated Pyrolysis

2.3.2.1. Process Design and Modelling

The techno-economic performance of CCS-abated pyrolysis and in-line steam reforming process is evaluated. The current TRL of pyrolysis for WtH conversion is relatively lower compared to gasification. A block flow diagram of MSW pyrolysis and the summary of mass and energy flows are illustrated in Figure 28. The process flow diagram and detailed mass and energy flows for the process design are included in Appendix 2. Similar to gasification, the feedstock used for pyrolysis is unsorted MSW. Initially, the MSW feedstock is pretreated via drying to remove excessive moisture and mechanical shredding to reduce the particle size. Then, the dry MSW undergoes a pyrolysis process in the absence of O₂, using steam as the fluidising agent. The products of pyrolysis, which mainly comprise pyrolysis oil along with H₂, CO, CO₂, and CH₄ are subsequently fed into a steam reforming to convert the oil into H₂. This increases the overall H₂ yield. The syngas that exits the steam reforming reactor is treated to remove impurities, compressed, and heated to the desired temperature and pressure. It then undergoes a water-gas shift reaction to reduce CO and increase H₂ production. Finally, the captured CO₂ is compressed, transported, and stored in the depleted gas fields in the North

Sea. The H₂ product is purified using pressure swing adsorption (PSA). More detailed information on the process description can be found in [Appendix 2](#). It is important to note that the developed process flow diagram in this study is an generic process design, and more detailed site-specific analysis is required.

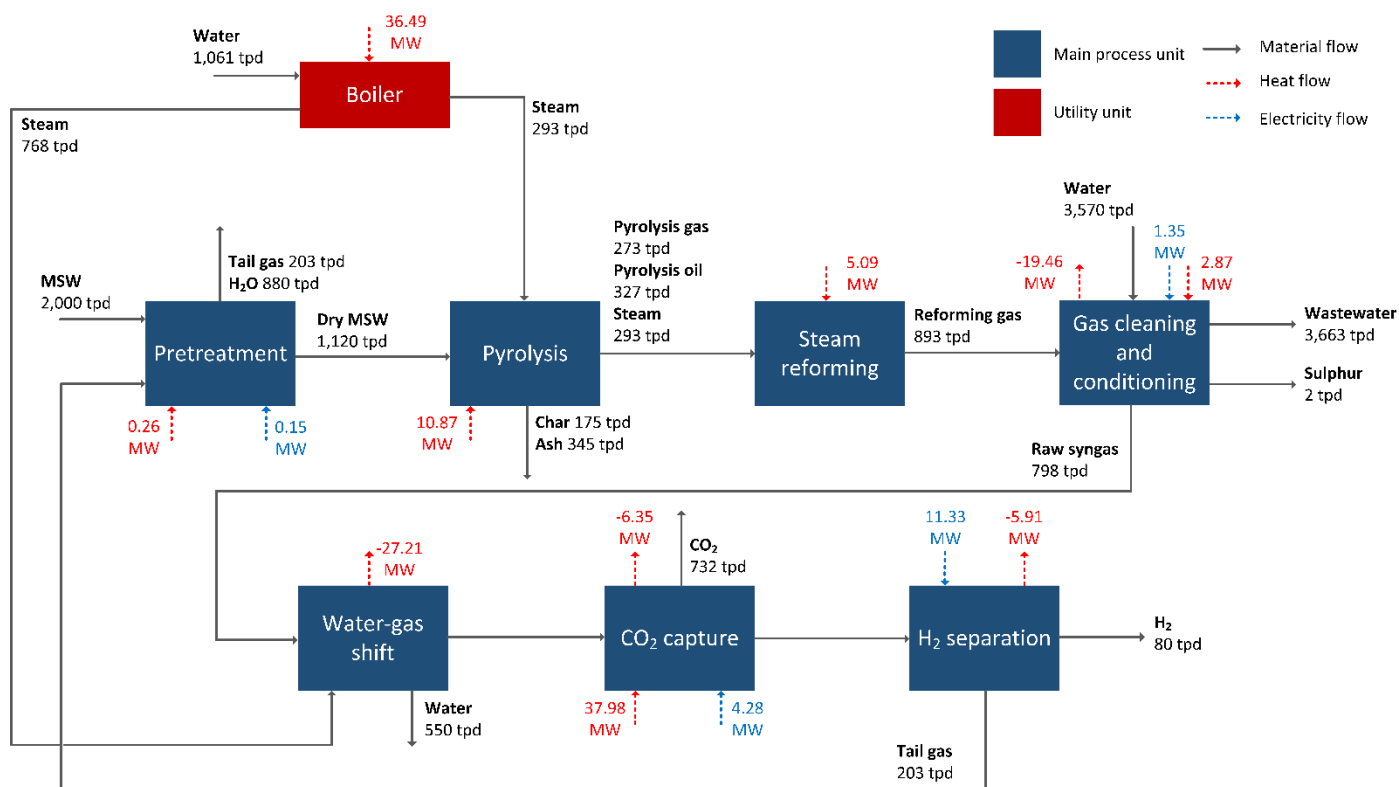


Figure 28. Block flow diagram with material and heat/electricity flows for CCS-abated MSW pyrolysis process.

Overall, the mass balance performed for the CCS-abated pyrolysis base case suggests 2,000 tpd of MSW would produce 80 tpd of hydrogen. Therefore, the obtained H₂ yield for this case is approximately 71.77 kg H₂/tonne dry MSW. Considering the typical average LHV of MSW (10.6 MJ/kg) and LHV of H₂ (120 MJ/kg), the LHV efficiency of MSW to hydrogen via pyrolysis is estimated to be 44.7%. In terms of CO₂ emissions, the total CO₂ generated from MSW pyrolysis is 771 tpd (688 kg CO₂/tonne dry MSW). Assuming 60% of the MSW is of biogenic origin, the biogenic CO₂ emissions from MSW pyrolysis are approximately 463 tpd (413 kg CO₂/tonne dry MSW). With a CO₂ capture rate of 95%, the total captured CO₂ capacity is 732 tpd. The net heating and electricity requirements of the system is estimated to be around 35.84 MW and 16.96 MW, respectively. In the base case scenario, the heating requirements of the MSW pyrolysis plant are supplied from renewable biomass (US\$15/GJ),⁽¹³⁴⁾ while the electricity is sourced from the electricity grid (US\$60/MWh).⁽¹³⁵⁾

2.3.2.2. Cost Analysis

The CAPEX and annual OPEX for the CCS-abated pyrolysis process, with a capacity of 2,000 tpd MSW generating 80 tpd H₂, are shown in [Figure 29a-b](#). The CAPEX was estimated by comparing it with similar equipment from literature reports ([Appendix 2](#)). The OPEX data used is shown in [Appendix 2](#). Overall, the total CAPEX is estimated to be US\$771.2M. The high cost of a pyrolysis reactor and steam reformer means they are the major contributors to plant CAPEX at 24% and 29%, respectively. The annual OPEX is US\$65.4M, driven mainly by the fixed O&M costs (42%) followed by energy costs for heating and electricity (34%). Once again, the waste feedstock cost for pyrolysis is assumed to be zero in the base case scenario.

A discounted cash flow analysis based on the CAPEX and OPEX estimations was performed to obtain the levelised cost of H₂ (LCOH). The LCOH for CCS-abated pyrolysis process, with a capacity of 2,000 tpd biomass generating 80 tpd H₂, is estimated to be US\$6.00/kg, which remains higher than the market price range of unabated H₂ from coal gasification and steam methane reforming (US\$0.91-2.21/kg).⁽¹³⁸⁾ The contributions to the LCOH for CCS-abated pyrolysis route

are shown in **Figure 29c**. The main cost component is the capital investment, which contributes 53% followed by the fixed O&M costs (19%) and energy costs (15%).

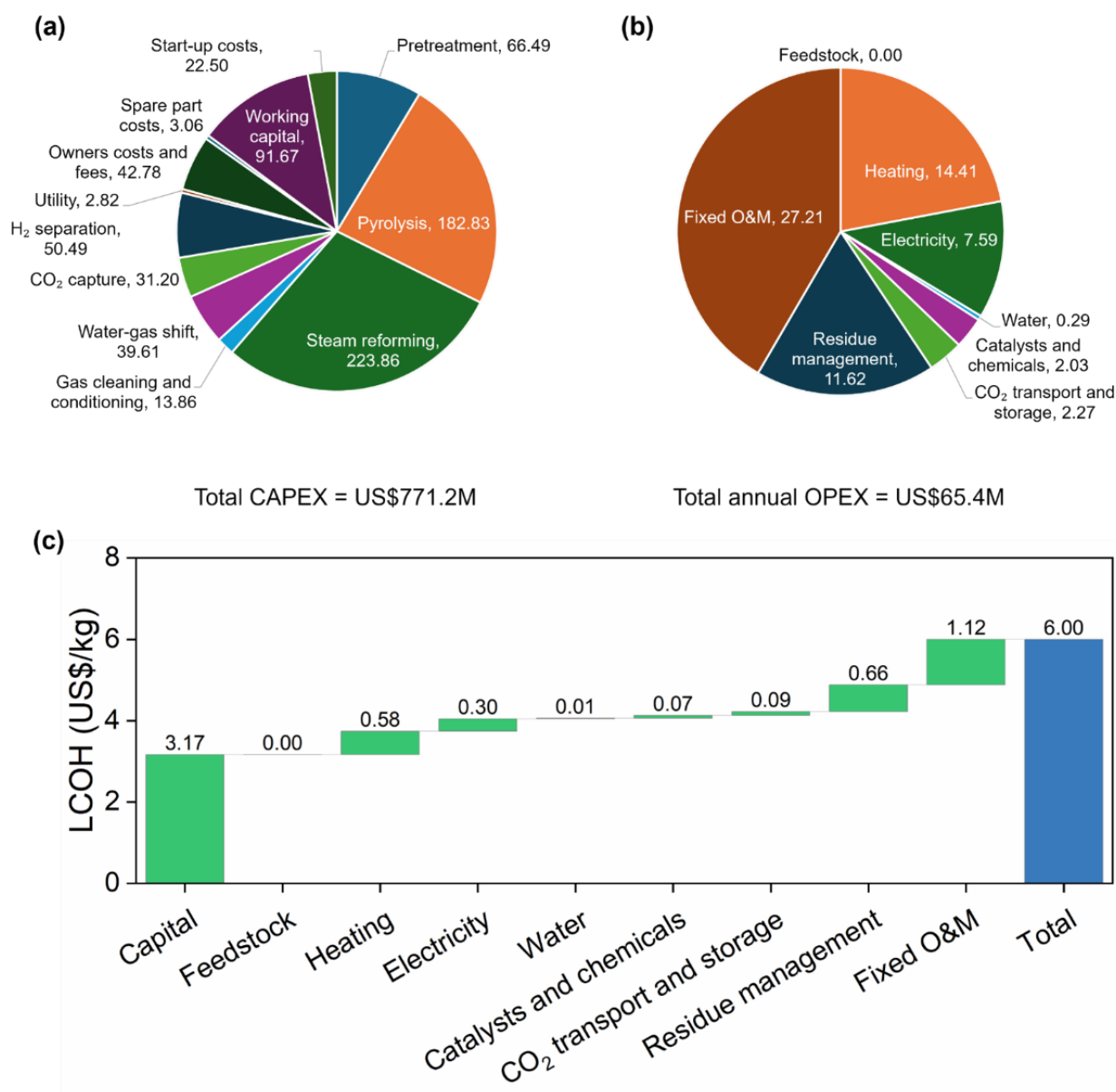


Figure 29. (a) Indicative CAPEX and (b) OPEX breakdown for CCS-abated MSW pyrolysis process with a MSW processing capacity of 2,000 tpd generating 80 tpd hydrogen. All values are in million US\$. (c) Indicative current LCOH breakdown for CCS-abated MSW pyrolysis process under base case scenario with a MSW processing capacity of 2,000 tpd generating 80 tpd hydrogen.

The LCOH of CCS-abated MSW pyrolysis process is highly dependent on the plant scale. The base case capacity of 2,000 tpd MSW is considered a large pyrolysis facility. Smaller CCS-abated MSW pyrolysis plants have higher LCOH as shown in **Figure 30a**. For instance, a small 100 tpd MSW pyrolysis plant with CCS has a LCOH of US\$16.67/kg, while a medium 500 tpd MSW pyrolysis with CCS is estimated to generate hydrogen at a cost of US\$9.28/kg. Therefore, the economic feasibility of the CCS-abated MSW pyrolysis process is strongly influenced by the economies of scale. Nevertheless, setting the designed plant capacity for a pyrolysis project must consider the availability of waste feedstock to ensure continuous operation. The sensitivity analysis in **Figure 30b** shows that the MSW supply fluctuation, represented by the capacity factor, impacts the LCOH. A decrease in the capacity factor to 60% would increase the LCOH by 27%.

A sensitivity analysis was also conducted to evaluate the impacts of other technical and economic parameters on the LCOH for the CCS-abated pyrolysis and in-line steam reforming process (**Figure 30b**). The LHV efficiency of MSW to hydrogen conversion has a considerable role in driving the LCOH. The efficiency may be affected by the catalytic efficiency in pyrolyser, steam reformer, and water-gas shift reactor, type and quality of feedstock, as well as the operating conditions, such as temperature, pressure, and steam ratio. Improving the LHV efficiency to 60% could

substantially reduce the LCOH by 15%. There is a large room for efficiency improvement in pyrolysis with in-line reforming process through the development of more efficient catalysts for the pyrolysis and consecutive oil reforming steps. Like gasification, waste pyrolysis is a capital-intensive process. Consequently, the CAPEX for the equipment to run the process plays a critical role in driving the LCOH. A 15% CAPEX reduction, for example, lowers the LCOH by 10%. In particular, there is a significant opportunity for cost reduction in the pyrolyser and steam reformer through efficiency improvement. The waste feedstock cost also has a substantial effect on the LCOH. In the event that a waste tipping fee of US\$46/t is imposed, the LCOH may decrease substantially to US\$5.34/kg. By contrast, an increase in the MSW cost to US\$33/t leads to a higher LCOH of US\$6.47/kg. Integrating CCS into MSW pyrolysis would enable access to carbon credits, which significantly helps to lower the LCOH. For example, using the average carbon price under the European Union Emissions Trading System (EU ETS) in 2023 (US\$90/t),⁽¹³⁸⁾ the LCOH reduces by 14%.

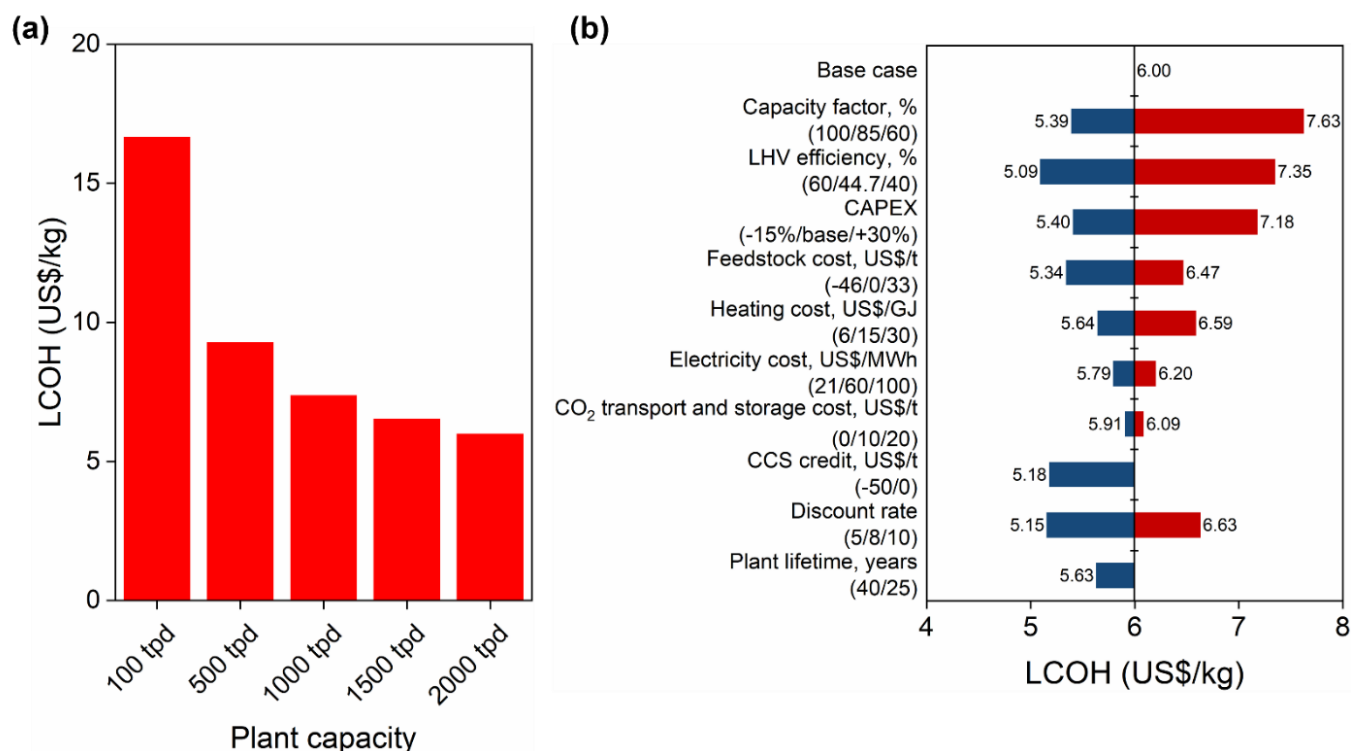


Figure 30. (a) Economies of scale for CCS-abated MSW pyrolysis process. **(b)** Cost sensitivity analysis for CCS-abated MSW pyrolysis process. Negative costs indicate revenue streams.

The sensitivity analysis indicates that the driving factors of LCOH for CCS-abated MSW pyrolysis process are similar to those for CCS-abated MSW gasification, including LHV efficiency, equipment CAPEX, CCS credit, and feedstock cost. As illustrated in [Figure 31](#), the LCOH for CCS-abated pyrolysis can be substantially reduced by improving the LHV efficiency to 60%. The H₂ yield can be increased by enhancing the efficiencies of the waste pyrolyser and steam reformer. In addition to technical improvements, lowering the CAPEX for process equipment plays a significant role. Low-interest loans may also help in reducing the high upfront CAPEX burden for waste pyrolysis deployment. Furthermore, imposing a CCS credit of US\$90/t CO₂ and a waste tipping fee at the current average waste disposal cost in the Netherlands (US\$46/t biomass) has prominent effects in reducing the LCOH for pyrolysis. These cost reduction opportunities demonstrate future directions for the development of CCS-abated MSW pyrolysis into low-carbon hydrogen.

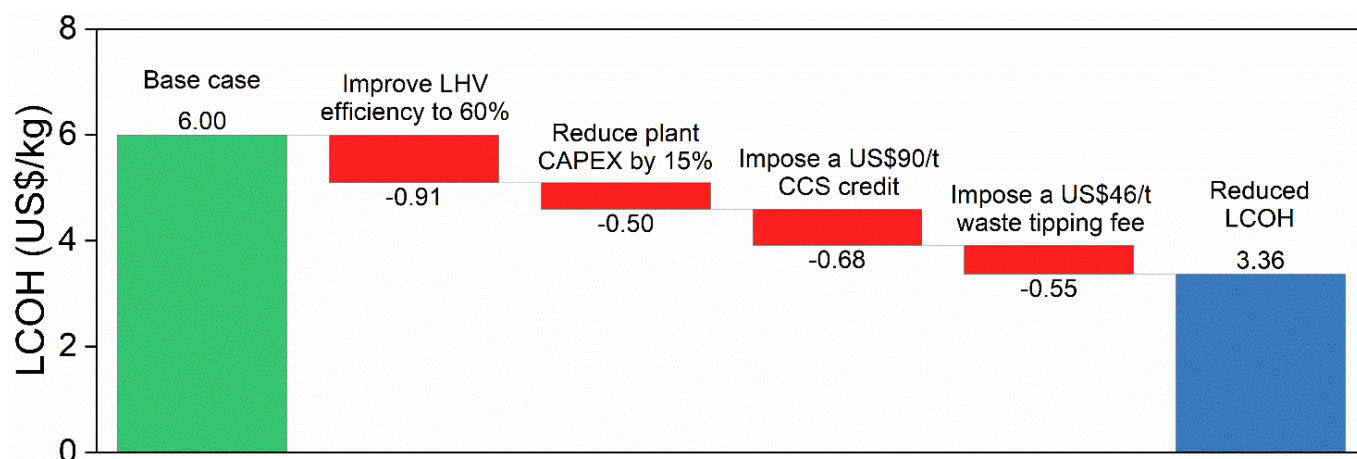


Figure 31. Economic feasibility improvement analysis of CCS-abated MSW pyrolysis process with a MSW processing capacity of 2,000 tpd.

2.3.3. CCS-abated Dark Fermentation

2.3.3.1. Process Design and Modelling

In addition to high-temperature WtH processes, the techno-economic performance of a milder biochemical pathway via CCS-abated dark fermentation is explored. A block flow diagram of CCS-abated dark fermentation and the summary of mass and energy flows are illustrated in **Figure 32**. The process flow diagram and detailed mass and energy flows for the process design are included in **Appendix 2**. It is important to note that the developed process flow diagram in this study is an generic process design, and more detailed site-specific analysis is required.

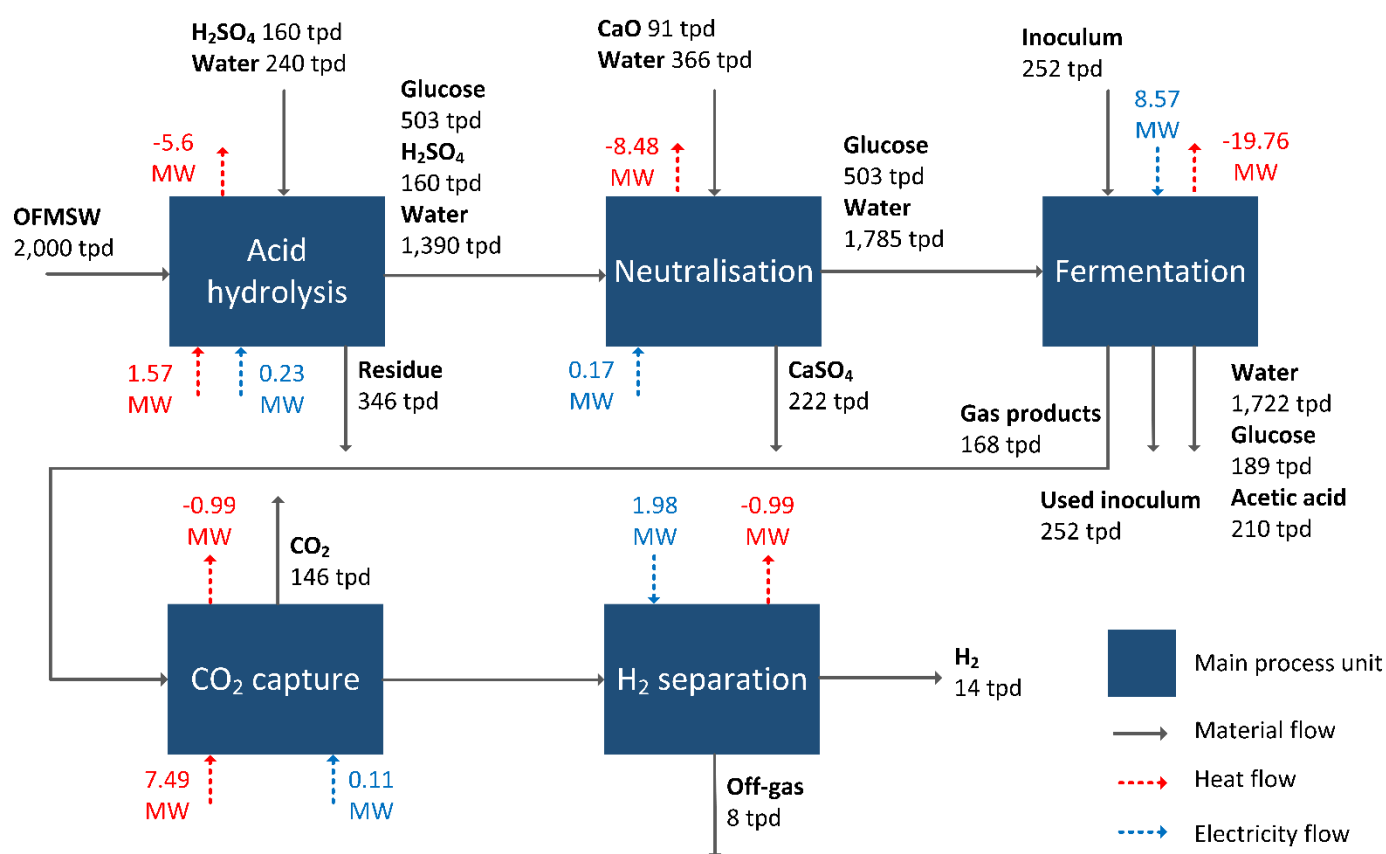


Figure 32. Block flow diagram with material and heat/electricity flows for CCS-abated dark fermentation process.

As dark fermentation process can only access the carbohydrate portion of MSW, the organic fraction of municipal solid waste (OFMSW) is used as the feedstock. The dark fermentation process in this study involves the shredding of OFMSW to reduce particle size, followed by the hydrolysis the carbohydrate portion of OFMSW, using H₂SO₄, into glucose. The

unreacted solid residue is separated and sent to third party for further solid waste treatment, where the lignin fraction can be combusted to produce energy. The excess H_2SO_4 is neutralised using $Ca(OH)_2$, and generates gypsum ($CaSO_4$). The glucose is subsequently sent to the fermentation unit with *Clostridium thermocellum* inoculum to digest the glucose into acetic acid, CO_2 , and H_2 via an acetate pathway ($C_6H_{12}O_6 + 2H_2O \rightarrow 4H_2 + 2CO_2 + 2CH_3COOH$). In the base case scenario, the H_2 production yield is estimated to be 2.5 mol H_2 per mol glucose feed. The gaseous products are collected and sent to CO_2 capture to reduce emissions. The captured CO_2 is compressed, transported, and stored geologically. Finally, the H_2 is purified using pressure swing adsorption (PSA). The liquid product containing unreacted glucose and acetic acid is sent to third party for wastewater treatment via anaerobic digestion. More detailed information on the process description can be found in [Appendix 2](#).

Overall, the mass balance performed for the CCS-abated dark fermentation base case suggests 2,000 tpd of OFMSW would produce 14 tpd of hydrogen. Therefore, the obtained H_2 yield in this case is around 17.5 kg H_2 /tonne dry OFMSW. Considering the typical average LHV of OFMSW (4.5 MJ/kg) and LHV of H_2 (120 MJ/kg), the LHV efficiency of OFMSW to hydrogen via dark fermentation is estimated to be 18.7%. The low LHV efficiency is attributed to the limitations of dark fermentation in accessing lignin, protein, and fat fraction of OFMSW. The undigested residue from OFMSW dark fermentation is assumed to be sent to third party for further treatment (US\$46/t). In addition, partial conversion of carbohydrate components of OFMSW into acetic acid product in dark fermentation also contributes to the resulting low LHV efficiency. In terms of CO_2 emissions, at 95% CO_2 capture rate, the captured CO_2 capacity is 146 tpd. The quantity of CO_2 captured for dark fermentation process is relatively small as majority of the carbon remains in the liquid solution as unreacted glucose and acetic acid byproduct. In the base case scenario, the liquid solution is assumed to be sent to third party for wastewater treatment via anaerobic digestion (US\$2/m³). In the base case scenario, the heating and electricity requirements are supplied from the electricity grid (US\$60/MWh).

2.3.3.2. Cost Analysis

The CAPEX and annual OPEX for the CCS-abated dark fermentation process, with a capacity of 2,000 tpd OFMSW generating 14 tpd H_2 , are shown in [Figure 33a-b](#). The CAPEX was estimated by using the price of similar equipment in literature reports ([Appendix 2](#)). The OPEX data used is shown in [Appendix 2](#). It is important to note that dark fermentation is an emerging technology at relatively lower TRL (5-6) compared to gasification and pyrolysis. Therefore, the cost estimation for this technology may have a higher level of uncertainty. Overall, the total CAPEX for a CCS-abated dark fermentation process under the base case scenario is estimated to be US\$205.3M. Acid hydrolysis and fermentation sections are the major contributors to CAPEX and total up to 64%. The annual OPEX is US\$38.6M. The most significant contributor is the fixed O&M costs, accounting for 34% of the annual OPEX. The next significant contributors are the residue management costs (32%) and the costs of catalysts and chemicals (19%). The waste feedstock cost is assumed to be zero in the base case scenario.

A discounted cash flow analysis based on the CAPEX and OPEX estimations was performed to obtain the levelised cost of H_2 (LCOH). The LCOH for the CCS-abated dark fermentation process, with a capacity of 2,000 tpd OFMSW generating 14 tpd H_2 , is estimated to be US\$13.70/kg, which is significantly higher than the market price range of unabated H_2 from coal gasification and steam methane reforming (US\$0.91-2.21/kg).⁽⁶⁵⁾ The contributions to the LCOH are shown in [Figure 33c](#). The main contributor is capital investment, which contributes 35% to the LCOH. The next most significant costs are for residue management, fixed O&M, and catalysts and chemicals which account for 22%, 22%, and 12% of the total LCOH, respectively.

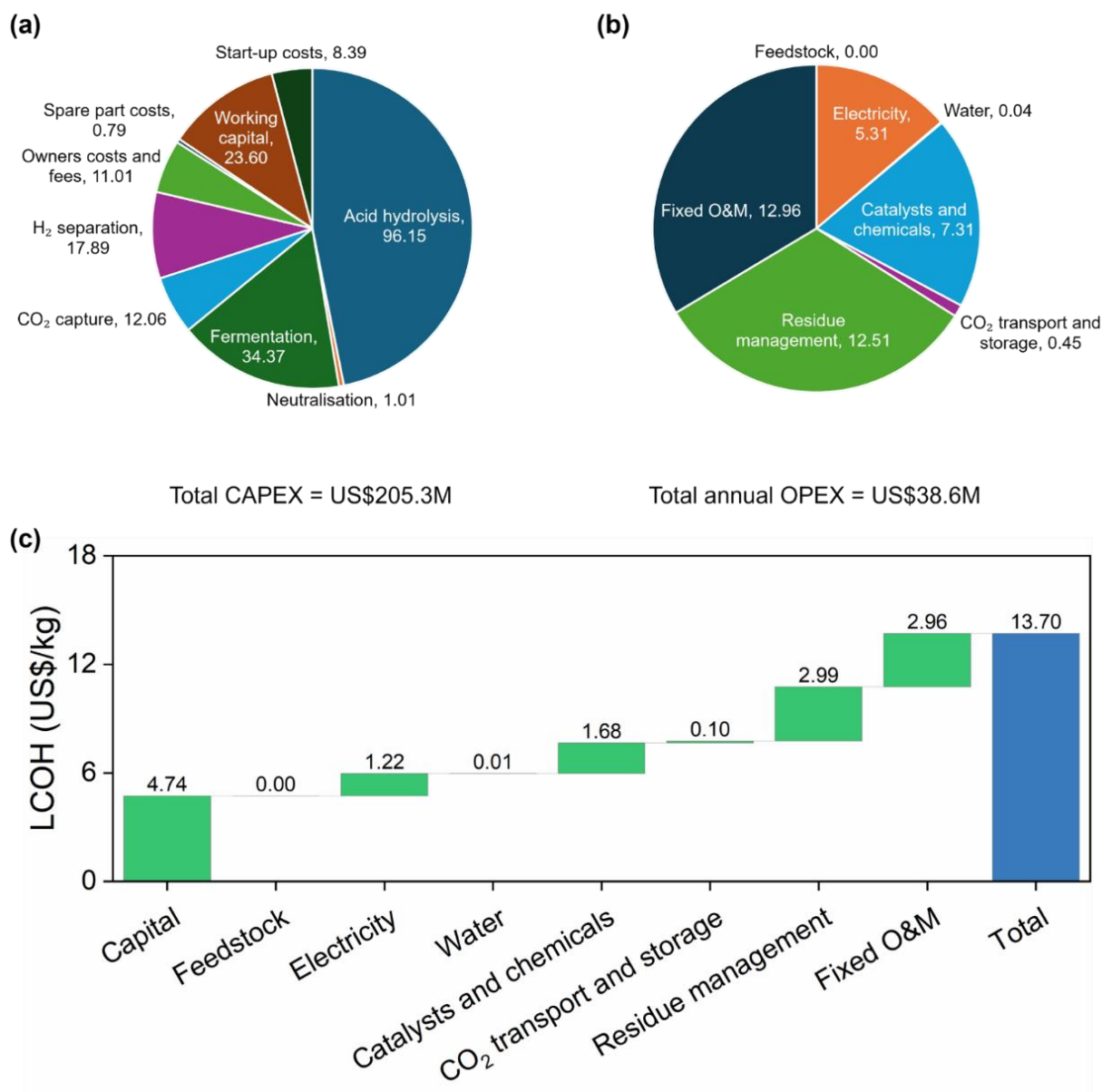


Figure 33. (a) Indicative CAPEX and (b) OPEX breakdown for CCS-abated OFMSW dark fermentation process with a OFMSW processing capacity of 2,000 tpd generating 14 tpd hydrogen. All values are in million US\$. (c) Indicative current LCOH breakdown for CCS-abated OFMSW dark fermentation process under base case scenario with a OFMSW processing capacity of 2,000 tpd generating 14 tpd hydrogen.

Similar to gasification and pyrolysis, the LCOH of CCS-abated OFMSW dark fermentation process is affected by the plant scale. Smaller scale of OFMSW dark fermentation plants are expected to have higher LCOH as illustrated in [Figure 34a](#). A small 100 tpd OFMSW dark fermentation plant with CCS is estimated to produce hydrogen at a cost of US\$43.79/kg. On the other hand, a medium 500 tpd OFMSW dark fermentation plant with CCS has a LCOH of US\$22.02/kg. Therefore, the economic feasibility of the OFMSW dark fermentation process is strongly affected by the economies of scale. However, setting the plant capacity for a waste dark fermentation project must consider the availability of suitable waste feedstock to ensure continuous operation. The sensitivity analysis of waste feedstock supply intermittency, represented by the capacity factor, demonstrates that LCOH is substantially influenced by the reliability of waste feedstock supply ([Figure 34b](#)). A lower plant capacity factor of 60% would lead to a nearly 22% increase in LCOH.

The impacts of other technical and economic parameters on the LCOH for dark fermentation process were also assessed, as presented in [Figure 34b](#). The H₂ yield in the dark fermenter, represented by the molar ratio of H₂ and glucose, is a critical parameter that determines the LCOH. Increasing the yield from 2.5 mol H₂/mol glucose in the base case scenario to 3.2 mol H₂/mol glucose (maximum H₂ yield for dark fermentation through acetate pathway is 4 mol

H_2 /mol glucose according to $C_6H_{12}O_6 + 2H_2O \rightarrow 4H_2 + 2CO_2 + 2CH_3COOH$) could reduce the LCOH by 14%. The feedstock cost also has a significant impact on the LCOH. In the event that a waste tipping fee of US\$46/t is imposed, the LCOH would decrease by around 20%.

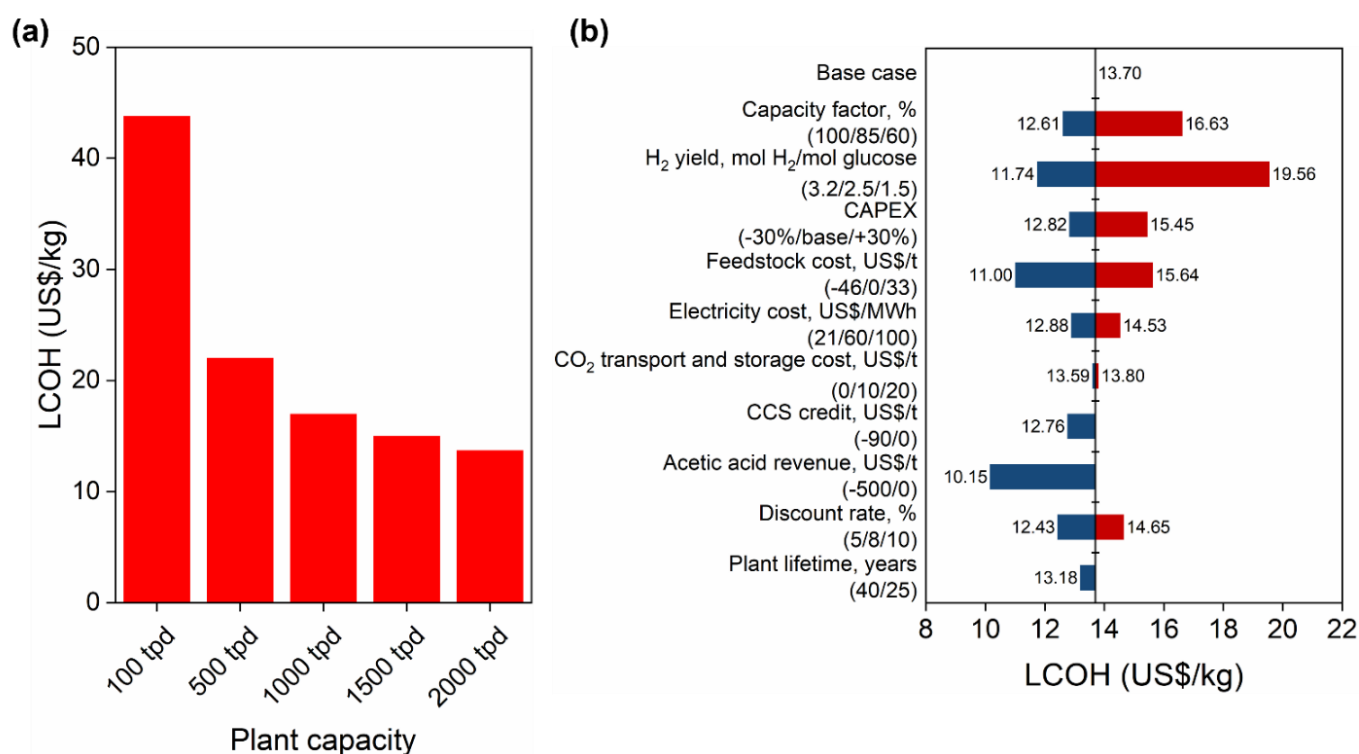


Figure 34. (a) Economies of scale for CCS-abated dark fermentation process. **(b)** Cost sensitivity analysis for CCS-abated dark fermentation process. Negative costs indicate revenue streams.

A dark fermentation process does not produce significant amounts of CO_2 as most of the carbon remains as an acetic acid byproduct in the solution. This renders the impact of CCS credit on the LCOH for CCS-abated dark fermentation process relatively small. The base case assumes that the liquid fermentation product containing acetic acid is sent to external anaerobic digestion wastewater treatment facility at US\$2/m³ cost. However, recovering the acetic acid product by retrofitting an extractive distillation unit (which significantly adds the CAPEX and annual OPEX by US\$34.4M and US\$13.6M, respectively at the base case capacity) and selling it at US\$500/t⁽¹⁴¹⁾ shows a prominent LCOH reduction to US\$10.15/kg.

The LCOH for CCS-abated OFMSW dark fermentation is primarily driven by the H_2 yield, acetic acid revenue, and feedstock cost. To identify cost reduction opportunity for dark fermentation process, a cost feasibility improvement analysis was conducted (Figure 35). Enhancing the H_2 yield from 2.5 mol H_2 /mol glucose to 3.2 mol H_2 /mol glucose, which can be done by optimising the dark fermentation process conditions, would significantly lower the LCOH by US\$1.96/kg. In addition, there is an opportunity for the coproduction of acetic acid byproduct by installing extractive distillation unit. Taking into account additional CAPEX and OPEX for acetic acid separation and purification unit, the LCOH could be reduced by US\$3.97/kg. Decreasing the plant CAPEX combined with imposing CCS credit and waste tipping fee would further bring down the LCOH to a projected value of US\$3.80/kg. These cost reduction opportunities offer future directions for the development of WtH conversion via CCS-abated dark fermentation process.

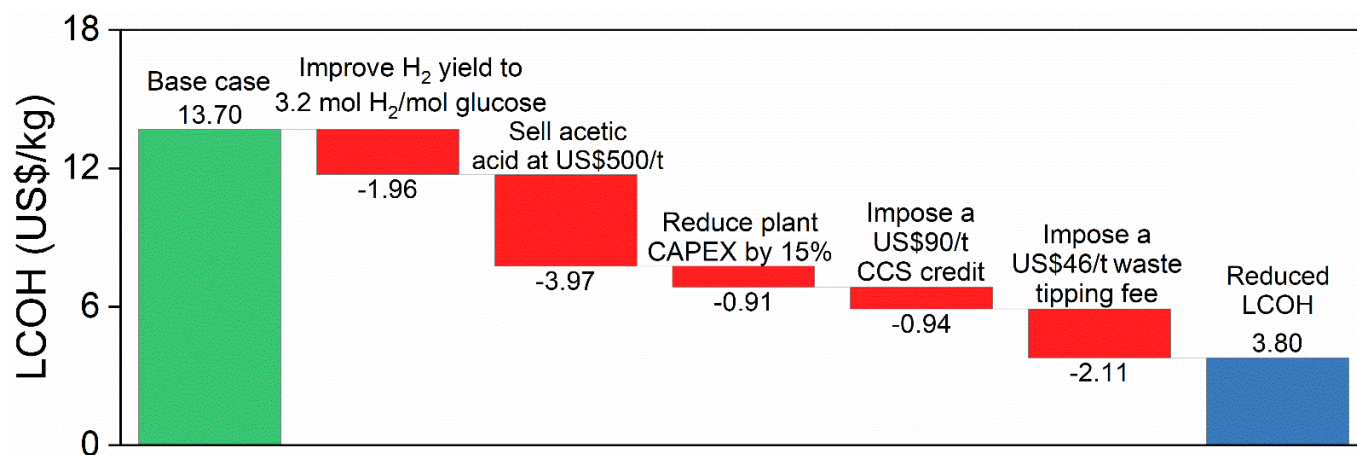


Figure 35. Economic feasibility improvement analysis of CCS-abated OFMSW dark fermentation process with a OFMSW processing capacity of 2,000 tpd.

2.3.4. CCS-abated Incineration-Water Electrolysis

2.3.4.1. Process Design and Modelling

In addition to direct thermochemical WtH processes such as waste gasification and pyrolysis, the techno-economic performance of indirect WtH conversion process, which involves waste-to-electricity (WtE) conversion via CCS-abated incineration followed by water electrolysis, was evaluated. A block flow diagram of CCS-abated MSW incineration coupled to water electrolysis and the summary of mass and energy flows are illustrated in [Figure 36](#). The process flow diagram and detailed mass and energy flows for the process design are included in [Appendix 2](#). It is important to note that the developed process flow diagram in this study is an generic process design, and more detailed site-specific analysis is required.

