A feasibility study on integrating electric buses with waste gasification for a green public transport system and solid waste management

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Abstract

Waste management and public transport are two major issues requiring decarbonisation in the face of climate change and environmental concerns related to global warming. Green transport systems are classified as zero or low carbon alternatives to the fossil fuel-based approach and vehicles. These systems rely on zero emission fuels such as hydrogen. Thermochemical processes (e.g., gasification) and biochemical technologies (e.g., fermentation) can convert carbon-based feedstock such as waste to produce desirable products like hydrogen. Waste-to-Hydrogen is proposed as a potential solution to provide both sustainable waste management and hydrogen production.

Waste-to-Hydrogen (WtH) is a hybrid solution that simultaneously combines sustainable waste management and non-fossil-fuel based hydrogen production. The concept of distributed WtH systems, based on gasification and fermentation, is to support hydrogen fuel cell buses in Glasgow is considered as a potential solution zero emission transport development. Hydrogen has potential to replace petrol and diesel fuels and consequently become part the zero-carbon measures to aid the transition to cleaner energy sources. When hydrogen is produced from renewable or sustainable energy sources it can help decarbonise the energy and transport sector. To be attractive to policymakers and investors it is necessary for the hydrogen from a WtH system to demonstrate its carbon footprint is lower than conventional methods. By supporting the effort to reach carbon emission reduction targets, hydrogen is part of the solution to limit climate change, a global emergency. Providing research to support the roadmap of hydrogen-powered public transport to shape the direction of future technological improvement and policy formulation.

As well as the potential to provide a clean versatile fuel through hydrogen, WtH can offer an alternative waste management practice that diverts waste away from landfill and incineration. By utilising and transforming waste into a useful energy resource, a value is applied which can encourage the development of sustainable disposal methods such as WtH conversion processes.

Glasgow was chosen as the location for the study due to the large population which would supply regular amounts of waste to be used as feedstock. The city council is also actively trying to decarbonise local industries including transport, this is seen by the strategies and targets in place such as Net Zero by 2045. An aim of this study is to demonstrate how low carbon hydrogen production technologies could fit into the city’s transport and energy plan

and support the hydrogen strategy, thereby benefitting the people of Glasgow. Whilst Glasgow does not currently use fuel cell electric buses (FCEB) for public transport, an intention to run a fleet has been presented through the publication of the Scottish Governments Hydrogen Policy Statement (2020) and Hydrogen Action Plan (2022). FCEB fleets in other parts of the UK notably London and Birmingham, have shown the environmental benefit through the annual carbon savings made. FCEBs are classified as zero emissions buses (ZEB) which the UK Department of Transport has stated can reduce carbon emissions by 46 tonnes per year and nitrogen oxide (NOx) by 23kg when compared to a diesel bus (UK Government Department for Transport, 2021).

This study contributes to the growing evidence of the benefits of using hydrogen as a transport fuel in terms of the carbon savings as an alternative to conventional fossil fuels. Whilst the main concerns of the underdeveloped industrial status, relatively immature technology and high costs are explored. In practice WtH is currently limited to laboratory and pilot scale systems and requires further investment and policy support for advancements to be made. These bottlenecks and limitations are considered in the discussion section of this study.

The research question centres around the economic and environmental feasibility of WtH within Glasgow. A feasible project would show the carbon savings compared to conventional methods in both aspects of waste management and hydrogen production. The feasibility is also a measurement of positive returns on economic investment where total project costs do not outweigh the environmental benefits associated with low carbon technologies. This study critically assesses the current situation for WtH development in terms of the environmental impact and potential carbon savings, economic implications, and cost benefits, plus transport and climate policy. The novelty of the study establishes a procedure for defining how WtH could support the growing hydrogen industry as a low carbon hydrogen production technique. The results from the environmental impact analysis and economic assessment add data sets to existing research in academia and energy industry. Life cycle assessment (LCA), cost benefit analysis (CBA) and multi-objective optimization (MOO) have been conducted to determine the feasibility of WtH projects to support green transport systems and sustainable waste management schemes. A variety of WtH scenarios were designed based on biomass waste feedstock, hydrogen production reactors, and upstream and downstream system components. The WtH systems selected use thermochemical and biochemical technologies to convert the different waste feedstocks available in Glasgow with suitable operational conditions according to the waste characteristics. The waste considered in this study is biodegradable, carbon based and organic including household, plastics, waste wood products, as well as the wet fraction of waste such as food and sewage sludge.

Five scenarios, four WtH technologies and one conventional hydrogen production technology of steam methane reforming (SMR), were designed to allow for comparison of environmental and economic results. The scenarios differ in waste feedstock type and technology leading to differences in hydrogen production rates, hydrogen yields, and process carbon emissions. Waste that is less suitable for thermochemical conversion processes can be utilised by biochemical technology to ensure the most efficient and least energy intensive method is applied.