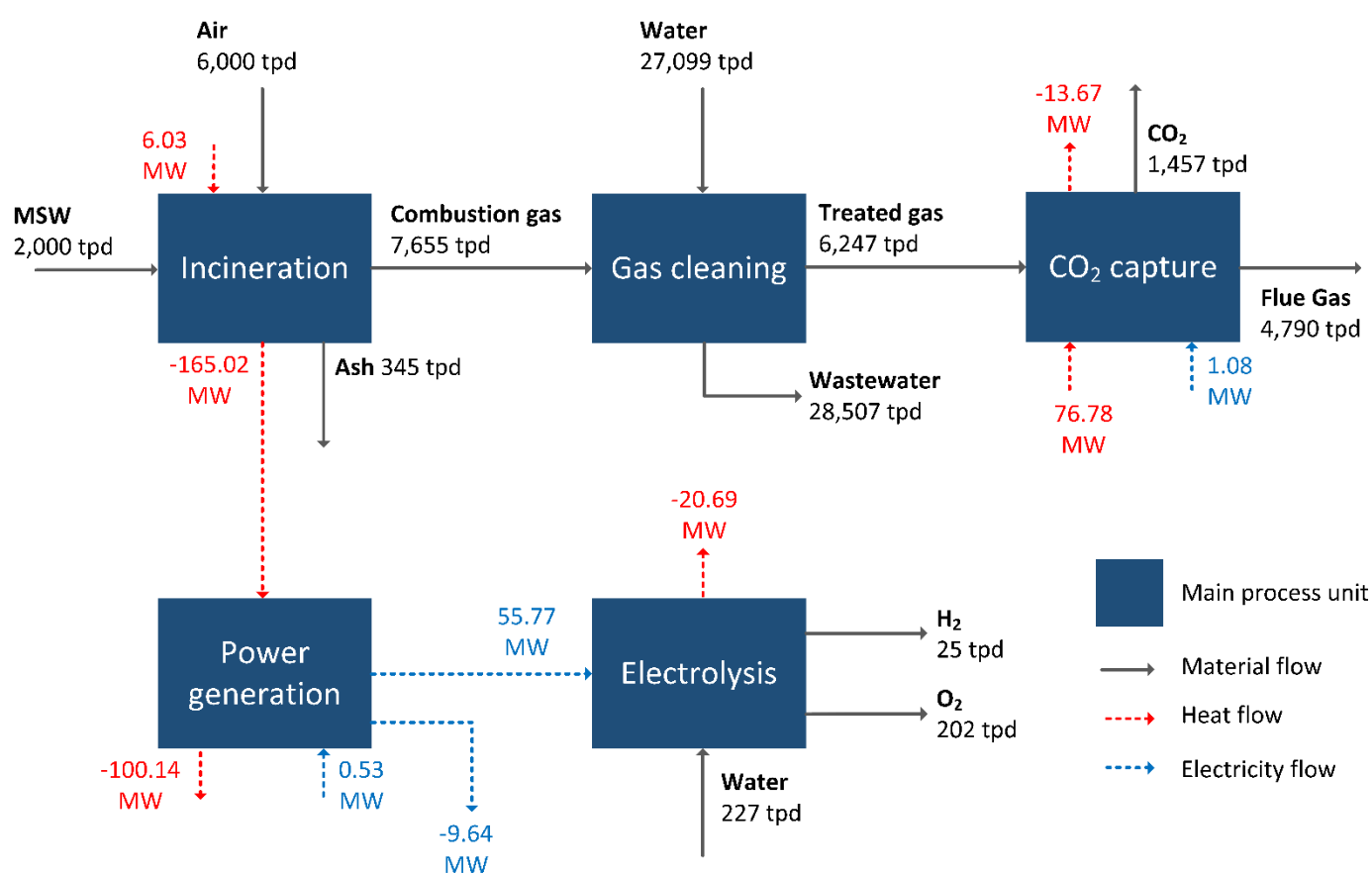


Figure 36. Block flow diagram with material and energy flows for CCS-abated MSW incineration-electrolysis process.

Like gasification and pyrolysis, the feedstock used for incineration-electrolysis is unsorted MSW. The WtE section involves mass-burn incineration using air as the O₂ source. The energy contained in the hot combustion gas is recovered to make steam using a boiler. The steam is used to generate electricity using a turbine. After recovering the heat, the combustion gas is treated with scrubber to remove hazardous impurities. Subsequently, the CO₂ is captured through a MEA absorption process. A portion of the electricity generated from the steam turbine is used to provide the electricity required for gas compression and pumping. The remaining electricity from the steam turbine powers a PEM electrolyser, which splits water into H₂ and O₂. More detailed information on the process can be found in [Appendix 2](#).

Overall, the mass balance performed for the CCS-abated incineration-water electrolysis base case suggests 2,000 tpd of MSW could produce 65.41 MW of electricity with 100.14 MW thermal energy byproduct. Given the LHV of MSW is 10.6 MJ/kg, the WtE efficiency in the base case scenario is estimated to be approximately 26.2%. The modelled efficiency lies well within the typical efficiency range of WtE plant (20-30%)⁽¹⁴²⁾. Around 9.64 MW of the power generated is used to supply electricity for pumps and compressors, while the remaining 55.77 MW is directed to a proton exchange membrane (PEM) electrolyser for hydrogen production. With a specific energy consumption of 53 kWh/kg H₂ in the base case scenario, the PEM electrolyser would generate 25 tpd of hydrogen. Consequently, the total MSW-to-H₂ efficiency via this process is approximately 14.0%, lower compared to gasification and pyrolysis. In terms of CO₂ emissions, the total CO₂ generated from MSW incineration is 1,534 tpd (1,369 kg CO₂/tonne dry MSW). Assuming 60% of the MSW is of biogenic origin, the biogenic CO₂ emissions from MSW incineration are 920 tpd (821 kg CO₂/tonne dry MSW). With a CO₂ capture rate of 95%, the total captured CO₂ capacity is 1,457 tpd.

2.3.4.2. Cost Analysis

The CAPEX and annual OPEX for a CCS-abated incineration-electrolysis process with a capacity of 2,000 tpd MSW and generating 25 tpd H₂, are shown in [Figure 37a-b](#). The CAPEX was estimated from similar equipment in literature reports. The OPEX data used is shown in [Appendix 2](#). Overall, the total CAPEX is estimated to be US\$673.4M. The WtE section, encompassing incineration, gas cleaning, and power generation, is the major contributor to the plant CAPEX, totalling up to 58%. The water electrolysis section is the second highest CAPEX contributor at approximately 15%. The annual OPEX is US\$47.2M. The OPEX is mainly driven by fixed O&M costs, followed by residue management costs and CO₂ transport and storage costs. The waste feedstock for the incineration-electrolysis process is assumed to be acquired at zero cost.

A discounted cash flow analysis based on the CAPEX and OPEX estimations, was performed to obtain the levelised cost of H₂ (LCOH). The LCOH for the incineration-electrolysis process, with a capacity of 2,000 tpd MSW generating 25 tpd H₂, was estimated to be US\$14.91/kg, which is higher than the market price range of unabated H₂ from coal gasification and steam methane reforming (US\$0.91-2.21/kg)⁽¹³⁸⁾. The contributions to the LCOH for the incineration-electrolysis route are shown in [Figure 37c](#). The main cost is capital investment, which contributes 59% to the LCOH. The next most significant contributor is fixed O&M costs (23% of the LCOH).

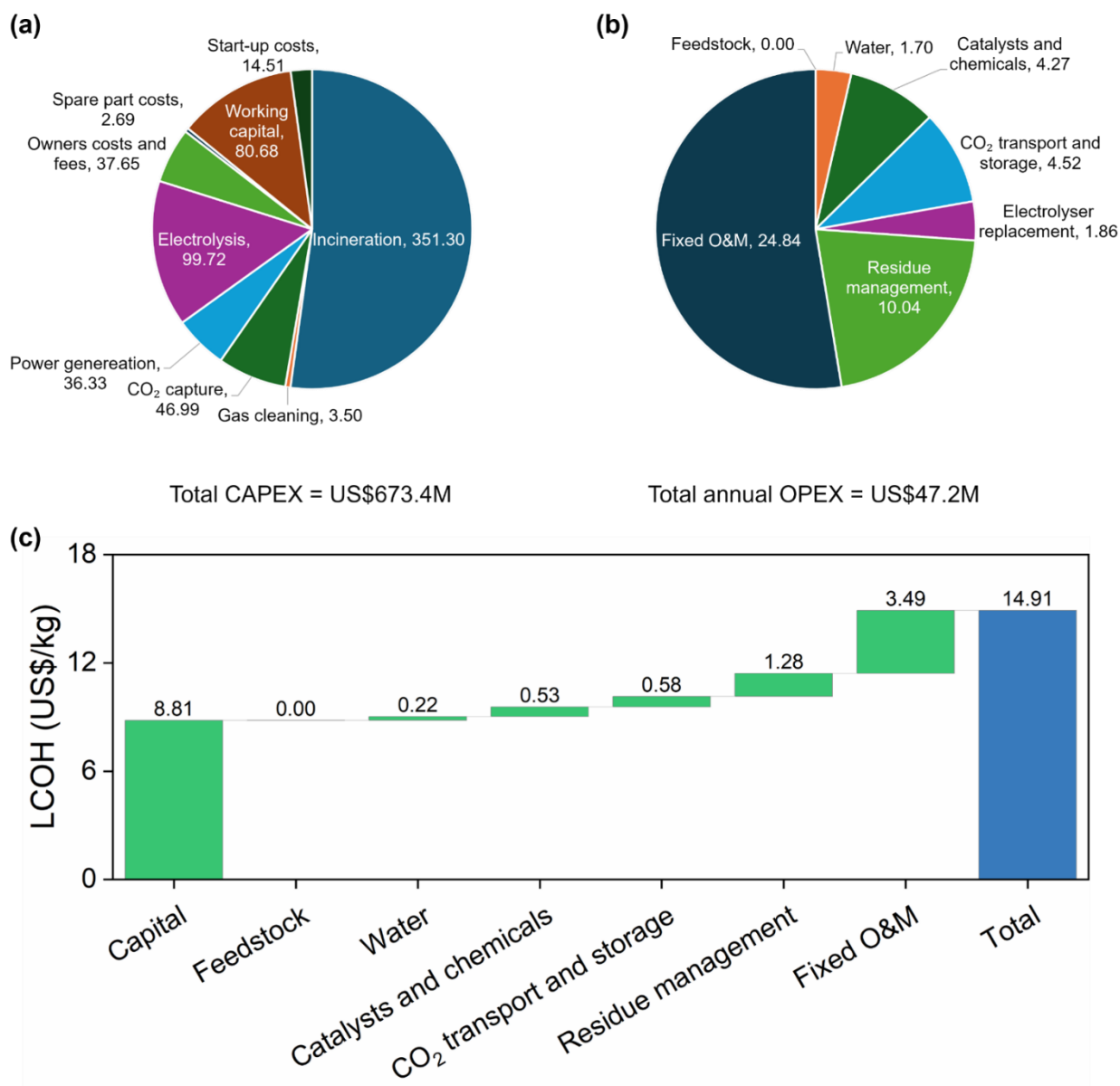


Figure 37. (a) Indicative CAPEX and (b) OPEX breakdown for CCS-abated MSW incineration-electrolysis process with a MSW processing capacity of 2,000 tpd generating 25 tpd hydrogen. All values are in million US\$. (c) Indicative current LCOH breakdown for CCS-abated MSW incineration-electrolysis under base case scenario with a MSW processing capacity of 2,000 tpd generating 25 tpd hydrogen.

The LCOH of CCS-abated MSW incineration-electrolysis is strongly influenced by the plant scale. Smaller scale of CCS-abated MSW incineration-electrolysis results in a higher LCOH as presented in [Figure 38a](#). A small 100 tpd MSW incineration-electrolysis with CCS has a LCOH of US\$37.77/kg, while a medium 500 tpd MSW incineration-electrolysis with CCS is estimated to exhibit a LCOH of US\$21.86/kg. While the LCOH of CCS-abated MSW incineration-electrolysis process is dependent on the economies of scale, setting the plant capacity of a CCS-abated MSW incineration-electrolysis process must consider the availability of waste feedstock. The reliability of waste feedstock supply has been identified as a critical factor that affects the LCOH. At a capacity factor of 60%, for example, the LCOH increases by around 32% ([Figure 38b](#)).

The effects of other technical and economic parameters on the LCOH for the CCS-abated incineration-electrolysis process were also evaluated ([Figure 38b](#)). The WtE efficiency, as determined by the performance of the incinerator and power generation unit, plays a considerable role in controlling the LCOH. Increasing the WtE efficiency from 26.2% (base case scenario) to 35%⁽¹⁴²⁾ would decrease the LCOH by up to 22%. The electrolyser efficiency, represented by its specific energy consumption, has a significant effect on the LCOH. An improved PEM electrolyser energy consumption from 53 kWh/kg H₂ to 42 kWh/kg H₂^(101, 143) could reduce the LCOH by 21%. In addition, CAPEX reduction for both WtE

and water electrolysis sections are crucial. Decreasing the WtE CAPEX by 15%, for instance, would lead to a nearly 10% LCOH reduction. The anticipated PEM electrolyser capital cost reduction from US\$1,700/kW to US\$700/kW by 2030⁽¹⁰¹⁾ could also lower the LCOH by approximately 10%. The waste feedstock cost plays a significant role in determining the LCOH. In the event that a waste tipping fee of US\$46/t is imposed, the LCOH may decrease substantially by 21%. Imposing a carbon credit would help to significantly lower the LCOH. At an average CO₂ price of US\$90/t⁽¹³⁸⁾ in 2023, the LCOH can be reduced to US\$9.71/kg.

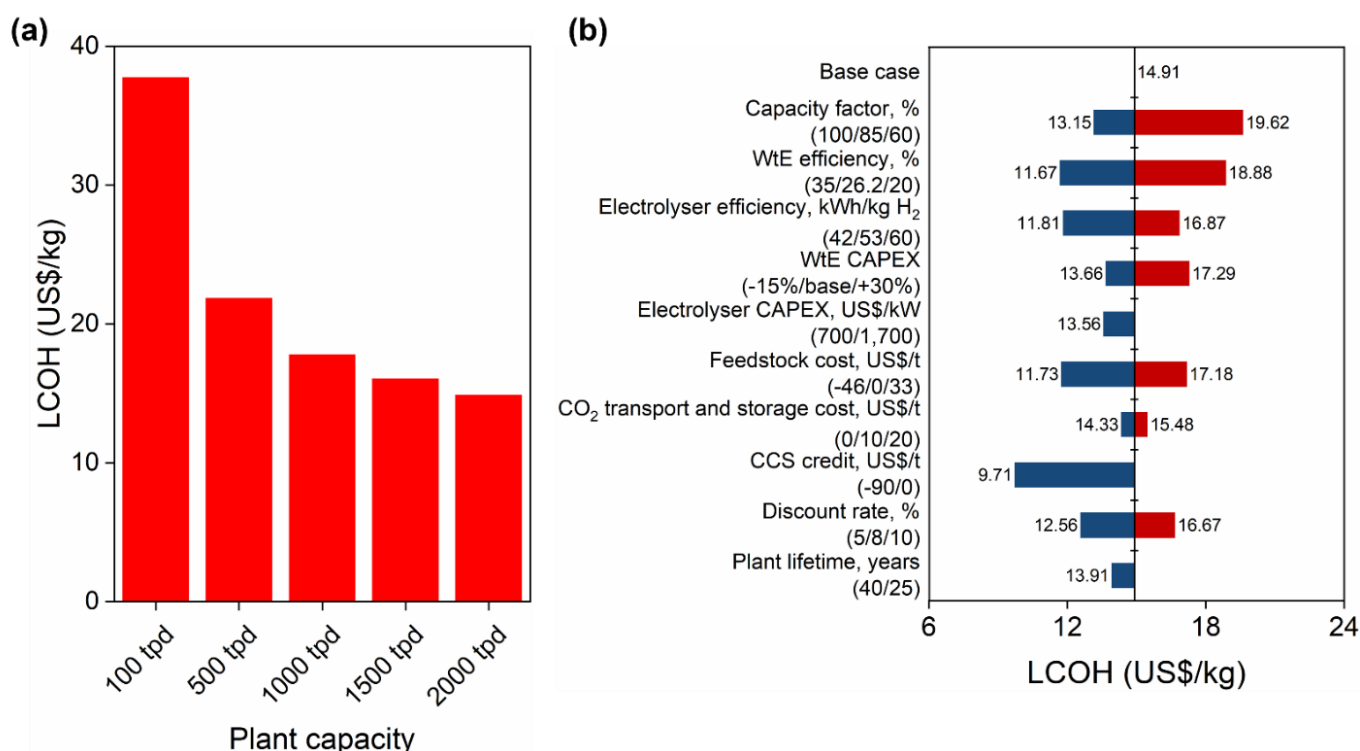


Figure 38. (a) Economies of scale for CCS-abated MSW incineration-electrolysis process. **(b)** Cost sensitivity analysis for CCS-abated MSW incineration- electrolysis process. Negative costs indicate revenue streams.

The primary driving factors of LCOH for CCS-abated MSW incineration-electrolysis process, which have been identified through the sensitivity analysis, include WtE and electrolyser efficiencies, equipment CAPEX, CCS credit, and feedstock cost. An economic feasibility improvement analysis was then carried out to map the potential cost reduction mechanism for CCS-abated MSW incineration-electrolysis process (Figure 39). The LCOH can be substantially lowered by improving the efficiency of the WtE plant to 35% and decreasing the PEM electrolyser specific energy consumption to 42 kWh/kg H₂. CAPEX reduction for WtE and water electrolysis is also crucial to further decrease the LCOH. In particular, there is a large room for cost improvement for the electrolyser technology. By 2030, it is anticipated that the CAPEX for PEM electrolyser can reach US\$700/kW. Additionally, imposing a CCS credit of US\$90/t CO₂ and a waste tipping fee at the current average waste disposal cost in the Netherlands (US\$46/t biomass) has substantial impacts in reducing the LCOH for incineration-electrolysis. This projected LCOH provides future directions for developing more cost-effective CCS-abated waste incineration-electrolysis process for hydrogen production.

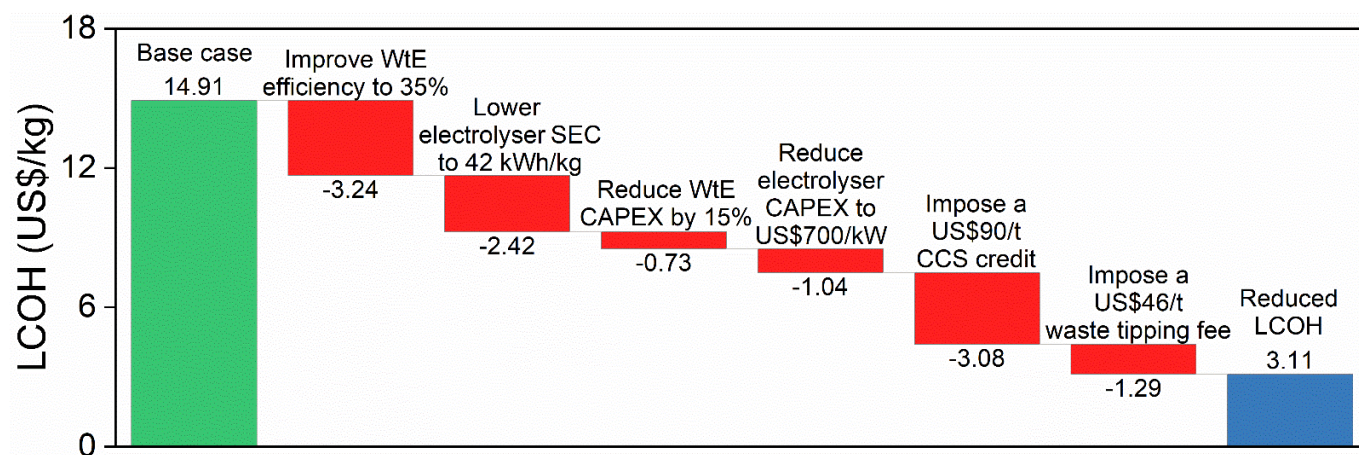


Figure 39. Economic feasibility improvement analysis of CCS-abated MSW incineration-electrolysis process with a MSW processing capacity of 2,000 tpd.

2.4. Cost Benchmarking

From a broader perspective, the waste-to-low-carbon-hydrogen processes studied in this report, offer an alternative technology to existing waste management methods, such as landfilling and incineration. Therefore, it is essential to comparatively evaluate the economics of WtH processes with landfilling and incineration as baselines. As shown in [Table 17](#), landfilling is considered as the most inexpensive option, with a specific CAPEX of US\$155-200/tpa waste⁽¹⁰⁰⁾ and specific OPEX of US\$11-14/t waste⁽¹⁰⁰⁾. Incineration, on the other hand, exhibits a higher specific CAPEX of US\$620-700/tpa waste⁽¹⁰⁰⁾ and specific OPEX of US\$25-40/t waste⁽¹⁴⁴⁾, though it comes with the benefit of substantially reducing waste volume in comparison to landfilling.

Table 17. Cost-benefit analysis of WtH-CCS processes compared to landfilling and incineration.

Technology	CAPEX (US\$/tpa waste)	OPEX (US\$/t waste)	Revenues (US\$/t waste)
Landfilling	US\$155-200/tpa	US\$11-14/t	-US\$46/t (tipping fee)
Incineration without CCS	US\$620-700/tpa	US\$25-40/t	-US\$93/t (tipping fee, electricity)
Gasification with CCS	US\$1,055/tpa	US\$93/t	-US\$190/t (tipping fee, H ₂ , CCS credit)
Pyrolysis with CCS	US\$1,056/tpa	US\$90/t	-US\$159/t (tipping fee, H ₂ , CCS credit)
Dark fermentation with CCS	US\$281/tpa	US\$53/t	-US\$67/t (tipping fee, H ₂ , CCS credit)
Incineration-electrolysis with CCS	US\$923/tpa	US\$65/t	-US\$137/t (tipping fee, H ₂ , CCS credit)

The specific CAPEX and OPEX for CCS-abated gasification, pyrolysis, incineration-electrolysis, and dark fermentation are then calculated according to the base case scenario. [Table 17](#) illustrates that gasification, pyrolysis and incineration-electrolysis processes exhibit significantly higher specific CAPEX and OPEX as compared to landfilling and incineration. Despite the higher specific CAPEX and OPEX, these processes offer potentially higher revenues from H₂ product and CCS credit in addition to waste tipping fee. In contrast, dark fermentation, which operates at milder conditions, has relatively lower CAPEX and OPEX compared to the other WtH pathways. However, the revenue streams

apart from waste tipping fee are lower than WtH processes involving high temperatures. This is attributed to the low H_2 yield of dark fermentation process. In addition, dark fermentation generates less amount of CO_2 as most carbon ends up as acetic acid in the wastewater sent for anaerobic digestion. Consequently, the access to CCS credit is limited unless dark fermentation is coupled to anaerobic digestion and steam reforming processes to convert acetic acid into H_2 and CO_2 .

2.5. Summary

This study has provided a comparative techno-economic assessment of various waste-to-low-carbon-hydrogen routes, including gasification, pyrolysis, incineration-electrolysis, and dark fermentation combined with carbon capture and storage. From a technical perspective, CCS-abated gasification and pyrolysis offer rapid direct conversion of MSW to low-carbon hydrogen, with LHV efficiencies of 49.4% and 44.7%, respectively. In contrast, incineration-electrolysis, an indirect WtH process, has a significantly lower LHV efficiency of 14.0% due to substantial energy losses in the WtE and water electrolysis stages. Nevertheless, incineration-electrolysis technology can leverage existing waste incineration facilities, thereby reducing upfront capital investment. Dark fermentation was also identified as an emerging alternative WtH technology to handle the organic fraction of MSW. While dark fermentation exhibits low LHV efficiency of 18.7%, this process operates at much milder reaction conditions compared to gasification, pyrolysis, and incineration-electrolysis.

Economically, WtH-CCS processes are currently not viable, as indicated by the significantly high LCOH compared to the costs of H_2 from coal (US\$1.20-2.21/kg without CCS or US\$2.10-2.62/kg with CCS) and natural gas (US\$0.91-1.79/kg without CCS or US\$1.21-2.11/kg with CCS).⁽⁶⁵⁾ The high LCOH for WtH-CCS is primarily driven by high CAPEX and OPEX due to the complexity and/or currently limited efficiency of the process. Compared to the current green hydrogen production costs in Europe (US\$3-8/kg)⁽¹⁴⁵⁾, the costs for gasification and pyrolysis with in-line reforming are comparable, while the costs for dark fermentation and incineration-electrolysis are estimated to be more expensive.

This study has also identified process efficiency, CAPEX, byproduct revenues, CCS credit, and/or waste feedstock cost as crucial parameters in determining the economics of WtH-CCS processes. The cost feasibility improvement analysis suggests that a combination of efficiency improvements, byproduct recovery, CAPEX reduction, and/or waste management and carbon incentives are required to lower the LCOH for CCS-abated gasification, pyrolysis, incineration-electrolysis, and dark fermentation. In addition, economies of scale are essential to establish a cost-effective waste-to-low-carbon-hydrogen conversion.

Finally, this study has further provided insights into the value of waste-to-low-carbon-hydrogen technology in waste management practices by comparing it with existing waste processing technologies such as landfilling and mass-burn incineration. Compared to landfilling and incineration, WtH conversion processes via CCS-abated gasification, pyrolysis, and incineration-electrolysis has higher specific capital and operational costs. However, potential revenue streams and incentives, such as H_2 and CCS credits, in addition to waste tipping fee, could significantly offset and lower the treatment costs. On the other hand, WtH conversion via dark fermentation, although has lower CAPEX and OPEX compared to the other WtH processes, exhibit limited additional revenue streams from H_2 and CCS credits.

Chapter 3. Life Cycle Assessment of Waste-to-Hydrogen Technology

3.1. Introduction

This section examines the environmental impact adoption of the established waste-to-hydrogen technologies, Life Cycle Assessment (LCA) serves as a valuable tool for evaluating the environmental impacts associated with WtH technologies, providing insights into their potential sustainability and comparing them through the use of a pre-defined set of assumptions. Hence, this report aims to use this methodology to examine the environmental impact of various WtH technologies, namely: gasification (Gas), pyrolysis (Pyro), dark fermentation (DF), and incineration-water electrolysis (IWE), which were identified as promising WtH pathways through a multi-criteria analysis framework conducted in the previous report, and during the comparative analysis conducted in [Chapter 2](#). Out of these processes, IWE is different to gasification, pyrolysis, and dark fermentation as IWE is an indirect waste to hydrogen pathway via electricity generation. These processes have been enhanced by the addition of carbon capture scrubbers via MEA (monoethanolamine) solutions, and the overarching objective is to provide a lucid understanding of the environmental impact, pinpoint potential areas for enhancement, and guide the industry towards practices that provide environmentally sound solutions within the current technical understanding. [Figure 40](#) shows the LCA framework according to ISO14040 (ISO, 2006), which is being used as the structure for this report.

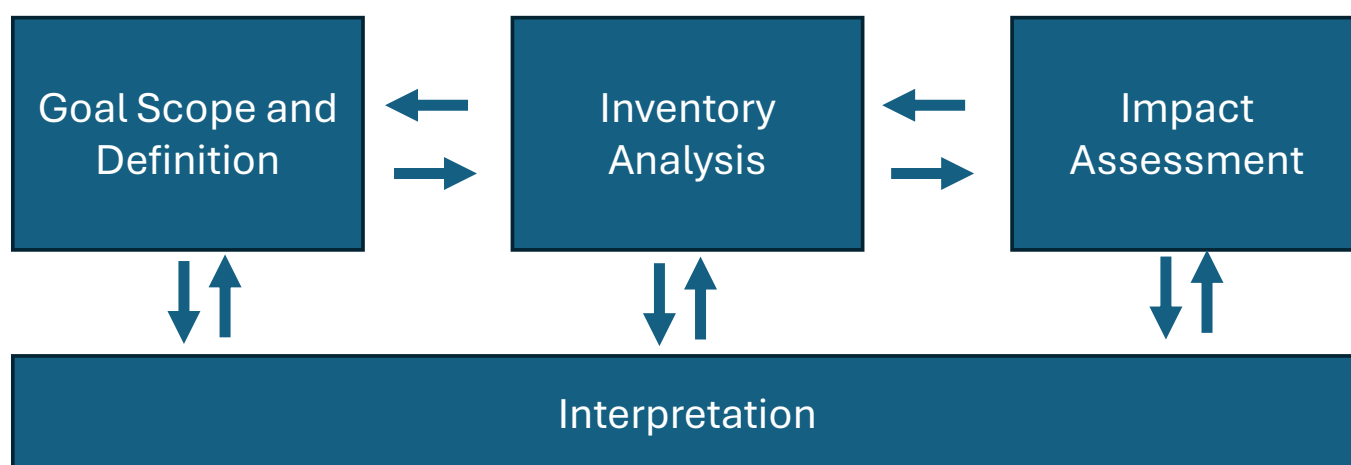


Figure 40. LCA flowchart according to ISO14040.

3.2. Methodology

3.2.1. Goal and Scope

In this LCA study, the functional unit (FU) for analysis is set as one kilogram of hydrogen (H_2). The database used is Ecoinvent version 3.6 through Allocation Cut-Off by Specifications. The analysis is conducted using the OpenLCA program. The scope of the study is Cradle-to-Gate, with resource extraction originating from Municipal Solid Waste (MSW) and other material productions ([Figure 41](#)). The WtH yielded secondary products in addition to hydrogen, along with other materials going into landfills and exiting as emissions. The mass balance and processes involved will be described in the next section. The chosen method for this LCA is ReCiPe Midpoint (H) V.1.13, selected for its relevance to the study's objectives. A summary of impact categories is presented in [Table 18](#).

Table 18. Impact categories adopted in this report.

Impact Category	Abbrev.	Unit	Description
Agricultural Land Occupation	ALOP	m ² a	Compares the footprint of the process originally intended for agricultural purposes but has been replaced by the given process.
Global Warming Potential	GWP100	kg CO ₂ -Eq	Compares the extent to which a substance contributes to global warming by trapping heat when released into the atmosphere. GWP100 estimates the excessive greenhouse gases of fossil and biogenic origin for 100 years.
Fossil Depletion	FDP	kg oil-Eq	Compares the extraction of non-renewable resources for the purposes of the process.
Freshwater Ecotoxicity	FETPinf	kg 1,4-DCB-Eq	Compares the potential of process emissions to influence the freshwater ecosystem.
Freshwater Eutrophication	FEP	kg P-Eq	Compares the risk of nutrient-rich pollutants entering aquatic systems, causing excessive growth of algae and other aquatic plants, leading to oxygen depletion in the water body and eventual harm to the ecosystem.
Human Toxicity	HTPinf	kg 1,4-DCB-Eq	Compares the potential of process emissions to influence marine ecosystems.
Ionising Radiation	IRP_HE	kg U ₂₃₅ -Eq	Compares the risk of nutrient-rich pollutants entering marine systems, causing excessive growth of algae and other aquatic plants, leading to oxygen depletion in the water body and eventual harm to the ecosystem.
Marine Ecotoxicity	METPinf	kg 1,4-DB-Eq	Compares the potential harm to human health caused by emissions of toxic substances into the environment, estimated by the software through various emissions.
Marine Eutrophication	MEP	kg N-Eq	Compares human health effects by measuring emissions that can interact with and alter molecules, potentially damaging or killing cells.
Metal Depletion	MDP	kg Fe-Eq	Similar to FDP but, instead of fossil fuel, it compares metal extraction.
Natural Land Transformation	NLTP	m ²	Compares the area consumed by the process for growing resources and/or material extraction.
Ozone Depletion	ODPinf	kg CFC-11-Eq	Compares the potential of a certain process to impact the ozone layer through ozone-depleting substances.
Particulate Matter Formation	PMFP	kg PM ₁₀ -Eq	Compares the impact scenario's contribution to the formation and generation of particulate matter (PM). Apart from PM, other compounds such as SO ₂ and NO _x may react with air molecules to form small PM.
Photochemical Oxidant Formation	POFP	kg NMVOC-Eq	Compares the scenario's gas emissions that lead to the formation of ground-level ozone. Volatile organic compounds (VOCs) and nitrogen oxides (NO _x) are common responsible compounds. POFP is an important indicator in estimating air quality deterioration and human health.
Terrestrial Acidification	TAP100	kg SO ₂ -Eq	Compares the emissions of acidic gases that may return to Earth, acidifying the soil and water via weather conditions. TAP100 compares the environmental harm caused by acidifying emissions, which may adversely affect ecosystems, aquatic life, and vegetation.
Terrestrial Ecotoxicity	TETPinf	kg 1,4-DCB-Eq	Compares the leaching of pollutants into soils and their potential to pollute the ground ecosystem.
Urban Land Occupation	ULOP	m ² a	Compares the spaces required for the given scenarios.
Water Depletion	WDP	m ³ water-Eq	Compares the water depletion caused by the scenarios.

3.2.2. Data Inventory

In this LCA, the scenarios were pre-defined based on the findings and recommendations in [Chapters 1-2](#). The summary of the process is summarised in [Table 19](#). In this work, the following are assumed:

1. Total heat consumption originates from fuel (natural gas or biomass, wood chips), while the total power consumption originates from grid energy mix source (Dutch or Icelandic).
2. MEA (monoethanolamine) solutions for CO₂ capture are assumed to be recycled in the process, with a degradation rate of 1.6 kg per tonne of CO₂ captured.⁽¹⁴⁶⁾
3. Water density is assumed to be 1000 kg/m³.
4. Steam as an emission is assumed to be inert.
5. Solid residues from thermal processes (ash and char) are assumed to be landfilled, and their emissions to soil are assumed via total leaching to unspecified level of population, for 100 years according to Birgisdottir et al.⁽¹⁴⁷⁾
6. Inoculum for DF is assumed not to require input.
7. CO₂ emission from thermal waste conversion is assumed to be of 60% biogenic and 40% fossil-fuel origin (plastic),⁽¹⁴⁸⁾ while the dark fermentation is assumed to be 100% biogenic.
8. Wastewater is assumed to require a standard wastewater treatment (WWT) meanwhile wastewater from DF residue and used inoculum is assumed to require advanced anaerobic wastewater treatment.

Table 19. Waste-to-hydrogen (WtH) scenarios evaluated in this work.

Process	Abbrev.	Description
Gasification	Gas	Thermochemical process that converts solid materials into syngas, which consists of hydrogen and carbon monoxide. The process uses only oxygen and captures some of the generated CO ₂ .
Pyrolysis	Pyro	Thermal decomposition process that involves heating organic materials in the absence of oxygen, which results in the production of biochar, bio-oil, and gases.
Dark Fermentation	DF	Microbial process in which bacteria break down organic compounds, typically complex organic matter like carbohydrates, in the absence of light. This anaerobic process results in the production of biohydrogen and organic acids.
Incineration with water electrolysis	IWE	Thermal combined process where incineration is used to burn waste, which produces heat that is then utilised in water electrolysis. During electrolysis, water is split into hydrogen and oxygen gases.

The data is adjusted according to the functional unit, while the input and output are assumed to be connected to various markets provided by the Ecoinvent 3.6 Database. These databases will be discussed further in LCA results and interpretation. The breakdown of the mass balance used in Open LCA is provided in [Appendix 3.1](#).

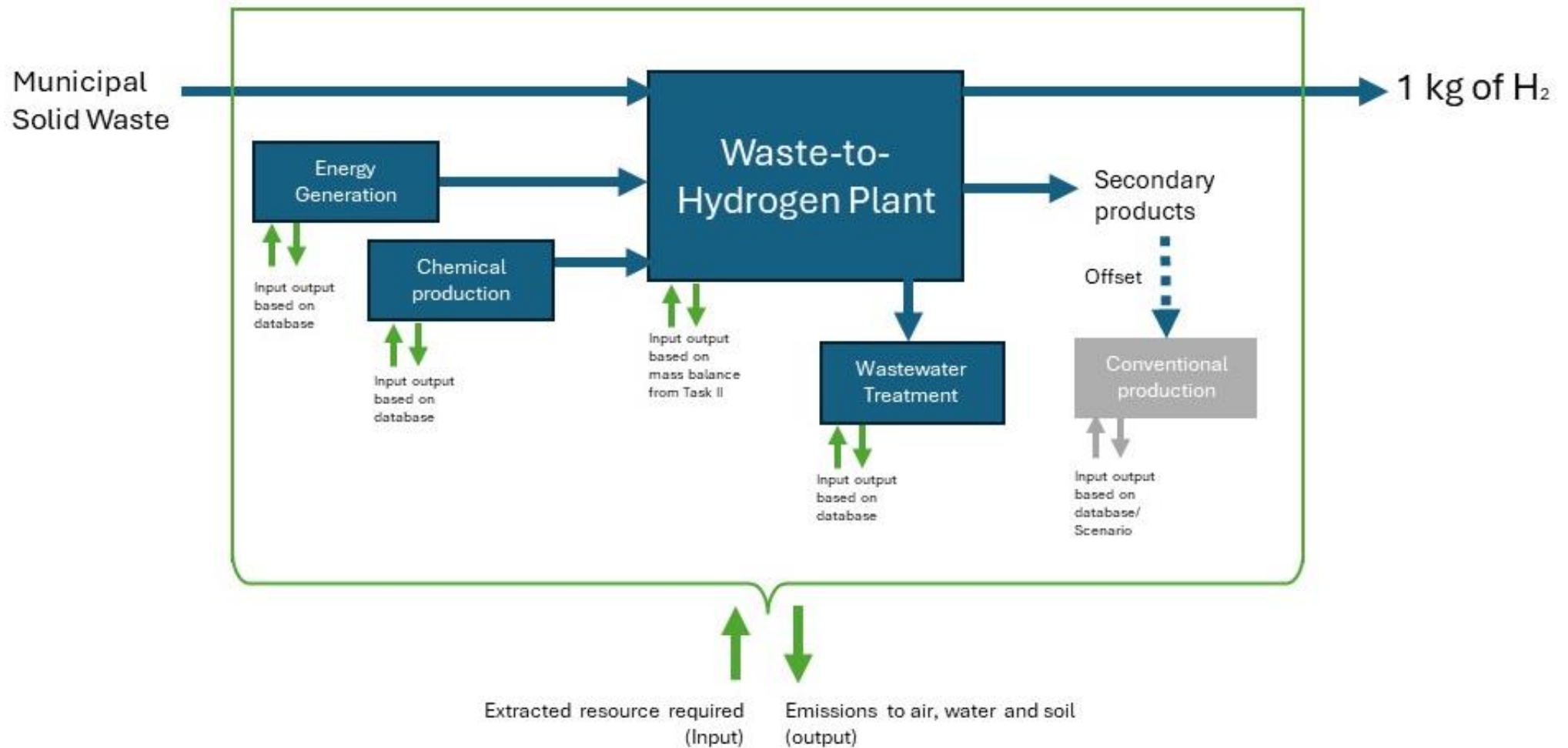


Figure 41. System boundary conditions, where the LCA comprise solely of the CCS-abated WtH operation (cradle-to-gate) and not the MSW generation, logistic and hydrogen distribution.

3.3. Result and Discussion

This section discusses the result and interpretation of the LCA impact assessment. The findings cascade from Business-as-usual ([Section 3.3.1](#)), to renewable substitutions in the grid, to the electrification of heating and 100% heat recovery ([Section 3.3.2](#)). Lastly, the study considers the potential inclusion of offset environmental impact from secondary products ([Section 3.3.3](#)) and the consideration of alternative functional units (1 kg of MSW) due to capacity discrepancies ([Section 3.3.4](#)), and finally comparing it with more traditional waste management treatment ([Section 3.3.5](#)).

3.3.1. Business-as-Usual (BAU)

The input required in BAU is highlighted in [Table 20](#). In this comparison, all WtH scenarios utilise the Dutch electricity grid for their power source, while the heating comes from natural gas combustion. The rest of the chemical productions are shown below.⁽¹⁴⁹⁾

Table 20. Summary of auxiliary and supporting processes for WtH scenarios.

Input	Database
Power	Electricity production in the Netherlands, based on IEA World Energy statistics, where the process is mainly originated from natural gas and coal. In 2016, the Netherlands reported using 82% fossil fuel for electricity generation. ⁽¹⁵⁰⁾
Heat	Natural gas combustion produces steam using a combined power and heat cycle at 400 MWe (Netherlands). In this study, this is assumed to be solely for heating purposes.
MEA production	The process produces MEA from liquid nitrogen, ethylene oxide, and ammonia, with mixed markets from Brazil and Europe. ⁽¹⁴⁹⁾
Water	Assumed to have originated from freshwater/river
Quicklime production	Obtained by calcination of crushed limestone by a Swiss company. ⁽¹⁴⁹⁾
Sulphuric acid production	The process includes the mining of sulphide ores and conversion into SO ₂ and SO ₃ to yield Sulphuric acid. ⁽¹⁴⁹⁾
WWT Standard	Activated sludge method and biofiltration technology based in Switzerland, with a capacity of 1.6 x 10 ⁸ litres per year.
WWT for Anaerobic Digestion	The process uses the activated sludge method with a capacity of 1E9 litres per year.

The LCA results are shown in [Figure 42](#) for the given impact categories along with its contributing sectors.

To produce 1 kg of H₂, pyrolysis and gasification stand out as the most environmentally beneficial processes across all impact categories, except in the categories of terrestrial ecotoxicity, photochemical oxidation formation, and ozone depletion. The environmental superiority of these processes is due to their higher reliance on heating as an energy source than power. The effect is that this scenario predominantly uses energy generated from natural gas combustion, as opposed to the fossil fuel mix from the power grid, which leads to cleaner energy generation and a reduced environmental impact.

However, this heightened dependence on natural gas means pyrolysis and gasification exhibit a higher ozone depletion potential (ODP), compared to DF or incineration, because on-site natural gas combustion for energy emits less emissions than the electricity network, consequently resulting in higher ODP.

In contrast, dark fermentation (DF) displays the highest environmental impact in most categories. This can be attributed to factors such as (1) the significant additional chemicals required for the process, (2) high power demands, which are sourced from a fossil-fuel dependent power grid, and (3) more complex wastewater treatment.

In DF, auxiliary processes add to the environmental impact caused by the high power requirement. Moreover, as a result of the assumption that it requires more advanced WWT, DF registers a high environmental impact in the categories of marine eutrophication and metal depletion. This may be caused by the high nutrient content and additional resources required.

Incineration consumes the most MSW (80 kg) to produce 1 kg of hydrogen and serves as an example that high waste processing does not necessarily equate to greater environmental benefit. Incineration with electrolysis shows that utilising energy to produce hydrogen rather than generating it directly from waste material can be ineffective, especially when compared to a thermochemical process that synthesises hydrogen directly from waste material, e.g. pyrolysis and gasification.

The environmental impacts of gasification and pyrolysis are relatively similar across a range of categories, as both processes consume a similar amount of power and heat. Interestingly, direct emissions play an insignificant role for the two processes, possibly due to CO₂ capture and air pollution control (APC). Direct emissions have a significant role in terrestrial ecotoxicity potential and freshwater ecotoxicity due to char and ash landfilling, and acid emissions (Sulphur and HCl), respectively. Pyrolysis has the lowest environmental impact in all categories apart than POFP, and slightly lower than gasification. This is because pyrolysis utilises more heating than grid power, which produces less environmental impact.

However, gasification and pyrolysis have a higher POFP than other processes. This is because both processes employ a partial oxidation process that produces carbon monoxide. For contrast, incineration causes a minimal POFP as complete combustion eliminates it.

In summary, the primary contributors to environmental impact across the processes are fossil-fuel-mix power generation, followed by auxiliary processes, such as chemical production and associated wastewater treatment. Although less impactful, direct emissions from the process can produce significant impact in certain categories, such as eco-toxicity and photochemical formation. Direct emissions low impact on GWP is due to the installed CO₂ carbon capture.