The environmental approach for this work focuses on the LCA method to evaluate environmental performance through the carbon saving potential using global warming potential (GWP) as the impact indicator for the WtH technologies. It was shown that WtH technologies could reduce <55% of CO_2-eq emissions per kg H_2 compared to SMR. Gasification treating municipal solid waste and waste wood had global warming potentials of 4.99 and 4.11 kg CO_2-eq/kg H_2 respectively, which were lower than dark fermentation treating wet waste at 6.6 kg CO_2-eq/kg H_2 and combined dark and photo fermentation at 6.4 kg CO_2-eq/kg H_2. The distance emissions of WtH-based electric fuel cell bus scenarios were 0.33-0.44 kg CO_2-eq/km as compared to 0.89 kg CO_2-eq/km for the SMR-based scenario.

The economic assessment in this study uses cost benefit analysis to determine whether the carbon savings outweigh the expected cost of a WtH system. The CBA was conducted to compare the economic feasibility of the different WtH systems with the conventional SMR. A database was that includes, direct cost data on construction, maintenance, operations, infrastructure, and storage, along with indirect cost data comprising environmental impacts and externalities, cost of pollution, carbon taxes and subsidies was collated. The results are in the form of economic indicators Net present value (NPV), Internal rate of return (IRR), Benefit cost ratio (BCR) and Levelized cost of hydrogen (LCoH). The LCoH was calculated as 0.49 GBP/kg for the gasification systems using MSW feedstock and 0.52 GBP/kg for waste wood gasification. The LCoH for dark fermentation was calculated to be 0.52 GBP/kg and 0.59 GBP/kg for combined dark and photo fermentation systems. Sensitivity analysis was conducted to identify the most significant influential factors of distributed WtH systems. The results indicate that the conversion efficiency and the energy density of the waste had the largest impact for biochemical technology and thermochemical technologies, respectively. It is concluded that WtH could be economically feasible for hydrogen production in Glasgow. However, limitations including high capital expenditure will require cost reduction through technical advancements and carbon tax on conventional hydrogen production methods to improve the outlook for WtH. The multi-objective optimisation results suggest that optimisation is possible with the best solution calculated to minimise both total cost and GWP for the four Scenarios assessed in this work.

The results from the three analysis types in this work, indicate the feasibility of WtH in Glasgow. The results suggest there is potential to utilise the waste generated within Glasgow to produce hydrogen, reduce the environmental impact of waste management practices, and provide economic benefit to both the energy and transport industry.

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Declaration

I declare that this thesis is a record of the original work carried out by myself under the supervision of Dr Siming You in the School of Engineering at the University of Glasgow, Scotland, during the period of October 2018 to December 2022.

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Nomenclature

atm	atmospheres
BCR	Benefit cost ratio
BECCS	Bioenergy with carbon capture and storage
BFB	Bubbling Fluidised Bed (gasifier)
CaO	Calcium Oxide
CAPEX	Capital expenditure
CBA	Cost Benefit Analysis
CCS	Carbon Capture and Storage
CFB	Circulating Fluidised Bed (gasifier)
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPS	Carbon pricing scheme
EfW	Energy from Waste
ER	Equivalence Ratio
EUR	Euro (€)
FU	Functional Unit
FW	Food Waste
GA	Genetic algorithm
GBP	Great British Pound (£)
GHG	Greenhouse Gases
GWP	Global Warming Potential
H_2	Hydrogen
HHP	Higher Heating Value
HTS	High Temperature Shift
HRS	Hydrogen Refuelling Station
HSC	Hydrogen Supply Chain
IRR	Internal rate of return
kg CO_2-eq	Kilogram carbon dioxide equivalent
LCoH	Levelized cost of hydrogen
LFG	Landfill Gas
LHV	Lower Heating Value
LTS	Low Temperature Shift
MDCM	Multi Decision Criteria Making
MEC	Microbial Electrolysis Cell
MFC	Microbial Fuel Cell
MOO	Multi-objective optimization
MSW	Municipal Solid Waste
MtCO_2-eq	Million tonnes carbon dioxide equivalent

MtOe	Million tonnes oil equivalent
NPV	Net Present Value
OPEX	Operational expenditure
PEMFC	Proton Exchange Membrane Fuel Cell
PSA	Pressure Swing Adsorption
RDF	Refuse Derived Fuel
RTFC	Renewable Transport Fuel Certificate
RTFO	Renewable Transport Fuel Obligation
S/B	Steam to Biomass ratio
SMR	Steam Methane Reforming
SOFC	Solid Oxide Fuel Cell
SRF	Solid Recovered Fuel
UK ETS	UK emissions tax
USD	United States Dollar ($)
VS	Volatile Solids
VSS	Volatile Suspended Solids
WGS	Water Gas Shift
WtH	Waste-to-Hydrogen
ww	Wet weight
ZEB	Zero Emission Bus

Chapter 1 Introduction

The introductory chapter outlines and introduces the waste-to-hydrogen concept with background and justifications for this work through defining the project aims and objectives. The contribution of this work to the research and the science community is included as are the published papers linked to this study.