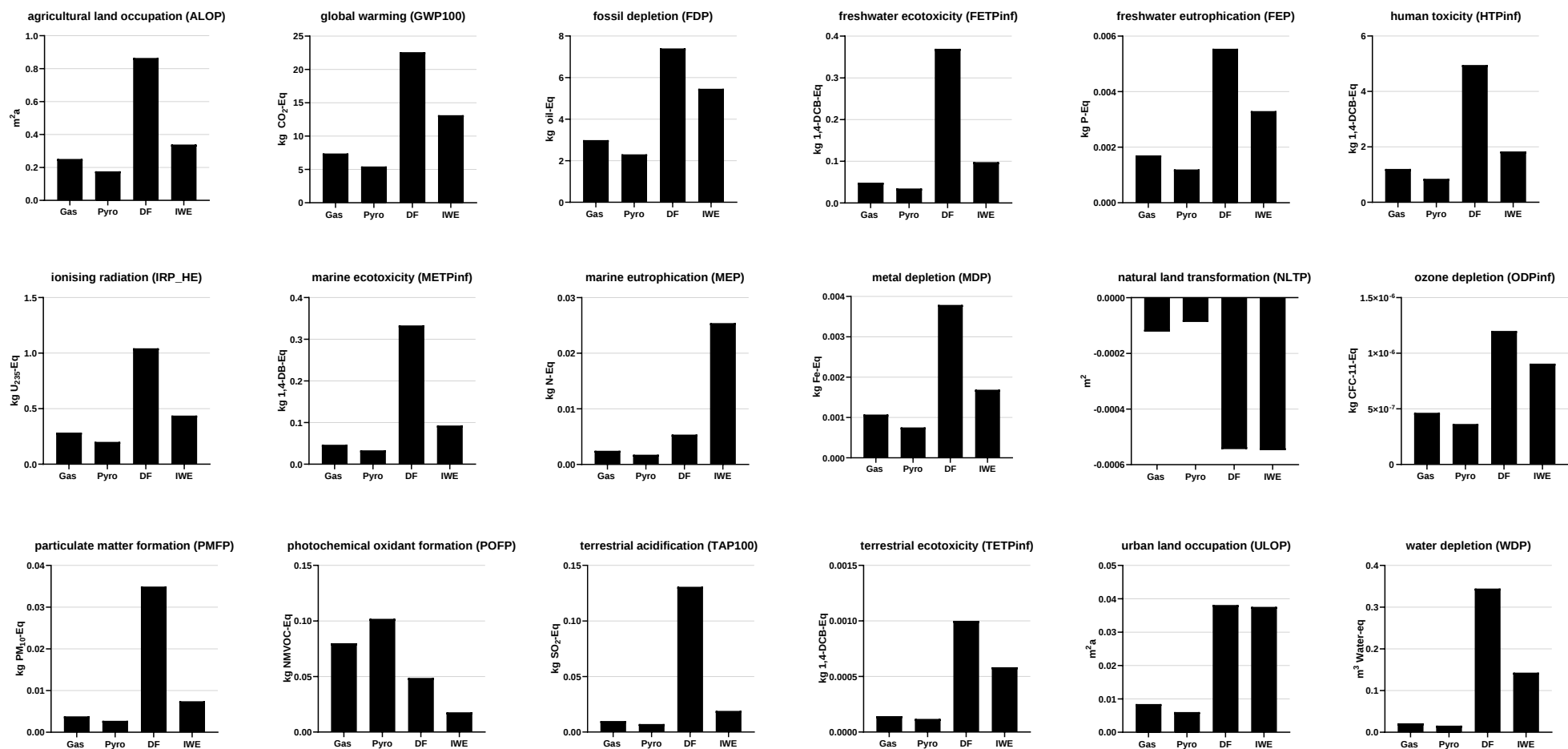


Figure 42. Environmental impact to produce 1 kg of H₂ through gasification (Gas), pyrolysis (Pyro), dark fermentation (DF), and incineration-water electrolysis (IWE) for business-as-usual (Netherlands 2014 grid) case.

3.3.2. Renewable Energy and Energy Recovery

As the Netherlands' grid mix, per Ecolnvent 2020 database, is dependent on fossil fuels, the next scenario is to substitute the grid with a more renewable mix. In this section, the scenarios are evaluated with renewable sources, using Iceland's power grid and woodchips heating respectively ([Table 21](#)).

[Figure 43](#) and [Figure 44](#) show the selected comparison of the four processes under the following scenarios:

- (A) Business-as-usual (BAU)
- (B) The WtH technologies operating under a mix of Icelandic power grid and biomass heating
- (C) The WtH technologies running on Icelandic renewable power grid achieved through heating electrification
- (D) BAU with 100% heat recovery.

Full result is provided in [Appendix 3.2](#).

Table 21. Summary of auxiliary and supporting processes for WtH renewable scenarios.

Input	Database information
Power	Electricity production in Iceland's grid mix, based on the IEA World Energy statistics. Renewable resources (hydro and geothermal) contribute 89% of Iceland's (IS) energy. ⁽¹⁵¹⁾
Heat	Generated via natural wood chip combustion in Europe, and equipped with APC to meet European air emissions standards.

A renewable power grid significantly reduces the environmental impact associated with power consumption. However, substituting to biomass heating increases the environmental impact in the categories of agricultural and urban land occupation and human toxicity. This is attributed to the spatial requirements for growing biomass and the potential human toxicity from the fumes during its combustion. Wood chip heating also substantially contributes to ionising radiation and freshwater ecotoxicity. In this case, the reliance of pyrolysis on heating—something that was previously a positive—is now shown to be a weakness as the high heating requirements lead to increased biomass combustion and result in higher emissions and environmental impact, especially when compared to gasification and incineration—despite their higher power requirements. This is evident in impact categories like GWP100, fossil depletion (FDP), and freshwater ecotoxicity potential (FETP) ([Appendix 3.2](#)).

Other sectors that support DF continues to be high contributors to various impact categories for Dark Fermentation, changes in renewable energy were unable to lower this environmental impact. For example, DF terrestrial acidification shows minimal change between the BAU and renewable grid scenarios. This is because of the requirement for sulphuric acid, which is the main contributor for this impact category. Substituting to renewable grid power also increases the environmental impact in the metal depletion and terrestrial ecotoxicity categories, possibly due to the renewable energy generation process (hydro-energy and geothermal).

Process electrification is proven to be effective in reducing the environmental impact for all thermal processes, across most scenarios. Relying on renewable grid energy eliminates the environmental impact associated with heating requirements from biomass combustion.

Lastly, in the BAU scenario, DF and incineration produce a significant amount of unused energy that is lost to the surroundings. If the system could recover 100% of the heat loss (an assumption established in [Chapter 2](#)), DF and incineration could achieve a self-sustaining process due their high exothermic conditions. In this scenario, DF and Incineration require no external power or heating, thereby reducing the environmental impact significantly across most categories and demonstrating the importance energy optimisation plays in both processes. Nevertheless, DF still shows a high acidification and global warming potentials due to the production of sulphuric acid and quicklime, respectively.

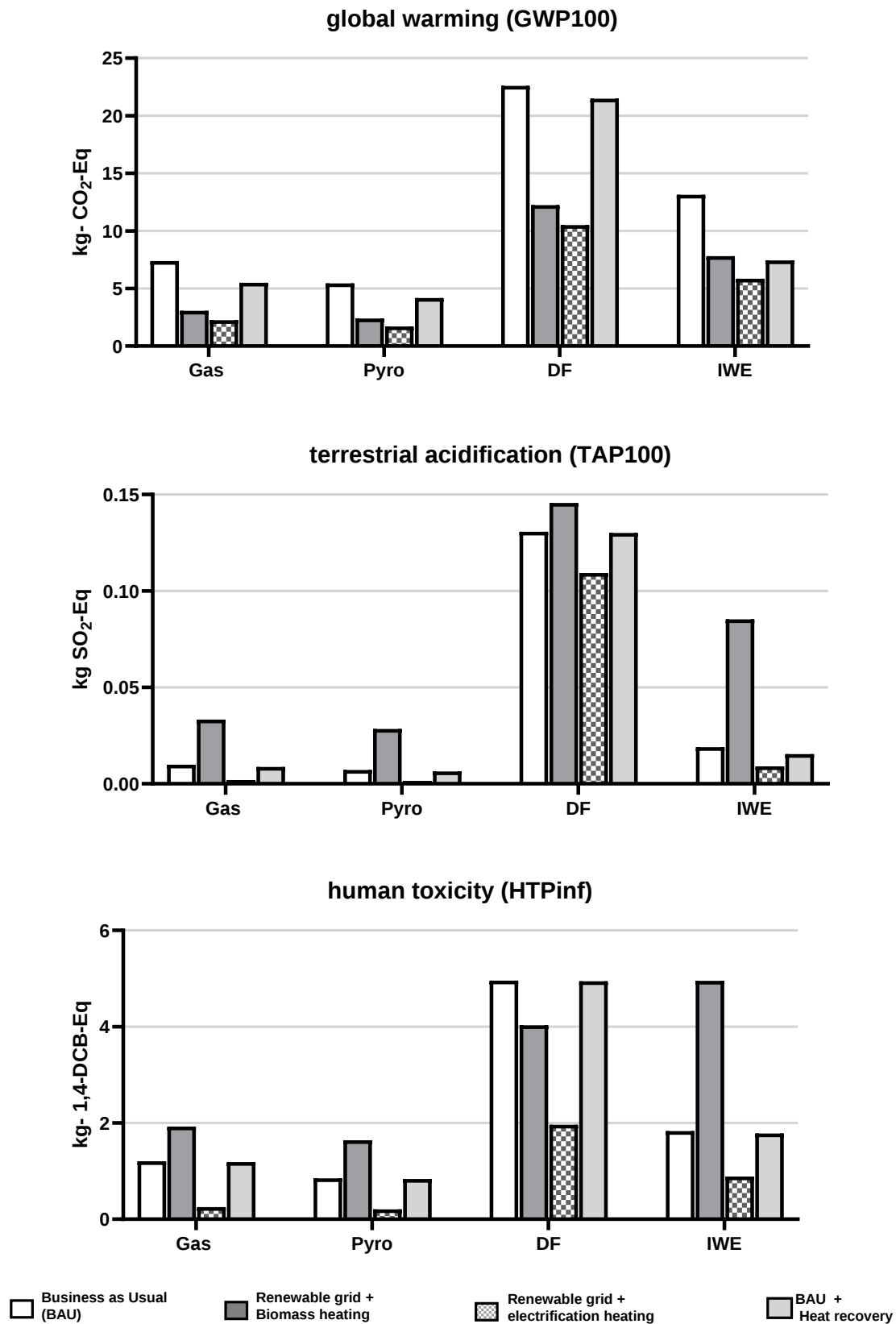


Figure 43. Selected environmental impact comparison between BAU, Renewable energy, process electrification, and BAU with heat recovery for four WtH processes. Full results are presented in Appendix 3.2. (Gas: Gasification, Pyro: Pyrolysis, DF: Dark Fermentation, IWE: Incineration Water Electrolysis).

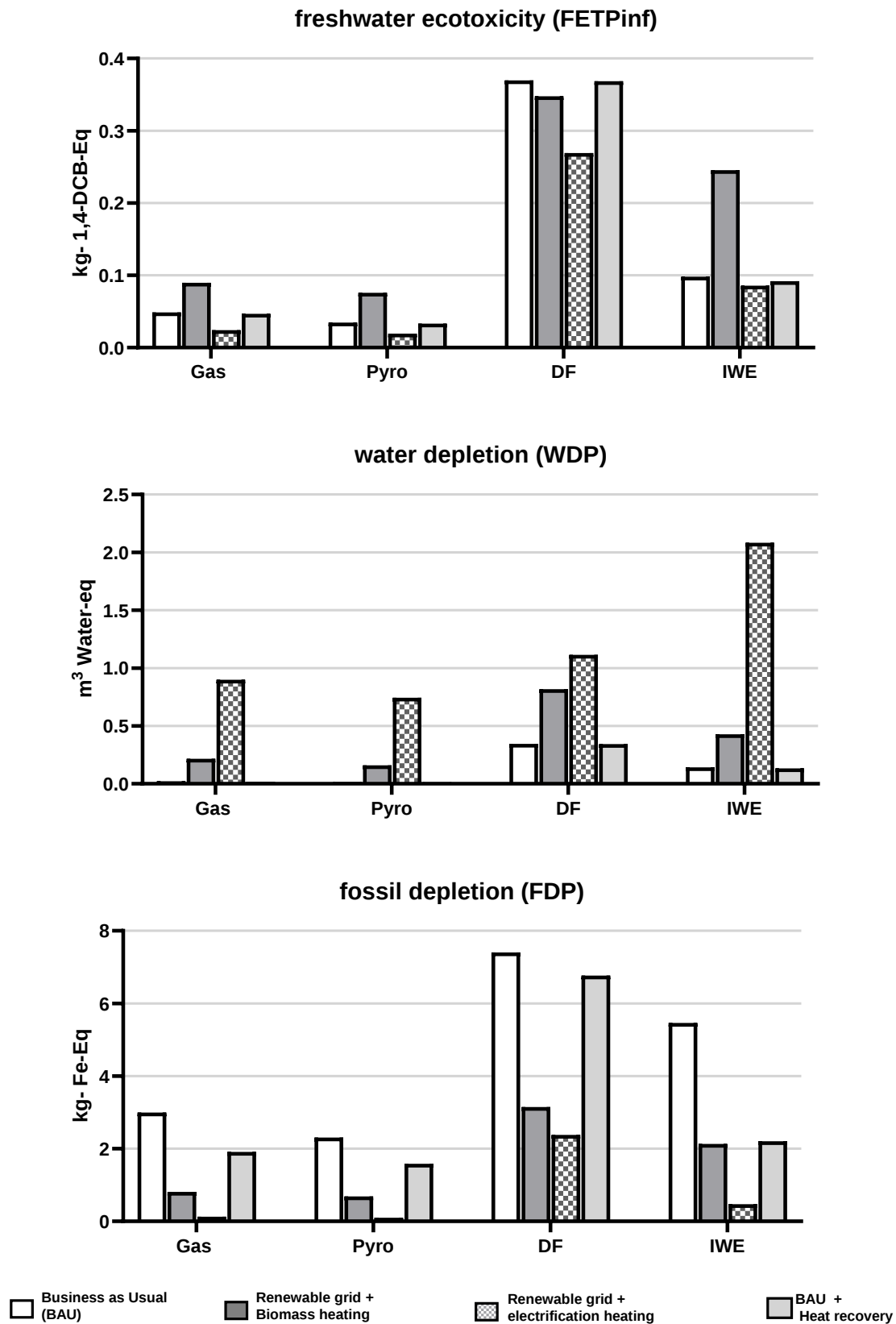


Figure 44. Selected environmental impact comparison between BAU, Renewable energy, process electrification, and BAU with heat recovery for four WtH processes. Full results are presented in Appendix 3.2. (Gas: Gasification, Pyro: Pyrolysis, DF: Dark Fermentation, IWE: Incineration Water Electrolysis).

3.3.3. Secondary Products Offset

In the four scenarios considered, recovering secondary products—in addition to hydrogen—may present an opportunity. These secondary products have the potential to replace conventional production processes, thereby mitigating the environmental impact associated with producing them in the conventional way. For example, the acetic acid produced during DF can be sold to the market and may create a substitution for the conventional acetic acid production. In this approach, the substitution of the conventional process may offset the direct environmental impacts of each Waste-to-Hydrogen processes.

However, this LCA approach is a topic of contention among experts. Many researchers argue that studies should primarily focus on direct emissions, suggesting that the consideration of secondary products offsetting the direct environmental impact may not be entirely relevant. This is grounded in the observation that secondary products from alternative processes often face challenges in successfully reaching the market and being used, let alone replacing the conventional processes and reducing their production rate.

Nevertheless, this section will consider the potential emissions savings by producing secondary products. Note that hydrogen is not considered to provide environmental offset due to its role as a functional unit. The traditional process being replaced is highlighted in [Table 22](#). It can be observed that neither gasification nor pyrolysis produces any secondary products, which result in a lack of environmental impact offset. Meanwhile, dark fermentation and incineration produces acetic acid and oxygen as secondary products, respectively.

Table 22. Summary of secondary products list, its production rate, and the conventional process being replaced with WtH processes (Gas: Gasification, Pyro: Pyrolysis, DF: Dark Fermentation, IWE: Incineration Water Electrolysis).

Output (Not emissions)	Unit	Gas	Pyro	DF	IWE	Offset
H ₂	kg	1	1	1	1	No, considered as products and functional unit
CO ₂	kg	14	9	10	58	No, captured and stored.
Sugar	kg	-	-	13.5	-	No, established in Chapter 2.
Acetic acid	kg	-	-	15	-	Yes, consuming additional 31.8 MW of heat.
O ₂	kg	-	-	-	4	Yes, O ₂ from H ₂ O splitting that can be secondary product
External power	MJ	-	-	-	33	No, Previous section has considered energy recovery
Heat loss	MJ	95	64	221	465	No, Previous section has considered energy recovery

[Figure 45](#) and [Figure 46](#) illustrates the comparison across BAU, the offsets from secondary products, and the final emissions for selected impact categories. The full result is provided in [Appendix 3.3](#).

In terms of gasification and pyrolysis, the absence of secondary product resulted in a high final environmental impact. Conversely, material-intensive processes such as dark fermentation (DF) and incineration generate a substantial amount of secondary products, which can effectively offset the original impact categories and even reduce them to negative values in some categories.

For impact categories such as Agricultural Land Occupation (ALOP), Global Warming Potential (GWP), Fossil Depletion (FDP), Ionizing Radiation (IR), Terrestrial Acidification Potential (TAP), Particulate Matter Formation Potential (PMFP), Urban Land Occupation Potential (ULOP), Water Depletion Potential (WDP), and Ozone Depletion Potential (ODP), the significant production of secondary products provides a noteworthy offset—even a negative result in some categories—compared to the original BAU scenario. This suggests a beneficial outcome for both DF and incineration.

However, secondary products contribute minimally to Marine Eutrophication Potential (MEP), possibly due to the high emissions of HCl, sulphur, char, and ash from the WtH processes ([Appendix 3.3](#)).

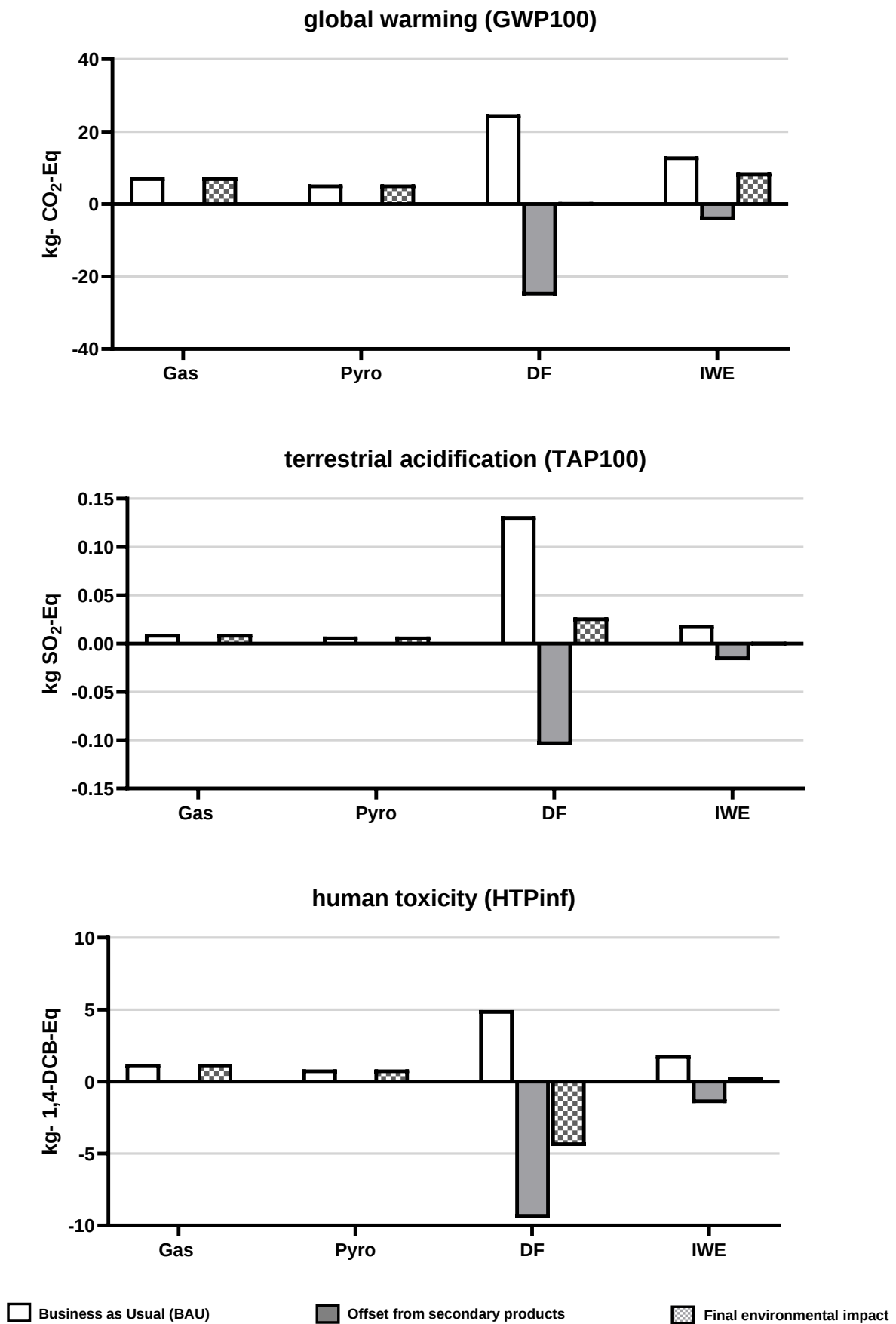


Figure 45. Selected environmental impact comparison between business-as-usual and its savings from secondary products production. Full result Appendix 3. (Gas: Gasification, Pyro: Pyrolysis, DF: Dark Fermentation, IWE: Incineration Water Electrolysis).

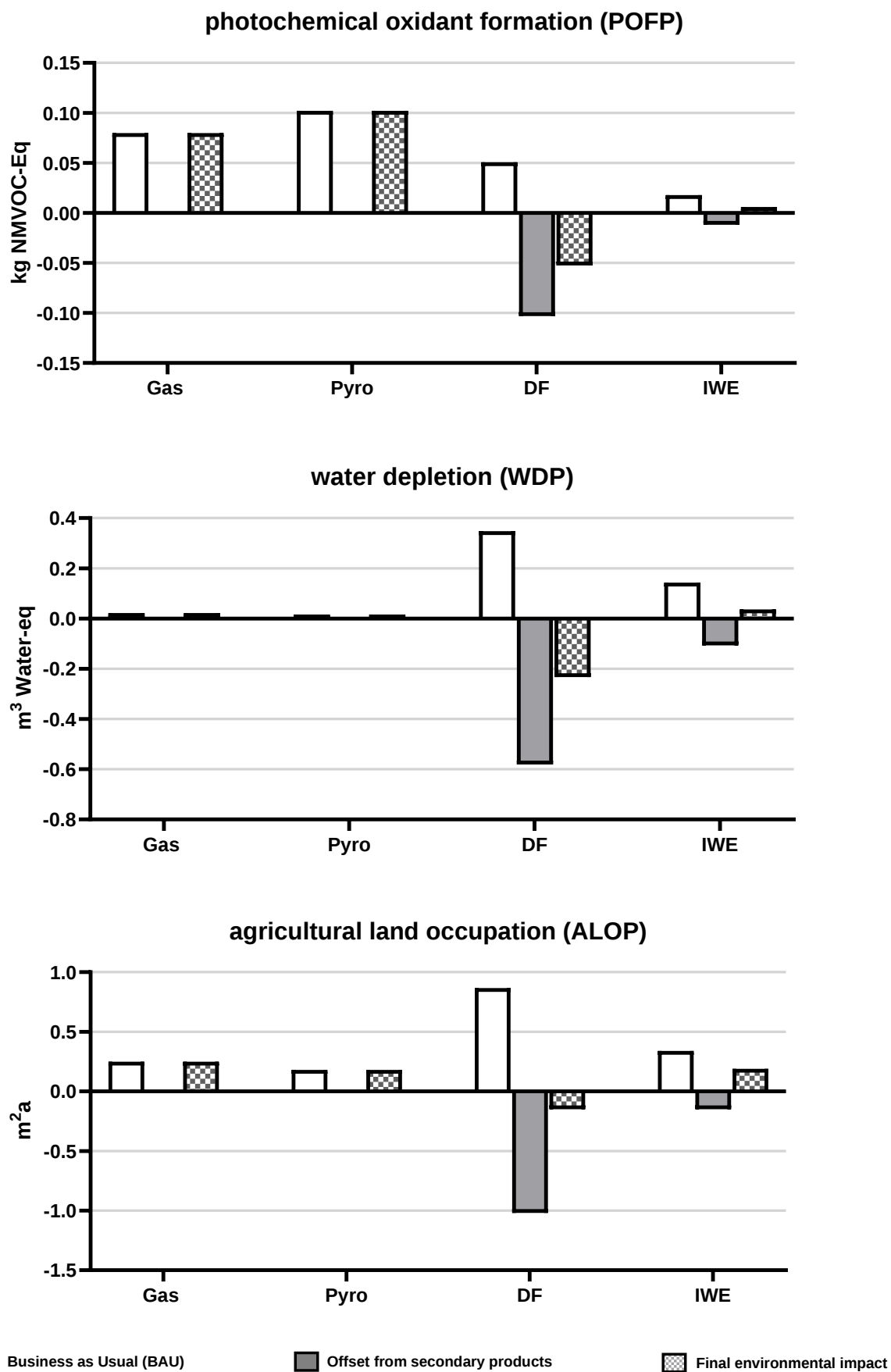


Figure 46. Selected environmental impact comparison between business-as-usual and its savings from secondary products production. Full result Appendix 3. (Gas: Gasification, Pyro: Pyrolysis, DF: Dark Fermentation, IWE: Incineration Water Electrolysis).

3.3.4. Impact of Capacity

Another aspect that was not addressed in the previous analyses is the role of plant capacity. Taking this into consideration can be challenging. In this work, the adoption of a functional unit is understandable as the objective is to assess environmental impact in relation to the production of 1 kg of hydrogen gas. This functional unit assesses the emissions in relation to hydrogen production, as per the goal of the study.

However, due to the diverse approaches to producing hydrogen from waste, this standardisation results in a wide variation in the requirement for MSW, ranging from 22 kg to 142 kg ([Appendix 3.1](#)). Because of this, the LCA of secondary offsets does not consider the potential emissions saved by “diverging” the MSW from landfill. Including this analysis would create a distorted result that favours DF and Inc heavily.

[Appendix 3.4](#) shows this result, including avoided emissions from landfilling in LCA for WtH can skew comparisons due to differing MSW requirements. DF and incineration require more MSW to produce 1 kg of hydrogen, leading to disproportionately high GHG savings compared to Gasification and Pyrolysis, which use less MSW. Hence, it's crucial to acknowledge that these results aren't meant for direct comparison due to the differing process yields.

Hence, this section compares the environmental impact of the process when the functional unit is standardised into 1 kg of MSW, shifting the perspective of the technology from hydrogen production into a waste treatment technology ([Figure 47](#)). Overall, incineration has the lowest environmental impact for most categories. This can be attributed to the high MSW capacity while producing low emissions. Incineration shows elevated impacts in terrestrial ecotoxicity due to its high ash productions.

Meanwhile, DF still has the highest acidification potential due to its sulphuric acid requirements. It has a low terrestrial eco-toxicity due to its lack of ash disposal. However, DF produces lower GWP than incineration and pyrolysis due to its biogenic origin of carbon emission. Gasification and pyrolysis produce similar environmental impacts, though gasification has a slightly lower impact in some categories due to its lower gas emissions. Gasification and pyrolysis produce the highest POFP due to its carbon monoxide emission.

Nevertheless, it is important to acknowledge that this result is analysed from the perspective of the WtH process as a waste conversion technology rather than one to produce hydrogen. This means that a highly efficient process like incineration may be more desirable when the main objective is to process waste instead of producing hydrogen.

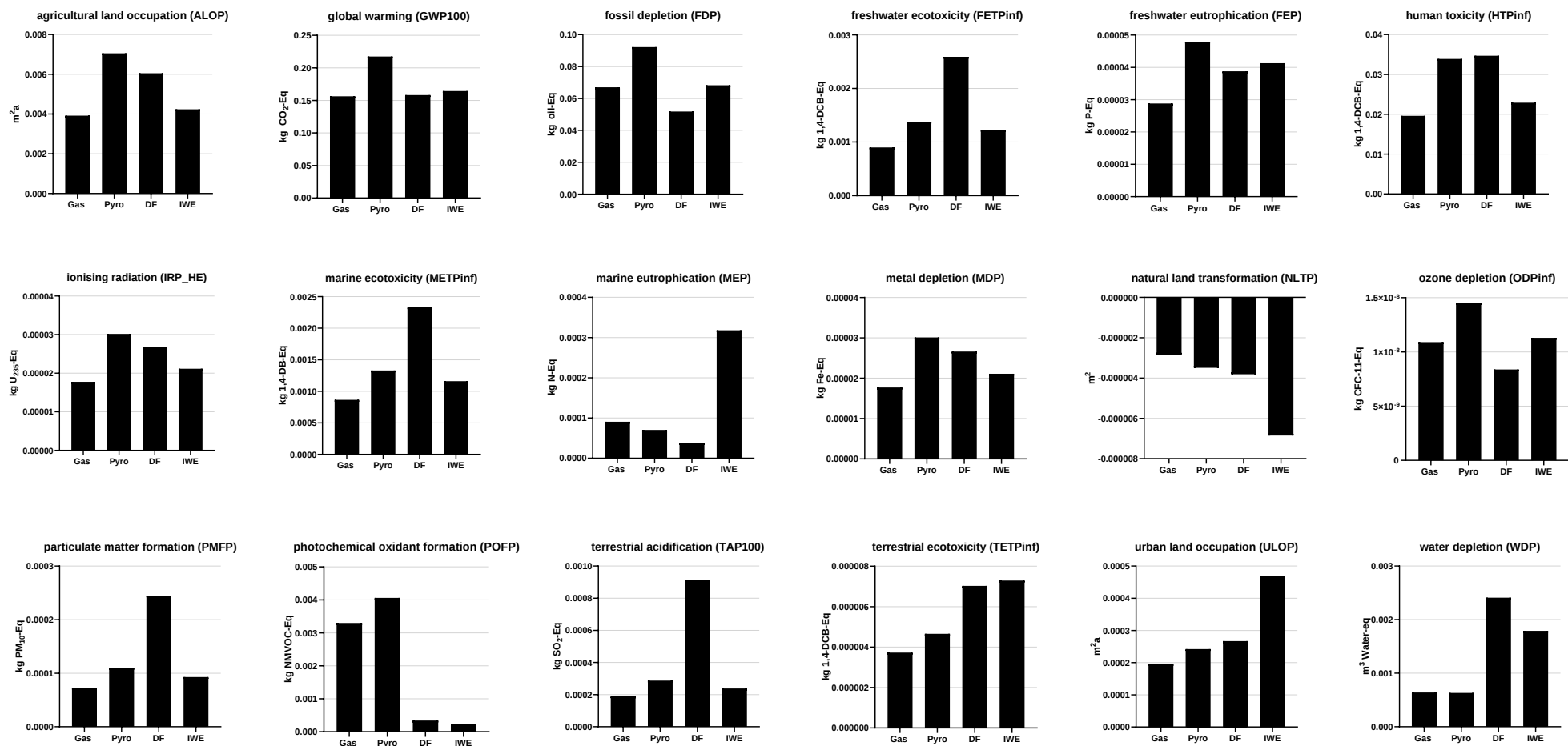


Figure 47. Environmental impact to process 1 kg of MSW through gasification (Gas), pyrolysis (Pyro), dark fermentation (DF), and incineration-water electrolysis (IWE) for business-as-usual.

3.3.5 Comparison with Traditional Waste Treatment

This section aims to compare the advanced waste to hydrogen technologies described in the report with traditional incineration and landfilling, where these readily available technologies have input and output available on the Ecoinvent Database ([Table 23](#)).

Table 23. Description of comparison for 1 kg of MSW waste treatment according to the Ecoinvent database

Database process	Abbreviation	Description
Incineration without Carbon capture	INC	Data origin from a MSW incineration facility in Netherland equipped with APC, with net production of 1.39 MJ/kg and 2.85 MJ/kg of power and heat respectively. Slag and ash are landfilled.
Sanitary landfill	FL	Generalised database with no specific location. LF is designed for untreated MSW equipped with base seal ad leachate collection system and treatment plant.
Unsanitary landfill	UN-FL	Generalised database of communal landfilling without leachate treatment.

However, LCA comparison between the result derived from the flowsheet simulation in [Chapter 2](#), and the data from Ecoinvent, may lead to inconsistencies due to the differing origins of the data. The mass-energy balance model in [Chapter 2](#) is fundamentally based on a set of modelling assumptions that simplify the complex realities of industrial processes, particularly those involving reaction kinetics used in the study. This simplification may result in outputs that do not fully capture the intricacies of real-world operations.

In contrast, the data available in Ecoinvent is typically collected from on-site facilities, reflecting the variability and real conditions of plant operations. However, while this real-world data is more representative. Factors such as site-specific variations and differences in data collection methods may introduce biases. Additionally, the database encompasses a more detailed spectrum of emissions and pollutant species compared to the flowsheet modelling approach.

Thus, it is important to note that an LCA comparison using different data sources—where one is model-driven, and the other is based on on-site measurements—may produce inconsistent results when normalised for a benchmark comparison. Therefore, the results from this section should be analysed with an understanding of the inherent discrepancies between the two data origins.

[Figure 48](#) shows the environmental impact comparison between the WtH technologies developed in this report and traditional waste management methods selected from the database. It can be seen that WtH technologies exhibit a lower global warming potential but score higher in metal and water depletion. For global warming potential, the carbon capture storage installed in WtH reduce carbon emission, resulting in a lower environmental footprint. Landfilling shows the highest GWP due to its methane emissions. In contrast, WtH technologies have higher metal depletion as they require more resources in the form of power and heat, while traditional incineration produces internal energy, and landfilling requires minimal energy consumption. Pyrolysis and gasification have the highest POFP due to carbon monoxide emissions. For acidification potential and water depletion, DF emerges as the highest due to its high sulphuric acid requirement.

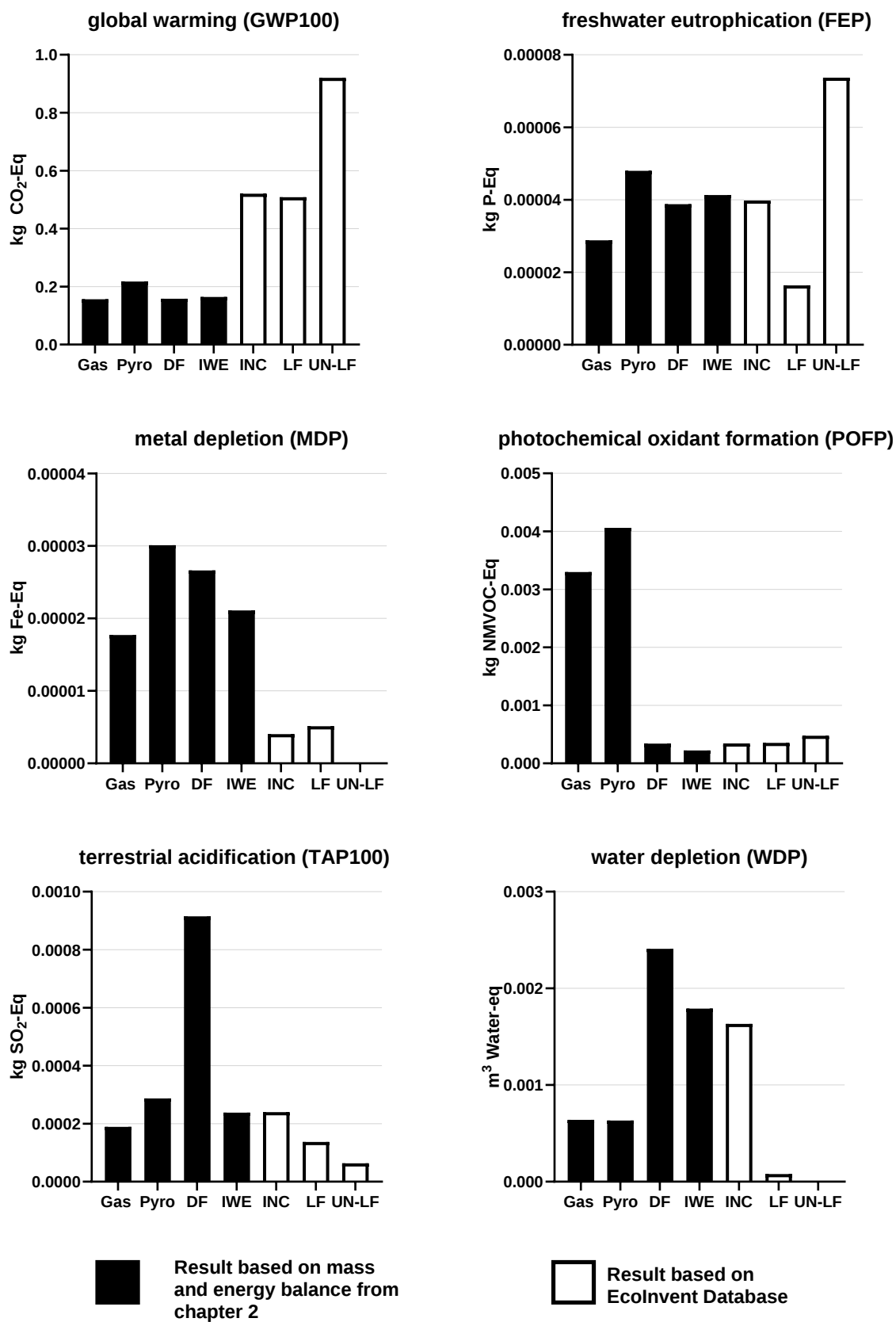


Figure 48. Selected environmental impact to process 1 kg of MSW through gasification (Gas), pyrolysis (Pyro), dark fermentation (DF), and incineration-water electrolysis (IWE) for business-as-usual of Waste to Hydrogen (WtH), along with the comparison with traditional waste management treatments for incineration (INC), sanitary landfill (LF) and unsanitary landfill (UN-LF), Full result Appendix 3.5.

3.4. Summary

This study has underscored the complex interplay of factors influencing the environmental impacts of four WtH technologies with CCS, namely gasification, pyrolysis, dark fermentation, and incineration-water-electrolysis.

Based on the reported material balances, and for the Business-as-Usual scenario, the LCA showed that pyrolysis and gasification emerge as the most environmentally favourable options for WtH production. Both processes have similar environmental impacts due to their direct and rapid hydrogen production. Conversely, DF shows the highest environmental impact for all categories due to its high chemical requirements and lower hydrogen yield.

Furthermore, substituting energy input with renewable energy offers reductions in most environmental impact categories, yet novel challenges arise in water consumption, land occupation, and metal depletion. Adoption of renewable energy can be accompanied by electrifying the process' heating system. This may lead to a lower environmental impact as it eliminates the need for a renewable-based heating system (i.e., biomass). However, this would warrant consideration of the LCA boundary expanding into other steps including the generation of renewable energy, manufacturing, and the recycling of renewable energy technologies. All of these are beyond the scope of this study but would be expected to influence the system-wide environmental impact.

In addition, the feasible integration of electrification input would need to be carefully assessed from a technical point of view. Dark fermentation and incineration-electrolysis produce significant amounts of energy that is lost to the surroundings. Hence, recovering this heat loss for internal use is crucial to lowering the environmental impacts. However, this approach will produce relatively less benefits for gasification and pyrolysis due to their reduced heat losses relative to the other technologies compared here.

Furthermore, the inclusion of secondary products proves effective in offsetting emissions, particularly for dark fermentation and incineration, which both consume a large volume of waste and, in return, produce large secondary products that may be useful for the market. Lastly, the LCA result favours incineration when the focus is shifted to waste conversion rather than hydrogen production. This is due to incineration's high-capacity operation and complete combustion efficiency, which results in less overall emissions. In comparison to traditional waste treatments (conventional incineration and landfilling), WtH carbon capture feature lowers the global warming impact but require more resources that result in a higher metal and water depletion.

Chapter 4. Comparative Analysis of Waste-to-Hydrogen and Alternative Waste-to-Energy Solutions

4.1. Introduction

WtH is a technology within the broader scope of waste-to-energy pathways. In addition to hydrogen, the conversion of waste into other types of energy such as heat, electricity, and synthetic fuels has received increasing attention. Therefore, it is crucial to benchmark waste-to-hydrogen technology against other waste-to-energy pathways to provide stakeholders with information to make informed choices in their decision-making.

It has been reported that the implementation of hydrogen into some sectors can be limited due to practical reasons. For instance, in the aviation sector, particularly medium- and long-haul flights, the application of non-emitting propulsion, such as green hydrogen and renewable electricity, to decarbonise the sector is likely to be limited due to the high energy required. Hence, sustainable aviation fuel (SAF) is seen as an alternative solution to decarbonise the aviation sector immediately. In addition, electrification is a competing decarbonisation pathway for a number of sectors, such as passenger vehicles and domestic cooking. In these sectors, the use of hydrogen is currently not feasible due to the lack of infrastructure and its lower efficiency compared to electrification—although there may be potential applications in these sectors as infrastructure develops and efficiency is improved. In this case, WtE could provide low-carbon electricity to meet the increasing demand for electrification. This report provides commentary of WtH technology compared with waste-to-sustainable aviation fuel (WtSAF) and waste-to-electricity (WtE) routes in terms of market potential, as well as cost and environmental impact.

4.2. Alternative Waste-to-Energy Pathways

4.2.1. Waste-to-Sustainable Aviation Fuel

Sustainable aviation fuel (SAF) is recognised as an immediate solution to decarbonise the aviation sector, which is aiming to achieve net-zero emissions by 2050. SAF is produced from a variety of sustainable feedstocks such as waste biomass. Compared to fossil jet fuel, SAF can reduce lifecycle carbon emissions by up to 80%.⁽¹⁵²⁾ SAF is seen as a drop-in fuel that can be directly and quickly integrated within the existing energy system by leveraging current storage and distribution networks. As such, end-users will not need to change their business models. With the pressing need for decarbonisation, SAF has been successfully used in numerous commercial flights. Notably, a historic transatlantic flight powered by 100% SAF took off in November 2023, from London Heathrow to New York, operated by Virgin Atlantic.⁽¹⁵³⁾

There are many pathways to produce SAF from various waste feedstocks that have been approved by the American Society for Testing Materials (ASTM). Herein, several ASTM-approved biogenic SAF production pathways with high potential for commercial deployment are discussed, including Hydrotreated Esters and Fatty Acids (HEFA), Gasification and Fischer-Tropsch (GFT), Catalytic Hydrothermolysis Jet (CHJ), Alcohol to Jet (ATJ), and Direct Fermentation of Sugar to Hydrocarbon (DSHC).

4.2.1.1. Hydrotreated Esters and Fatty Acids (HEFA)

Hydrotreated Esters and Fatty Acids (HEFA) is a scalable SAF production pathway that involves the hydroprocessing of oils and fats, as shown in **Figure 49**. Several feedstocks suitable for HEFA include waste and residue lipids, as well as purposely grown oil trees. HEFA can reach a carbon efficiency⁵ of 90% and an energy conversion efficiency⁶ of 76%, significantly higher than other biomass-to-liquid processes.^(7, 154) The yields to total output of hydrocarbons are 46% for both jet and road fuel, including gasoline and diesel. Compared to fossil jet fuel, HEFA offers a GHG emission saving potential of 75%-84%, with potential for a further reduction if green hydrogen is used in the hydro-processing step.⁽⁷⁾

⁵ Carbon conversion is defined as the proportion of the biomass carbon that ends up in synthetic fuels.

⁶ Energy conversion is defined as the ratio between the input energy and output energy in synthetic fuels reflected by the lower heating values.

Nevertheless, HEFA suffers from numerous key challenges including feedstock availability and vulnerability to supply chain shocks.

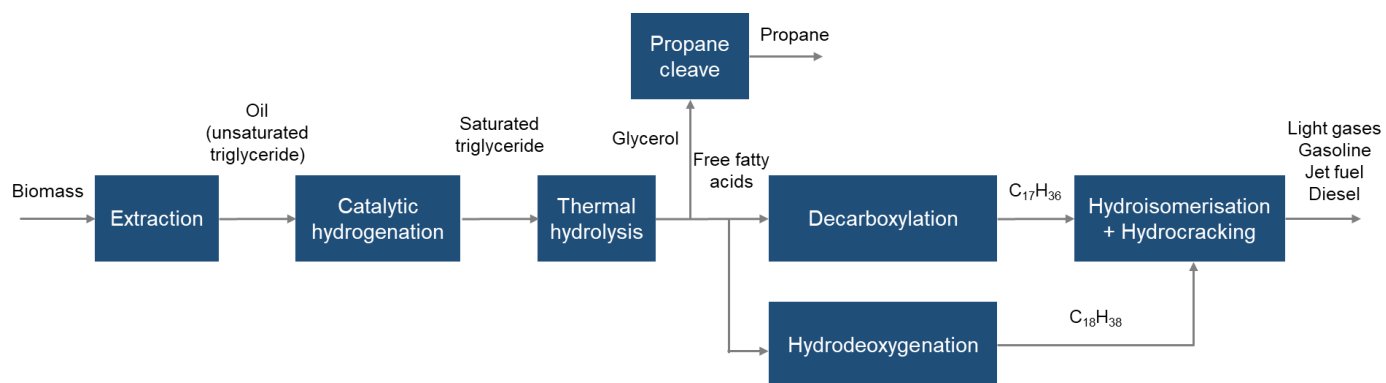


Figure 49. Process flow of HEFA. Source: Author.

HEFA is deemed a mature technology with a TRL of 8-9,^(155, 156) reflected by a number of commercial projects that already exist across the globe. Neste, for example, has successfully deploy commercial-scale HEFA-based NextBTL technology. The technology can produce synthetic fuels, including SAF and renewable diesel, from waste and residue raw materials, including animal waste fat, used cooking oil, and residue streams from the vegetable oil industry.⁽¹⁵⁷⁾ Neste's SAF is available at many major airports, including San Francisco International, Heathrow, and Frankfurt airports, and is currently being used by many leading commercial airlines. For ASTM certification, the maximum blend ratio for SAF produced via HEFA is 50%. However, flight trials have recently been performed with 100% HEFA jet fuel. In particular, aviation leaders such as Airbus, Rolls Royce, and the German Aerospace Center launched the first 100% SAF commercial passenger jet flight with HEFA fuel provided by Neste.⁽¹⁵⁸⁾



Porvoo Refinery, Finland



Singapore Refinery, Singapore

Figure 50. Neste HEFA plants of Porvoo refinery in Finland ⁽¹⁵⁹⁾ and Singapore refinery in Singapore ⁽¹⁶⁰⁾.

4.2.1.2. Gasification and Fischer-Tropsch (GFT)

Gasification and Fischer-Tropsch (GFT) involves the conversion of biomass waste-to-syngas (a mixture of carbon monoxide and hydrogen) via gasification, followed by the Fischer-Tropsch synthesis generating liquid fuels, as illustrated in **Figure 51**. The H₂/CO ratio in syngas has a critical impact on hydrocarbon product distribution. Feedstocks suitable for GFT include agricultural and forestry residues, municipal solid waste, and purposely grown cellulosic crops. The GFT conversion pathway has a carbon conversion efficiency of 41% and an energy conversion efficiency of 51%.^(7, 161) The yields to the total output of hydrocarbons (optimised for SAF production) are 60% jet fuel and 22% road fuel including gasoline and/or diesel. Compared to fossil jet fuel, GFT offers a GHG emission saving potential of 85-94%.⁽⁷⁾ Nevertheless, GFT suffers from numerous key challenges including feedstock availability and vulnerability to supply chain shocks.

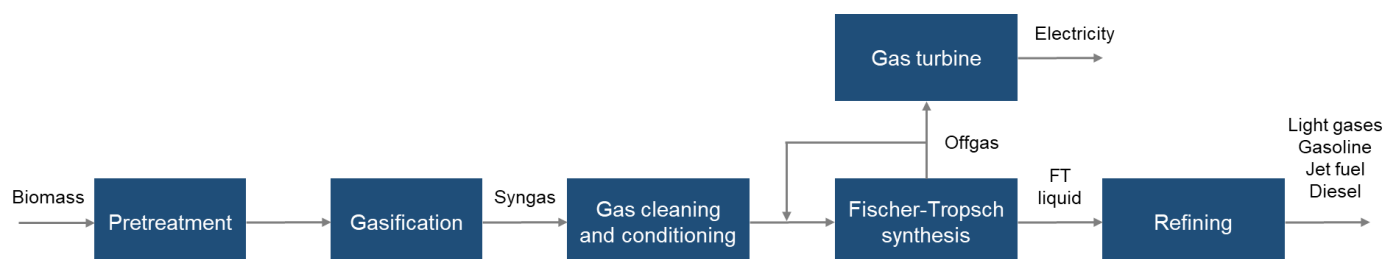


Figure 51. Process flow of GFT. Source: Author.

This pathway is now just approaching commercialisation with a current TRL of 7-8,⁽¹⁵⁶⁾ and several projects are already in pilot stage. The jet fuel produced through the GFT route has been certified by ASTM and can be blended up to 50% with fossil jet fuel. In France, Thyssenkrupp is working on the next generation of BioTfuel.⁽¹⁶²⁾ This project aims to achieve the conversion of lignocellulosic biomass into SAF and renewable diesel via entrained flow gasification and Fischer-Tropsch technologies. It is envisaged that commercial-scale BioTfuel will have a capacity of up to 5,000 barrels per day. The demonstration has been conducted successfully in Venette and Dunkirk. In addition, a collaboration between British Airways and Velocys aims to establish a Fischer-Tropsch BtL plant in the UK. Other notable commercial plants that are based on GFT production using sustainable feedstock are found in the USA (e.g., Red Rock Biofuels and Sierra Biofuels).⁽¹⁵⁸⁾



Figure 52. Thyssenkrupp BioTfuel projects in Venette and Dunkirk, France ⁽¹⁶³⁾.

4.2.1.3. Catalytic Hydrothermolysis Jet Fuel (CHJ)

CHJ, also called hydrothermal liquefaction (TRL 6)⁽¹⁵⁶⁾, transforms waste oils into jet fuel by combining clean free fatty acid (FFA) from waste oils with preheated feed water in a catalytic hydrothermolysis reactor, as shown in **Figure 53**. Under very high temperature and pressure, a single phase is formed comprising FFA and supercritical water wherein the FFA is cracked, isomerised, and cyclised into paraffin, isoparaffin, cycloparaffin, and aromatic compounds. The CH process can use waste oil and triglyceride-based feedstocks such as jatropha oil, carinata oil, camelina oil, and tung oil to produce SAF. The CH process consists of catalytic decarboxylation and dehydration steps at a temperature range of 250 to 380 °C and a pressure range of 5 MPa to 30 MPa. The treated products are cracked, isomerised, and cyclised to form n-alkanes, iso-alkanes, cyclo-alkanes, and aromatics (6-28 carbon numbers). The final products go through a fractionation step to produce naphtha, diesel, and jet fuel. The maximum allowable blend ratio for the SAF produced from CH is 50%.

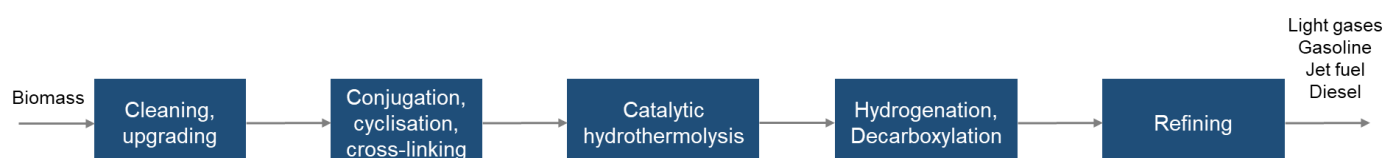


Figure 53. Process flow of CHJ. Source: Author.

4.2.1.4. Alcohol-to-Jet (AtJ)

AtJ is the catalytic conversion of alcohol into jet fuel and diesel. According to the ASTM specifications, two alcohol types (isobutanol and ethanol) are certified for SAF production. Isobutanol to jet was qualified under ASTM D7566 Annex 5 in April 2016. Ethanol was included as an AtJ feedstock later, in April 2018. Several feedstocks are suitable for this pathway, including biomass that can be converted into ethanol and isobutanol, for example, agricultural and forestry residues, municipal solid waste, and purposely grown cellulosic energy crops.

In the AtJ process, the alcohol feedstock is initially dehydrated to form alkenes. Then, C1 - to C4 alcohols are converted into C2 to C5 alkenes using zeolite and metal oxides catalysts. The dehydrated products are then oligomerised to get olefins with desired hydrocarbon chain lengths (typically from 8 to 16 carbons for the kerosene stage). The products are then passed through the hydrogenation unit to saturate the double bonds of the olefins, consequently producing paraffin. The paraffin is then fractionated, resulting in jet fuel and other co-products, as shown in **Figure 54**. The AtJ conversion pathway has a carbon conversion efficiency of 16% and an energy conversion efficiency of 33%.^(164, 165) The yields to the total output of hydrocarbons optimised for SAF production are 77% jet fuel and 6% road fuel including gasoline and/or diesel.⁽⁷⁾ Compared to fossil jet fuel, AtJ offers a GHG emission saving potential of 85-94%.⁽⁷⁾ However, AtJ suffers from a critical challenge given ethanol is produced today as a road gasoline blend and chemical feedstock, which compete as outlets for sustainable biomass.

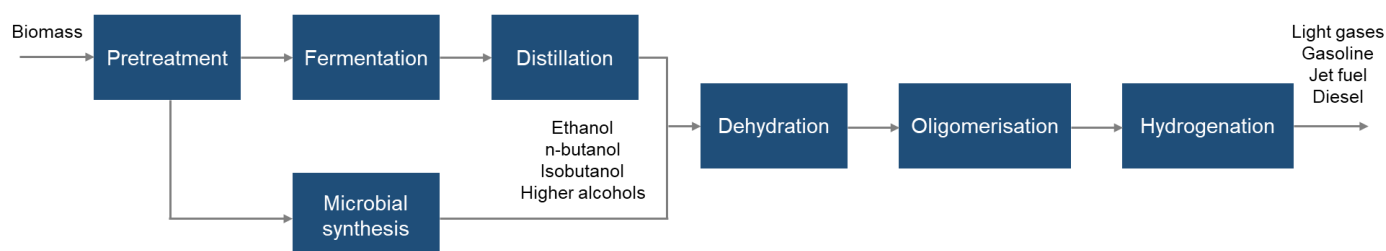


Figure 54. Process flow of AtJ. Source: Author.

AtJ is another route that is approaching commercialisation (TRL 7-8)⁽¹⁵⁶⁾, with pilot demonstration projects now being developed. The blend limit for both isobutanol to jet and ethanol to jet is 50%. In 2018, Virgin Atlantic completed the first commercial flight with AtJ fuel produced by LanzaTech. LanzaTech, via a spin-off called LanzaJet, aims to be amongst the leaders in the emerging SAF market. LanzaJet AtJ technology can process any source of sustainable ethanol, including ethanol produced from municipal solid waste, agricultural residues, industrial off-gases, and biomass. LanzaJet Freedom Pines Fuels in Georgia is the world's first ethanol-to-jet production plant.⁽¹⁶⁶⁾ The facility produces 10 million gallons of SAF and renewable diesel per year from ethanol, using a range of sustainable, low-carbon intensity ethanol, including from waste feedstocks. Another key player in the AtJ pathway is the Colorado renewable fuels producer Gevo.⁽¹⁵⁸⁾ The Oneworld Alliance members will use Gevo's SAF for operations in California including San Diego, San Francisco, San Jose, and Los Angeles International Airports.



Figure 55. LanzaJet Freedom Pines Fuel in Georgia, USA ⁽¹⁶⁷⁾ and Gevo Luverne in Minnesota, USA based on AtJ process ⁽¹⁶⁸⁾.

4.2.1.5. Direct Fermentation of Sugar to Hydrocarbon (DSHC)

DSHC (TRL 7-8 for conventional sugar feedstock, TRL 5 for lignocellulosic sugar feedstock)⁽¹⁵⁶⁾ utilises a fermentation process to convert a sugar feedstock into a hydrocarbon molecule that can be blended into conventional jet fuel. Unlike AtJ that requires an alcohol intermediate, DSHC directly produces alkane-type fuels from sugar. This pathway involves six major steps: pretreatment and conditioning, enzymatic hydrolysis, clarification of hydrolysate, biological conversion, hydroprocessing, and final purification, as shown in **Figure 56**. The DSHC process commonly uses modified yeast to ferment sugar feedstock into a C15 hydrocarbon molecule called farnesene ($C_{15}H_{24}$). Farnesene can be transformed into different products, such as jet fuel and diesel. Farnesene is further hydro-processed to form farnesane ($C_{15}H_{32}$), which can be blended with conventional jet fuel. The chemical structure of farnesane depends on different microbial biosynthesis pathways and conditions for fermentation. In addition, other fermentation products are also possible and vary with the process, microbial species used, and the substrate feedstock.

In this pathway there is no need for chemical catalysts and high temperature or pressure reactions. However, one of the problems associated with this DSHC process is a low energy output due to the low-temperature fermentation process. Nevertheless, it is still an up-and-coming and emerging option for SAF production. The DSHC process uses sugar cane, beet, and maize feedstock. Also, lignocellulosic biomass can be used in DSHC after some pretreatment. The maximum fuel blend for jet fuel derived from DSHC process is currently limited to 10%.



Figure 56. Process flow of DSHC. Source: Author.

Globally, SAF production from waste biomass has gained traction to rapidly decarbonise the aviation sector, especially long-haul flights where batteries and hydrogen are not feasible solutions. Several existing, ongoing, and planned SAF projects across the world are summarised in **Appendix 4**.

4.2.2. Waste-to-Electricity

Waste-to-energy (WtE) projects are tackling global waste management challenges by converting various solid waste, such as waste biomass and municipal solid waste (MSW), into usable electricity. This pathway is especially important in areas with high population densities and where landfill space is scarce. To date, incineration is the most common method in which heat from the combustion of waste is used to drive steam turbines to drive generators. This process is best exemplified by efforts in Singapore, whereby the TuasOne Incineration plant processes 3600 metric tons of MSW to generate 120 MW to the national grid daily.⁽¹⁶⁹⁾ Apart from incineration, there are gasification and pyrolysis processes, however, these two technologies are still mostly in the pilot or developmental stage due to their relatively lower efficiency and throughput capacities.

While WtE offers a promising waste management solution, concerns linger over potential air and water pollution. Advanced emission control technologies and stricter regulations are being developed to mitigate these risks. Process efficiency also varies across different WtE plants due to factors like waste composition (better efficiency with well-sorted and high caloric content waste), technology type (inherent efficiency gap between incineration, gasification and pyrolysis in terms of energy capture), and plant design and operational practices (i.e., combustion temperature, air flow controls, maintenance regime of boilers).

4.2.2.1. Incineration

Incineration is a method primarily utilised for disposing of waste in a furnace, which involves controlled combustion at high temperatures ranging between 750 and 1100°C.⁽¹⁷⁰⁾ The primary objective of this method is the decomposition and elimination of organic components within municipal solid waste (MSW), utilising oxygen to reduce both its weight and volume, and converting it into heat and energy, as illustrated in **Figure 57**. It has the capability to reduce nearly

70% of the total waste mass and 90% of the total volume, or solid wastes by 80-85%, depending on the composition and the extent of recovery of certain materials, such as metals, from the ash for recycling.

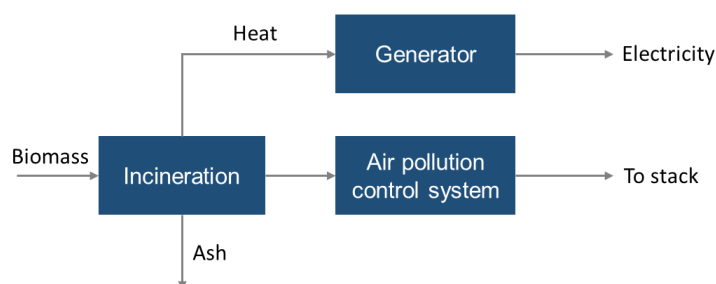


Figure 57. Process flow of waste incineration. Source: Author.

Incineration is a process that generates gaseous pollutants such as SO_x , CO_x , NO_x , polyaromatic hydrocarbons (PAH), and heavy metals, which are hazardous and require additional treatment through state-of-the-art flue-gas cleaning systems before final emission into the atmosphere (Figure 57). The primary significance of incineration lies in the production of heat and steam from MSW. The quantity and thermal potential of the collected material, the efficiency of the processing system, and the nature of energy produced are major factors that determine waste-to-energy (WtE) recovery. The energy efficiency for heat generation, cogeneration (steam and electricity), and pure electricity ranges from 80%, to 20-30%, and 20%, respectively.

Incineration has been widely implemented as a WtE technology across the world for a long time. The Klemestrud WtE plant in Norway, based on combined heat and power (CHP) incineration, is one of the oldest incineration plants in the world and has been operating since 1986 (Figure 58). The plant can process around 1205 tons of solid waste per day and generate 114 MW electricity as the output. In 2022, an agreement to incorporate carbon capture technology into this CHP incineration system was signed to reduce emissions.⁽¹⁷¹⁾ The captured CO_2 will be transported and stored by Northern Lights deep below the seabed in the North Sea. In Singapore, Hyflux Ltd and Mitsubishi Heavy Industries developed a large-scale waste incineration plant to produce electricity (Figure 58). The plant, known as TuasOne WtE plant, started operation in 2021 and has a capacity of 3600 tonnes of solid waste per day. It can generate 120 MW electricity per day. There has also been a plan to fit the incineration plant with carbon capture.⁽¹⁷²⁾ The captured CO_2 can be potentially used to produce greenfuels for Singapore’s aviation and maritime sector. Alternatively, the CO_2 can serve as a feedstock to treat the incineration ash, to form building materials for use in construction. In late 2023, CCS integration was successfully demonstrated at the Amager Bakke waste-to-energy facility in Copenhagen.⁽¹⁷³⁾ The plant captures up to 4 tonnes of CO_2 per day from flue gas and converts it into liquid form. The captured CO_2 is of food-grade quality and is sold for industrial applications, including vegetable cultivation at Østervang, Zealand.



Figure 58. CHP incineration plant in Klemetsrud, Norway and TuasOne WtE plant in Singapore.

4.2.2.2. Integrated Gasification Combined Cycle

Gasification involves the partial oxidation of carbonaceous materials with oxygen, which is typically generated by an air separation unit (ASU) and steam at elevated temperatures, resulting in the conversion of these materials into

syngas (comprising CO_2 , H_2 , CO , CH_4). Gasification processes are distinguished based on temperature, with conventional gasification operating between $800\text{--}1200^\circ\text{C}$, while plasma gasification reaches much higher temperatures, ranging from 5000°C up to $15,000^\circ\text{C}$. The integrated gasification combined cycle (IGCC) is a common technology that uses conventional gasification (**Figure 59**), whereas the integrated plasma gasification combined cycle (IPGCC) employs plasma gasification. Both methods facilitate carbon capture, leading to power generation with zero CO_2 emissions.⁽¹⁷⁰⁾

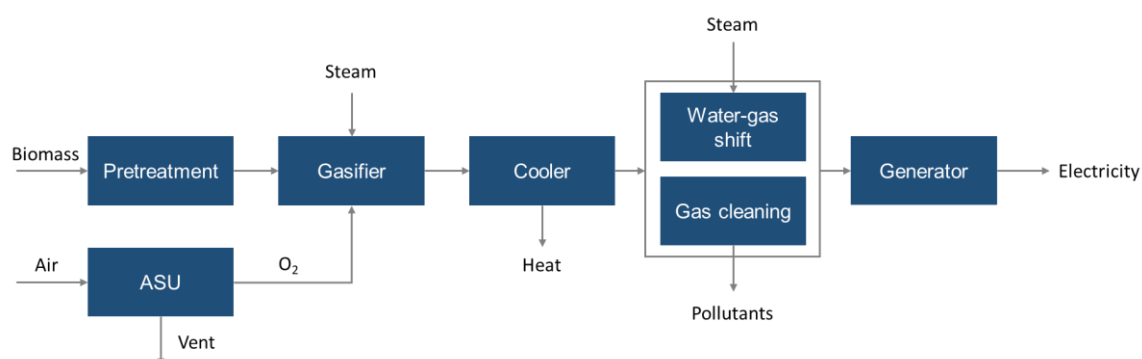


Figure 59. Process flow of integrated gasification combined cycle. Source: Author.

Numerous studies have investigated plants utilising MSW gasification and plasma gasification, as well as co-gasification of waste with other fuels, to produce not only electricity but also district heat and gaseous hydrogen. Overall, these studies conclude that gasification-based systems are highly efficient and capable of handling challenging low-grade fuels. Additionally, gasification plants demonstrate considerable flexibility, with the choice of gasifying agent depending on the desired end product. For instance, injecting steam into the reactor is preferred for hydrogen production, whereas oxygen-enriched air is recommended for electric power generation.

While gasification shows promise as a waste management method, there is currently only one commercial plant utilising waste as an energy source in the gasification process for electricity and heat production. Moreover, the cost associated with gas cleaning is higher compared to waste incineration.

Waste-to-electricity has found recent appeal in a number of countries. Several existing, ongoing, and planned waste-to-electricity plants across the world are summarised in **Appendix 4**.

4.2.2.3. Landfill Gas Combustion

A landfill is a waste disposal area where waste is generally buried below ground. It is one of the oldest and most common waste disposal options utilised around the world and ensures that rubbish is separated from the surrounding areas. A variety of gases are released in landfills, however the major one (over 50% of the total amount) is methane, which is a contaminating greenhouse gas. Methane is around 21 times more powerful than carbon dioxide and the major concern when it comes to landfill gas—man made waste is the third largest source of methane.

To produce methane, waste that is deposited into a landfill first undertakes an aerobic (or ‘with oxygen’) decay stage, which results in very low methane levels. Generally, after less than a year, anaerobic (or ‘without oxygen’) circumstances are created and methane-producing bacteria begin their decomposition of the waste, which produces methane. The landfill gas can then be used to generate electricity using a biogas combustion engine as the main component of the process as illustrated in **Figure 60**.⁽¹⁷⁴⁾

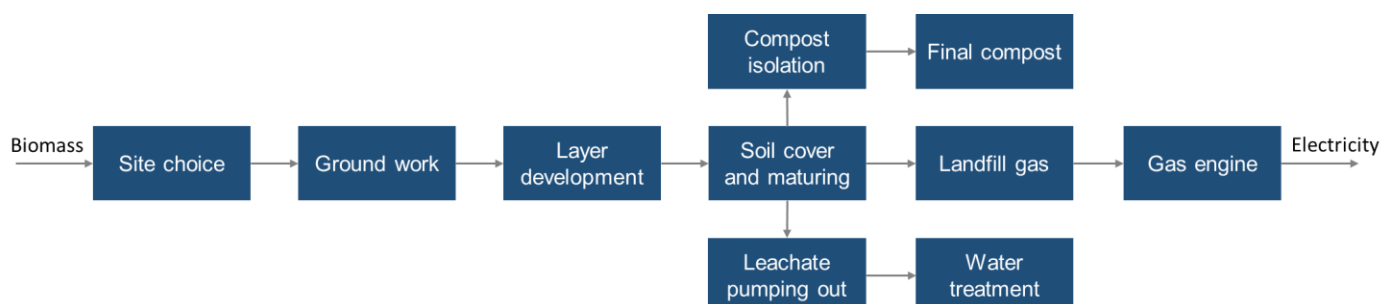


Figure 60. Schematic of landfill gas combustion for power generation.⁽¹⁷⁰⁾

This WtE process is best exemplified by the Malaysian Government's efforts to deploy a 12 MW WtE plant at Bukit Tagar Enviro Park (BTEP) that can convert methane gas from solid waste at the landfill, into electricity.⁽¹⁷⁵⁾ This plant channels around 339 million kWh of electricity to the electricity grid.

4.2.2.4. Microbial Fuel Cell

Microbial fuel cell (MFC) uses bacteria to convert organic waste into electrical energy. The use of MFC as an alternative source for power generation is considered as a clean emerging process, which utilises renewable methods and does not produce any toxic byproduct. An MFC is a system in which microbes convert chemical energy produced by the oxidation of organic/inorganic compounds into ATP by sequential reactions in which electrons are transferred to a terminal electron acceptor to generate an electrical current.⁽¹⁷⁶⁾

A typical MFC consists of anode and cathode compartments, which are separated by a cationic membrane (Figure 61). Microbes reside in the anode compartment, where they metabolise organic compounds such as glucose which act as an electron donor. The metabolism of these organic compounds generates electrons and protons. Electrons are then transferred to the anode surface. From the anode, the electrons move to the cathode through the electrical circuit, while the protons migrate through the electrolyte and then through the cationic membrane.

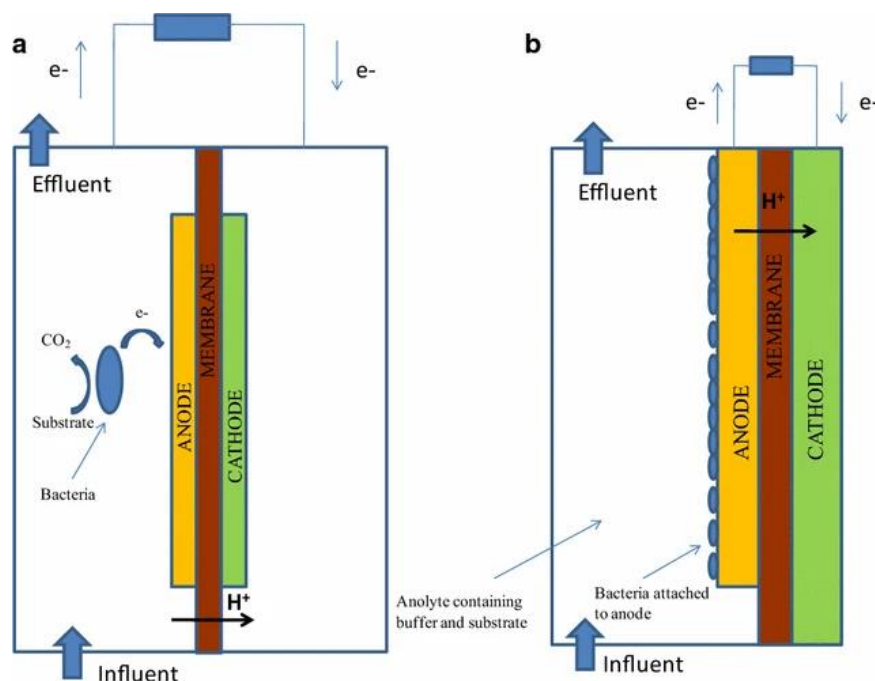


Figure 61. Schematic illustration of (a) dual-chambered MFC and (b) single-chambered MFC ⁽¹⁷⁶⁾. Copyright © 2016 Springer Nature.

While MFC is a promising emerging WtE technology, the power density obtained is still relatively low. This hinders its applicability to waste management and electricity generation. In addition, the material used in the cathode/anode and membrane during the scale up of MFC is costly, and results in a high levelised cost of electricity.

4.3. Comparative Analysis of Waste-to-Energy Pathways

Various technologies are utilised to recover energy from solid waste, and each is suited to different types of waste feedstock. Every waste-to-energy alternative exhibits distinct advantages and limitations. Hence, it is crucial to optimise alternatives or combinations thereof, to maximise the benefits. Identifying the ideal waste-to-energy technology is a complex undertaking that cannot rely on a single criterion. Instead, it entails navigating a multifaceted problem, necessitating the prioritisation of alternatives through a multi-criteria decision-making process. In selecting

the most suitable option for energy recovery from municipal solid waste, market, technical, environmental and economic factors must all be taken into account.

4.3.1. Methodology

A multi-criteria assessment (MCA) approach has been developed to comparatively evaluate waste-to-hydrogen (WtH) with other waste-to-energy pathways, specifically waste-to-SAF (WtSAF) and waste-to-electricity (WtE). The MCA involves assessing the most mature process for each pathway, including Gasification (WtH), Fischer-Tropsch (WtSAF), and Incineration (WtE) across different market, technical, environmental, and economic metrics. CO₂ capture is considered in WtH and WtE pathways to produce a low-carbon energy carrier. The MCA framework summarised in **Table 24** is applied to determine the overall performance rating for each waste-to-energy pathway. The rating ranges from 1 to 5, with 1 representing the least favourable performance metric and 5 representing the most favourable. A balanced weighting for each criterion and subcriterion here is assumed. However, it is worth noting that the weighting should be determined on a case-by-case basis through stakeholder consultations.

Table 24. Multi-criteria assessment framework for WtH, WtSAF, and WtE.

Main criteria	Subcriteria	Description	Weighting	Rating
Market (25%)	Potential maximum market size (100%)	Potential maximum market size is assessed based on the projected demand in 2050 of each energy product, representing the fossil fuel displacement potential.	20%	1: <1,000 TWh 2: 1,000-10,000 TWh 3: 10,000-15,000 TWh 4: 15,000-20,000 TWh 5: ≥20,000 TWh
Technical (25%)	Energy efficiency (33.3%)	Energy production efficiency is assessed based on the product yield percentage (MWh energy product per MWh energy input).	15%	1: 0-30% 2: 30-40% 3: 40-50% 4: 50-60% 5: 70-100%
	Infrastructure readiness (33.3%)	Infrastructure readiness is assessed based on the existence of supporting infrastructure in the Netherlands to enable the overall value chain.	10%	1: Low 3: Medium 5: High
	Process complexity (33.3%)	Process complexity is assessed based on the level of complexity of the technology, considering the required main process units as well as upstream and downstream units.	5%	1: High 3: Medium 5: Low
Environmental (25%)	Climate change impact (50%) ^{a)}	Climate change impact is assessed based on the potential amount of CO ₂ emitted during the lifecycle of the plant. The level of impact is measured based on the GWP values normalised against their lower heating values, compared to the corresponding traditional pathway without carbon abatement.	15%	1: ≥ 1x 3: 0.5-1x 5: ≤0.5x
	Pollution potential (50%)	Pollution potential is assessed based on the environmental impacts of the technology on water, soil, and air.	10%	1: High 3: Medium 5: Low
Economic (25%)	Initial CAPEX (50%) ^{b)}	CAPEX of the technology is assessed based on the specific capital investment required in US\$/MWh energy product compared to the typical CAPEX of the corresponding traditional pathway without carbon abatement.	15%	1: >2x 3: 1.5-2x 5: <1.5x
	Production cost (50%) ^{c)}	Production cost of the technology is evaluated and compared based on levelized cost of energy product (US\$/MWh) compared to the typical production cost of the corresponding traditional pathway without carbon abatement.	10%	1: >2x 3: 1.5-2x 5: <1.5x

^{a)} GWP values for fossil H₂ production (0.33 kgCO₂-eq/kWh for SMR and 0.69 kg CO₂-eq/kWh for coal gasification)⁽¹⁷⁷⁾, jet fuel production (0.32 kg CO₂-eq/kWh)⁽¹⁷⁸⁾, and electricity production (0.82 kg CO₂-eq/kWh)⁽¹⁷⁹⁾.

^{b)} Initial CAPEX for fossil H₂ production (US\$5-10/MWh) and electricity production (US\$27/MWh for coal power plant).

^{c)} Production costs of fossil H₂ (US\$27-66/MWh), jet fuel (US\$70/MWh), electricity (US\$60/MWh).

4.3.2. Multi-Criteria Analysis Results

The MCA assesses each waste-to-energy pathway based on 4 main criteria including market, technical, environmental, and economic aspects, which can be broken down into a total of 8 sub-criteria. The scoring and data used to determine the score are summarised in [Table 25](#).

Table 25. MCA results for comparative analysis of WtH, WtSAF, and WtE. CO₂ capture is considered in WtH and WtE cases.

Main criteria	Subcriteria	WtH Gasification	WtSAF Fischer-Tropsch	WtE Incineration
Market (25%)	Potential market size (100%)	5,000-17,000 TWh/year (2050)	4,000-5,340 TWh/year (2050)	70,000 TWh/year (2050)
Technical (25%)	Energy efficiency (33.3%)	~50%	~50%	~20-30%
	Infrastructure readiness (33.3%)	Low	Medium-High	High
	Process complexity (33.3%)	Medium-High	Medium-High	Medium-High
	Sub-rating	2	3	2.7
Environmental (25%)	Climate change impact (50%)	Low (-0.121 kgCO ₂ /kWh)	Low (0.216 kgCO ₂ /kWh)	Low (-0.262 kgCO ₂ /kWh)
	Pollution potential (50%)	Medium-High	Medium-High	High
	Sub-rating	3.5	3.5	3
Economic (25%)	CAPEX (50%)	US\$80/MWh	US\$130/MWh	US\$100/MWh
	Production cost (50%)	US\$155/MWh	US\$156/MWh	US\$120-170/MWh
	Sub-rating	1	1	1
Overall rating		2.1	2.4	2.9



*) The rating in the MCA results table reflects the performance for each metric, with 1 representing the least favourable metric performance and 5 representing the most favourable metric performance.

Market size

In terms of the market, the potential market size for WtE is anticipated to be the highest, given that global electricity demand by 2050 is expected to reach 70,000 TWh/year.⁽¹⁸⁰⁾ The global demand for H₂ is expected to reach between 5,000-17,000 TWh/year by 2050,^(145, 181) dominated by niche applications across the industrial, transport, energy, and building sectors. This suggests that WtH has a relatively small-medium market potential. The SAF market is also considered limited as it primarily serves the aviation sector, which is estimated to contribute around 4,000-5,340 TWh/year by 2050⁽¹⁸²⁾—lower than WtH and WtE. Therefore, the market potential for SAF is assessed to be small-medium.

Energy efficiency

Energy efficiency is considered the primary sub-criteria under technical performance. Currently, WtH via gasification exhibits moderate energy efficiency of approximately 50%, as suggested in [Chapter 2](#). Similarly, WtSAF via Fischer-Tropsch has moderate energy efficiency of 46%.^(183, 184) On the other hand, WtE via waste incineration suffers from low electricity production efficiency, primarily due to inefficient incineration processes and the thermodynamic limitations of the Rankine cycle in power generation. It is estimated that electricity generation efficiency is around 20-30%.⁽¹⁸⁵⁾

Infrastructure readiness

Often, the primary challenge in implementing new technologies lies in the lack of infrastructure. Therefore, assessing the readiness of existing infrastructure to support the waste-to-energy pathway is crucial. WtE has the highest rating in terms of infrastructure readiness, as the electricity distribution network in the Netherlands is available throughout the country and can be readily retrofitted to include WtE plants. Additionally, there are already existing incineration plants in the Netherlands.⁽¹³³⁾ WtSAF has medium to high infrastructure readiness, as SAF closely resembles conventional jet fuel. Consequently, SAF can serve as drop-in fuel for aviation (currently the highest blending ratio allowed by ASTM is 50%) with the possibility to even use 100% SAF. Furthermore, the Netherlands can leverage existing jet fuel storage and distribution networks to support the SAF value chain. Conversely, the infrastructure readiness to support the WtH pathway is evaluated as low. This is because widespread use of hydrogen will require modifications to end-use technologies and extensive infrastructure to facilitate hydrogen delivery.

Process complexity

The complexity of the technology is assessed based on the main process units as well as the level of pretreatment and post-treatment required for the overall process. In this instance, WtH, WtSAF, and WtE are evaluated to have medium-high process complexity particularly due to the complex nature of MSW that may contain various contaminants. This renders these waste-to-energy processes complex, particularly for the gas cleaning step.

Climate change impact

The climate change impact of the technology pathways is evaluated based on the potential amount of greenhouse gas emissions during its project lifecycle. For the assessment, we consider the calculated GWP100 values for gasification (WtH) from [Chapter 3](#) and compare it against the literature GWP values of an MSW incineration plant (WtE) that incorporates CCS,⁽¹⁸⁶⁾ and a Fischer-Tropsch (FT) SAF plant that uses MSW with 40% non-biogenic carbon content (WtSAF). The result demonstrates WtSAF with the highest GWP (0.216 kgCO₂/kWh SAF)⁽¹⁸⁷⁾ followed by WtH (-0.121 kgCO₂/kWh H₂ for business-as-usual with landfill credit from [Chapter 2](#)) and WtE (-0.262 kgCO₂/kWh). The values are considered 'low' impact compared to the existing fossil-based processes.

Pollution potential

The pollution potential is assessed based on the potential release of pollutants into the environment, excluding greenhouse gas emissions, as these components are included in the climate change impact metric. WtE via incineration is considered to have high pollution potential due to the possibility of emitting hazardous and toxic compounds such as polycyclic aromatic hydrocarbons (PAH), dioxins, and furans, which may form due to incomplete combustion and/or poor control of operating temperature.^(170, 188) Similarly, WtH and WtSAF processes, despite having lower climate change impact, use more resources and thus leading to a higher impact on other environmental impacts such as metal and

water depletion, as suggested in [Chapter 3](#) for WtH. Therefore, the pollution potential for WtH and WtSAF is evaluated as ‘medium-high’ impact.

CAPEX

The feasibility in terms of CAPEX is assessed based on the estimated specific CAPEX required per MWh of energy product, in comparison to the conventional technologies needed to produce the target energy product. For instance, WtE-CCS via incineration is considered CAPEX-intensive due to the substantial capital investment needed, amounting up to US\$100/MWh electricity.⁽¹⁸⁹⁾ This CAPEX is considerably higher than the typical CAPEX for a coal power plant, which is estimated at US\$27/MWh electricity.⁽¹⁹⁰⁾ Similarly, the CAPEX for WtH-CCS and WtSAF remain higher compared to existing conventional processes. For example, the CAPEX for WtH with CCS, as per [Chapter 2](#), is estimated to be US\$80/MWh H₂, significantly higher than the CAPEX for unabated steam methane reforming (US\$5/MWh)⁽¹⁹¹⁾ and coal gasification (US\$10/MWh)⁽¹⁹²⁾. Similarly, the CAPEX for WtSAF via the Fischer-Tropsch pathway is quite high, reaching US\$130/MWh. This figure alone exceeds the current average value of conventional jet fuel, which stands at US\$70/MWh jet fuel.⁽¹⁹³⁾ These CAPEX figures for WtH, WtSAF, and WtE position these waste-to-energy processes at a low ranking in terms of CAPEX feasibility.

Production cost

WtH and WtSAF exhibit higher production costs compared to the corresponding conventional fossil fuel pathways. The H₂ production cost via WtH-CCS is estimated to be US\$155/MWh, five times higher than unabated steam methane reforming and coal gasification (US\$27-66/MWh). The SAF production cost from waste (US\$156/MWh) is also significantly higher compared to the current jet fuel cost of US\$70/MWh. Similarly, electricity production cost from a WtE currently ranges between US\$120-170/MWh, which stands higher than market price around US\$60/MWh. These production cost figures position these technologies at a low ranking in terms of current production cost feasibility.

Overall, the MCA results suggest that WtH, WtSAF, and WtE exhibit low-moderate ratings, with WtE (2.9 out of 5) is slightly higher than WtSAF (2.4 out of 5) and WtH (2.1 out of 5). The higher ranking of WtE is primarily driven by the anticipated higher market potential in 2050 as the world races to decarbonise via electrification using low-carbon energy. On the other hand, WtH and WtSAF could play a role in niche applications, particularly for hard-to-abate sectors. In addition, WtH is likely to be constrained on the limited existing infrastructure for hydrogen transport, storage, and utilisation. This renders the viability of WtH to be lower compared to WtSAF and other synthetic fuels such as gasoline and diesel, which can be easily integrated into current energy infrastructure. From environmental point of view, these three waste-to-energy pathways offer competitive advantages to existing fossil fuel-based pathways to reduce GHG emissions. However, waste processing to generate energy products may lead to higher impacts on other environmental impacts such as metal and water depletion. Another crucial point is that the economics of WtH, WtSAF, and WtE are currently constrained by high upfront CAPEX, a challenge shared by several other clean energy technologies. These MCA results indicate that WtH shares technical and economic challenges with other waste-to-energy solutions like WtSAF and WtE. Consequently, technology improvements and cost reductions become essential to improve the viability of waste-to-energy applications including WtH, WtSAF, and WtE. Moreover, the future application of WtH is likely to be more limited particularly compared to WtE.

4.4. Summary

Waste-to-hydrogen falls within the realm of waste-to-energy technologies, where waste is repurposed into various useful energy products. One appealing alternative within this domain is the conversion of waste feedstock into sustainable aviation fuel (SAF), facilitating the immediate decarbonisation of the aviation sector. Numerous pathways for waste-to-SAF conversion have been certified by the American Society for Testing and Materials, including hydrotreated esters and fatty acids, gasification and Fischer-Tropsch, catalytic hydrothermolysis jet fuel, alcohol to jet, and direct fermentation of sugar to hydrocarbon. Specifically, gasification and Fischer-Tropsch process offers a pathway to utilise MSW for SAF production. Furthermore, waste-to-electricity presents another viable waste-to-energy technology, which has seen widespread adoption globally. Incineration stands out as the most commonly

utilised process, primarily owing to its technological maturity. Alternative waste-to-electricity technologies, such as integrated gasification combined cycle, landfill gas combustion, and microbial fuel cells have also been developed, although they have been less extensively implemented than incineration.

To benchmark waste-to-hydrogen against other waste-to-energy technologies, a comparative study has been conducted, comparing waste-to-hydrogen with waste-to-SAF and electricity. Municipal solid waste serves as the feedstock, and the established processes for handling these waste types have been chosen. Gasification, gasification and Fischer-Tropsch, and incineration were selected to represent waste-to-hydrogen, SAF, and electricity technologies, respectively. The comparative analysis, considering various criteria such as market potential, technical aspects, economic viability, and environmental impact, revealed that waste-to-hydrogen, SAF, and electricity demonstrate moderate performance. Despite the competitive advantage in lowering climate change impact compared to existing fossil fuel-based processes, shared technical and cost challenges for implementing these waste-to-energy technologies leads to low to moderate current feasibility performance. The overall viability of waste-to-hydrogen application is likely to be more limited compared to waste-to-electricity and waste-to-sustainable aviation fuel primarily due to the niche applications of hydrogen and the lack of existing infrastructure for hydrogen transport, storage, and utilisation.