1.1. Background of the Waste to Hydrogen concept

The concept of waste-to- hydrogen (WtH) originates as a dual-purpose method to utilise waste materials to generate an energy product in the form of hydrogen. WtH technologies are designed to convert carbon-based waste, a readily available feedstock, into hydrogen which is a fuel with considerable potential to be part of the future energy mix replacing fossil fuels. In 2021 global primary energy consumption reached 595.15 EJ with UK energy consumption reaching 7.16 EJ (BP, 2022). In 2022 carbon dioxide (CO_2) emission originating from fossil fuels related to global energy use, reached 36.8Gt CO_2 (IEA, 2023).

The value of WtH arises from both potential economic savings and environmental benefits for low carbon alternatives for both waste management and hydrogen production. This can be attributed to costs avoided from carbon tax and penalties associated with carbon emissions and air pollution from conventional fossil fuel use. Costs associated with landfill and incineration can also be avoiding by providing alternative waste management strategies. Environmental solutions are equally as important factors to consider for WtH projects as the economic factors, plus the potential advantage of localised energy production. The environmental benefits arise from reducing the carbon emissions of waste management and hydrogen production and lead to a larger scale effect on limiting the impact of climate change and aiding decarbonisation efforts whilst contributing towards climate targets. Transition and integration to a hydrogen society is motivated by the ambition to reduce fossil fuel use amid the growing concern for climate change. Viewing waste as an abundant and cheap resource available for reuse and further utilisation could in part reduce the negative impact of humans on the environment and provide a step to lessen global warming.

Hydrogen is a low carbon, zero emission fuel which produces water when used in a fuel cell to generate electricity or combusted to produce heat. Hydrogen has an important role as a transition fuel shifting use away from fossil-based fuels of petrol, diesel, and natural gas. However the current hydrogen production methods are through the transformation of fossil fuels such as natural gas, coal, naphtha, and heavy oils with only a small fraction met by low emission methods such as electrolysis (IEA, 2018). In 2022 the emission value associated with hydrogen production was 900 million tonnes CO_2 (IEA, 2022). Most industrial hydrogen production demand is met by steam methane reforming (SMR) at 62% which of industrial hydrogen production which is linked to negative environmental impacts (IEA, 2022).

Hydrogen is considered as an alternative for conventional transport fuels due to its chemical properties such as high energy density, and zero emissions when used in a fuel cell. Hydrogen has a gravimetric energy density of 141.8 MJ kg^{-1} at 1 atm (atmospheric pressure) making it comparable as a fuel with diesel (Dutta, 2014). Sustainably produced hydrogen could be competitive with other renewable energy technologies such as solar, wind and tidal, as it is an efficient, high-energy density, flexible fuel. Hydrogen demand was 94 Mt in 2021 with 0.04 % of the demand coming from new applications, mainly from road transport and the growth of fuel cell vehicles (IEA, 2021). The demand in hydrogen has been increasing since the 1970s and is expected to continue (Ajanovic and Haas, 2021). This is in line with the growing interest in clean energy resources. The increase in the number of hydrogen infrastructure projects, hydrogen refuelling stations, and hydrogen transport projects in the UK, Europe and globally suggest hydrogen is gaining popularity as a clean fuel for the future. Fujii et al. (2019) discuss the formation of a hybrid industry to diversify current fossil fuels resources along with recycling and renewable energy with the intention of lowering carbon emissions. Providing zero carbon fuel alternatives for transport is an important step in decarbonising the public transportation system.

In 2019 the Scottish government announced a climate emergency due to the evidence provided by the IPCC on increasing average global temperatures. Plans to implement strategies and mitigation efforts to reduce carbon emissions where put in place. Additional climate change targets were announced for Scotland and Glasgow in 2020 including zero net emissions by 2045 as part of the Climate Change Act (2020). Scotland has also released a hydrogen strategy and plans for decarbonisation of transport to reach the climate change targets.

Current waste management strategies in Scotland consist of landfill and incineration (Scottish Government, 2019a). A landfill ban for MSW will be in place from 2025, consequently the Scottish government requires alternative management schemes to comply with the new law (SEPA, 2019). Waste conversion technology should provide an attractive solution for both waste management and low carbon hydrogen production. Adapting waste reduces landfill and incineration and the negative environmental effects associated (Arancon et al., 2013). The type of waste considered for energy conversion is organic or carbon based such as various household, commercial, agricultural, and industrial.

The different feedstocks used in the study for WtH technologies are both the wet and dry waste types available in Glasgow. The characteristics, volume and proportions of each waste type are important in deciding the suitable treatment technology. Multiple technologies are considered to allow all the useable waste generated in Glasgow to be included for conversion. The larger the volume of waste utilised the higher hydrogen production. Therefore, improving the prospects of WtH as waste management strategy and minimising the use of incineration or landfill for waste disposal.

Glasgow was chosen for this study due to recognition of the challenges the city with the largest traffic volume in Scotland faces with adapting to changing climates and the efforts needed to decarbonise. The city of Aberdeen which has a fleet of 25 FCEB and two hydrogen refuelling stations is an example of how hydrogen buses could be successfully operated in Scotland (Aberdeen City, 2020). Glasgow has made efforts to reduce the carbon footprint by implementing the fleet strategy amongst other aims, however a system like WtH could further the progress.