Chapter 5. Waste-to-Hydrogen in the Context of Environmental Justice

5.1. Introduction

The concept of environmental justice emerged in the United States in the 1970s and underscores the importance of equitable and inclusive considerations in the pursuit of sustainable energy solutions. It addresses the disproportionate environmental burdens faced by marginalised communities, who often suffer the brunt of pollution and environmental damage due to harmful practices and policies, and lax enforcement.^(194, 195) Environmental justice (EJ) is multifaceted—there is considerable variation and overlap in understanding across different communities and disciplines, and this reflects the different philosophical and ethical perspectives.^(195, 196) This report acknowledges this complexity and positions itself within a specific subset of EJ understandings that are relevant to the evaluation of WtH projects. It focuses on ensuring equitable and inclusive considerations in the pursuit of sustainable energy solutions. When assessing the potential success of WtH project, it is important to understand that there is a distinction between fairness and equity. Fairness ensures equal opportunity in participation and benefits, whereas equity recognises historical disadvantages and provides additional support to level the playing field. Thus, environmental justice requires both procedural fairness (participation) and distributive fairness (benefit/burden distribution). It also promotes inclusivity (diverse voices) and strives for equity (addressing past injustices and supporting disadvantaged communities). Moving forward in this report, where the term ‘fairness’ is used, for the sake of clarity it will cover equity as well.

To evaluate WtH projects, we drew insights from reported EJ frameworks in energy production.⁽¹⁹⁷⁻¹⁹⁹⁾ F. Müller et al notably reported a 6-element justice framework for qualitatively evaluation the injustices in hydrogen projects⁽²⁰⁰⁾ and, as WtH projects share a technical and stakeholder landscape with conventional hydrogen production, this framework can be adapted to provide a foundation for assessing the equitable distribution of benefits and burdens in WtH projects.

This report proposes a methodology for qualitatively and quantitatively assessing how the benefits and burdens associated with WtH projects are distributed across six distinct justice dimensions. To demonstrate its applicability, we apply the framework to a real-world case study of a WtH initiative (FUREC project) in the Netherlands.⁽²⁰¹⁾ It is important to note that this report focuses on the assessment methodology itself, rather than delving into specific policies, legislation, or the success metrics for mitigating burdens or enhancing benefits arising from WtH projects. While crucial, addressing these issues often involves complex legislative frameworks and stakeholder negotiations, which fall outside the scope of this report. The primary focus here is to provide a robust tool for evaluating the distribution of benefits and burdens and pave the way for informed decision-making and potential future policy development.

5.2. Adapting Existing EJ Dimensions for WtH Evaluation

Existing hydrogen EJ frameworks like F. Müller et al’s⁽²⁰⁰⁾ work offer valuable guidance, however they require further refinement in order to be applied to WtH projects. While both WtH and conventional hydrogen projects share the overarching goal of generating hydrogen for energy storage, WtH projects add the complexity of municipal waste management and its associated environmental and social justice concerns. As such, frameworks designed specifically for hydrogen production might not adequately capture these nuances. The specific technologies and processes involved in WtH also differ from those used in conventional hydrogen production, which could potentially lead to distinct benefit and burden scenarios.

F. Müller et al.⁽²⁰⁰⁾ outlined the six justice dimensions as: procedural, relational, recognitional, distributive, restorative, and epistemic justice. Among the six, recognitional justice overlaps with procedural and relational justice in its focus on acknowledging local and historically marginalised communities (i.e., indigenous, low-income residents) that are impacted by environmental decisions. This overlap suggests that a streamlined framework for WtH projects is possible. Sovacool et al.⁽²⁰²⁾ proposed an alternative framework that incorporates cosmopolitan justice, which considers

broader global implications. In the context of WtH, this translates to evaluating the project's contribution to climate change mitigation. While WtH's local environmental impacts are important, a sustainable WtH project can reduce greenhouse gas emissions compared to traditional waste management, offering a global scale benefit.

This report's proposed framework considers six key social justice dimensions for WtH projects (**Table 26**), along with potential metrics and recommended levels of community engagement for each. The level of community involvement varies depending on the specific dimension and the scale of potential impacts:

- **Procedural and relational justice** require high levels of local participation. Residents should be directly involved in decision-making processes (procedural justice) and relationship building activities (relational justice). Examples include community meetings, workshops, and citizen advisory boards specifically designed for the affected communities.
- **Distributive and restorative justice** also emphasise the need for high participation from residents, potentially including historically marginalised groups. Community members should have a say in how the project's benefits and burdens are distributed (distributive justice) and how any past environmental harms are addressed (restorative justice). This can involve identifying local impacts, co-developing mitigation plans that address local needs, and monitoring project outcomes to ensure fairness.
- **Epistemic justice** focuses on valuing diverse forms of knowledge. In the local context, this might involve incorporating indigenous knowledge about waste management practices and the ecosystem into project planning. Collaboration with scientific experts is also crucial for a comprehensive understanding of potential environmental impacts.
- **Cosmopolitan justice**, as previously mentioned, focuses on global implications. However, in the context of WtH, it can extend to national-level concerns. If the project utilises waste from multiple regions within a country, ensuring equitable distribution of benefits (e.g., clean energy access) across these regions becomes important.

Table 26. Environmental justice dimensions and their specific context to WtH projects and level of community involvement. Modified from F.Müller et al. ⁽²⁰⁰⁾ and Sovacool et al. ⁽¹⁹⁷⁾

Dimension	Description	Example of metrics	Community involvement *	Ref.
Procedural Justice	Fair and inclusive decision-making	Public participation (number & diversity), Transparency & access to information, Conflict resolution mechanisms	Local community (primarily)	(202, 203)
Relational Justice	Respectful and trusting relationships	Community ownership & benefits, Cultural competency training, Community partnerships		(204)
Restorative Justice	Addressing past environmental injustices	Community engagement in remediation, Investment in community health & well-being, Recognition & compensation for past harms	Local Community & Potentially Historical Marginalised Groups	(205)
Distributive Justice	Fair distribution of benefits and burdens	Air & water pollution impacts, Health impacts, job creation & access		(206)
Cosmopolitan Justice	Global implications of local projects	Greenhouse gas emissions reduction, Resource & energy use, Life cycle assessments	National to International scale	(207)
Epistemic Justice	Recognising diverse forms of knowledge	Inclusion of local knowledge, Community-based research & monitoring, Culturally appropriate communication	Local knowledge holders & broader scientific community	(200, 208)

* Base community involvement for each justice dimension, may extend beyond defined boundary based on specific project circumstances

5.3. Application of EJ dimensions for WtH evaluation

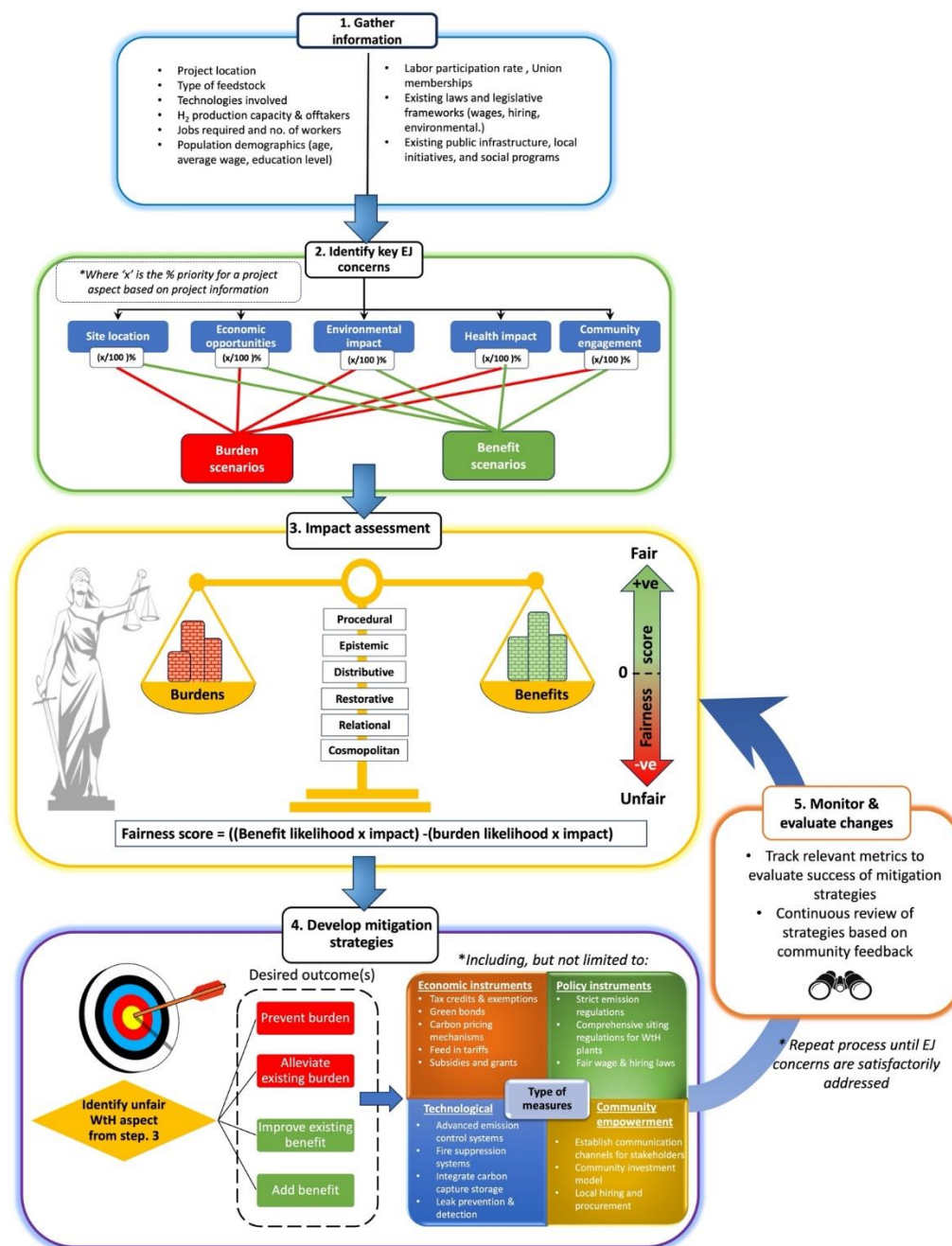


Figure 62. Proposed methodology flow chart for applying a 6-dimension EJ framework for WtH projects. Source: Author.

In this section, we propose a 5-step process to evaluate the fairness and equity of WtH projects within the context of the 6-dimension EJ framework proposed by F. Muller et al. **Figure 62** above shows the flow chart showing each phase of the evaluation process.

1. Gather Information:

- **Project Details:** Gather comprehensive information about the proposed WtH project, including its location, technology, waste feedstock, potential pollution emissions, economic benefits, employment opportunities, and community engagement plans.
- **Community Context:** Understand the demographics, history, cultural values, and environmental concerns of the communities surrounding the project. Identify local organisations and leaders who can represent community voices.
- **Regulatory Landscape:** Research existing EJ laws, policies, and guidelines applicable to the project's location, ensuring compliance and identifying opportunities for strengthening EJ protections.

2. Identify Key EJ Concerns:

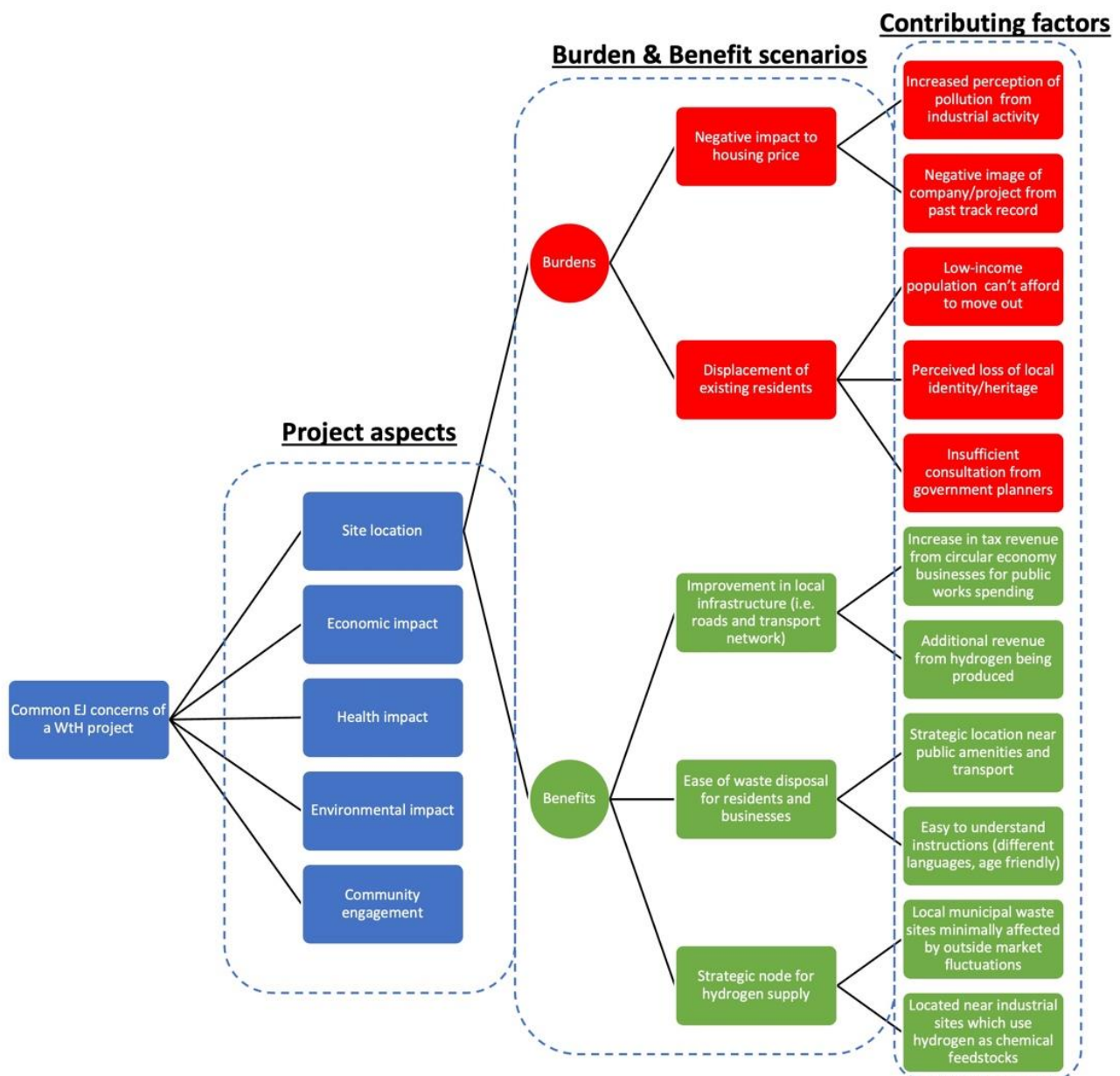


Figure 63. Mapping out key environmental justice concerns using probable burden and benefits scenario associated with common project aspects of a WtH project. The example above shows the burdens and benefit scenarios associated with site location and their contributing factors based on EJ metrics. Source: Author.

Based on the background information collected, we move on to identifying the possible EJ concerns. **Figure 63** shows an example of a framework outlining the process. First, we can consider the different project aspects associated with a WtH plant such as: site location, economic impact, health impact, environmental impact, and community engagement. Subsequently for each aspect, we can list the likely burdens and benefit scenarios (**Figure 64** and **Figure 65**) based on the 6-EJ dimensions in **Table 26**. Identifying burdens and benefits is typically associated with distributive and restorative justice. Applying this to other justice dimensions can offer valuable insights into the fairness of WtH projects and their intersections. For instance, consider a scenario where a company proposes a WtH facility in a remote community. The company frames the project as a source of economic development that promises job creation and infrastructure improvements. While these might be perceived as benefits for the community, the reality might be different. The community engagement process may be limited, neglecting the concerns and traditional knowledge of the residents. The facility's construction and operation could disrupt cultural practices and damage the local environment, leading to long-term health risks for the community. This scenario highlights how focusing solely on the perceived economic benefits for the community might overlook the potential burdens associated with the project, particularly when considering relational, procedural, and epistemic dimensions of EJ.

In this report, we focus primarily on the affected community as the reference point for both burdens and benefits. For each scenario, there is/are a contributing factor(s) which can be derived from the collected background data. It is vital to recognise that the 6-EJ dimensions are not an exhaustive checklist. Each WtH project has its own aims, stakeholders, geography constraints, and development stages. Based on this information a project may in certain cases include additional justice dimensions outside of the 6-EJ framework. By creating a stakeholder map (Figure 73), we can also assign priority weights to each aspect of a WtH project to conduct fairness impact assessment in Step 3. These weight % scores can be assigned subjectively based on the specific geographical and socio-economic context in consultation with relevant stakeholders. For example, a WtH project situated near a residential community would be assigned a higher % weight to site location, health impact, and environmental impact. Whereas a project funded predominantly using taxpayer funding would prioritise economic opportunities and community engagement. To minimise bias in assigning priorities, a facilitator experienced in environmental justice principles could guide the weighting process and ensure all stakeholder concerns are considered objectively.⁽²⁰⁹⁾



Figure 64. Flowchart of burden and benefit scenarios of environmental impact and economic opportunities aspects in a WtH project.

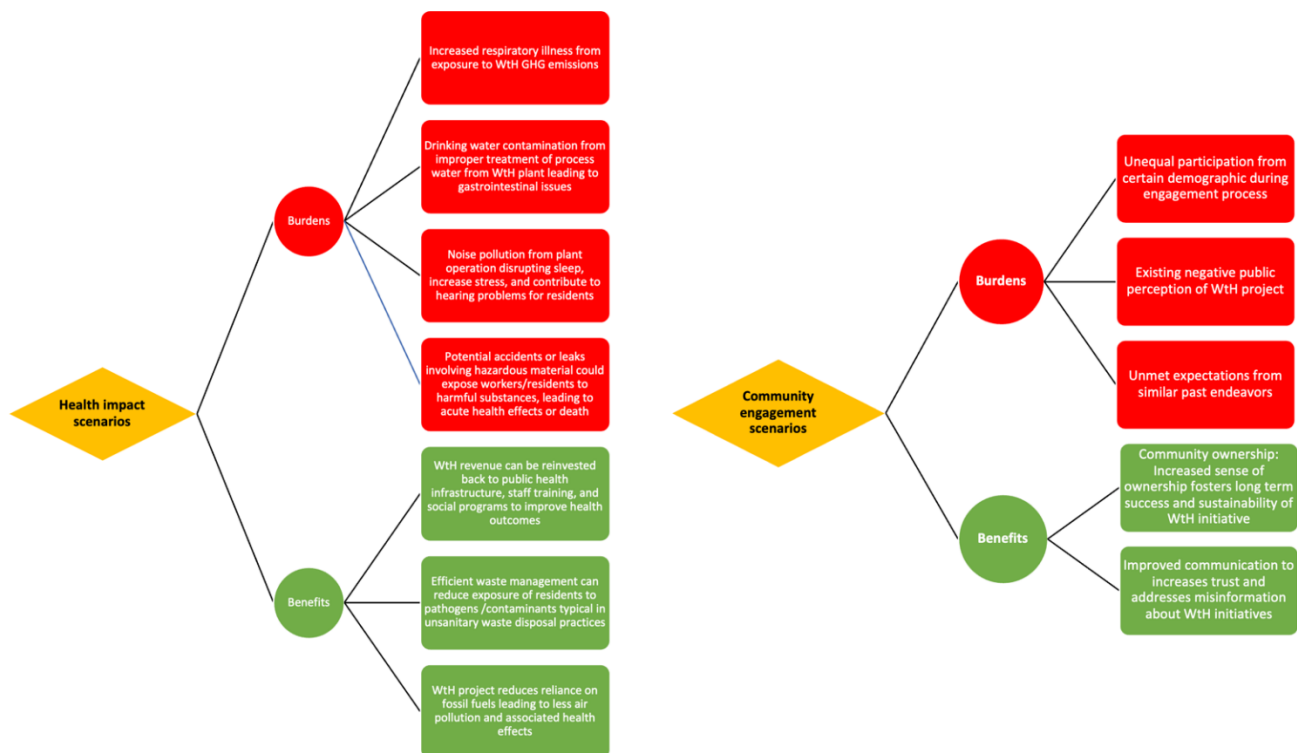


Figure 65. Flowchart of burden and benefit scenarios of health impact, and community engagement aspects in a WtH project.

3. Assess Impacts:

- Evaluate Project Impacts: Analyse the project's potential impacts on each EJ dimension, considering community feedback, scientific evidence, and applicable regulations.
- Use Criteria Matrix: Create a matrix to visualise and compare impacts, with rows representing EJ dimensions and columns representing project components. Rate or describe potential impacts within each cell [Criteria Matrix for EJ framework, with dimensions as rows and project components as columns.⁽²¹⁰⁻²¹²⁾

Hypothetical example:

Table 27. Example of local context needed for fairness evaluation of jobs economic impact from WtH plant.

Jobs specific context of WtH project	
<u>Project data</u> ○ Site location and aim ○ Funding information, stage of project ○ Roles required (i.e. technical, administrative, etc.) ○ No. of direct jobs anticipated ○ Timeline of vacancies to be filled ○ Existing partnerships with any third-party entity	<u>Government policy/laws (if any)</u> ○ Fair wage laws ○ Anti-discrimination laws ^(213, 214) ○ Skilled migration caps for certain job sectors ⁽²¹⁵⁾ ○ Skills training and revocation initiatives ⁽²¹⁶⁾ ○ Dialogue with Labour unions ^(217, 218)
<u>Population demographics</u> ○ Age distribution of workforce ○ Migration statistics ○ Education/ skill level ○ Average wage or unemployment rate ○ Labour union participation rate	<u>Industry initiatives (if any)</u> ○ Blind hiring recruitment ^(219, 220) ○ Collaboration with local institutions ⁽²²¹⁾ ○ Diversity and local inclusion initiatives (DEI) ⁽²²²⁾ ○ Workforce development programmes

Consider the economic impact of job creation when a new WtH plant is built near a residential neighbourhood. For the evaluation, we identified possible burdens and benefit scenarios associated with job creation. The scenarios arising from job creation revolve around the issues of distributive justice, procedural justice, and epistemic justice. Based on the job-specific context of the project (**Table 27**), we can assign a corresponding score (1-5) to its likelihood and impact based on the perceived EJ concerns in **Table 28**. With 1 being the lowest and 5 being the highest. If there are no anti-discrimination laws, the likelihood of the unequal job opportunities can increase significantly. Hence, warranting a score of 4.

Conversely, with those laws present, we can assign a lower likelihood of 2. The burden scenarios listed can cause public dissatisfaction among the local community from a distributive and procedural justice point of view. The negative impact can be perceived as moderate as there is likely a proportional benefit to the local economy in other areas such as roads, infrastructure, and increase in earning power. Based on this rationale we can assign a subjective score of 3 to all the job burden scenarios. However, in practice, assigning this score must be done in consultation with the relevant stakeholder or subject matter expert. The overall score for a scenario can then be calculated using **Equation 14**.

$$\text{Fairness score} = -(\text{burden likelihood} \times \text{impact score}) + (\text{benefit likelihood} \times \text{impact score}) \quad (14)$$

The burden component of the equation carries a negative weight, while the benefit component carries a positive weight. Using 'Unequal job opportunities' as an example of a burden and the increase in local employment as a benefit, we calculate the fairness score with and without mitigative actions to isolate their effects on the project. **Table 29** indicates that the mitigative actions had a significant positive effect on the fairness score.

Table 28. Fairness evaluation of a job creation aspect for a WtH plant built in a residential neighbourhood using a probable scenario method.

Aspect	Burden scenarios	Likelihood (1-5)		Impact score (1-5)	Benefit scenarios	Likelihood		Impact score (1-5)
		w/o mitigation	with mitigation			w/o mitigation	with mitigation	
Economic opportunity (Job creation)	1. Unequal employment opportunities	4	1	3	1. Increase employment opportunities for locals	1	3	5
	2. Wage disparities	4	2	3	2. Increase in earning power	1	4	5
	3. Housing unaffordability and displacement	4	3	3	3. Diversification of local economy from creation of supporting businesses	1	5	5

* Reflected likelihood and impact scores are for demonstration purposes only

Table 29. Comparison of fairness scores with and without mitigative actions.

Scenario	w/o mitigative actions			w mitigative actions		
	Burden score	Benefit score	Net score	Burden score	Benefit score	Net score
1	-12	5	-12	-3	15	12
2	-12	5	3	-6	20	14
3	-12	5	3	-9	25	16
		Cumulative:	-6		Cumulative:	42

It is crucial to recognise that not all project aspects will have an equal number of benefits and burdens. Ideally, a 'fair' project aspect would yield a net positive score due to the higher likelihood and impact of benefits compared to burdens. These scores require further qualitative evaluation to address the intrinsic environmental justice concerns. The same methodology can be applied to other typical aspects of WtH projects, such as **site selection, health impact, environmental impact, and community engagement**. Individual scores for each aspect can then be assigned a percentage weight, (totalling 100%) based on their influence on the project's objectives. This weight assignment should involve consultation with stakeholders or subject matter experts to minimise bias.

Table 30 below shows an example of the evaluation and weight assignment for all aspects of a WtH project. In this example, a higher % weight has been assigned to the environmental impact. The high weighting can be justified based on the laws/standards placed by the landowner and local government on local air, water, and soil quality. The positive score suggests the project advances goals of environmental justice and reasonably fair distribution of benefits and burdens. However, a closer examination reveals room for improvement in the environmental impact aspect. Enhancing this element is vital to address the equitable distribution of environmental burdens from the WtH plant and the transboundary impact of potential greenhouse gas emissions—which fall under cosmopolitan justice. In such cases, developing mitigation strategies with stakeholders becomes necessary. Involving primary stakeholders, such as the local community, in the discussion process would also address the procedural justice aspect of the project.

Table 30. List of aspects associated with a WtH plant with mitigative actions in place.

Aspect	Cumulative fairness score	Weight %	Total weighted score
Site location	30	10	3
Economic opportunities	42	15	6.3
Environmental impact	10	40	4
Health impact	22	15	3.3
Community engagement	30	20	6
		Final score:	16.6

4. Develop and implement Mitigation Strategies:

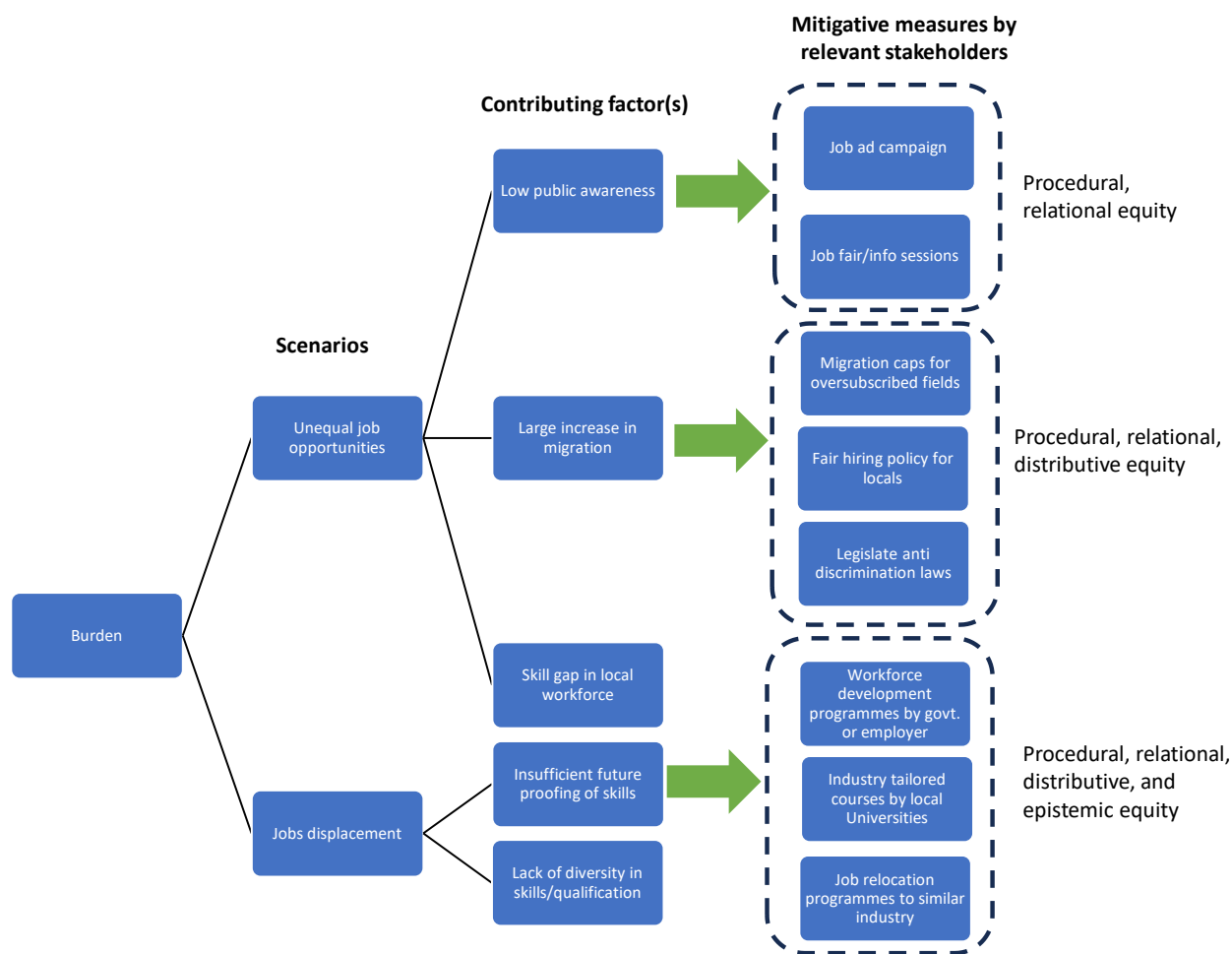


Figure 66. Decision flowchart for identifying suitable mitigation actions/measures for EJ fairness. The example shows possible actions to address unfairness in economic impact from WtH job opportunities. Source: Author.

In project aspects lacking fairness, it becomes necessary to investigate the systemic root causes of injustices, identify lead and lag indicators, and develop effective mitigative actions to either reduce burdens or enhance the cost-benefit aspects associated with environmental justice concerns in the project. The process of identifying strategies is like identifying EJ concerns in step 2, except it goes further and identifies commonalities in the root causes to improve efficiency when formulating possible actions/measures. Ultimately, the successful implementation of mitigative actions or mechanisms by the relevant stakeholders facilitates a reassessment of the EJ fairness of the project in a follow up evaluation.

5. Monitor and Evaluate:

Following the implementation process we can conduct the following actions:

- **Track Implementation:** Monitor the implementation of mitigation strategies and their effectiveness in addressing EJ concerns.
- **Gather Feedback:** Continuously collect feedback from communities to ensure their concerns are heard and addressed.

Depending on the project goal(s) and aim(s), we can pivot back to step 4 until all the environmental justice concerns have been satisfactorily addressed.

5.4. Applying Justice Metrics to an Existing WtH Case Study

The following sub-sections detail what a fairness evaluation of the environmental justice aspects of a WtH project would look like, using an existing case study in the Netherlands previously outlined in [Chapters 1-3](#).

5.4.1. Background- FUREC project (Limburg, Netherlands)

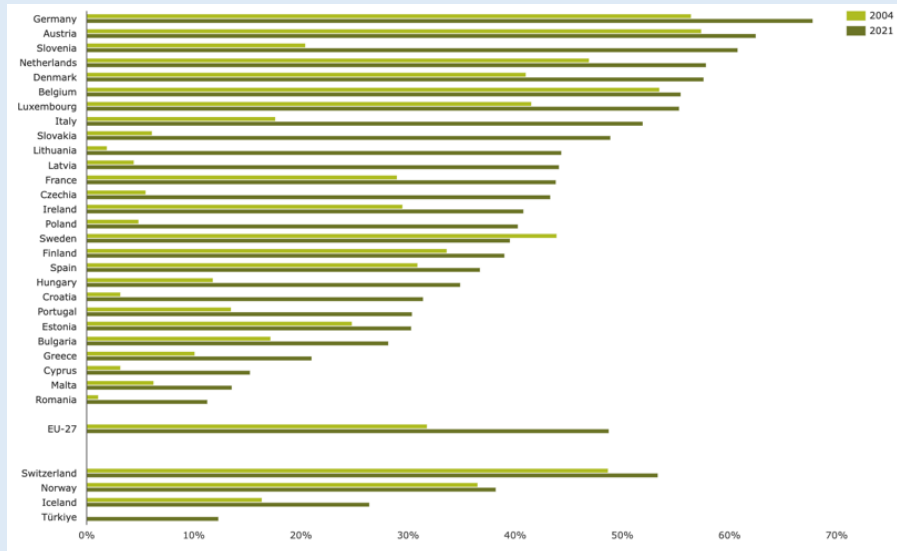


Figure 67. Aerial photograph of Chemelot Industrial park in Limburg, Netherlands.

Project recap: The FUREC (FUse REuse ReCycle) project (established in 2021) is a circular economy initiative currently being developed by the RWE SE group to utilise non-recyclable solid waste streams for producing hydrogen sustainably in the Netherlands.⁽²²³⁾ A typical process begins with the recovery of solid municipal landfill waste, which is then converted into raw pellet materials on-site near Zevenellen. These pellets are subsequently mixed with sewage sludge and transformed into hydrogen at the Chemelot Industrial Park in Limburg. The plant employs a combination of torrefaction and gasification technologies to extract hydrogen from the waste pellets. Carbon dioxide generated during the process can be captured, stored, or utilised as a raw material for other manufacturing processes. [Table 31](#) shows publicly available information concerning various aspects of the FUREC project in Limburg. Based on this information, we can make assumptions regarding burden and benefit scenarios, along with their corresponding impact and likelihood.

Table 31. Existing context of FUREC project in Limburg, Netherlands based on publicly available information.

Aspect	Existing context
Site location	Limburg demographic: ▪ Average wage in Limburg, Netherlands in 2021 is €45,500 with a high end of €71,600 for couples with children.⁽²²⁴⁾ ▪ OECD data shows 56.4% of people aged 25-34 in the Netherlands have attained at least a tertiary level education (8th highest among OECD and partner countries).⁽²²⁵⁾ However, a mere 11.3% of individuals aged 25-64 possess qualifications in engineering, manufacturing, and construction (rank 27/31). Likewise, only 19.2% of the same age range have STEM qualifications (rank 26/29). ▪ In 2021, the number of health care and social workers has increased by 42,000 since 2020, amounting to a total of 1.6 M nationally in the Netherlands.⁽²²⁶⁾ Increased skill migration: In 2022, 403,108 people immigrated to the Netherlands which is an increase of almost 30% from 2021 arrivals.⁽²²⁷⁾ Approximately two thirds of the arrivals are EU citizens and have full working rights in the Netherlands. Potential hydrogen offtakers: ▪ Plant to be located near an ammonia production plant in Chemelot industrial park, which secures a hydrogen customer. ▪ Hydrogen produced to be transported to Rotterdam and the German Ruhr area for usage/sale.

Economic impact	Investments: ▪ RWE received €108 million grant from European Union Innovation fund for the FUREC project, with a final investment decision to be made in 2024.⁽²²⁸⁾ ▪ Dutch Government to set aside €9 Billion in the next decade from 2023 to fund the rollout of hydrogen projects, from a total fund of €35 Billion set aside for the transition to renewables from fossil fuels by 2030.⁽²²⁹⁾ Job creation: The FUREC project is anticipated to bring at least 125 direct jobs to Limburg according to an RWE report.⁽²²³⁾ Catalyst for change: The FUREC circular hub model if successful can be applied elsewhere in the European Union.⁽²⁰¹⁾																																																																																																			
Health Impact	Lower than national average health score in Limburg Urban areas in Limburg have lower health scores than the rest of the Netherlands. The local government initiative,⁽²³⁰⁾ Program Trendbreuk, established in 2018, aims to reduce a quarter of the region's health gap compared to the rest of the Netherlands, by 2030. It specifically targets the enhancement of overall health and wellbeing among Limburg residents, with a special focus on children. Chemelot park safety record Since 2015, Chemelot industrial park has experienced 4 industrial accidents resulting in workers’ deaths, injury and or discharge of harmful pollutants.⁽²³¹⁾ These incidents put the nearby communities of Sittard-Geleen, Stein and Beek at risk and disrupted daily activities such as schooling.																																																																																																			
Environmental impact	Landfill waste reduction A single plant can process 700,000 kilo tonnes/ year of waste material from municipal landfills and sewage.⁽²²⁸⁾ Potential plant output The plant aims to produce 54,000 tonnes of hydrogen/year and reduce the use of natural gas in Chemelot by 200 million m³/year. Which is equivalent to the demand of 140,000 households, resulting in a reduction of 380,000 tonnes of CO₂/ year.⁽²²³⁾ <u>Economic instruments to discourage land filling and incineration in the Netherlands.</u> <table><thead><tr><th>Country</th><th>2004 (%)</th><th>2021 (%)</th></tr></thead><tbody><tr><td>Germany</td><td>58</td><td>68</td></tr><tr><td>Austria</td><td>55</td><td>65</td></tr><tr><td>Slovenia</td><td>20</td><td>60</td></tr><tr><td>Netherlands</td><td>48</td><td>58</td></tr><tr><td>Denmark</td><td>45</td><td>55</td></tr><tr><td>Belgium</td><td>42</td><td>52</td></tr><tr><td>Luxembourg</td><td>40</td><td>50</td></tr><tr><td>Italy</td><td>38</td><td>48</td></tr><tr><td>Slovakia</td><td>35</td><td>45</td></tr><tr><td>Lithuania</td><td>32</td><td>42</td></tr><tr><td>Latvia</td><td>30</td><td>40</td></tr><tr><td>France</td><td>28</td><td>38</td></tr><tr><td>Czechia</td><td>25</td><td>35</td></tr><tr><td>Ireland</td><td>22</td><td>32</td></tr><tr><td>Poland</td><td>20</td><td>30</td></tr><tr><td>Sweden</td><td>18</td><td>28</td></tr><tr><td>Finland</td><td>15</td><td>25</td></tr><tr><td>Spain</td><td>12</td><td>22</td></tr><tr><td>Hungary</td><td>10</td><td>20</td></tr><tr><td>Croatia</td><td>8</td><td>18</td></tr><tr><td>Portugal</td><td>5</td><td>15</td></tr><tr><td>Estonia</td><td>3</td><td>13</td></tr><tr><td>Bulgaria</td><td>2</td><td>12</td></tr><tr><td>Greece</td><td>1</td><td>11</td></tr><tr><td>Cyprus</td><td>0</td><td>10</td></tr><tr><td>Malta</td><td>0</td><td>9</td></tr><tr><td>Romania</td><td>0</td><td>8</td></tr><tr><td>EU-27</td><td>32</td><td>46</td></tr><tr><td>Switzerland</td><td>50</td><td>55</td></tr><tr><td>Norway</td><td>45</td><td>50</td></tr><tr><td>Iceland</td><td>40</td><td>45</td></tr><tr><td>Türkiye</td><td>12</td><td>15</td></tr></tbody></table>	Country	2004 (%)	2021 (%)	Germany	58	68	Austria	55	65	Slovenia	20	60	Netherlands	48	58	Denmark	45	55	Belgium	42	52	Luxembourg	40	50	Italy	38	48	Slovakia	35	45	Lithuania	32	42	Latvia	30	40	France	28	38	Czechia	25	35	Ireland	22	32	Poland	20	30	Sweden	18	28	Finland	15	25	Spain	12	22	Hungary	10	20	Croatia	8	18	Portugal	5	15	Estonia	3	13	Bulgaria	2	12	Greece	1	11	Cyprus	0	10	Malta	0	9	Romania	0	8	EU-27	32	46	Switzerland	50	55	Norway	45	50	Iceland	40	45	Türkiye	12	15
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	<u>Stringent waste treatment standards by Netherlands government and European Union</u> To tackle environmental pressures associated with waste management, rigorous standards have been implemented. These include standards for soil protection, the quality of secondary materials upcycled from waste, air quality standards for incineration, the quality of fertilizers derived from biomass waste, and a prohibition on landfill disposal for waste streams classified as recoverable or combustible.⁽²³⁴⁾ ▪ EU: Directive on Landfilling Waste (1999/31/EC)⁽²³⁵⁾ ▪ EU: Landfill directive (2003/33/EC)⁽²³⁶⁾ ▪ NL: Decree on Landfilling and Soil protection⁽²³⁷⁾ ▪ NL: Soil quality decree⁽²³⁸⁾ ▪ EU: Water framework directive (2000/60/EC)⁽²³⁹⁾ ▪ EU: Groundwater directive (2006/118/EC)⁽²⁴⁰⁾ ▪ NL: Water decree⁽²³⁷⁾
Community engagement	Role of Netherlands in phasing out fossil fuel ▪ The Netherlands recently initiated an international coalition at the COP28 summit in Dubai to phase out fossil fuel tax subsidies.⁽²⁴¹⁾ This development follows a national enquiry which found that its fossil fuel tax subsidies were between €39.7 – 46.4 billion in 2022.⁽²⁴²⁾ The member countries pledged to take similar action to evaluate the amount of fossil fuel tax subsidies in each country by COP29 to provide transparency on the discussion for phasing out fossil fuels. ▪ International discussions were also agreed upon to facilitate a joint framework for phasing out tax benefits for fossil fuels and collaborative efforts to address carbon leakage.⁽²⁴¹⁾ Legislative action by Dutch government to ensure job market fairness: ▪ Labour market discrimination action plan⁽²⁴³⁾ ▪ Statutory minimum wage law⁽²⁴⁴⁾ Work development program for hydrogen sector The Waterstof Werkt ("Hydrogen Works") program is an educational initiative focused on building a skilled workforce in the hydrogen sector, particularly in the Northern Netherlands, which is envisioned as a future 'Hydrogen Valley'.⁽²⁴⁵⁾ It aims to develop a continuous learning program on hydrogen across various educational levels (vocational, tertiary, professional). The initiative is a collaboration between ROC Alfa-college, ROC Noorderpoort, Hanze UAS Groningen and University of Groningen.

Key Assumptions for Fairness Evaluation for FUREC Project

For the evaluation of the Environmental Justice (EJ) fairness framework, we utilise a scenario-based approach for each aspect of the WtH project in Limburg. Currently in the feasibility stage, the FUREC project's assumptions are derived from potential lead and lag indicators. It is crucial to recognise that assigning weight scores to any decision matrix is inherently subjective and carries the risk of oversimplifying the nuance of each project aspect or concern. Prioritising an individual EJ concern without considering its adjacent effects may result in a biased outcome. The use of the EJ framework in this report is meant to illustrate a basis for future refinements.

Table 32. Key assumptions for likelihood and impact scores for site location burden and benefit scenarios.

Site location burden scenarios	
1. Negative impact on nearby housing prices:	A potential burden scenario is the negative impact on nearby housing prices due to perceived pollution in Chemelot. While direct data on this impact is unavailable, a study by De Vor et al. ⁽²⁴⁶⁾ using a hedonic pricing model showed that individuals in the Netherlands are less willing to pay for residential land near industrial activity. The data indicates a more pronounced negative effect for larger industrial sites, as seen in Figure 69 , with Randstad and North Brabant serving as well-demonstrated examples. Chemelot has faced industrial accidents and discharge of contaminants to nearby Limburg communities, prompting evacuations and disruptions to activities, including schooling. ⁽²⁴⁷⁾ In this context, a likelihood score of 4 can be assigned. The adverse impact on housing prices from industrial activity disproportionately affects low-income individuals, who may struggle to afford relocation, potentially influencing their long-term health outcomes and earning power. Therefore, a burden impact score of 4 is warranted.