The current status of WtH development suggests WtH technologies are immature and underdeveloped at larger scales and requires additional technical and political support to advance. Improvements in areas such as operational efficiencies, production rates and reducing feedstock inconsistencies are required. WtH may have a place in decentralised energy systems compared to the larger power stations when considering the extra carbon emissions associated with storage requirements, infrastructure, and transport. Academic studies suggest there are positive indications, for example thermochemical technologies have flexibility with composition of feedstock, potential for reasonable hydrogen production yields, cost effectiveness and the capacity to have carbon saving benefits (Pandey et al., 2019). For WtH systems to become competitive in a future consisting of zero emission and clean energy industries and markets, improving the economic outlook is necessary.

The study of WtH can encourage innovation through requirements for process improvements and advancements to conversion technology, hydrogen purification and storage. Various thermochemical (e.g., gasification and pyrolysis) and biochemical (e.g., fermentation and photolysis) technologies were assessed to determine the most suitable for the available waste generated in Glasgow depending on waste characteristic (composition, quality, and volume).

The technologies convert the selected feedstock though either heat or the action of microbes to produce a product gas with a high heating value such as a syngas or biogas (mainly carbon monoxide, hydrogen and methane). Hydrogen is then separated from the product gas, compressed, and stored until needed. The conversion processes in thermochemical technologies such as gasification rely on relatively high temperatures which cause modifications in the chemical structure of the waste (Lombardi et al., 2015). Thermochemical processes require specific operating conditions and materials including an anoxic environment, reaction agents, and catalysts. The performance of the gasifier is dependent on the properties of the feedstock such as waste composition, lower heating value (LHV), moisture content bulk density, particle size, ash content and contaminants (such as heavy metals, alkalis and sulphur) (Arena, 2013). Biochemical processes such as fermentation are less energy intensive, requiring optimal environments (temperature and pressure) and nutrients for the microorganisms to interact with the waste feedstock (Bičáková and Straka, 2012). Therefore, both the wet waste and dry solid waste fraction can be utilised when allocated to the appropriate technology. It was determined wet waste is better for biochemical technology while dry solid waste would be most appropriate for thermochemical technologies. This is to reduce energy loss though excess pre-treatment requirements and achieve higher process efficiencies. It will also limit process waste directed to landfill or incineration.

The analyses conducted in this study are designed to determine the environmental and economic feasibility of WtH technology in Glasgow. The LCA uses academic and industrial data to determine the carbon dioxide equivalent emissions for each WtH process to establish the global warming potential (GWP) which can be used for comparison amongst WtH and conventional technologies. It is therefore a valuable decision-making tool for analysing alternative systems by analysing energy use and environmental impacts. The CBA uses UK government reports and data to assign a value to each system over a 25-year lifetime to calculate the total cost along with economic indicators of net present value, levelized cost of hydrogen, internal rate of return and benefit cost ratio. Sensitivity analyses evaluate the influences of various process parameters for both LCA and CBA. The economic and environmental values are then used in a multi-objective optimisation to determine the Pareto optimal front for the scenarios proposed in the study.

1.2. Aims and Objectives

The aims of the study are to analyse the use of carbon-based waste in thermochemical or biochemical conversion technologies for the production of hydrogen and assess the environmental impact and economic viability. An objective is also to evaluate WtH technology and processes that use waste as feedstock in comparison with current waste management techniques (landfill and incineration) to determine potential carbon savings and systems cost. Additionally, to assess WtH as a hydrogen production method and compare it with conventional hydrogen production techniques for both carbon savings and cost. It is important to determine whether WtH can satisfy both economic and environmental impact assessment criteria, a multi-objective optimisation designed to test this.

A discussion on the benefits and disadvantages of WtH considering climate and transport policy will establish if there is a need or support for such systems in Glasgow. Hydrogen as a fuel for low emission vehicles is important for public transport applications especially in populated areas therefore making hydrogen fuel cell vehicles strategically important for future public transport plans.

The results and discussion will indicate areas for further research and provide recommendations for further work leading on from this study. All these aspects will go towards determining the feasibility of WtH in Glasgow for public transport. Fig 1-1. displays the stages of this project, with the methods, analyses, and software used to achieve the aims.