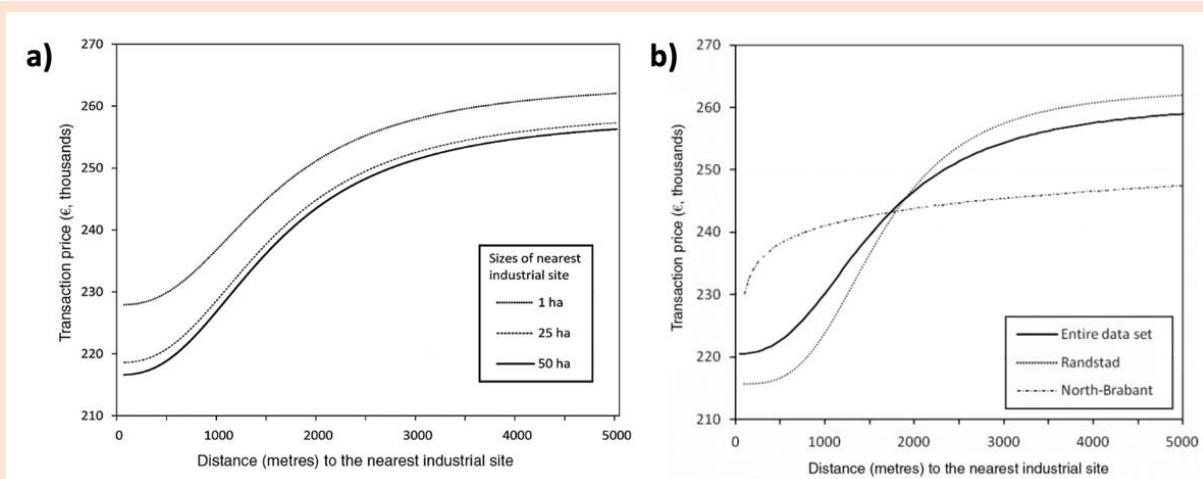


Figure 69. (a) Transaction price gradient functions for the sizes of various sites, (b) Transaction price gradient functions for different regional samples. Modified from ref. ⁽²⁴⁶⁾

- 2. Job displacement due to project cancellation/ change in direction:** The FUREC project is still being studied for feasibility and a pending investment decision is expected in 2024.⁽²²⁸⁾ Should there be a project cancellation or a radical change in project direction, there is a moderate likelihood (3) that the WtH jobs within the circular economy model will be displaced. Job displacement would disproportionately affect the local workers who are unable to relocate or reskill for another vocation, leading to negative perception of similar green initiatives. An impact score of 4 can be assumed.

Site location benefit scenarios

- 1. Diversification of energy storage options in Limburg:** By converting municipal waste into hydrogen, the region reduces its dependency on coal and natural gas imports from external sources in the EU, thus enhancing its resilience against supply disruptions. The hydrogen produced can be strategically utilised to address energy storage challenges, serving as a versatile and efficient means of storing renewable energy generated from intermittent sources like wind and solar power. Existing landfills can also be repurposed as supply nodes, fostering the creation of jobs and recycling efforts in different regions. Based on this context, we could assign a likelihood score of 4. The benefits of energy security and diversification touches on the distributive, cosmopolitan, and relational fairness of the FUREC project, earning an impact score of 4.

Table 33. Key assumptions for likelihood and EJ impact scores for economic opportunities burdens and benefit scenarios for FUREC project.

Economic opportunity burdens scenarios

- 1. Unequal employment opportunities:** The FUREC project is expected to create 125 jobs at the Chemelot industrial park in Limburg, but there is a risk that many of these positions may not be filled by local workers. This challenge is exacerbated by two factors: competition for skilled labour from neighbouring EU countries and a low percentage of STEM, engineering, and manufacturing qualification holders in the Netherlands. The Dutch Government has implemented an anti-discrimination labour action plan; however, the time-sensitive nature of the job vacancies and the substantial duration required to train local workers might disproportionately disadvantage Limburg locals. Given this context, a moderate likelihood score of 3 can be assigned. Perceived unfairness in job competition in a tough economy may cause locals to harbour resentment towards the project and any related government initiative, and lead to a low labour participation rate for the sector.^(248, 249) Hence, warranting an impact score of 4.
- 2. Unfair working and wage conditions:** A 2022 Statista survey reported that only an average total of 16.3% of Dutch workers engaged in trade-union activities.⁽²⁵⁰⁾ In transport and engineering fields the participation rate is only slightly higher by 5-8%. With such a low participation rate, there is an increased risk of unfair working conditions and hours due to limited negotiation avenues and leverage, warranting a high burden likelihood of 4. The low labour union participation rate introduces potential challenges in distributive, procedural, relational, and epistemic aspects. Consequently, we can consider the burden impact to be high (4) when few workers have a say in their working conditions, wages, and rights.

Economic opportunity benefits scenarios

- 1. Creation of new jobs in Limburg:** The circular waste management model in Chemelot can lead to the creation of new industries and jobs, not inclusive of the 125 direct jobs from the plant's construction. A 2019 report by the CSIRO estimated the global circular economy to be US\$4.5 trillion dollars by 2030 in terms of commerce opportunities.⁽²⁵¹⁾ The type of jobs that support the main business can include but are not limited to sorting, transporting and developing innovative uses for the recycled material. The potential success of the FUREC model could also serve as model for the rest of the Netherlands. Additionally, based on similar 'proof of concepts' studies in other countries (e.g., China ⁽²⁵²⁻²⁵⁴⁾, Japan ⁽²⁵⁵⁻²⁵⁷⁾, France ⁽²⁵⁸⁾, Germany ⁽²⁵⁹⁾, South Korea ^(260, 261), Thailand ⁽²⁶²⁾), we can assign a likelihood score of 4. The impact addresses the distributive, relational, and cosmopolitan justice of the region, to which a score of 4 can be assigned.
- 2. Increase in earning power for Limburg locals:** The WtH workers needed in Chemelot are likely to require various skill levels (vocational, tertiary, and professional) in terms of construction, planning, operation, and maintenance. The average salary for a hydrogen process operator in the Netherlands is €59,097 as of 2024.⁽²⁶³⁾ An entry level operator (1-3 yr. exp.) earns on average €42,420, whereas a senior (+8 yrs. Exp.) earns €72,824. Assuming most of the WtH jobs are within this range, it represents a potential wage increase for Limburg workers. However, considering the time needed to train workers and address the local skill shortage, we can assume a moderate likelihood (3) for this benefit scenario. The benefit impact of increased earning power mainly addresses the distributive and relational justice of the project, an impact score of 4 can be assigned.
- 3. Increase tax revenue for public works:** By converting landfill-bound waste into valuable hydrogen, these projects stimulate economic growth and job creation, resulting in increased taxable income. In the Netherlands, the implementation of landfilling taxes and tipping fees further amplifies the financial benefits.⁽²³³⁾ This additional income, combined with heightened economic activity, enables strategic investments in public services and infrastructure, fostering a resilient and thriving community. Based on existing policies in the Netherlands and EU, we could assign a likelihood score of 4. The success of the FUREC model can serve as an ideal model elsewhere in the EU. The injected tax revenue not only improves local distributive justice but also tackles energy challenges in participating countries. For example, by decreasing reliance on coal or natural gas, EU countries enhance their energy security, which is particularly emphasised during winter.⁽²⁶⁴⁾ This holistic approach earns an impact score of 4.
- 4. Reduced waste management costs:** Current studies estimate the future levelised cost of producing hydrogen from bio-waste gasification between US\$2-3.^(264, 265) However, this cost can be significantly reduced by capturing the value of landfill taxes and tipping fees. In Limburg, landfill taxes amount to €33.58 per tonne, and tipping fees can reach up to €80 per tonne for landfillable waste.⁽²³³⁾ By diverting waste from landfills to WtH conversion, Limburg residents can avoid landfilling taxes and tipping fees, thereby reducing the cost of waste disposal. Hydrogen produced by WtH plants can be sold as a clean fuel, creating a new revenue stream. This revenue can be used to offset the operational costs of the WtH facilities, further reducing the overall cost of waste management. Given the low landfilling rate in the Netherlands (<2.0%), the likelihood of the FUREC project further lowering cost of waste management is high at 5. The benefit of this scenario shares a similar impact score of 4 like the previous scenario.

Table 34. Key assumptions for likelihood and EJ impact scores for environmental burden and benefit scenarios.

Environmental burdens scenarios

- 1. Potential air pollution:** The FUREC plant plans to use a combination of torrefaction and gasification technologies to convert the solid waste material to hydrogen. Carbon dioxide is emitted as a side byproduct, and is planned to be either stored and captured, or sold as a raw material for chemicals manufacturing to nearby plants in the Chemelot. Typical carbon capture storage targets 90% efficiency,⁽²⁶⁶⁾ so we can assume a burden likelihood score of 2. The burden impact of greenhouse gas emissions mostly affects distributive and cosmopolitan justice. Given the planned mitigative measures, this can be assigned an impact score of 2.
- 2. Potential soil pollution:** The envisioned WtH plant aims to process 700 kilo tonnes of solid non-recyclable municipal waste. This high-capacity target poses potential risks of adverse health and environmental impacts throughout the supply chain. However, The Netherlands and the European Union have had in place a comprehensive set of waste treatment standards to mitigate the common issues associated with soil, water, and air pollution from waste management since the 1990s. Based on this information, a low likelihood score of 2 can be assigned. The existence of mitigating policies by the Dutch Government likely addresses the distributive, procedural, and cosmopolitan justice of the project. For the burden impact, a low score of 2 can be assigned as well.

Environmental benefits scenarios

- 1. Offset of CO₂ otherwise generated by natural gas burning:** While the gasification process generates CO₂ as a by-product, the amount of hydrogen generated as an energy source is likely to offset the potential CO₂ emitted from burning natural gas in the Netherlands for electricity. An analysis done by RWE estimates a 3.6 Mt of CO₂ will be offset in the first 10 years of operation.⁽²⁰¹⁾ Based on this estimate, a benefit likelihood of 4 can be assumed. The impact of the CO₂ offset potentially alleviates the distributive burden of greenhouse gas emissions for the surrounding community and the cosmopolitan burden of climate change, so an impact score of 4 is assumed.
- 2. Increase in waste management efficiency:** From 2016 to 2020, the incineration of waste in the Netherlands declined to 41.8%. Concurrently, the recycling rate increased to 56.8% in 2020, with a consistently low landfilling rate of 1.4% over the 4-year period (Figure 70). This achievement is attributed, in part, to the reintroduction of landfilling and incineration taxes in 2015, aimed at discouraging reliance on residual waste treatment and promoting recycling. Additionally, the government prohibited the landfilling of solid waste from 60 different waste streams, encompassing combustible and inorganic materials. With these measures in place, a continuous decline in the landfilling and incineration rates of municipal solid waste can be anticipated, justifying a likelihood score of 5. The efficient recycling of waste and the optimised use of landfill space contribute to alleviating environmental and relational burdens on the local community, justifying an impact score of 4.

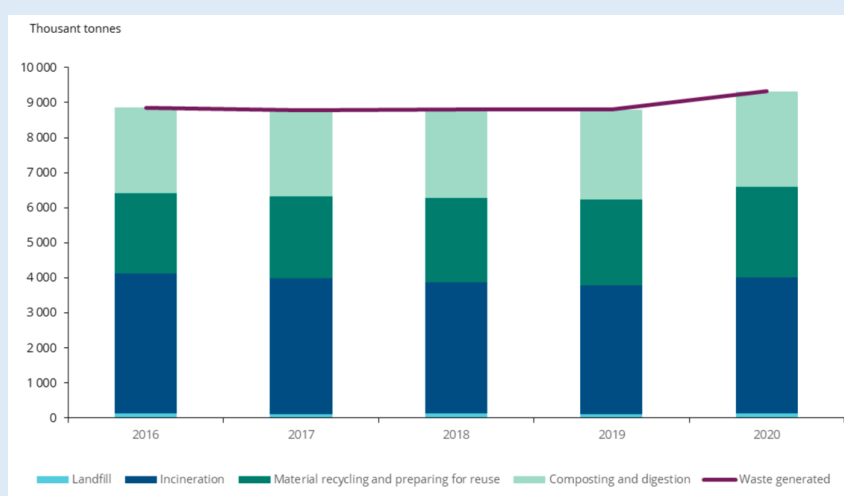


Figure 70. Municipal waste generation and treatment in the Netherlands between 2016 and 2020 in thousand tonnes.⁽²³³⁾

Table 35. Key assumption for likelihood and impact scores in Health burden scenario.

Health burden scenario

- 1. Increased healthcare costs due from WtH GHG emissions:** The WtH plant in Chemelot is likely to generate greenhouse gases during its eventual operation. Establishing a link between its operation and an increase in healthcare costs due to greenhouse gas emissions can prove challenging. Firstly, numerous plants and factories within the park emit various pollutants which can make isolating the WtH plant's GHG emissions to any increase in health effect difficult. Areas with industrial activity like Limburg often face pre-existing health inequalities, making it difficult to discern the WtH plant's specific impact. Lastly, health effects from GHG emissions can be cumulative, which makes short-term analysis unreliable.⁽²⁶⁷⁾ Given these complexities, assigning a score and impact without a comprehensive investigation is not feasible at this point.
- 2. Potential noise pollution and odour:** The non-recyclable municipal landfill waste in Zevenellen serves as the primary feedstock for the WtH process. It undergoes pelletisation at landfill sites to produce solid raw fuel (SRF) pellets. The process removes inorganic and non-incinerable materials, compacting and enriching the organic content. The resulting material is dry, odorless, and can be stored for up to 3 years without degradation, facilitating easy transportation.⁽²⁶⁸⁾ The likelihood of noise pollution affecting local communities is also considered low, as the process occurs within an enclosed space. Based on this information, a burden likelihood score of 1 can be assigned. An impact score of 2 can be assumed based on potential health burdens.

Health benefit scenario
1. Program Trendbreuk shorten health gap in Limburg: Similar to economic benefit scenario #3, the additional tax revenue from the WtH can potentially be reinvested to public healthcare programs such as Program Trendbreuk. Based on the program's recent achievement and duration needed for changes in health outcomes to occur, we can assume a moderate likelihood score of 3. Additional funds to social health care programs can help alleviate the distributive burdens linked to pollution, and improve the public perception towards WtH initiative (relational and restorative), warranting an impact score of 4

Table 36. Key assumption for likelihood and impact scores in community engagement benefit scenario

Community engagement benefit scenario
1. Transfer of technical knowledge to locals: The Waterstof Werkt initiative is expected to bridge the existing skill gap required for the WtH plant in Chemelot, especially considering the low percentage of individuals holding qualifications in engineering and STEM fields in Limburg. Consequently, a likelihood score of 4 can be assigned. Regarding benefit impact, the project is poised to address the epistemic concerns inherent in the WtH project. Additionally, participants from the local community engaging in the initiative stand to gain procedural and relational benefits from the apprenticeship model. Based on these considerations, a benefit impact score of 4 can be assigned.

Fairness Score Evaluation of FUREC Project

Table 37. Fairness evaluation of FUREC project in Limburg, Netherlands using scenario-based method.

Aspect	Burden scenarios	Likelihood (1-5)	Impact score (1-5)	Benefit scenarios	Likelihood (1-5)	Impact score (1-5)
Site location	1. Property value concerns: Building of a WtH plant near residential area poses concern of negative perception over pollution	3	4	1.Diversification of energy storage options in Limburg: less affected by external supply fluctuations	4	4
	2. Jobs displacement because of project cancellation or change in direction	3	3			
Economic impact	1. Unequal job opportunities due to inherent skill gaps and competition from external labour	3	4	1. Increase earning power for Limburg locals	3	4
	2. Unfair working conditions: wage disparities and long hours	4	4	2.Increase in job opportunities in Limburg	4	4
				3. Increase in tax revenue for public works and infrastructure	4	4
				4. Reduced waste management costs from hydrogen revenues	5	4

Environmental impact	1. Increased in greenhouse gas emissions	2	2	1. Increased efficiency in solid non-recyclable waste management	4	5
	2. Potential soil and water contamination from municipal land fill waste	2	2	2. Offset potential CO ₂ generated from natural gas use (specific to Netherlands)	4	4
Health impact	1. Increase in health care costs associated with greenhouse gas emissions from WtH plant	uncertain	uncertain	Program Trendbreuk manages to shorten health gap of Limburg with additional funding from WtH tax revenue	3	4
	2. Increase in noise pollution and odour pollution from waste transport	1	2			
Community engagement	No direct burdens			1. Transfer of technical knowledge to local hiring force	4	4

Table 37 shows the EJ fairness evaluation criteria matrix for the FUREC project. Based on the positive scores on each aspect we can consider the FUREC project to be reasonably fair based on available context of the Chemelot facility in Limburg. Analysing each aspect individually (**Table 38**), we can see the initiative scoring high on the environmental and economic opportunity aspects. The Netherlands' pre-existing environmental protection laws and strong circular economy industry strongly mitigate the possible burdens associated with the collection, transport, and processing of the municipal solid waste-to-hydrogen gas. However, the FUREC WtH site location choice in Chemelot scores very poorly in terms of fairness, which can be attributed to its proximity to residential areas and the current uncertainty of the FUREC funding status.

Table 38. List of fairness aspects associated with a WtH plant with mitigative actions in place. * In this example, each aspect is assumed to carry equal weight for simplification.

Aspect	Cumulative fairness score	Weight %	Total weighted score
Site location	-5	20	-1
Economic opportunities	36	20	7.2
Environmental impact	28	20	5.6
Health impact	10	20	2
Community engagement	16	20	3.2
		Final score:	17

Based on the results reflected in **Table 38**, we proceed to the next step of developing mitigation strategies to alleviate burdens based on Step 4 in the EJ methodology flowchart (**Figure 62**). For site location, the main issues were the potential negative impact of the WtH plant towards nearby housing prices and jobs displacement in the event the FUREC project is cancelled or changes direction. **Figure 71** shows the identified EJ concerns and their proposed mitigative actions for site location burdens.

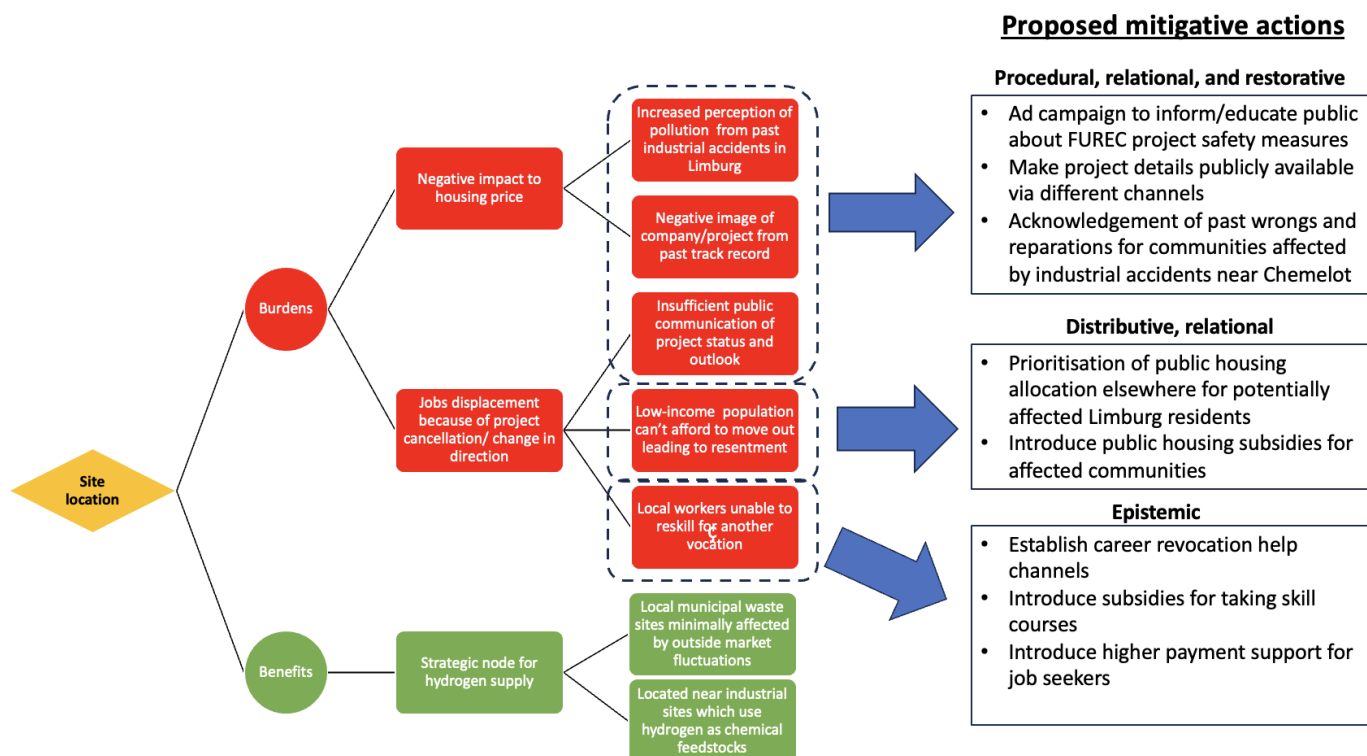


Figure 71. Proposed mitigative actions for site location aspect burden scenarios in FUREC project.

Based on the initial scope outlined in this report, we would not go into specific detail on the legislative procedure or stakeholder negotiation process to implement these recommended mitigative actions. Based on the type of actions proposed, the timeline for the changes to take place is not immediate and likely to occur over a longer time scale (1-3 years). For such a situation, we recommend reviewing the fairness impact assessment annually to determine if the scores have improved and whether there are any new issues arising.

5.5. Summary

We propose a preliminary methodology using six EJ dimensions to assess the fairness of WtH projects. This approach provides a structured method for evaluating potential environmental and social impacts, empowering stakeholders to actively participate in shaping the project's design. Notably, the framework's modularity allows for customisation based on specific project contexts. However, implementing robust EJ processes presents practical challenges. Balancing the time and cost associated with these processes in the short term with the potential long-term benefits, such as securing social license and fostering a fairer society, requires careful consideration. Further research is necessary to refine the framework's scoring system and ensure its effectiveness across diverse scenarios. Additionally, exploring alternative data collection and analysis methods could enhance accessibility and broaden stakeholder participation. By addressing these areas, the framework can evolve into a powerful tool for ensuring fairness and promoting community wellbeing alongside WtH advancements.

Chapter 6. Conclusions and Recommendations

6.1. Conclusions

The study presents a systematic review of WtH technologies and performs a comprehensive analysis of the technological, economical, environmental, and social aspects of the waste-to-low carbon hydrogen technologies. The findings provide valuable insights into the opportunities, obstacles, and potential remedies to encourage and accelerate the adoption of WtH projects.

State of Play in WtH Technology

The key findings on WtH technologies as a sustainable future pathway have been summarised. Through emphasising the critical role of feedstock selection, we highlight how choosing the appropriate waste stream impacts economic viability, environmental sustainability, and scalability. We have also prioritised streams that don't compete with food production for land and water resources. Following this analysis, we evaluated various WtH pathways: thermochemical, biochemical, photochemical, and electrochemical methods.

Currently, thermochemical processes, such as gasification, pyrolysis with in-line reforming, and chemical looping hydrogen, outperform other WtH pathways for the conversion of MSW to hydrogen. These thermal processes benefit from the relatively higher H₂ yield compared to other pathways. From economic perspective, CCS-abated waste gasification, pyrolysis with in-line reforming, and chemical looping hydrogen exhibit relatively lower H₂ production costs compared to other pathways but remain higher compared to the levelised costs of H₂ from coal and natural gas. The commercial performances for these thermochemical processes are relatively low and the commercial upscaling has remained to be demonstrated. Biochemical processes, like dark fermentation, offer an environmentally friendly approach that uses microorganisms at lower temperatures, but face challenges with feedstock diversity and lower hydrogen yields. Photochemical processes hold promise in terms of harnessing solar energy but remain in their early stages. Electrochemical processes offer a potential direct conversion approach at lower temperatures but are currently limited by high capital and operational costs.

Coupling WtH with CCS has the potential to further cut greenhouse gas emissions. By diverting waste from landfilling or incineration through an integrated WtH and CCS technology (WtH-CCS), the greenhouse gas emissions from waste generation can be avoided.

Despite its potential, deploying WtH-CCS to produce clean hydrogen does face hurdles. Logistically, the coordination of transport and storage for waste feedstock, the CO₂ captured, and the hydrogen produced is complex. Building the necessary infrastructure, especially for CO₂ storage, requires high upfront costs and makes small-scale, geographically dispersed WtH-CCS less economical. Most importantly, most WtH pathways have zero track record on a fully commercial scale. The complex large-scale WtH projects and the variability of waste feedstock availability and quality have remained the main technical and operational problems. In addition, high capital costs have rendered WtH conversion a high-risk technology. The uncertainties in policy and regulations that govern carbon accounting, pricing, and WtH project approvals create an unattractive environment for investment. Finally, social acceptance remains a hurdle; public concerns about land use, waste sourcing, and project transparency can generate opposition and discourage financing. Addressing these social barriers through strong policies and open communication is crucial for WtH-CCS to gain traction.

Techno-Economic Aspect of WtH Technology

A comparative techno-economic assessment of the WtH technologies has been presented. We evaluated gasification, pyrolysis with in-line reforming, dark fermentation, and incineration-electrolysis with CCS for their economic viability and potential to produce low-carbon hydrogen. The study identified that WtH-CCS processes are currently not viable, as indicated by the significantly high LCOH compared to the costs of hydrogen from coal and natural gas. The high LCOH for WtH-CCS is primarily driven by high CAPEX and OPEX due to the complexity and/or currently limited efficiency of the process. This study has also identified process efficiency, CAPEX, byproduct revenues, CCS credit, and/or waste

feedstock cost as crucial parameters in determining the economics of WtH-CCS processes. The cost feasibility improvement analysis suggests that a combination of efficiency improvements, byproduct recovery, CAPEX reduction, and/or waste management and carbon incentives are required to lower the LCOH for CCS-abated gasification, pyrolysis, incineration-electrolysis, and dark fermentation. In addition, economies of scale are essential to establish a cost-effective waste-to-low-carbon-hydrogen conversion.

The study also explored the value proposition of WtH technologies within the broader context of waste management practices. When compared to traditional methods like landfilling and unabated mass-burn incineration, WtH technologies may have higher upfront capital and operational costs. However, this can be offset by potential revenue streams and incentives, such as H₂ and CCS credits, in addition to waste tipping fee.

Environmental Aspect of WtH Technology

The life cycle assessment (LCA) of the four CCS-abated WtH technologies: gasification, pyrolysis with in-line reforming, dark fermentation, and incineration-water-electrolysis was explored to evaluate the environmental impacts. The LCA results revealed that a complex interplay of factors influences their environmental impact. Under a business-as-usual scenario, the LCA identified CCS-abated gasification and pyrolysis as the most environmentally friendly options, due to their direct and rapid hydrogen production processes. Conversely, CCS-abated dark fermentation exhibited the highest environmental impact across all categories. This can be attributed to its high chemical input requirements and lower hydrogen yield.

While substituting fossil fuels with renewable energy sources generally reduces environmental impact across most categories, it introduces new challenges in water consumption, land use, and metal depletion. The LCA also highlights the role of secondary products in offsetting emissions. Dark fermentation and incineration, which consume large volumes of waste and produce substantial marketable secondary products, benefit significantly from this factor.

Interestingly, the LCA suggests that incineration-water electrolysis might be a more favourable option when the focus shifts from hydrogen production to waste management. This is attributed to incineration's high-capacity operation and waste processing efficiency, which results in lower overall emissions. Ultimately, in comparison to traditional waste treatments (conventional incineration and landfilling), WtH-CCS features lower the global warming impact but require more resources that result in a higher metal and water depletion.

WtH Technology within the Waste-to-Energy Landscape

WtH was positioned within the waste-to-energy landscape by comparing its cost and environmental impact to established alternatives: waste-to-sustainable aviation fuel (WtSAF) and waste-to-electricity (WtE). WtSAF offers immediate decarbonisation for aviation, with several certified pathways. Whereas WtE utilises incineration, a mature but environmentally challenging process for electricity generation. We compared WtH (gasification) against WtSAF (gasification-Fischer-Tropsch) and WtE (incineration). The analysis revealed WtH, WtSAF, and WtE demonstrate moderate feasibility performance. Despite the competitive advantage in lowering climate change impact compared to existing fossil fuel-based processes, shared technical and cost challenges for implementing these waste-to-energy technologies leads to moderate current feasibility performance. The overall viability of WtH applications is likely to be constrained compared to WtE and WtSAF, primarily due to the niche applications of hydrogen and the lack of existing infrastructure for hydrogen transport, storage, and utilisation.

Environmental Justice Aspect of WtH Technology

A 5-step methodology framework was proposed to perform a quantitative and qualitative assessment of the 'fairness' of existing waste-to-hydrogen projects through the lens of environmental justice (EJ). Fairness in this context covers both the equitable access to information, resources, and benefits related to WtH to disadvantaged and historically marginalised communities, as well as acknowledging and addressing the environmental and socio-economic burdens that are often overlooked when planning WtH infrastructure projects.

Leveraging the overlap between conventional hydrogen and WtH projects, we adapted a well-established hydrogen justice framework to evaluate fairness in WtH implementation. This framework assessed six key justice dimensions:

procedural, distributive, relational, restorative, cosmopolitan, and epistemic. These dimensions encompass the distribution of benefits and burdens across five crucial WtH aspects: site location, economic opportunities, environmental impact, health impact, and community engagement. For each aspect, we employed a subjective scoring system that considered the specific context of the WtH project. This scoring system integrated project data, local demographics, existing legislation, and industry initiatives.

The decision to implement a WtH facility hinges on a careful evaluation of its impact on environmental justice (EJ) principles. We weighed the perceived benefits against the potential burden on the local community, while considering the specific geographical and socio-economic context.

- **Environmental impact:** This focused on potential greenhouse gas emissions from the WtH plant, considering existing emission controls and relevant environmental regulations.
- **Health impact:** We assessed changes in community health outcomes before and after the project's implementation. This evaluation considered factors like local healthcare infrastructure, social programs, and existing health concerns.
- **Socio-economic impact:** This analysis had two key aspects: site location and economic opportunities. Site location examined disruptions to daily life, such as housing prices, job displacement, and construction noise. Economic opportunities focused on job creation (direct and indirect) and potential tax revenue to support public works.
- **Community engagement:** This assessed how the public perceived the project. It considered transparency in information dissemination, inclusion of community voices in decision-making, and acknowledgement of past injustices, if any.

Our methodology incorporated a step to identify the root causes of burdens associated with WtH projects. This step is vital in proposing targeted mitigative actions that can alleviate or eliminate these burdens. Additionally, in some cases, these actions may also aim to enhance existing benefits or introduce new ones. It's important to acknowledge that the proposed mitigative actions are presented as ideal solutions and may not fully account for the complexities of stakeholder negotiations during policy or legislation development.

6.2. Recommendations

In this study, WtH technology was assessed through technological, economical, environmental, and social lenses. Several further actions and studies are recommended to solidify the competitive edge and accelerate the adoption of WtH technology.

Further action should be devoted to deploying demonstration trial to identify potential operational challenges of WtH processes and to ultimately improve the commercial viability. In addition, strategies to reduce the upfront capital expenditure associated with WtH facilities should be explored. This could involve increasing energy efficiency through technology improvement and energy recovery, investigating modular designs, standardised construction methods, or even retrofitting existing energy infrastructure. Additionally, alternative financing models, such as public-private partnerships or carbon-credit trading mechanisms, warrant investigation to attract investment and overcome economic challenges. Advocating for policies that incentivise the development and deployment of WtH technologies is essential. This could include feedstock availability and pricing regulations, carbon pricing mechanisms, and streamlined permit processes for WtH projects.

Further regional techno-economic-environmental assessment is also recommended. The techno-economic and life-cycle assessment frameworks developed in this study can be easily modified and repurposed for different WtH cases. For example, Asia, as the most populated continent, is a region with a significant potential to produce energy from waste. In addition, the frameworks in this study can be used to further investigate the impacts of policy leverages and incentives in different countries on the hydrogen production cost.

To refine the environmental justice framework, pilot tests on existing WtH projects are recommended. This approach will assess its effectiveness and inform improvements, especially in scoring objectivity. Additionally, exploring online surveys, community forums, and spatial data analysis can enhance accessibility and data collection for the framework.

A cost-benefit analysis is needed to compare the long-term gains from robust EJ processes (reduced delays, social acceptance, improved health) with the initial investment in time and resources. In addition, the modular framework for environmental justice assessment can be implemented in developing countries with different regulations and socio-economic conditions.

While hydrogen is an attractive fuel and chemical feedstock, the use of hydrogen in a sector like aviation has its own challenges. In this case, SAF emerges as a promising immediate solution. Additionally, municipal solid waste conversion into chemicals also presents a promising alternative waste valorisation approach. Conducting comprehensive techno-economic and life cycle assessments of waste-to-SAF and waste-to-chemicals would provide a more nuanced understanding of the cost and environmental impacts across waste valorisation solutions.

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Appendix 1

Technology readiness level (TRL) is a scale for measuring the maturity of a technology. The TRL describes the performance history of a given system, subsystem, or component relative to a set of levels first described at NASA HQ in the 1980s. The TRL describes state of a given technology and provides a baseline from which maturity is gauged and advancement defined.⁽⁷²⁾

TRLs range from 1 – Basic Technology Research to 9 – System Test, Launch, and Operations. **Figure 72** provides a high-level illustration of the TRL level scale for increasing technology maturity starting with basic research and progressing through flight system operation.

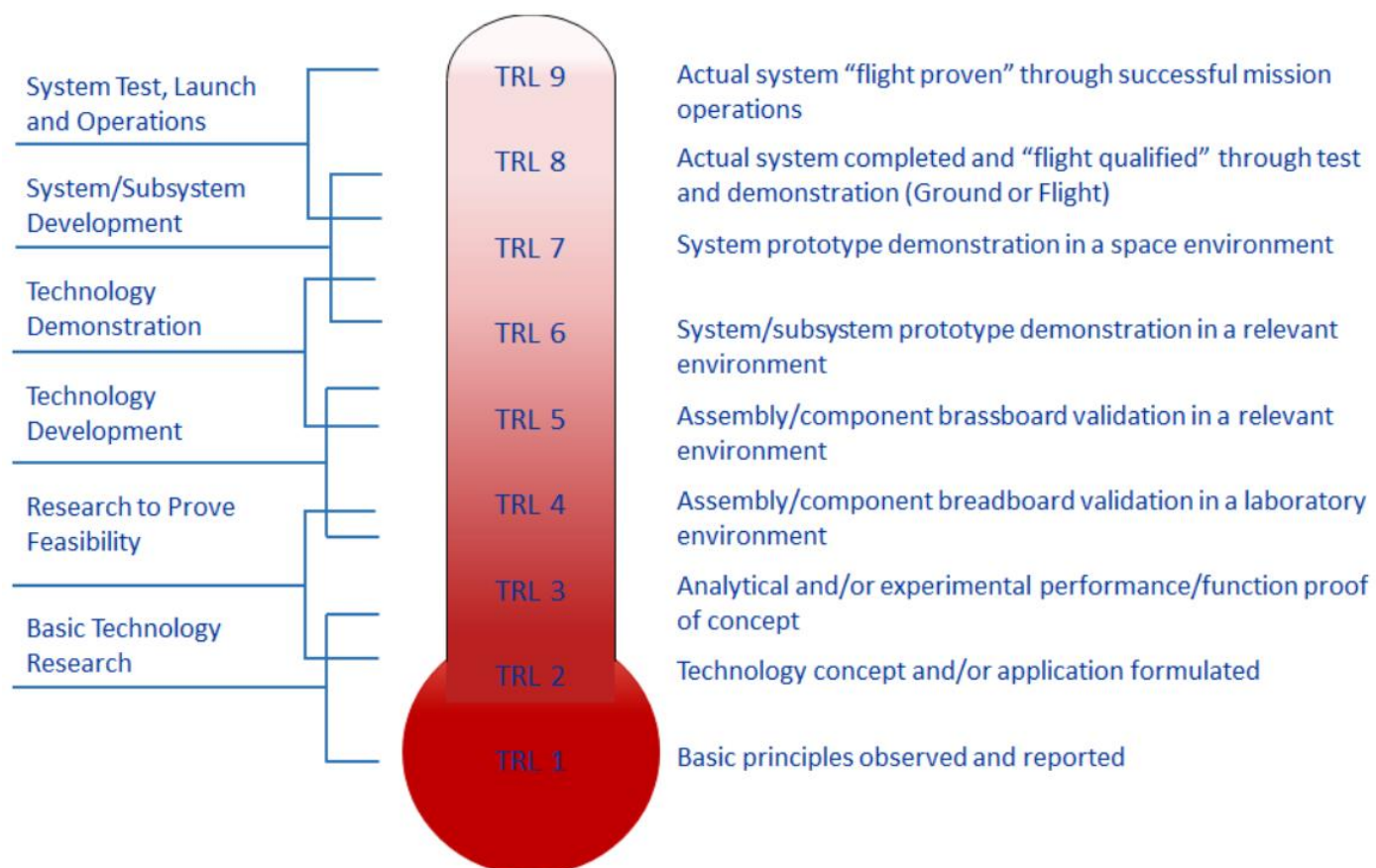


Figure 72. Scale for NASA’s technology readiness levels.⁽⁷²⁾

Appendix 2

A2.1. Techno-Economic Criteria

The main technical criteria to be used in this study are listed in **Table 39**.⁽¹³¹⁾

Table 39. Technical criteria for techno-economic analysis.

Plant location	
Country	Netherlands
Plant site	Chemelot Industrial Park
Site condition	Clear, level, no special civil works
Seismic risk	Negligible
Plant capacity	
2,000 tpd MSW or OFMSW	
H₂ outlet conditions	
Pressure	20 bar
Maximum temperature	30°C
CO₂ capture rate	
95%	
CO₂ conditions - pipeline transport	
CO ₂ pressure	110 bar
CO ₂ maximum temperature	30°C

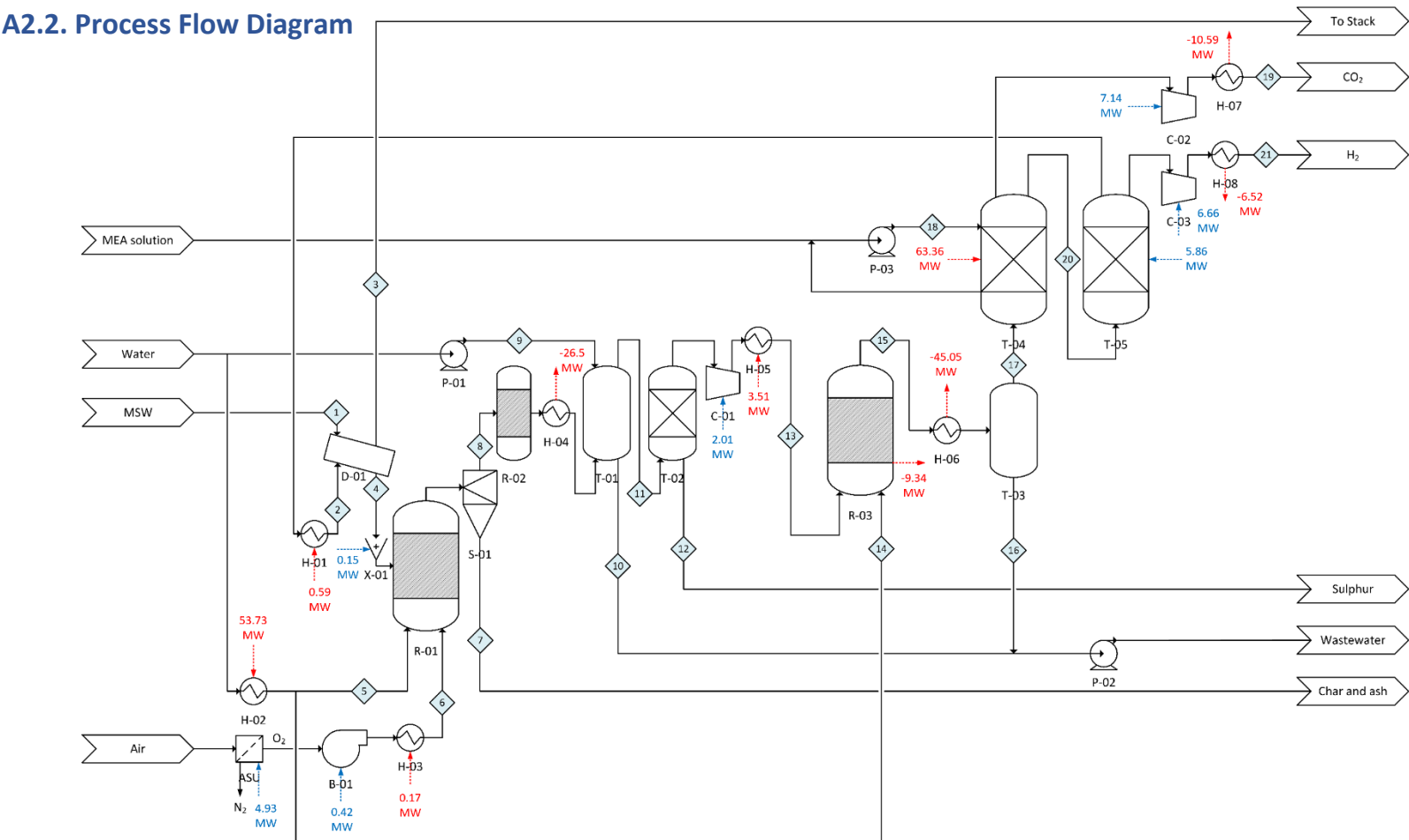
The main economic criteria to be used in this study are listed in **Table 40**.⁽¹³¹⁾ Cost estimates in this study are presented in the United States Dollars (US\$) currency. If the costs are not derived in US\$, the costs are converted to US\$ using the current market exchange rate: Euro (€1 = US\$1) and Australian Dollars (AU\$1 = US\$0.7).

Table 40. Economic criteria for techno-economic analysis.