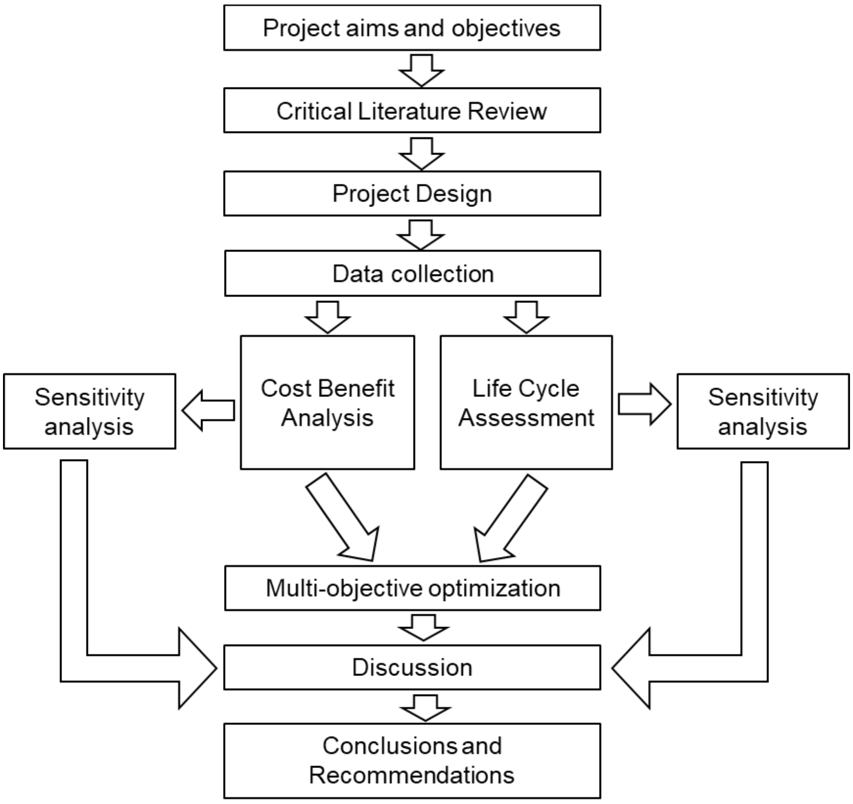

Fig. 1-1. Project flow chart with the different stages of the study with the analyses used. The arrows show the direction and how the processes interconnect and support the research questions and aims of the study.

1.3. Contribution of the thesis

The novelty of the thesis is to provide analysis of the Waste-to-Hydrogen concept using thermochemical and biochemical technologies for waste conversion to produce hydrogen as a zero-emissions transport fuel. A knowledge gap had been identified in the literature on the economic feasibility and environmental impact of the technologies used for WtH systems. There are also gaps in knowledge connecting the process chain involved in WtH from conversion technology to hydrogen production (via synthetic gas). There is a lack of analysis on the environmental impact of WtH and limited availability of systematic databases on WtH-based to support deployment for green transport needed to support future planning of hydrogen economy for which WtH serves one of the low-carbon hydrogen options. The conventional hydrogen production technology, SMR, is used as a comparison case for both thermochemical and biochemical technologies which does not exist in the literature.

The city of Glasgow in Scotland provides the waste data (type, composition, and amount) and the location for a WtH facility which currently has not been the focus of a research study on waste conversion technologies or hydrogen production methods. Extending the discussion towards potential bottlenecks and issues involved in upscaling to industrial size within a city setting have also not been assessed.

By combining LCA, CBA and multi-objective optimisation in one study, this reasearch aims to complete the system analysis and fill the knowledge gap of a complete WtH technology system with environmental and economic considerations. Furthermore, to provide results in support of, and areas of concern for green public transport development and decarbonisation efforts.

The contribution of this study to research into carbon footprint calculation integrating it with economic analysis with the intention to optimise the whole WtH process considering both environmental and economic aspects ads these are important for the advancement of the concept and for policymakers to see the potential in WtH.

1.4. Published work related to the WtH

Three papers have been published in relation to this project:

Lui, J., Chen, W-H, L., Tsang, D C W., You, S. (2020). A critical review on the principles, applications and challenges of waste-to-hydrogen technologies. Renewable and Sustainable Energy Reviews 134, 110365. https://doi.org/10.1016/j.rser.2020.110365

Lui, J., Paul, M. C., Sloan, W., You, S., (2022). Techno-economic feasibility of distributed waste-to-hydrogen systems to support green transport in Glasgow. International Journal of Hydrogen Energy, 47, 13532-12331. https://doi.org/10.1016/j.ijhydene.2022.02.120

Lui, J., Sloan, W., Paul, M. C., You, S., (2022). Life cycle assessment of waste-to-hydrogen systems for fuel cell electric buses in Glasgow, Scotland. Bioresource Technology, 359, 127464. https://doi.org/10.1016/j.biortech.2022.127464

The structure of the thesis is designed to describe the current waste management strategies and hydrogen production methods. This is followed by three analyses to determine the feasibility of selected WtH technologies deemed appropriate for a Glasgow considering the type and volume of waste produced. The economic and economic assessments provide data for the multi-objective optimisation to aid the discussion on WtH feasibility. The results, interpretation, and discussion of the LCA, CBA and multi-objective optimisation are included at the end of each chapter. A final review, discussion and concluding remarks are in Chapter 8 which summaries the research objects and the aims to answer the main research question of the feasibility of WtH in Glasgow

The introduction Chapter 1 has described the aims the WtH feasibility study, the concept behind WtH, the potential of WtH for both sustainable waste management and low emission hydrogen production, plus the novelty of a fully connected WtH process system. The environmental and economic implications have been highlighted as the main methods to determine the feasibility of WtH.