Total Plant Cost (TPC)	
Plant materials and labour costs	Estimated based on the purchased equipment costs (PE), installation costs (multiply PE with installation factor), and instrumentation and controls costs (10% of PE)
Engineering contractor's fees	10% of TPC
Project contingency	10% of TPC
Total Capital Requirement (TCR)	
Owners costs and fees	7% of TPC
Spare parts	0.5% of TPC
Construction time	
3 years	
Capital expenditure schedule, % of TPC, Year 1-3	
20%/45%/35%	
Start-up costs	
Maintenance and operating and support labour costs	3 months
Maintenance materials	1 month

Chemicals, consumables, and waste disposal costs	1 month
Fuel cost, % of full load	25% of 1 month
Modifications	2% of TPC
Working capital	15% of TPC
Decommissioning cost	0
Capacity factor	
All except Year 1	85%
Year 1	60%
Operating life	25 years
Fuel prices	
Electricity	US\$60/MWh
Heating	US\$15/GJ
Fixed operating costs	
Maintenance costs	2% of TPC
Operating labour cost	US\$60,000/person-year
Number of operators	4 per shift
Number of operating shifts	5
Administrative/support labour	30% of operating labour
Insurance cost	0.5% of TPC
Local taxes and fees	0.5% of TPC
Variable operating costs	
Raw process water	US\$0.2/m ³
Limestone	US\$20/t
Monoethanolamine	US\$2.1/kg
LO-CAT® chemicals	US\$150/t
Solid waste disposal cost	US\$45.7/t
Wastewater treatment cost	US\$2/m ³
CO ₂ transport and storage	US\$10/t CO ₂ stored
Acetic acid market price	US\$500/t
CCS credit	US\$90/t CO ₂ stored

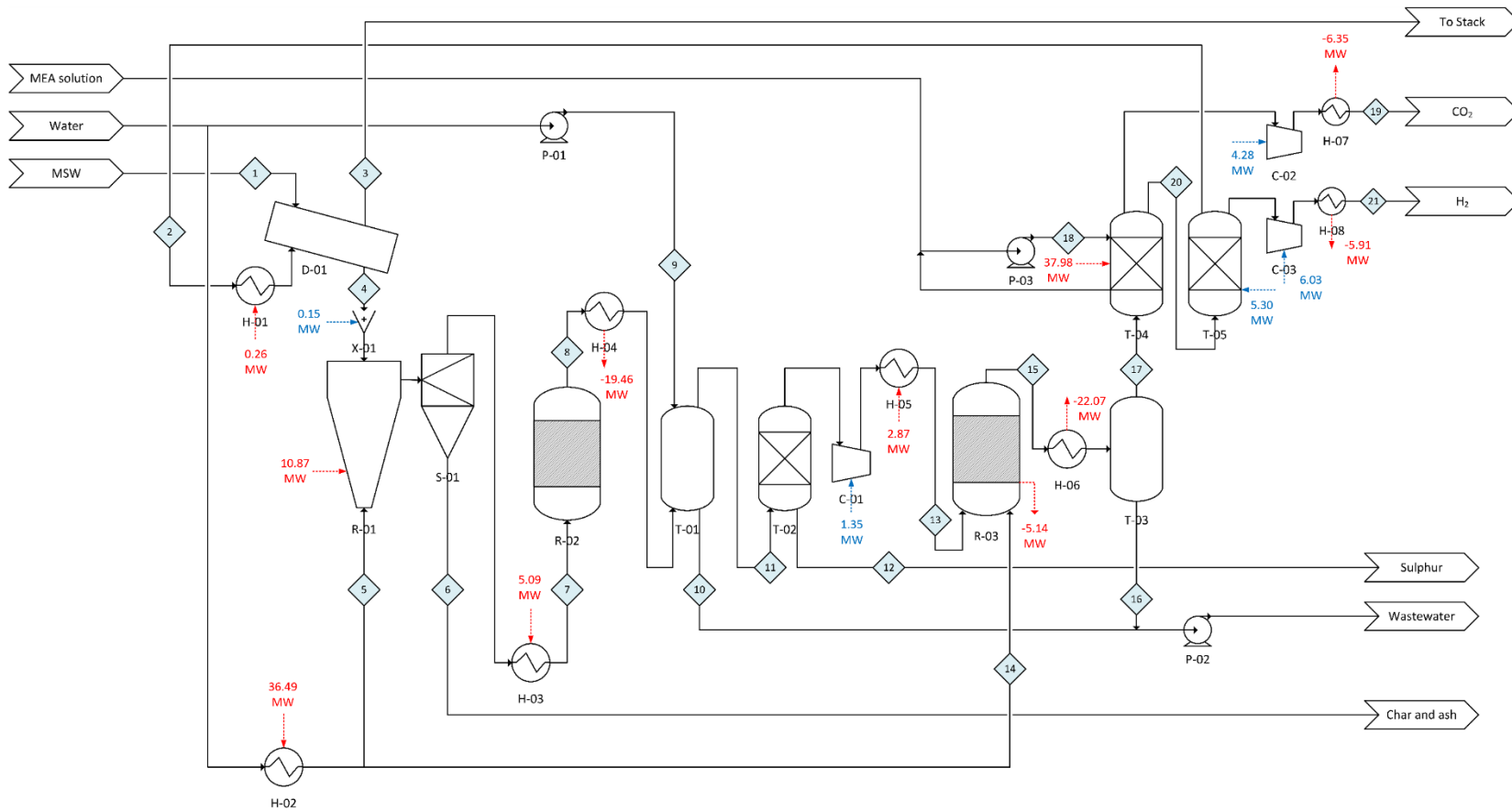
A2.2. Process Flow Diagram



Eq. No.	Eq. Name
R-01	Gasifier
R-02	Tar Reformer
R-03	WGS Reactor
T-01	Scrubber
T-02	LO-CAT® Unit
T-03	Flash Drum
T-04	CO ₂ Capture Unit
T-05	PSA H ₂ Separator
S-01	Gasifier Cyclone
D-01	MSW Dryer
H-01	Drying Gas Heater
H-02	Boiler
H-03	O ₂ Heater
H-04	Gasification Outlet Cooler
H-05	Syngas Heater
H-06	WGS Outlet Cooler
H-07	CO ₂ Cooler
H-08	H ₂ Cooler
B-01	O ₂ Compressor
C-01	Syngas Compressor
C-02	CO ₂ Compressor
C-03	H ₂ Compressor
P-01	Water Pump
P-02	Wastewater Pump
P-03	MEA Pump
X-01	MSW Shredder
ASU	Air Separation Unit

Gasification

Component	Unit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21				
Temperature	°C	25	150	85	40	250	121	985	985	25	60	60	60	270	250	270	40	40	40	30	40	30				
Pressure	bar	1	1	1	1	2	2	2	2	1	1	1	1	2	2	2	1	1	1	110	1	20				
Total flow	tpd	2,000	435	1,315	1,120	100	500	362	1,358	5,433	5,445	1,346	2	1,343	1,461	2,804	1,064	1,741	13,925	1,216	524	89				
Dry MSW	tpd	1,120	0	0	1,120	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Ash	tpd	0	0	0	0	0	0	345	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Char	tpd	0	0	0	0	0	0	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
H ₂	tpd	0	0	0	0	0	0	0	44	0	0	44	0	44	0	89	0	89	0	0	89	89				
O ₂	tpd	0	225	225	0	0	500	0	225	0	0	225	0	225	0	225	0	225	0	0	225	0				
H ₂ O	tpd	880	0	880	0	100	0	0	10	5,433	5,443	0	0	0	1,461	1,064	1,064	0	8,355	0	0	0				
S	tpd	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0				
H ₂ S	tpd	0	0	0	0	0	0	0	2	0	0	2	0	0	0	0	0	0	0	0	0	0				
N ₂	tpd	0	11	11	0	0	0	0	11	0	0	11	0	11	0	11	0	11	0	0	11	0				
NH ₃	tpd	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
HCl	tpd	0	0	0	0	0	0	0	2	0	2	0	0	0	0	0	0	0	0	0	0	0				
CH ₄	tpd	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
CO	tpd	0	136	136	0	0	0	0	754	0	0	754	0	754	0	136	0	136	0	0	136	0				
CO ₂	tpd	0	64	64	0	0	0	0	310	0	0	310	0	310	0	1,280	0	1,280	0	1,216	64	0				
MEA	tpd	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5,570	0	0	0				



Eq. No.	Eq. Name
R-01	Pyrolyser
R-02	Steam Reformer
R-03	WGS Reactor
T-01	Scrubber
T-02	LO-CAT® Unit
T-03	Flash Drum
T-04	CO ₂ Capture Unit
T-05	H ₂ PSA Separator
S-01	Pyrolyser Cyclone
D-01	MSW Dryer
H-01	Drying Gas Heater
H-02	Boiler
H-03	Reformer Inlet Heater
H-04	Reformer Outlet Heater
H-05	Syngas Heater
H-06	WGS Outlet Cooler
H-07	CO ₂ Cooler
H-08	H ₂ Cooler
C-01	Pyrolysis Gas Compressor
C-02	CO ₂ Compressor
C-03	H ₂ Compressor
P-01	Water Pump
P-02	Wastewater Pump
P-03	MEA Pump
X-01	MSW Shredder

Pyrolysis with In-Line Reforming

Component	Unit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21				
Temperature	°C	25	150	42	42	250	500	850	850	25	40	40	40	270	250	270	40	40	40	30	40	30				
Pressure	bar	1	1	1	1	2	2	2	2	1	1	1	1	2	2	2	1	1	1	110	1	20				
Total flow	tpd	2,000	203	1,083	1,120	293	520	893	893	3,570	3,663	800	2	798	768	1,566	550	1,016	8,129	732	284	80				
Dry MSW	tpd	1,120	0	0	1,120	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Ash	tpd	0	0	0	0	0	345	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Char	tpd	0	0	0	0	0	175	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
H ₂	tpd	0	0	0	0	0	0	13	56	0	0	56	0	56	0	80	0	80	0	0	80	80				
O ₂	tpd	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
H ₂ O	tpd	880	0	880	0	293	0	293	80	3,570	3,650	0	0	0	768	550	550	0	4,877	0	0	0				
S	tpd	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0				
H ₂ S	tpd	0	0	0	0	0	0	2	2	0	0	2	0	0	0	0	0	0	0	0	0	0				
NH ₃	tpd	0	0	0	0	0	0	11	11	0	11	0	0	0	0	0	0	0	0	0	0	0				
HCl	tpd	0	0	0	0	0	0	2	2	0	2	0	0	0	0	0	0	0	0	0	0	0				
CH ₄	tpd	0	0	0	0	0	0	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
CO	tpd	0	165	165	0	0	0	90	504	0	0	504	0	504	0	165	0	165	0	0	165	0				
CO ₂	tpd	0	39	39	0	0	0	129	237	0	0	237	0	237	0	771	0	771	0	732	39	0				
Pyrolysis oil	tpd	0	0	0	0	0	0	327	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
MEA	tpd	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3,252	0	0	0				

A2.3. Process Description

A2.3.1. Gasification

The gasification process design can be divided into several process sections, including pretreatment, gasification, gas cleaning and conditioning, water-gas shift, CO₂ capture, and H₂ separation.

Pretreatment

First, waste feedstock is dried using rotary dryer D-01. The drying medium is flue gas from H₂ separation section, which is preheated first to 150°C in heater H-01. The dried waste exits the dryer at temperature of 42°C and is shredded in shredder X-01 before entering the gasification section, while the drying gas is emitted to the atmosphere through the stack.

Gasification

Dry waste is fed into gasifier R-01 at 985°C, 2 bar. The gasification agent is steam (250°C, 2 bar) from boiler H-02 and O₂ from air separation unit (ASU). The O₂ from ASU is fed into gasifier using blower B-01 and preheated to 121°C, 2 bar using heater H-03. The steam/dry biomass ratio is 0.1 kg steam/kg dry waste, while the O₂/dry waste ratio is 0.48 kg O₂/kg dry waste.⁽¹³²⁾ The product then undergoes a tar reforming reactions in tar reformer R-02. The removal of particulate, including char and ash, is performed through cyclone separator S-01. In the gasification process, tar formation is neglected as steam is used as the gasification agent and high temperature is employed.⁽¹³²⁾

Gas cleaning and conditioning

The raw syngas from the gasifier is cooled by cooler H-04 and passed through water scrubber T-01 to reach 60°C, 1 bar conditions. Water scrubbing also removes impurities, such as ammonia and hydrochloric acid. The water/gas ratio used in the scrubber is 4 kg water/kg gas.⁽²⁶⁹⁾ The excess scrubber water is sent off site to wastewater treatment plant. Subsequently, sulphur removal is performed using a liquid phase oxidation process (LO-CAT®) in LO-CAT® unit T-02. Elemental sulphur is produced and stockpiled for disposal. The clean syngas is preconditioned via compression using compressor C-01 and preheating using heater H-05 prior to water-gas shift (WGS) reaction.

Water-gas shift

Water-gas shift (WGS) reaction is performed to convert the CO in syngas using steam into CO₂ and H₂ ($\text{CO} + \text{H}_2\text{O} \rightleftharpoons \text{CO}_2 + \text{H}_2$). The preconditioned syngas is fed into WGS reactor R-03 at 270°C, 2 bar with a steam/CO molar ratio of 3. The catalyst used for WGS is CuO/ZnO/Al₂O₃ with gas hourly space velocity of 40,000 h⁻¹.⁽²⁷⁰⁾ The WGS outlet stream is cooled to 40°C, 1 bar using cooler H-06, and excess water is separated from the gas phase in flash drum T-03.

CO₂ capture

The CO₂ is separated from the gas stream in CO₂ capture unit T-04 using monoethanolamine (MEA) as the solvent. The aqueous MEA solution (40 wt%) flow rate is calculated based on MEA/gas flow ratio of 8 to ensure a high CO₂ capture rate of 95%.⁽²⁷¹⁾ The recovered CO₂ is compressed by compressor C-02 and passed through cooler H-07 to reach final CO₂ conditions of 30°C, 110 bar, suitable for pipeline transport.⁽¹³¹⁾

H₂ separation

The H₂ is purified using pressure swing adsorption (PSA) unit T-05. The tail gas is sent to pretreatment section for drying purposes. The H₂ outlet condition is 30°C, 20 bar.

A2.3.2. Pyrolysis with In-Line Reforming

The pyrolysis with in-line reforming process design can be divided into several process sections, including pretreatment, pyrolysis, steam reforming, gas cleaning and conditioning, water-gas shift, CO₂ capture, and H₂ separation.

Pretreatment

First, waste feedstock is dried using rotary dryer D-01. The drying medium is flue gas from H₂ separation section, which is preheated first to 150°C in heater H-01. The dried waste exits the dryer at temperature of 42°C and is shredded in shredder X-01 before entering the pyrolysis section, while the drying gas is emitted to the atmosphere through the stack.

Pyrolysis

Dry waste is fed into fluidised bed pyrolyser R-01 at 500°C, 2 bar. The fluidising medium is steam (250°C, 2 bar) from boiler H-02. In the pyrolysis process, 23% of the waste is sequestered as char, while the pyrolysis oil and gas yields are 43% and 34%, respectively. The pyrolysis gas comprises H₂, CO, CO₂, and other impurities. The pyrolysis oil is modelled as a mixture of four components typically found in pyrolysis oil: acetic acid, acetol, guaiacol, and furfural. The particulates including char and ash is removed from the gas stream using cyclone separator S-01. The pyrolysis products are then fed into steam reforming section to increase the H₂ yield.

Steam reforming

The volatiles from pyrolysis section are preheated using heater H-03 to 700°C, 2 bar and introduced to steam reformer R-02 operated at 700°C, 2 bar. In steam reforming process, the hydrocarbon components, including methane and bio-oil components, undergo conversion via reforming ($C_xH_y + n H_2O \rightleftharpoons (n+m)/2 H_2 + n CO$) to increase the overall H₂ yield. Ni/Al₂O₃ is used as the catalyst for steam reforming of bio-oil with gas hourly space velocity of 0.22 g_{catalyst} h/g_{oil}.⁽²⁷²⁾

Gas cleaning and conditioning

The reformed gas is passed through cooler H-04 and water scrubber T-01 to reach 40°C, 1 bar conditions. Water scrubbing also removes impurities, such as ammonia and hydrochloric acid. The water/gas ratio used in the scrubber is 4 kg water/kg gas.⁽²⁶⁹⁾ The excess scrubber water is sent off site to wastewater treatment plant. Subsequently, sulphur removal is performed using a liquid phase oxidation process (LO-CAT®) in LO-CAT® unit T-02. Elemental sulphur is produced and stockpiled for disposal. The clean reformed gas is preconditioned via compression using compressor C-02 and preheating using heater H-05 prior to water-gas shift (WGS) reaction.

Water-gas shift

Water-gas shift (WGS) reaction is performed to convert the CO in reformed gas using steam into CO₂ and H₂ ($CO + H_2O \rightleftharpoons CO_2 + H_2$). The preconditioned reformed gas is fed into WGS reactor R-02 at 270°C, 2 bar with a steam/C molar ratio of 3. The catalyst for WGS is CuO/ZnO/Al₂O₃ with gas hourly space velocity of 40,000 h⁻¹.⁽²⁷⁰⁾ The WGS outlet stream is cooled to 40°C, 1 bar using cooler H-06, and excess water is separated from the gas phase in flash drum T-03

CO₂ capture

The CO₂ is separated from the gas stream in CO₂ capture unit T-04 using monoethanolamine (MEA) as the solvent. The aqueous MEA solution (40 wt%) flow rate is calculated based on MEA/gas flow ratio of 8 to ensure a high CO₂ capture rate of 95%.⁽²⁷¹⁾ The recovered CO₂ is compressed by compressor C-02 and passed through cooler H-07 to reach final CO₂ conditions of 30°C, 110 bar, suitable for pipeline transport.⁽¹³¹⁾

H₂ separation

The H₂ is purified using pressure swing adsorption (PSA) unit T-05. The tail gas is sent to pretreatment section for drying purposes. The H₂ outlet condition is 30°C, 20 bar.

A2.3.3. Dark Fermentation

The fermentation process design can be divided into several sections, acid hydrolysis, neutralisation, fermentation, CO₂ capture, and H₂ separation.

Acid hydrolysis

First, waste feedstock is shredded in shredder X-01 and subjected to a hydrolysis pretreatment in acid hydrolyser R-01 to break down cellulose and hemicellulose into glucose. The hydrolysis process is carried out at 100°C, 1 bar, using 10 wt% aqueous H₂SO₄ solution that is pre-mixed in H₂SO₄ mixer M-01. In acid hydrolysis step, it is assumed that only cellulose and hemicellulose can be broken down into glucose, with a glucose yield of 95%, while the remaining biomass leave hydrolyser as residue. The hydrolyser effluent is subsequently cooled down in cooler H-01 to 60°C. The solid residue is separated from the acidic product solution by rotary drum filter F-01.

Neutralisation

In neutralisation stage, Ca(OH)₂ slurry is made by mixing CaO and water in mixer M-02. The Ca(OH)₂ slurry neutralises H₂SO₄ in neutraliser M-03, forming CaSO₄ solid. Finally, CaSO₄ solid is separated from the glucose solution using rotary drum filter F-02.

Fermentation

Glucose solution is then pre-conditioned by heater H-02 to reach the desired operating temperature of 55°C and mixed with *Clostridium thermocellum* inoculum for fermentation process in fermenter R-02. In the fermentation process, *Clostridium thermocellum* digests glucose via acetate pathway into H₂, CO₂, and acetic acid ($C_6H_{12}O_6 + H_2O \rightarrow CO_2 + H_2 + CH_3COOH$). Through this fermentative pathway, the H₂ yield that can be achieved is only 2.5 mol H₂/mol glucose under the base case scenario.⁽²⁷³⁾ The liquid product of the fermentation process is fed into rotary drum filter F-03 to separate the used inoculum, while the liquid product can be treated for value-added chemical recovery or further processed.

CO₂ capture

The gaseous product, which contains CO₂ and H₂, is fed into CO₂ capture unit (T-01) using monoethanolamine (MEA) as the solvent. The aqueous MEA solution (40 wt%) flow rate is calculated based on MEA/gas flow ratio of 8 to ensure a high CO₂ capture rate of 95%.⁽²⁷¹⁾ The recovered CO₂ is compressed by compressor C-01 and passed through cooler H-03 to reach final CO₂ conditions of 30°C, 110 bar, suitable for pipeline transport.⁽¹³¹⁾

H₂ separation

The H₂ is purified using pressure swing adsorption (PSA) unit T-05. The tail gas is emitted to atmosphere through the stack. The H₂ outlet condition is 30°C, 20 bar.

A2.3.4. Incineration-Electrolysis

The incineration-water electrolysis process design can be divided into several sections, including incineration, gas cleaning, CO₂ capture, power generation, and electrolysis and H₂ compression.

Incineration

Dry biomass is fed into incinerator R-01. Air is preheated to 190°C using heater H-01 and introduced to the incinerator for combustion reactions. The combustion products exiting incinerator at temperature of 1,200°C. The removal of particulate, including char and ash, is performed through cyclone separator S-01. The hot gas is cooled using cooler H-02 to 60°C, where the heat is recovered for power generation.

Gas cleaning

The gas is passed through scrubber T-01 to remove impurities, such as ammonia and hydrochloric acid. The water/gas ratio used in the scrubber is 4 kg water/kg gas.⁽²⁶⁹⁾ The excess scrubber water is sent off site to wastewater treatment plant. Subsequently, sulphur removal is performed using a liquid phase oxidation process (LO-CAT®) in LO-CAT® unit T-02. Elemental sulphur is produced and stockpiled for disposal.

CO₂ capture

The CO₂ is separated from the gas stream in CO₂ capture unit T-03 using monoethanolamine (MEA) as the solvent. The aqueous MEA solution (40 wt%) flow rate is calculated based on MEA/gas flow ratio of 8 to ensure a high CO₂ capture rate of 95%.⁽²⁷¹⁾ The recovered CO₂ is compressed by compressor C-01 and passed through cooler H-03 to reach final CO₂ conditions of 30°C, 110 bar, suitable for pipeline transport.⁽¹³¹⁾ The tail gas is sent to pretreatment section for drying purposes.

Power generation

The recovered heat from H-02 is used to produce steam (700°C, 2 bar) in boiler H-05. The steam is passed through turbine ST-01, generating power. The low-pressure steam exiting the turbine is then condensed in condenser H-05 and pumped back to boiler.

Electrolysis

The generated electricity from the power generation unit is partially used to meet electrical requirements for gas compression and pumping. The remaining power is directed to PEM electrolyser R-02 to split water into H₂ and O₂. The operating temperature and pressure of the electrolyser system is maintained at 40°C, 20 bar. The specific energy consumption of the PEM electrolyser for the base case is 53 kWh/kg.⁽²⁷⁴⁾ The O₂ generated from the anode is purged into the atmosphere, while the H₂ stream is passed through demister (T-07) first to remove residual water in the stream.

A2.3. CAPEX and OPEX Estimations

Capital costs include Total Plant Cost (TPC) and Total Capital Requirement (TCR). TPC is the installed cost of the plant including installation cost, instrumentation and controls cost, engineering contractor's fees, as well as contingencies. TCR includes TPC, interest during construction, owners costs, spare parts, working capital, and start-up costs.

CAPEX for process equipment are obtained from literature. To scale the purchased costs found in the literature to the capacities explored in this study, the economy of scale was considered using the scaling factors from the literature. To adjust equipment CAPEX costs found in the literature to the year of analysis (2023), Chemical Engineering Plant Cost Indices were used. **Equation 15** is used to calculate the adjusted process equipment CAPEX.⁽⁶⁵⁾

$$\text{Adjusted CAPEX} = \text{Reference CAPEX} \times \frac{\text{CEPCI 2023}}{\text{CEPCI reference year}} \times \left(\frac{\text{Base case capacity}}{\text{Reference capacity}} \right)^{\text{Scaling factor}} \quad (15)$$

Installation cost, instrumentation and controls cost, engineering contractor's fees, and contingencies are then added to the adjusted CAPEX based on the assumptions stated in **Table 40**. TCR is then calculated by considering the owners costs, spare parts, working capital, and start-up costs. Owners costs cover the costs of feasibility studies, surveys, land purchase, construction or improvement to road and railways, water supply, owners engineering staff costs, permitting and legal fees, arranging financing and other miscellaneous costs. Start-up costs consist of: (i) 2% of TPC to cover modifications to equipment that will be needed to bring the unit up to full capacity; (ii) 25% of the full capacity fuel cost for one month, to cover inefficient operation that occurs during the start-up period; (iii) 3 months of operating and maintenance labour costs to include training; and (iv) 1 month catalysts, chemicals, and waste disposal costs.

Operating costs include the variable costs of feedstocks, chemicals and fuels, waste stream charges, byproduct credits, CO₂ transport and storage, and fixed operating costs, including maintenance costs, operating labour, administrative and support labour, insurance cost, and local taxes and fees. The costs for chemicals and fuels are listed in **Table 40**.

The annual average operating capacity factor will depend on the technical availability of the plant and feedstock supply reliability. Plant will operate at 'base load' at a capacity factor of 85%. The capacity factor in the first year of service is assumed to be 60% to allow start-up and debugging.

A2.3.1 CAPEX Estimation Results

Table 41. CAPEX estimation for gasification process.

Unit	Reference CAPEX (US\$)	Reference year	CEPCI of reference year	CEPCI of analysis year (2023)	Reference capacity	Base case capacity	Scaling factor	Installation factor	Adjusted installed CAPEX, including engineering contractors fees and contingency (US\$)	Ref.
Shredder (X-01)	1,005,789	2019	607.5	793.3	83,333 kg/h	46,667 kg/h	0.60	2	2,914,980	(275)
Gasifier (R-01)	33,260,043	2019	607.5	793.3	83,333 kg/h	46,667 kg/h	0.70	4	181,928,303	(275)
Gasifier Cyclone (S-01)	3,000,000	2002	395.6	793.3	34.20 m ³ /s	46.01 m ³ /s	0.70	1.6	16,441,130	(276)
Tar Reformer (R-02)	24,446,771	2019	607.5	793.3	83,333 kg/h	46,667 kg/h	0.70	4	133,720,800	(275)
Scrubber (T-01)	411,000	2016	541.7	793.3	75,709 kg/h	56,592 kg/h	0.60	1.6	1,270,859	(277)
WGS Reactor (R-03)	12,200,000	2002	395.6	793.3	8,819 kmol/h	2,652 kmol/h	0.60	2.47	43,486,257	(276)
LO-CAT® Unit (T-02)	2,469,142	2002	395.6	793.3	81,372 kg/h	56,066 kg/h	0.65	2.61	15,940,753	(278)
Flash Drum (T-03)	321,048	2002	395.6	793.3	160,764 kg/h	116,848 kg/h	0.60	2.47	2,063,486	(278)
CO ₂ Capture Unit (T-04), Includes MEA Pump (P-03)	29,358,000	2013	567.3	793.3	560,000 kg/h	50,686 kg/h	0.60	2.61	39,838,855	(279)
PSA H ₂ Separator (T-05)	11,993,041	2002	395.6	793.3	6,468 kg/h	3,699 kg/h	0.60	1.9	51,346,983	(278)
MSW Dryer (D-01)	18,839,801	2002	395.6	793.3	166,667 kg/h	83,333 kg/h	0.75	1.8	63,540,734	(278)
Drying Gas Heater (H-01)	2,143	2019	607.5	793.3	1 m ²	20 m ²	0.51	2.47	50,213	(280)
Boiler (H-02)	696,000	2018	603.1	793.3	65,000 kg/h	65,038 kg/h	0.60	2.47	3,554,679	(281)
O ₂ Heater (H-03)	2,143	2019	607.5	793.3	1 m ²	6 m ²	0.51	2.47	26,488	(280)
Gasification Outlet Cooler (H-04)	2,143	2019	607.5	793.3	1 m ²	883 m ²	0.51	2.47	354,934	(280)
Syngas Heater (H-05)	2,143	2019	607.5	793.3	1 m ²	117 m ²	0.51	2.47	125,570	(280)
WGS Outlet Cooler (H-06)	2,143	2019	607.5	793.3	1 m ²	1,502 m ²	0.51	2.47	466,228	(280)
CO ₂ Cooler (H-07)	2,143	2019	607.5	793.3	1 m ²	353 m ²	0.51	2.47	221,511	(280)
H ₂ Cooler (H-08)	2,143	2019	607.5	793.3	1 m ²	217 m ²	0.51	2.47	172,632	(280)
Air Separation Unit (ASU)	30,622	2022	802.9	793.3	1 kg/h	20,833 kg/h	0.64	1.8	47,622,436	(282)
Syngas Compressor (C-01)	9,624	2019	607.5	793.3	1 kW	2,010 kW	0.46	1.8	1,175,691	(283)
CO ₂ Compressor (C-02)	9,624	2019	607.5	793.3	1 kW	7,140 kW	0.46	1.8	2,106,319	(283)
H ₂ Compressor (C-03)	9,624	2019	607.5	793.3	1 kW	6,660 kW	0.46	1.8	2,039,957	(283)
Water Pump (P-01)	3,500	2019	607.5	793.3	1 kW	7 kW	0.41	2.47	39,380	(284)
Wastewater Pump (P-02)	3,500	2019	607.5	793.3	1 kW	9 kW	0.41	2.47	42,683	(284)
Total Plant Cost (TPC) including installation cost, engineering contractor's fees, and contingency									610,491,861	
Owners costs and fees									42,734,430.26	
Spare parts costs									3,052,459.30	
Working capital									91,573,779.14	
Start-up costs									22,467,999.83	
Total Capital Requirement (TCR)									770,320,529	

Table 42. CAPEX estimation for pyrolysis process.

Unit	Reference CAPEX (US\$)	Reference year	CEPCI of reference year	CEPCI of analysis year (2023)	Reference capacity	Base case capacity	Scaling factor	Installation factor	Adjusted installed CAPEX, including engineering contractors fees and contingency (US\$)	Ref.
Shredder (X-01)	1,005,789	2019	607.5	793.3	83,333 kg/h	46,667 kg/h	0.60	2	2,914,980	(275)
Pyrolyser (R-01), Includes Pyrolyser Cyclone (S-01)	7,881,573	2016	541.7	793.3	10,000 kg/h	46,667 kg/h	0.60	4	182,831,248	(277)
Steam Reformer (R-02)	4,930,889	2022	802.9	793.3	1 MW	21 MW	0.65	4	223,712,490	(282)
WGS Reactor (R-03)	798,957	2002	395.6	793.3	8,819 kmol/h	2,141 kmol/h	0.65	2.47	37,831,235	(276)
Scrubber (T-01)	411,000	2016	541.7	793.3	75,709 kg/h	37,191 kg/h	0.60	1.6	987,892	(277)
LO-CAT® Unit (T-02)	2,469,142	2002	395.6	793.3	81,372 kg/h	33,318 kg/h	0.65	2.61	11,365,624	(278)
Flash Drum (T-03)	321,048	2002	395.6	793.3	160,764 kg/h	65,242 kg/h	0.60	2.47	1,454,601	(278)
CO ₂ Capture Unit (T-04), Includes MEA Pump (P-03)	29,358,000	2013	567.3	793.3	560,000 kg/h	30,520 kg/h	0.60	2.61	29,384,616	(279)
PSA H ₂ Separator (T-05)	11,993,041	2002	395.6	793.3	6,468 kg/h	3,349 kg/h	0.60	1.9	48,378,915	(278)
MSW Dryer (D-01)	18,839,801	2002	395.6	793.3	166,667 kg/h	83,333 kg/h	0.75	1.8	63,540,645	(278)
Drying Gas Heater (H-01)	2,143	2019	607.5	793.3	1 m ²	9 m ²	0.51	2.47	32,953	(280)
Boiler (H-02)	696,000	2018	603.1	793.3	65,000 kg/h	44,172 kg/h	0.60	2.47	2,818,317	(281)
Reformer Inlet Heater (H-03)	2,143	2019	607.5	793.3	1 m ²	170 m ²	0.51	2.47	152,003	(280)
Reformer Outlet Heater (H-04)	2,143	2019	607.5	793.3	1 m ²	649 m ²	0.51	2.47	302,844	(280)
Syngas Heater (H-05)	2,143	2019	607.5	793.3	1 m ²	96 m ²	0.51	2.47	113,227	(280)
WGS Outlet Cooler (H-06)	2,143	2019	607.5	793.3	1 m ²	736 m ²	0.51	2.47	323,082	(280)
CO ₂ Cooler (H-07)	2,143	2019	607.5	793.3	1 m ²	171 m ²	0.51	2.47	152,769	(280)
H ₂ Cooler (H-08)	2,143	2019	607.5	793.3	1 m ²	197 m ²	0.51	2.47	164,133	(280)
Pyrolysis Gas Compressor (C-01)	9,624	2019	607.5	793.3	1 kW	1,350 kW	0.46	1.8	978,986	(283)
CO ₂ Compressor (C-02)	9,624	2019	607.5	793.3	1 kW	4,280 kW	0.46	1.8	1,664,513	(283)
H ₂ Compressor (C-03)	9,624	2019	607.5	793.3	1 kW	6,030 kW	0.46	1.8	1,948,807	(283)
Water Pump (P-01)	3,500	2019	607.5	793.3	1 kW	13 kW	0.41	2.47	51,361	(284)
Wastewater Pump (P-02)	3,500	2019	607.5	793.3	1 kW	17 kW	0.41	2.47	56,615	(284)
Total Plant Cost (TPC) including installation cost, engineering contractor's fees, and contingency									611,161,863	
Owners costs and fees									42,781,330	
Spare parts costs									3,055,809	
Working capital									91,674,279	
Start-up costs									22,503,807	
Total Capital Requirement (TCR)									771,177,089	

Table 43. CAPEX estimation for dark fermentation process.

Unit	Reference CAPEX (US\$)	Reference year	CEPCI of reference year	CEPCI of analysis year (2023)	Reference capacity	Base case capacity	Scaling factor	Installation factor	Adjusted installed CAPEX, including engineering contractors fees and contingency (US\$)	Ref.
Shredder (X-01)	1,005,789	2019	607.5	793.3	83,333 kg/h	46,667 kg/h	0.60	2	4,128,911	(275)
Acid Hydrolyser (R-01)	19,812,400	2009	521.9	793.3	36.7 m ³	60 m ³	0.60	1.4	86,692,862	(285)
Fermenter (R-02)	17,500,000	2014	576.1	793.3	11,000 m ³	6,869 m ³	0.60	1.4	33,738,471	(281)
H ₂ SO ₄ Mixer (M-01)	236,000	2009	521.9	793.3	447 m ³	238 m ³	0.70	1.4	494,706	(281)
CaO Mixer (M-02)	236,000	2009	521.9	793.3	447 m ³	90 m ³	0.70	1.4	250,446	(281)
Neutraliser (M-03)	236,000	2009	521.9	793.3	447 m ³	52 m ³	0.70	1.4	171,343	(281)
CO ₂ Capture Unit (T-04), Includes MEA Pump (P-04)	29,358,000	2013	567.3	793.3	560,000 kg/h	6,092 kg/h	0.60	2.61	11,174,919	(279)
PSA H ₂ Separator (T-02)	11,993,041	2002	395.6	793.3	6,468 kg/h	583 kg/h	0.60	1.9	16,946,839	(278)
Residue Rotary Filter (F-01)	254,000	2023	793.3	793.3	101 m ²	100 m ²	0.66	1.4	540,876	(281)
CaSO ₄ Rotary Filter (F-02)	254,000	2023	793.3	793.3	101 m ²	105 m ²	0.66	1.4	557,221	(281)
Inoculum Rotary Filter (F-03)	254,000	2023	793.3	793.3	101 m ²	99 m ²	0.66	1.4	536,795	(281)
Hydrolyser Outlet Cooler (H-01)	2,143	2019	607.5	793.3	1 m ²	124 m ²	0.51	2.47	129,227	(280)
Fermenter Inlet Cooler (H-02)	2,143	2019	607.5	793.3	1 m ²	27 m ²	0.51	2.47	59,483	(280)
CO ₂ Cooler (H-03)	2,143	2019	607.5	793.3	1 m ²	33 m ²	0.51	2.47	65,532	(280)
H ₂ Cooler (H-04)	2,143	2019	607.5	793.3	1 m ²	33 m ²	0.51	2.47	65,532	(280)
CO ₂ Compressor (C-01)	9,624	2019	607.5	793.3	1 kW	910 kW	0.46	1.8	816,711	(283)
H ₂ Compressor (C-02)	9,624	2019	607.5	793.3	1 kW	1,070 kW	0.46	1.8	879,885	(283)
Hydrolyser Pump (P-01)	3,500	2019	607.5	793.3	1 kW	4 kW	0.41	2.47	32,364	(284)
Neutraliser Pump (P-02)	3,500	2019	607.5	793.3	1 kW	4 kW	0.41	2.47	31,947	(284)
Liquid Products Pump (P-03)	3,500	2019	607.5	793.3	1 kW	4 kW	0.41	2.47	30,647	(284)
Total Plant Cost (TPC) including installation cost, engineering contractor's fees, and contingency									161,473,630	
Owners costs and fees									11,014,130	
Spare parts costs									786,724	
Working capital									23,601,708	
Start-up costs									8,384,856	
Total Capital Requirement (TCR)									205,261,048	

Table 44. CAPEX estimation for incineration-electrolysis process.

Unit	Reference CAPEX (US\$)	Reference year	CEPCI of reference year	CEPCI of analysis year (2023)	Reference capacity	Base case capacity	Scaling factor	Installation factor	Adjusted installed CAPEX, including engineering contractors fees and contingency (US\$)	Ref.
Incinerator (R-01), Includes Incinerator Cyclone S-01)						730,000 tpa		-	350,229,602	
PEM Electrolyser (R-02), Includes O ₂ Separator (T-04), H ₂ Separator (T-05) and H ₂ Demister (T-06)	1,700	2022	802.9	793.3	1 kW	55,770 kW	0.90	-	99,656,160	(286)
Scrubber (T-01)	411,000	2016	541.7	793.3	75,709 kg/h	282,284 kg/h	0.60	1.6	3,333,179	(277)
CO ₂ Capture Unit (T-02), Includes MEA Pump (P-03)	29,358,000	2013	567.3	793.3	560,000 kg/h	60,689 kg/h	0.60	2.61	44,385,178	(279)
Water Electrolyser Tank (T-03)	165,800	1997	386.5	793.3	5 m ³	2,325 m ³	0.50	1.4	33,817	(281)
Air Heater (H-02)	2,143	2019	607.5	793.3	1 m ²	201 m ²	0.51	2.47	165,837	(280)
Incinerator Outlet Cooler (H-03)	2,143	2019	607.5	793.3	1 m ²	5,501 m ²	0.51	2.47	908,684	(280)
CO ₂ Cooler (H-04)	2,143	2019	607.5	793.3	1 m ²	456 m ²	0.51	2.47	252,571	(280)
Boiler (H-05)	696,000	2018	603.1	793.3	65,000 kg/h	117,317 kg/h	0.65	2.47	5,064,287	(281)
Steam Turbine Cooler (H-06)	130	2019	607.5	793.3	1 m ²	3,035 m ²	0.51	2.47	2,188,048	(280)
Steam Turbine (ST-01)	4,405	2019	607.5	793.3	1 kW	43,750 kW	0.70	1.8	28,845,008	(283)
CO ₂ Compressor (C-01)	9,624	2019	607.5	793.3	1 kW	9,110 kW	0.46	1.8	2,356,142	(283)
Water Feed Scrubber Pump (P-01)	3,500	2019	607.5	793.3	1 kW	44 kW	0.41	2.47	83,665	(284)
Wastewater Pump (P-02)	3,500	2019	607.5	793.3	1 kW	45 kW	0.41	2.47	84,329	(284)
Steam Turbine Pump (P-04)	3,500	2019	607.5	793.3	1 kW	528 kW	0.41	2.47	231,872	(284)
Water Feed Electrolyser Pump (P-05)	3,500	2019	607.5	793.3	1 kW	0.44 kW	0.41	2.47	12,648	(284)
Electrolyser Circulation Pump (P-06)	3,500	2019	607.5	793.3	1 kW	0.44 kW	0.41	2.47	12,648	(284)
Total Plant Cost (TPC) including installation cost, engineering contractor's fees, and contingency									537,843,677	
Owners costs and fees									37,649,057	
Spare parts costs									2,689,218	
Working capital									80,676,552	
Start-up costs									14,506,309	
Total Capital Requirement (TCR)									673,364,813	

A2.3.2. OPEX Estimation Results

Table 45. Annual OPEX estimate for gasification process.

OPEX component	Annual capacity	Cost per unit	Annual OPEX (US\$)
Variable OPEX (First Year of Operation)			
MSW	245,280 t (dry basis)	0	0
Electricity	142,238 MWh	US\$60/MWh	8,534,259
Heating	442,009 GJ	US\$15/GJ	6,630,129
CO ₂ transport and storage	266,406 t CO ₂	US\$10/t CO ₂ stored	2,664,062
MEA	399,609 kg MEA	US\$2.1/kg MEA	835,183
Raw water	1,531,632 t water	US\$0.2/t water	310,550
Tar reformer catalyst			2,850,000
WGS catalyst			200,000
LO-CAT® chemicals	442 t sulphur	US\$150/t sulphur	66,248
Wastewater treatment	1,425,519 t	US\$2/m ³	2,879,547
Char and ash disposal	79,260 t	US\$45.7/t	3,622,218
Sulphur disposal	442 t sulphur	US\$45.7/t	20,184
Variable OPEX (Subsequent Years of Operation)			
MSW	347,480 t biomass (dry basis)	0	0
Electricity	201,503 MWh	US\$60/MWh	12,090,200
Heating	626,179 GJ	US\$15/GJ	9,392,682
CO ₂ transport and storage	377,409 t CO ₂	US\$10/t CO ₂ stored	3,774,088
MEA	566,113 kg MEA	US\$2.1/kg MEA	1,183,177
Raw water	2,169,811 t water	US\$0.2/t water	433,962
Tar reformer catalyst			4,037,500
WGS catalyst	594 kg catalyst	US\$20/kg	93,852
LO-CAT® chemicals	626 t sulphur	US\$150/t sulphur	104,088
Wastewater treatment	2,019,484 m ³	US\$2/m ³	4,079,359
Char and ash disposal	107,093 t	US\$45.7/t	5,131,475
Sulphur disposal	626 t sulphur	US\$45.7/t	28,594
Fixed OPEX			
Maintenance costs			12,209,837
Operating labour costs			5,700,000
Administrative/support labour costs			3,175,180
Insurance costs			3,052,459
Local taxes and fees			3,052,459
Total Annual OPEX (First Year of Operation)			55,798,092
Total Annual OPEX (Subsequent Years of Operation)			67,718,157

Table 46. Annual OPEX estimate for pyrolysis process.

OPEX component	Annual capacity	Cost per unit	Annual OPEX (US\$)
Variable OPEX (First Year of Operation)			
MSW	245,280 t (dry basis)	0	0
Electricity	89,277 MWh	US\$60/MWh	5,356,645
Heating	678,150 GJ	US\$15/GJ	10,172,252
CO ₂ transport and storage	160,411 t CO ₂	US\$10/t CO ₂ stored	1,604,106
MEA	240,616 kg MEA	US\$2.1/kg MEA	502,887
Raw water	1,014,072 t water	US\$0.2/t water	202,814
Pyrolysis catalyst			594,720
Steam reforming catalyst			107,816
WGS catalyst			200,000
LO-CAT® chemicals	176 t sulphur	US\$150/t sulphur	26,405
Wastewater treatment	2,289,532 m ³	US\$2/m ³	4,624,854
Char and ash disposal	113,866 t	US\$45.7/t	3,571,923
Sulphur disposal	176 t sulphur	US\$45.7/t	8,045
Variable OPEX (Subsequent Years of Operation)			
MSW	347,480 t (dry basis)	0	0
Electricity	126,476 MWh	US\$60/MWh	7,588,581
Heating	960,713 GJ	US\$15/GJ	14,410,691
CO ₂ transport and storage	227,248 t CO ₂	US\$10/t CO ₂ stored	2,272,483
MEA	340,872 kg MEA	US\$2.1/kg MEA	712,423
Raw water	1,436,603 t water	US\$0.2/t water	287,321
Pyrolysis catalyst			842,520
Steam reforming catalyst			152,740
WGS catalyst			283,333
LO-CAT® chemicals	249 t sulphur	US\$150/t sulphur	37,408
Wastewater treatment	3,243,504 m ³	US\$2/m ³	6,551,877
Char and ash disposal	161,311 t	US\$45.7/t	5,060,225
Sulphur disposal	249 t sulphur	US\$45.7/t	11,397
Fixed OPEX			
Maintenance costs			12,223,237
Operating labour costs			5,700,000
Administrative/support labour costs			3,176,788
Insurance costs			3,055,809
Local taxes and fees			3,055,809
Total Annual OPEX (First Year of Operation)			54,184,113
Total Annual OPEX (Subsequent Years of Operation)			65,422,642

Table 47. Annual OPEX estimate for dark fermentation process.