Chapter 2 Literature review

In the critical literature review chapter, current academic knowledge on WtH will be evaluated and the status of WtH related technology, application and climate and energy policy assessed. The literature review will guide the technology and system design configuration outlined in the feasibility study. The WtH conversion processes and system design will be determined by data gathered from literature to find best options and practices. The content from this chapter has been published Lui et al., (2020).

2.1. Climate change, energy, and transport policy

The IPCC has been reporting the effects of fossil fuels on the changing climate and global temperatures since the 1980s to highlight the importance of cutting carbon emissions from human activities to keep greenhouse gases (GHG) below the 1.5°C threshold (IPCC, 2022). Treaties and polies such as The Paris Agreement (UN, 2015), United Nations Framework on Climate Change (UNFCC) and UN climate conferences (COP) have been written with goals to limit the temperature rise and recommendations to deal with global decarbonisation. These are aimed at energy intensive industries such as the energy and transport sectors and high GHG emitters to encourage the increase of zero carbon energy production. COP26 in Glasgow (2021) furthered carbon emissions targets and called for an increase in the commitments for decarbonisation including the need for innovation in transport to reduce global emissions. The UN Sustainable Development Goals set targets to improve standards for countries and communities. The UN targets for 2030 include sustainable energy production and environmentally sound management of waste to reduce the release harmful emissions to the environment to minimize effects of human health and the environment (UN, 2015). The IEA, a group of 38 countries working with governments for sustainable energy solutions, released a Global Energy and CO_2 Status Report detailing trends in energy and emissions every year and in 2018 energy demand rose, energy consumption rose, electricity demand rose as well as the demand for fuels. In 2021 global energy related consumption global primary energy consumption reached 595.15 EJ with global energy related CO_2 emissions at 36.8Gt CO_2 in 2022 (IEA, 2022). In 2022 energy related GHG reached 41.3 Gt CO2-eq while methane emission reached 4 Gt CO2-eq (135 Mt CH_4) (IEA, 2022).

In 2021 the UK total energy consumption was reached 7.16 EJ and carbon dioxide emissions from energy were 337.7 million tonnes from combustion of fossil fuels, with 348.4 million tonnes CO_2-eq from energy, process emissions, methane, and flaring (BP, 2022). In 2020, 99 $MtCO_2e$ of emissions came from domestic transport with transport the largest emitting sector at 24% (Department of Transport, UK Government, 2022). Consequently, the transport sector is the main area targeted for carbon emissions reduction.

Various studies have been conducted, for example by Itaoka et al., (2017) and Matsuda and Kubota (2016) in Japan, detailing the public perception of hydrogen and how government strategies can be developed for a hydrogen society. This includes integration of hydrogen technologies and developing hydrogen fuel cells and setting out a "Hydrogen Highway", which can be applied globally. The UK Department of Transport released the Decarbonising Transport report in 2021 which states that the application of hydrogen in the transport sector is one of main methods for carbon abatement (Department for Transport, 2021a). The former UK department of Business, Energy, Industry Strategy (BEIS) (Department for Energy Security & Net Zero from 2023) similarly has conducted studies and released reports on sustainable energy frameworks, these have included hydrogen a fuel of interest for future energy policies. The UK hydrogen policy published in 2021 sets a target of 5GW of low carbon hydrogen by 2030.

The UK government has further stated the intention for hydrogen fuel in the Hydrogen Strategy Report (2021) for increases in the production and use of hydrogen as an alternative to fossil fuels for transport applications. They also propose FCEB's as alternatives to diesel fuel buses. The 2021 National Bus Strategy from the UK Government enforces the move towards alternative fuels with the ending of sales of diesel buses and replacing them with zero emission vehicles. Diesel-based vehicles contribute significantly to carbon emissions and replacing these with fuel cell vehicles using renewable sources of hydrogen could reduce CO_2 emissions by 93% (IEA, 2018). The use of renewable and low carbon energy sources within the transport sector needs to see further increases to meet long term climate change goals (Paris Climate Change Agreement, 2015).

In Scotland a climate emergency was announced in Scotland in May 2019 and a commitment to achieve net zero emissions by 2045 with a transition to clean energy generation was made. Scotland had greenhouse gas emissions value of 47.8 MtCO2e in 2019, 12.0 million tonnes CO_2 equivalent ($MtCO_2$-eq) (CO_2-eq.) or 37% of the total emissions in 2019 came from domestic transport (Scottish Government, 2019b). Transport is consequently the largest source of net emissions more than industries such as business, agriculture, and energy supply. It is therefore one of the main focuses for decarbonisation to help achieve the net zero targets in line with climate policies. The Climate Change (Emissions Reduction Targets) (Scotland) Act 2019 specifies a reduction of GHG emissions to 75% on 1990 levels by 2030 and by 90% by 2040, reaching net zero by 2045.

Scotland gained devolved powers from the UK Government in 1998 for certain sectors including environment and many parts of transport, though refers to the UK Government for energy matters. Therefore, many aspects of decarbonisation of energy and the transition to net zero need to reference both the UK and Scottish governments.