OPEX component	Annual capacity	Cost per unit	Annual OPEX (US\$)
Variable OPEX (First Year of Operation)			
OFMSW	175,275 t (dry basis)	US\$0/t	0
Electricity	62,425 MWh	US\$60/MWh	3,745,516
CO ₂ transport and storage	32,021 t CO ₂	US\$10/t CO ₂ stored	320,214
MEA	48,032 kg MEA	US\$2.1/kg MEA	100,387
Raw water	126,270 t water	US\$0.2/t water	25,254
Quicklime (CaO)	20,032 t CaO	US\$10/t CaO	200,314
Inoculum	55,157 t inoculum	US\$10/t inoculum	2,757,823
Sulphuric acid (H ₂ SO ₄)	35,055 t H ₂ SO ₄	US\$60/t H ₂ SO ₄	2,103,302
Wastewater treatment	464,469 m ³	US\$2/m ³	929,340
Solid residue disposal	75,894 t	US\$45.7/t	3,468,362
CaSO ₄ disposal	48,648 t	US\$45.7/t	2,223,204
Used inoculum disposal	55,1567 t	US\$45.7/t	2,520,650
Variable OPEX (Subsequent Years of Operation)			
OFMSW	248,307 t (dry basis)	US\$0/t	0
Electricity	88,436 MWh	US\$60/MWh	5,306,148
CO ₂ transport and storage	45,364 t CO ₂	US\$10/t CO ₂ stored	453,636
MEA	68,045 kg MEA	US\$2.1/kg MEA	142,215
Raw water	178,882 t water	US\$0.2/t water	35,776
Quicklime (CaO)	28,378 t CaO	US\$10/t CaO	283,779
Inoculum	78,138 t inoculum	US\$10/t inoculum	3,906,916
Sulphuric acid (H ₂ SO ₄)	49,661 t H ₂ SO ₄	US\$60/t H ₂ SO ₄	2,979,678
Wastewater treatment	657,997 m ³	US\$2/m ³	1,316,564
Solid residue disposal	107,517 t	US\$45.7/t	4,913,513
CaSO ₄ disposal	68,918 t	US\$45.7/t	3,149,540
Used inoculum disposal	78,138 t	US\$45.7/t	3,570,921
Fixed OPEX			
Maintenance costs			3,146,894
Operating labour costs			5,700,000
Administrative/support labour costs			2,087,627
Insurance costs			786,724
Local taxes and fees			786,724
Total Annual OPEX (First Year of Operation)			30,902,337
Total Annual OPEX (Subsequent Years of Operation)			38,566,656

Table 48. Annual OPEX estimate for incineration-electrolysis process.

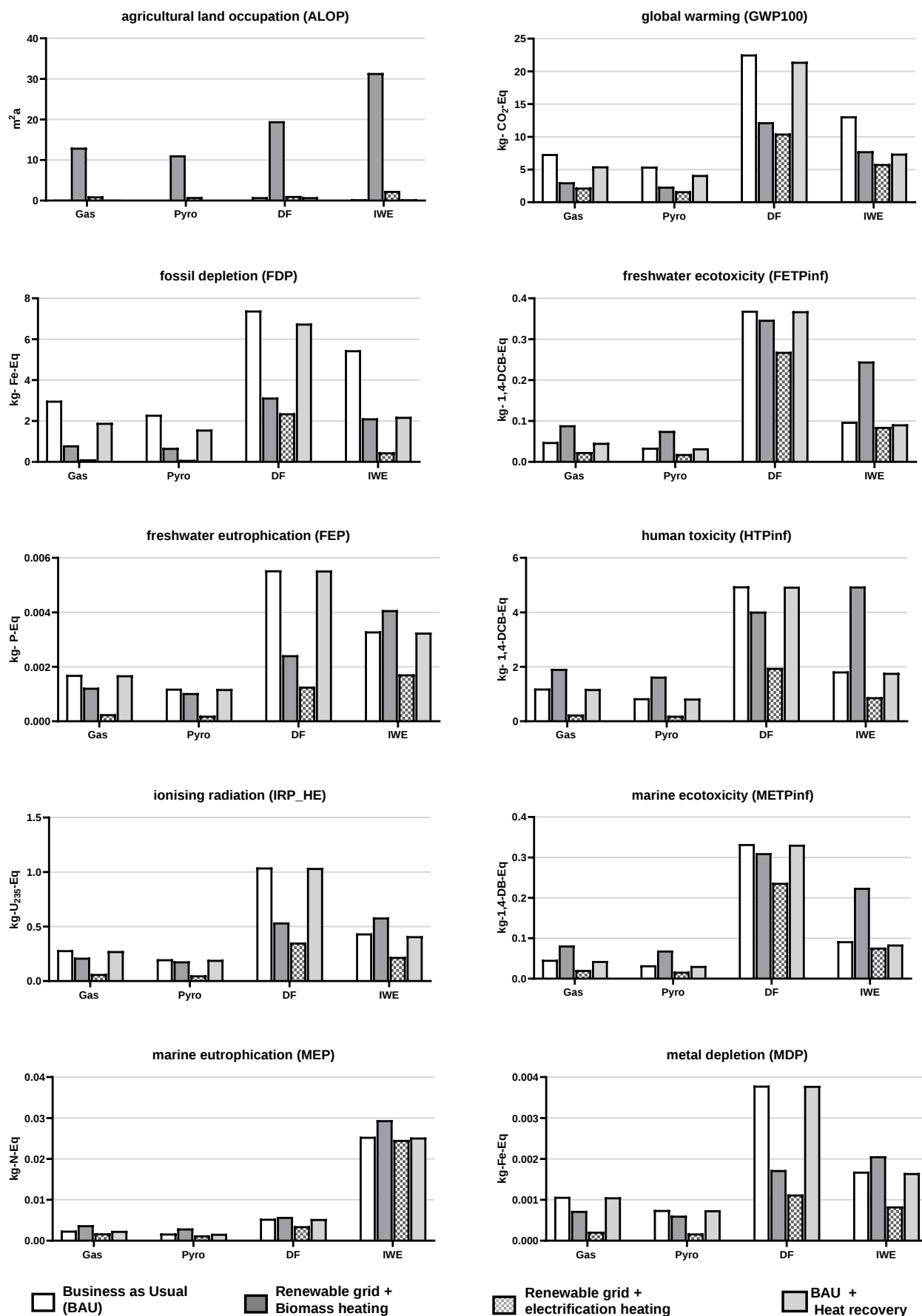
OPEX component	Annual capacity	Cost per unit	Annual OPEX (US\$)
Variable OPEX (First Year of Operation)			
MSW	245,280 t (dry basis)	0	0
CO ₂ transport and storage	318,980 t CO ₂	US\$10/t CO ₂ stored	3,189,795
MEA	478,469 kg MEA	US\$2.1/kg MEA	1,000,001
Raw water	5,974,006 t water	US\$0.2/t water	1,194,801
Electrolyser stack replacement		20% of installed electrolyser cost	513,696
Other consumables			1,000,001
Wastewater treatment			3,630,199
Char and ash disposal			3,454,706
Variable OPEX (Subsequent Years of Operation)			
MSW	347,480 t (dry basis)	0	0
CO ₂ transport and storage	451,888 t CO ₂	US\$10/t CO ₂ stored	4,518,877
MEA	677,832 kg	US\$2.1/kg MEA	1,416,668
Raw water	8,463,175 t water	US\$0.2/t water	1,692,635
Electrolyser stack replacement		20% of installed electrolyser cost	727,736
Other consumables			2,850,000
Wastewater treatment			5,142,782
Char and ash disposal			4,894,167
Fixed OPEX			
Maintenance costs			10,756,874
Operating labour costs			5,700,000
Administrative/support labour costs			3,000,825
Insurance costs			2,689,218
Local taxes and fees			2,689,218
Total Annual OPEX (First Year of Operation)			39,617,223
Total Annual OPEX (Subsequent Years of Operation)			47,209,341

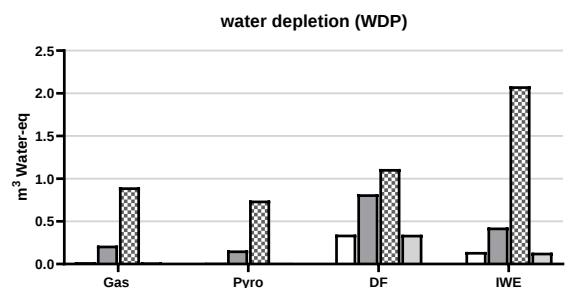
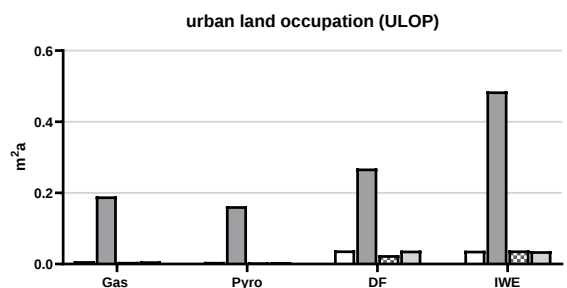
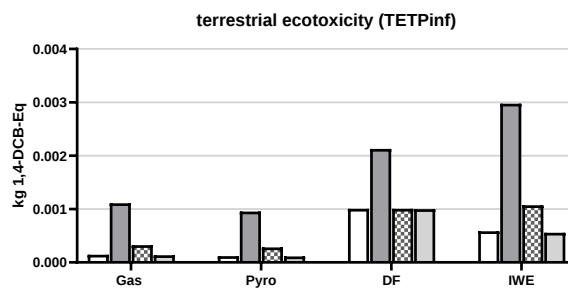
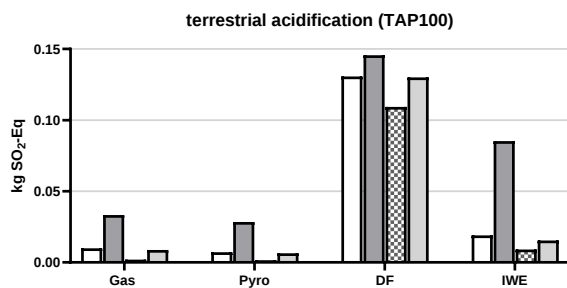
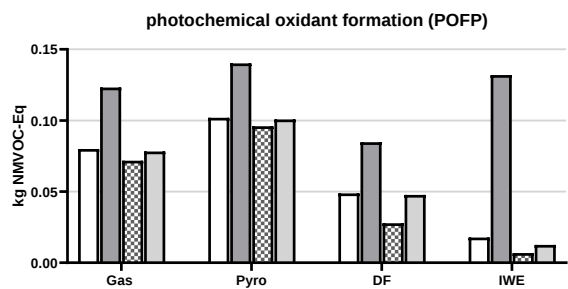
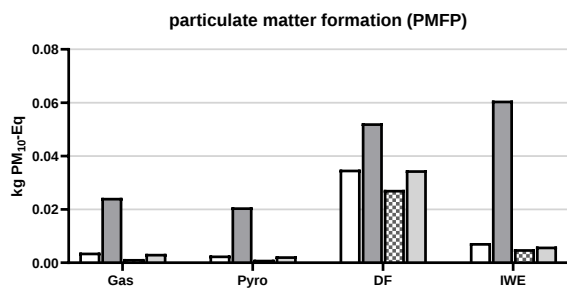
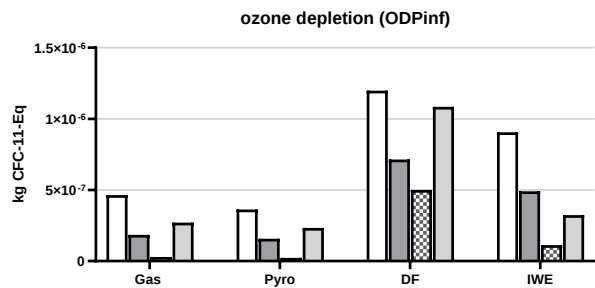
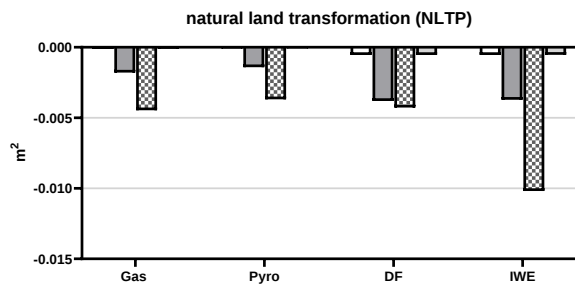
Appendix 3

A3.1. Input and Output Normalised for 1 kg of H₂

Input	GAS	PYRO	DF	IWE	Unit
Wet MSW/OFMSW	22.47	25.00	142.86	80.00	kg
MEA solution*	0.02	0.01	0.02	0.09	kg
Air	24.11	0.00	0.00	240.00	kg
H ₂ SO ₄			11.43		kg
CaO			6.50		kg
Inoculum			18.00		kg
Water - Total	78.58	57.89	43.29	1093.04	kg
Water - Total	0.08	0.06	0.04	1.09	m ³
Heat input	1.36	1.17	0.65	3.31	MW
Power Input	0.30	0.21	0.84	0.36	MW
Heat excess	1.10	0.74	2.42	5.77	MW
Power excess	0.00	0.00	0.00	0.39	MW
Output					
H ₂	1.00	1.00	1.00	1.00	kg
N ₂	18.49			184.52	kg
CO ₂	13.66	9.15	10.43	58.28	kg
Sugar			13.50		kg
Acetic acid			15.00		kg
O ₂				4.04	kg
Air emissions					
CO (From PT)	1.53	2.06	0.00	0.00	kg
CO ₂ (From PT)	0.72	0.49	0.57	3.08	kg
O ₂ (From PT)	2.53				kg
WW Total	59.10	129.94	123.00	1140.00	kg
Sulphur	0.02	0.03		386.56	kg
HCl	0.02	0.03		0.08	kg
NH ₃		0.14			kg
H ₂ SO ₄				0.16	kg
HNO ₃				0.04	kg
Solids (Sanitary Landfill)					
Char	0.19	2.19			kg
Ash	3.88	4.31		13.80	kg
CaSO ₄			15.86		kg
Residue			24.71		kg
Used Inoculum			18.00		kg

A3.2. Full Comparison of BAU, Renewable Energy, Renewable Energy & Electrification, and BAU & Heat Recovery





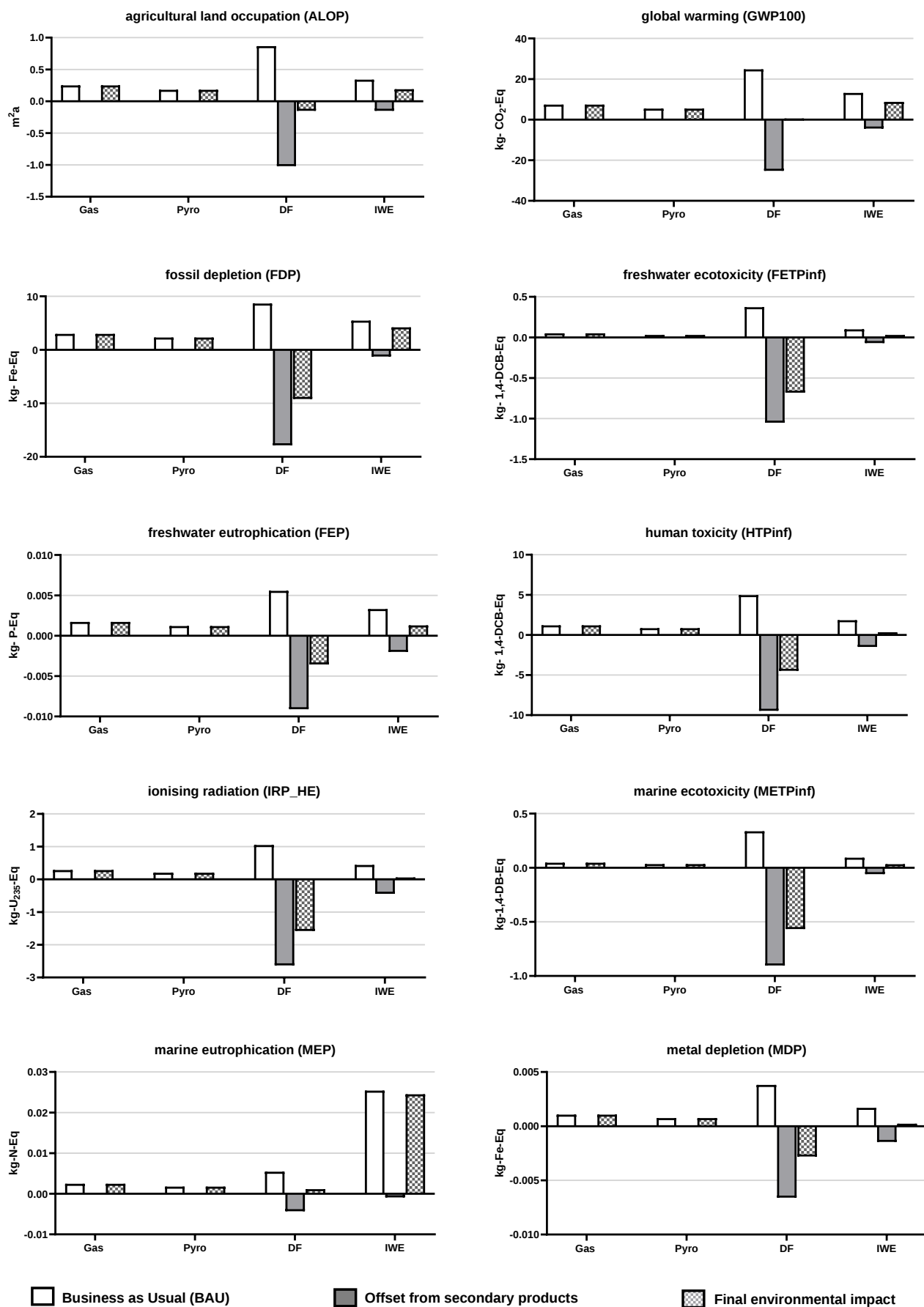
Business as Usual (BAU)

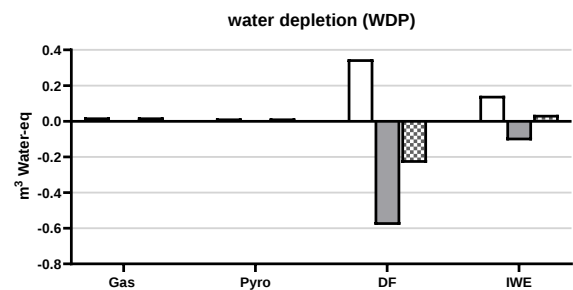
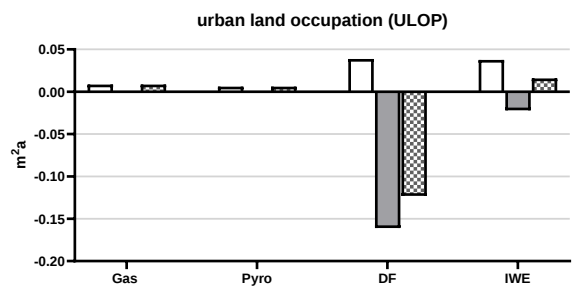
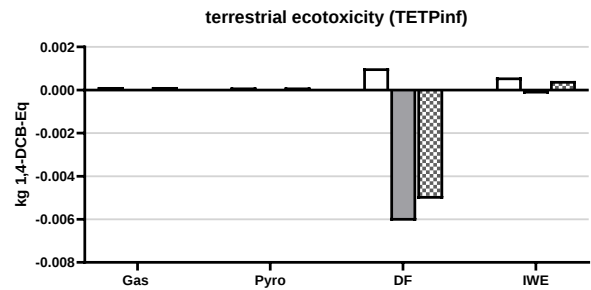
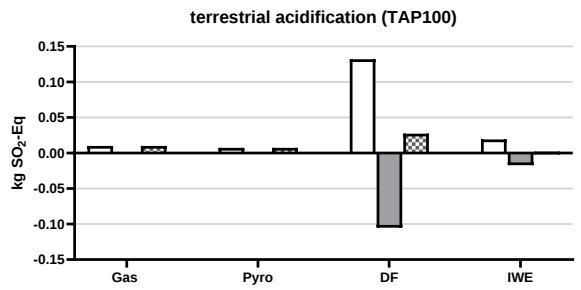
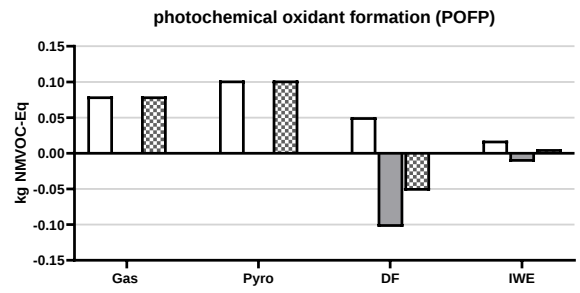
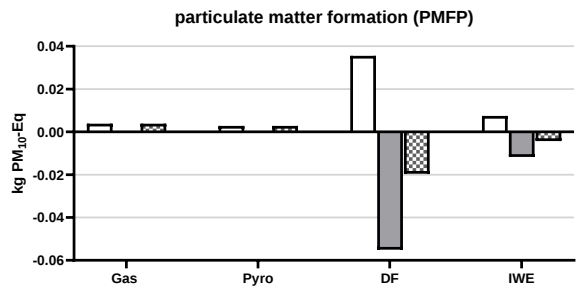
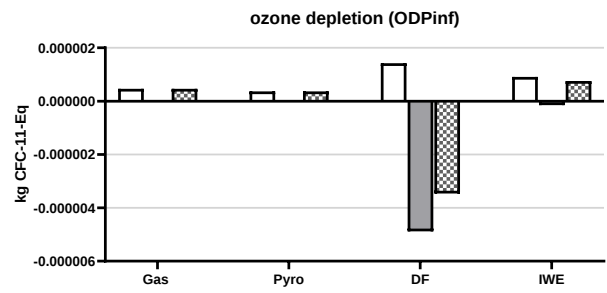
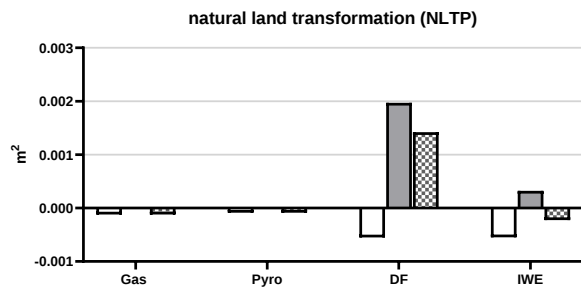
Renewable grid + Biomass heating

Renewable grid + electrification heating

BAU + Heat recovery

A3.3. Full Comparison of BAU, Offsets from Secondary Products, and Final Environmental Impact





□ Business as Usual (BAU)

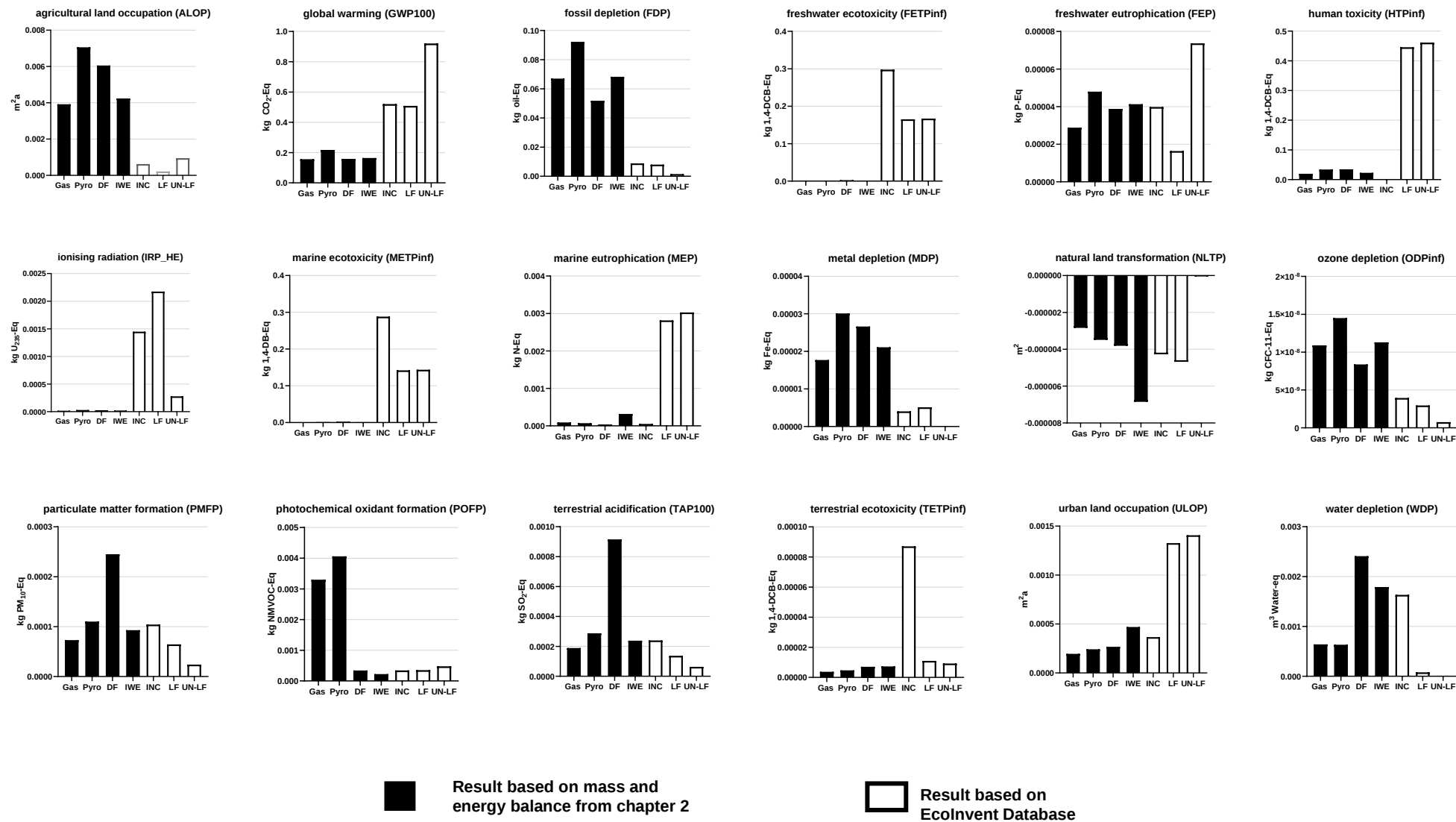
■ Offset from secondary products

▨ Final environmental impact

A3.4. Avoided Emission from Landfilling

Impact category	BAU				Offset from Secondary Product				Offset from Landfilling				Final comparison			
	Gas	Pyro	DF	IWE	Gas	Pyro	DF	IWE	Gas	Pyro	DF	IWE	Gas	Pyro	DF	IWE
agricultural land occupation (ALOP)	0.25	0.18	0.87	0.34	-	-	1.02	0.15	0.00	0.01	0.03	0.02	0.25	0.17	-0.18	0.17
climate change (GWP100)	7.39	5.44	24.79	13.14	-	-	25.24	4.40	11.42	12.71	72.60	40.66	-4.03	-7.26	-73.05	-31.91
fossil depletion (FDP)	2.99	2.31	8.66	5.46	-	-	17.85	1.25	0.18	0.20	1.15	0.64	2.81	2.11	-10.34	3.57
freshwater ecotoxicity (FETPinf)	5E-02	3E-02	4E-01	1E-01	-	-	1E+00	7E-02	4E+00	4E+00	2E+01	1E+01	-4E+00	-4E+00	-2E+01	-13.17
freshwater eutrophication (FEP)	2E-03	1E-03	6E-03	3E-03	-	-	9E-03	2E-03	4E-04	4E-04	2E-03	1E-03	1E-03	8E-04	-6E-03	0.00
human toxicity (HTPinf)	1.20	0.85	4.97	1.83	-	-	9.45	1.49	10.02	11.14	63.68	35.66	-8.81	-10.30	-68.16	-35.32
ionising radiation (IRP_HE)	0.28	0.20	1.05	0.44	-	-	2.63	0.44	0.05	0.05	0.31	0.17	0.24	0.15	-1.89	-0.18
marine ecotoxicity (METPinf)	5E-02	3E-02	3E-01	9E-02	-	-	9E-01	6E-02	3E+00	4E+00	2E+01	1E+01	-3E+00	-4E+00	-2E+01	-11.32
marine eutrophication (MEP)	2E-03	2E-03	5E-03	3E-02	-	-	4E-03	9E-04	6E-02	7E-02	4E-01	2E-01	-6E-02	-7E-02	-4E-01	-0.20
metal depletion (MDP)	1E-03	8E-04	4E-03	2E-03	-	-	7E-03	1E-03	1E-04	1E-04	7E-04	4E-04	1E-03	6E-04	-4E-03	0.00
natural land transformation (NLTP)	-1E-04	-9E-05	-6E-04	-5E-04	-	-	-2E-03	-3E-04	-1E+02	-1E+02	-7E+02	-4E+02	1E+02	1E+02	7E+02	374.40
ozone depletion (ODPinf)	5E-07	4E-07	1E-06	9E-07	-	-	5E-06	1E-07	7E-08	7E-08	4E-07	2E-07	4E-07	3E-07	-4E-06	0.00
particulate matter formation (PMFP)	4E-03	3E-03	4E-02	7E-03	-	-	5E-02	1E-02	1E-03	2E-03	9E-03	5E-03	2E-03	1E-03	-3E-02	-0.01
photochemical oxidant formation (POFP)	8E-02	1E-01	5E-02	2E-02	-	-	1E-01	1E-02	8E-03	9E-03	5E-02	3E-02	7E-02	9E-02	-1E-01	-0.02
terrestrial acidification (TAP100)	1E-02	7E-03	1E-01	2E-02	-	-	1E-01	2E-02	3E-03	4E-03	2E-02	1E-02	7E-03	4E-03	7E-03	-0.01
terrestrial ecotoxicity (TETPinf)	1E-04	1E-04	1E-03	6E-04	-	-	6E-03	2E-04	2E-04	3E-04	2E-03	9E-04	-1E-04	-2E-04	-7E-03	0.00
urban land occupation (ULOP)	0.01	0.01	0.04	0.04	-	-	0.16	0.02	0.03	0.03	0.19	0.11	-0.02	-0.03	-0.31	-0.09
water depletion (WDP)	0.02	0.02	0.35	0.14	-	-	0.58	0.11	0.00	0.00	0.01	0.01	0.02	0.01	-0.24	0.03

A3.5. Full Comparison of WtH BAU and Traditional Waste Treatment for 1 kg of MSW



Appendix 4

Table 49. Non-exhaustive list of current sustainable aviation fuel projects/plants in select geographical regions.

Project	Location	Technology	Feedstock	Production capacity (bbl [*] /yr.)	Ref
Neste Tuas South plant	Tuas, Singapore	HEFA	Cooking oil and animal fats	7.86 M (as of 2023)	(287)
Neste Rotterdam SAF plant	Rotterdam, Netherlands	HEFA	Cooking oil and animal fats	3.93 M (as of 2023) with planned increase to 9.43 M (by 2026)	(288, 289)
Project Speedbird	Northeast, UK	Ethanol to Jet	Waste wood to biomass	0.642 M (slated 2028)	(290, 291)
Project Dragon	South Wales, United Kingdom	Ethanol to Jet	Waste CO ₂ from adjacent Tata steelworks	0.642 M (slated 2030)	(290, 292)
Project AtmosFUEL	Unspecified location, United Kingdom	Ethanol to Jet	Atmospheric CO ₂ and green hydrogen	0.642 M (slated 2030)	(290)
Project Ulysses	Queensland, Australia	Ethanol to Jet	Waste agriculture byproducts	0.642 M (construction to begin 2024)	(293)
EcoCeres	Johor, Malaysia	HEFA	Waste cooking oil, and waste water from palm oil processing	2.75 M (announced in 2023)	(294)
Sinopec Zhenhai refinery	Zhejiang province, China	HEFA	Waste cooking oil, animal fats, and palm oil	0.786 M (as of 2022)	(295, 296)
Honeywell Maoming SAF refinery	Guandong province, China	HEFA and ethanol to jet	Non-edible natural oils, animal fats, waste biomass	7.86 M (announced in 2022)	(296)
Raven SR SAF facility	California, USA	Fischer-Tropsch	Agricultural waste, forestry residues, and algae.	0.393 M (slated 2025), planned 1.57 M (by 2034)	(297)
Honeywell-Granbio demonstration plant	Georgia, USA	Ethanol to Jet	Waste wood and sugarcane bagasse	0.0629 M (slated 2027)	(298)
HIF Haru Oni eSAF facility	Southern Patagonia, Chile	Methanol to jet	Atmospheric CO ₂ & green hydrogen	4.02 M (slated 2030)	(299)
ANRPC Petroleum SAF plant	Alexandria, Egypt	HEFA	Waste cooking Oil	0.943 M (slated 2026)	(300)
PT Kilang Pertamina Internasional Green Refinery	Cilacap, Indonesia	HEFA	Refined Bleached Deodorized Palm Kernel Oil	1.095 M (as of 2022), planned increase to 2.19 M (by 2026)	(301)
EDL Anlagenbau Gesellschaft mbH (EDL) HyKero plant	Leipzig, Germany	Fischer-Tropsch CANS TM (302)	CO ₂ (unspecified source) & green hydrogen	0.590 M (slated 2027)	(303)

* where, one metric ton of SAF is equivalent to 1250 litres ⁽³⁰⁴⁾ and one standard oil barrel 'bbl' is equivalent to 159 litres of SAF ⁽³⁰⁵⁾, projects announced are still in feasibility stage and those marked 'slated' are in construction

Table 50. Non-exhaustive List of currently operational Waste to Energy (WtE) projects in select geographical regions.

Project name	Developer(s)	Location	Technology used	Yr. operational	Daily MSW throughput (top) & power generation (bottom)	Ref.
TuasOne WtE plant	Hyflux Ltd and Mitsubishi Heavy Industries	Tuas, Singapore	Incineration	2021	3600 tons	(306)
					120 MW	
Bukit tagar Enviro park (BTEP) WtE plant	No publicly available information	Selangor, Malaysia	Biogas combustion	2023	2500 tons	(307, 308)
					12 MW	
Soc Son WtE plant	MCC corporation, Thien Environmental Energy Co.	Hanoi, Vietnam	Incineration	2022	4000 tons	(309)
					75 MW	
Nong Khaem WtE plant	Newsky Energy Ltd , C&G Environmental protections Ltd	Bangkok, Thailand	Incineration	2016	1000 tons	(310, 311)
					35 MW	
USS Gerald Ford (CVN-78) PAWDS	Pyrogenesis Canada. Inc	Virginia, USA	Plasma arc gasification	2012	200 kg (per hour)	(312)
					No publicly available data	
Minato WtE plant	Mitsubishi Heavy Industries	Tokyo, Japan	Incineration	1999	900 tons	(313)
					22 MW	
Maishima WtE plant	Hitachi Zosen	Osaka, Japan	Incineration	2001	900 tons	(314, 315)
					32 MW	
Changsha WtE plant	Hitachi Zosen	Hunan province, China	Incineration	2018	5100 tons	(314, 316)
					100 MW	
Fangshan WtE plant	Keppel Seghers	Beijing, China	Incineration	2020	1000 tons	(317, 318)
					20 MW	
Shanghai Jiangqiao WtE plant	Veolia China	Shanghai, China	Incineration	2008	1500 tons	(319)
					25 MW	
Créteil WtE plant	SUEZ group	Ile-de-France, France	Biogas combustion	2022	945 tons	(320, 321)
					19.2 MW	
Ferrybridge Multifuel (FM)2, UK	Hitachi Zosen INOVA AG	West Yorkshire, UK	Incineration	2019	1849 tons	(314, 322)
					68 MW	
Essen-Karnap WtE plant	RWE Power	Essen, Germany	Incineration	1987	2027 tons	(323)
					38 MW	
Abali WtE plant	No publicly available data	Tehran, Iran	Biogas combustion	2017	300 tons	(324, 325)
					3 MW	

Mallorca WtE plant	Hitachi Zosen INOVA AG	Balearic islands, Spain	Incineration	1996	1139 tons	(326, 327)
					124 MW	
Klemestrud WtE plant	City of Oslo, Hitachi Zosen INOVA, ABB i Norge	Klemetrud, Norway	Combined heat and power (CHP)	1986	1205 tons	(328)
					114 MW	
Dubai Waste Management Centre	Dubai holding, Itoshu, Hitachi Zosen Inova, Besix group	Warsan, Dubai UAE	Incineration	2024 (slated)	5500 tons	(329)
					200 MW	
Kwinana WtE plant	Acciona, Veolia & Keppel Segher.	Perth, Australia	Incineration	2025 (slated)	1096 tons	(330)
					36 MW	
Quezon WtE plant	Covanta Holdings	Quezon, Philippines	Incineration	2026 (slated)	No publicly available data	(331)
					42 MW	
Abu Rawash WtE plant	Renergy Group Partners LLC	Giza, Egypt	Incineration	2030 (planned)	1200 tons	(332)

Appendix 5

A5.1. EJ Dimensions Definition

This section outlines the specific definitions of each justice dimension in the proposed EJ framework.

Procedural justice

Procedural justice revolves around ensuring meaningful engagement of local and potentially regional communities throughout the project lifecycle. This goes beyond merely informing the public. It entails empowering them to actively participate in decision-making processes that directly impact their lives and environments. This engagement can occur through various methods, including collaborative workshops, joint committees, and project advisory boards. The goal is to foster a sense of ownership and shared responsibility among community members, ensuring their voices are heard and considered throughout the project's development and implementation.^(202, 203)

Relational justice

This justice dimension emphasizes the quality of relationships between project developers, communities, and other stakeholders in WtH initiatives.⁽³³³⁾ It transcends procedural fairness and focuses on cultivating mutual respect, trust, and recognition of interdependence. This approach seeks to address historical injustices and power imbalances, fostering collaborative governance where knowledge and power are shared.

Distributive justice

Distributive justice focuses on the equitable allocation of benefits and burdens among affected communities specifically local and potentially regional. It underscores the ethical distribution of both positive and negative outcomes, ensuring that the advantages and disadvantages of WtH initiatives are shared.⁽²⁰⁶⁾ In the context of WtH, distributive justice requires a systematic assessment to prevent disproportionate environmental or socio-economic impacts on specific groups. This involves considering factors such as access to benefits, potential health effects, and economic implications to guarantee that no community bears an undue share of the project's consequences. By prioritizing fairness in the distribution of outcomes, distributive justice contributes to a more ethical and socially responsible implementation of WtH projects, aligning with principles of equity and balance in resource allocation.

Cosmopolitan justice

Cosmopolitan justice is a philosophical and ethical concept that transcends national boundaries and emphasizes the idea that ethical principles and considerations should apply universally to all individuals, regardless of their nationality or affiliation.⁽²⁰⁷⁾ In the context of waste-to-hydrogen (WtH) projects, cosmopolitan justice would advocate for the fair and equitable treatment of all communities impacted by such initiatives, regardless of their geographical location. It underscores the need for global cooperation and shared responsibility in addressing environmental challenges, ensuring that the benefits and burdens of WtH projects are distributed justly on a global scale. This perspective encourages a broader, inclusive approach that recognizes the interconnectedness of environmental and social issues across borders.

Epistemic justice

Epistemic justice delves into the realm of knowledge and power sharing.^(200, 208) It questions who possesses and controls knowledge related to WtH, how different forms of knowledge are valued, and how power dynamics influence decision-making processes.

Restorative justice

This dimension involves an approach that seeks to repair harm, foster healing, and rebuild relationships within the affected communities.⁽²⁰⁵⁾ It emphasizes acknowledging the impacts of WtH initiatives on both the environment and the community, with a focus on addressing any social, economic, or environmental injustices that may arise. In the

event of adverse effects, restorative justice principles advocate for collaborative and inclusive processes to identify and implement measures that mitigate harm.

A5.2. Considerations for Using EJ Dimensions for WtH Evaluation

While the six-dimensions for environmental justice (EJ) offers a valuable tool for assessing the injustices of waste-to-hydrogen (WtH) projects, its adaption requires several considerations. Recognising these considerations is crucial for ensuring comprehensive and nuanced evaluations that accurately represent the concerns of various stakeholders.

1. Complexity and Interconnections:

- **Interdependence:** The dimensions are interconnected, and addressing one often requires attention to others. Focusing on procedural justice without addressing distributive or relational aspects may lead to incomplete solutions.
- **Non-Linearity:** EJ issues are complex and dynamic, with relationships between dimensions not always linear. A high score in one dimension might not guarantee overall fairness

2. Context-Specificity:

- **Varying Priorities:** The relative importance of each dimension can differ across communities and contexts. Assigning arbitrary weights without considering local values and priorities can misrepresent community concerns.
- **Unique Histories:** Historical and cultural factors shape community experiences of injustice, necessitating tailored approaches to each project and location.^(204, 334-336)

3. Measurability and Data:

- **Quantification Challenges:** Some dimensions, like relational or epistemic justice, are difficult to quantify using traditional metrics.⁽³³⁷⁾ Qualitative data and community narratives are crucial for comprehensive assessment.
- **Data Availability:** Collecting data on all dimensions can be resource-intensive, and available data might not adequately capture lived experiences or social inequalities.

4. Power Dynamics and Participation:

- **Tokenism:** Procedural justice efforts can be tokenistic if those with power control decision-making processes.⁽³³⁸⁾ True empowerment involves sharing power and decision-making authority with affected communities.
- **Marginalized Voices:** Ensuring meaningful participation of underrepresented groups requires addressing structural barriers and fostering inclusive engagement strategies.

5. Temporal and Spatial Considerations:

- **Long-Term Effects:** EJ impacts of WtH projects can manifest over time and beyond immediate project boundaries. Evaluations must consider long-term and cumulative effects,⁽³³⁹⁾ as well as potential impacts on distant communities through supply chains or global pollution.
- **Cumulative Impacts:** WtH projects might contribute to cumulative impact burdens in areas already facing multiple environmental stressors. Assessing EJ requires understanding broader environmental and social contexts.

6. Intersectionality with Other Social Justice Issues:

- **Intersectional Challenges:** EJ concerns intersect with other social justice issues like race, gender, class, and disability. A framework solely focused on EJ dimensions might overlook these interconnected inequities.
- **Holistic Lens:** A comprehensive evaluation requires considering how WtH projects might exacerbate or mitigate existing social inequalities beyond environmental concerns.

Based on the above considerations, the following strategies can be used:

- **Contextualise and Adapt:** Tailor the framework to specific projects and communities, considering local values, histories, and priorities.
- **Prioritise Community Engagement:** Actively involve diverse stakeholders throughout the evaluation process, ensuring meaningful participation and co-creation of knowledge.
- **Embrace Mixed Methods:** Employ both quantitative and qualitative data, including community narratives and lived experiences, to capture the full complexity of EJ concerns.
- **Incorporate Intersectionality:** Consider how EJ issues intersect with other social justice dimensions to ensure a holistic and inclusive evaluation.
- **Adopt Adaptive Management:** Recognize the dynamic nature of EJ and continuously monitor and adapt evaluation approaches to reflect evolving contexts and community needs.

A5.3. Identifying Stakeholders in WtH Projects Using Stakeholder Mapping



Figure 73. Proposed stakeholder map for WtH projects. White lines denote indirect relationship/interaction and red lines denote direct interactions. Note that this stakeholder relation map may change depending on the circumstances of the project. Source: Author.

The success of WtH projects in achieving positive environmental and social outcomes depends on the effective identification and engagement of relevant stakeholders. **Figure 73** shows an example of a stakeholder relation map for a WtH project. Depending on the local context and specific aim(s) of the project, the stakeholder classifications can be adjusted as necessary based on their adjacent relationship to another and their level of impact to the project.

IEAGHG

ieaghg.org
+44 (0)1242 802911
mail@ieaghg.org

IEAGHG, Pure Offices, Cheltenham Office Park,
Hatherley Lane, Cheltenham, GL51 6SH, UK



IEAGHG