Public transport is at the forefront for decarbonisation efforts and includes buses, refuse trucks and service vehicles. The National Transport strategy states the aim to help deliver the net zero target with a focus on sustainability and protecting the health and wellbeing of the population (Transport Scotland, 2020). The government in Scotland has a wish to provide green transport choices and is changing the way they design the transport system to allow alternative methods. The Scottish Government hydrogen policy released in 2020 was devised to use hydrogen to help reach net zero by 2045, meet energy demands and be part of energy transition as well as for generating economic opportunities in Scotland (Scottish Government, 2020a). The Hydrogen Action Plan followed in 2021 and highlights a £100 million investment received for a period of 5 years to support hydrogen policies. Both low carbon and renewable energies such as wind sourced electrolysers are supported. The Scottish Cities Alliance also aims to develop the hydrogen economy in Scotland by attracting investment, promoting sustainable projects, and encouraging innovation. They promote large scale deployment of hydrogen fuel cell buses with infrastructure to support it (Scottish Cities Alliance, 2022).

Glasgow has the largest volume of traffic of all the local authorities in Scotland and the transport industry emits the most greenhouse gases in Scotland (Glasgow City Council, 2020). Glasgow City Council has implemented various policies such as The Fleet Strategy (2020-2030) with aims for a zero emissions fleet by the end of 2029 (Glasgow City Council, 2018). A Low Emission Zone (LEZ), part of Cleaner Air for Scotland, was introduced in 2018 with the aim to reduce air pollution (nitrogen dioxide) in the city centre by encouraging cleaner transport with higher emissions standards (SEPA, 2020). The LEZ is currently applied to local bus services, with plans to expand the scheme to all vehicles from mid-2023. Glasgow City Council has also shown a wish to invest and supply greener public vehicles. This is demonstrated by the plans to purchase hydrogen fuel cell electric refuse trucks and gritters (Glasgow City Council, 2018). The transition to zero emissions vehicles would be a positive step towards widespread use of hydrogen as a fossil fuel alternative.

Glasgow City Council is implementing various schemes and projects to reduce the carbon footprint of waste generated in the city. The Resource and Recycling strategy 2020-2030 sets out the strategy for Glasgow to become a zero-waste city and reduce the carbon footprint of waste management and become more sustainable (Glasgow City Council, 2020). The Waste Strategy for Glasgow aims to change the view of waste into a resource with value and to provide the technology to improve the potential of waste whilst improving sustainability (Glasgow City Council 2015).

2.2. Waste Management strategies in Scotland

Waste management is of global concern with the challenge to provide strategies to tackle the increasing volume of waste produced by an increasing global population. Total waste generation is predicted to reach 6 million tonnes a day by 2025 (World Energy Council, 2016) as the world population increases at a rate of (1.18%) each year (IEA, 2017). Implementing sustainable waste management practices are necessary to safeguard the health and sanitation of the population whilst reducing the negative impact to air and water environments. Organisation and governments such as World Energy Council, UN, and the EEA have released numerous reports on how to deal with waste efficiency and sustainably. Potential energy from unsustainable waste management techniques is lost at a large scale as seen through an example of the EU losing 1,409PJ in landfill and 1,805PJ from incinerators in 2012 ((European Commission, 2016). Smaller percentages of waste are recycled (approx. 45% in Scotland in 2018), went to composting facilities, or transported to energy from waste (EfW) plants.

Traditional waste management has relied on landfill and incineration to dispose of waste and is becoming increasingly unsustainable. The carbon footprint of landfill in the UK is 0.395 tCO_2-eq/t MSW and for incineration is 0.290 tCO_2-eq/t MSW (without energy recovery) (Jeswani et al., 2013). Landfill sites act as storage for all types of organic and inorganic waste which decompose to produce landfill gases (LFG) comprising GHG methane (50-60%), carbon dioxide (35%) and volatile organic compounds <1% which pollute air, water, and soil (dioxins and leachate) (Jeswani et al., 2013). Fig 2-1 illustrates the possible routes for the management of waste streams from which WtH originates. The main routes highlighted for waste that does not fit the reuse or recycling criteria are shown as gasification or fermentation. Fig 2-1 also shows how these waste conversion technologies could be applied together and fit into a sustainable waste management strategy.

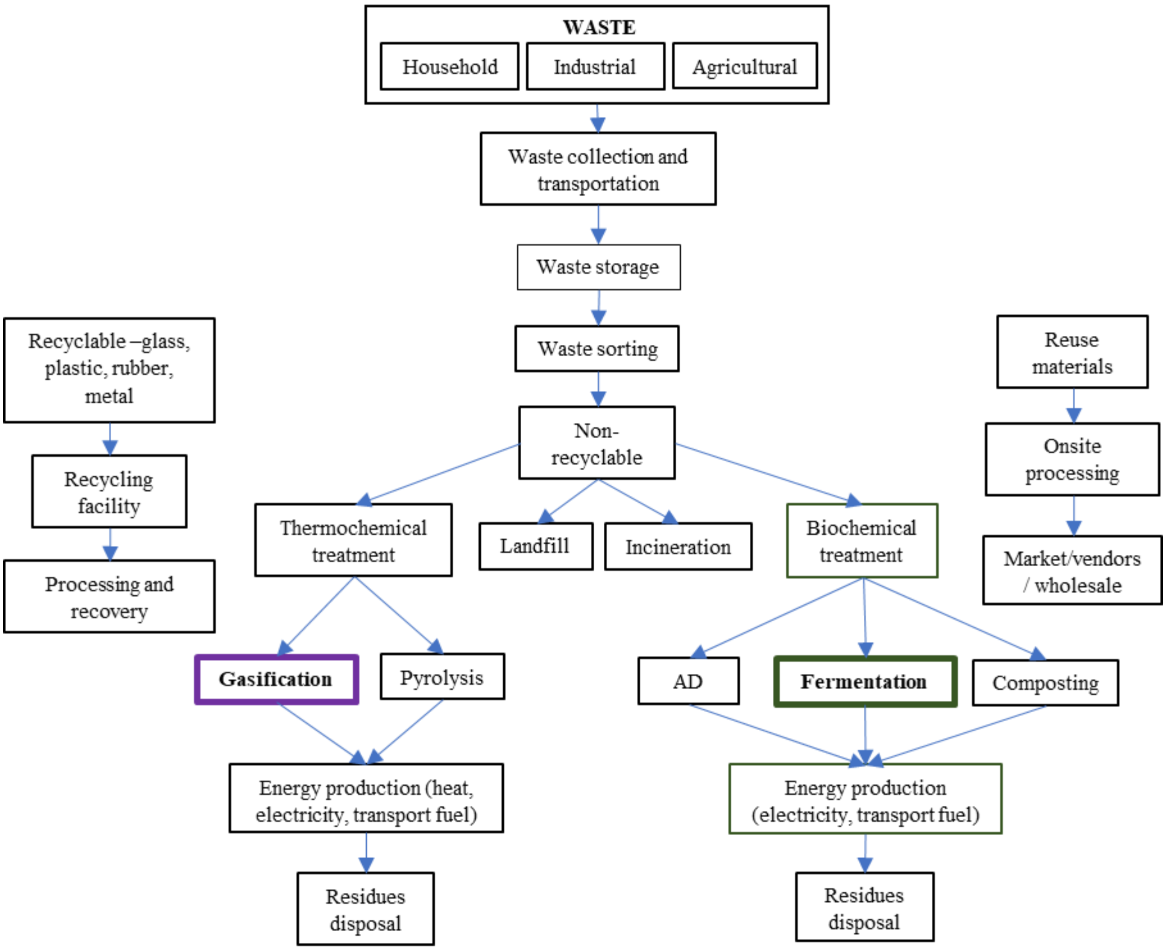

Fig. 2-1. Flow chart of routes for waste management including the WtH systems of gasification and fermentation

The wet waste fraction contains animal and mixed food waste, fats, oils, greases, and vegetal waste as well as common sludges, dredging spoils and sorting residues. Wet waste is described as waste with a moisture content higher that 40 wt.% which can reduce the energy efficiency of thermochemical technologies. Low moisture content is considered below 15%. Sewage sludge varies slightly with a mean average of carbon at 51 wt.%

carbon, oxygen with a mean average 33 wt.%, hydrogen with a mean average of 7.3 wt.% and nitrogen with a mean average of 6.1 wt.% (Vassilev et al., 2009). The high moisture content of food waste and sewage sludge, whilst possible for valorisation purposes will affect the practical use and lead to energy losses (Pham et al., 2013). Biochemical technologies that do not rely on high temperature are less impacted by the moisture content and are therefore more applicable for the wet waste category.

Carbon-based waste is appropriate for use in thermochemical processes, which have are important for sustainable integrated waste management, specifically MSW (Arena, (2012). The MSW category consists of household waste, packaging, plastic and textiles. Biomass wood waste includes agricultural woody-based plant material, non-recyclable paper and cardboard, timber, and other wood wastes. Biomass waste has a high carbohydrate, mineral and nutrient content (Eker and Sarp, 2017) and a general moisture content of 30-60% and high volatile matter content of 70-80 wt.% (Asadullah, 2014) The main chemical components and composition of woody biomass are; carbon at a mean average of 52 wt.%, oxygen at a mean average of 41 wt.%, hydrogen at a mean average of 6.2 wt.% and nitrogen at a mean average of 0.4 wt.% (Vassilev et al., 2009). The sulphur content of biomass is generally low at less than 2% (Basu, 2013). As a feedstock biomass has a low bulk density compared to coal oil and natural gas and requires modification via treatment to increase energy values and therefore conversion efficiencies (Chen et al., 2015). Moisture content also effects the operations such as bed temperature during gasification and benefits from feedstock drying to reduce energy losses (Pham et al., 2015). The moisture content of the waste therefore effects the suitability of certain thermochemical technologies and the overall energy required.

There are many studies and review papers that study the properties of biomass, generally agricultural waste, as fuel for thermochemical processes such as gasification or pyrolysis. However, the use of MSW, wet waste, woody biomass waste as a feedstock for energy conversion is steadily increasing as factors such as availability, the benefits of diverse energy sources and sustainability are becoming more relevant in energy generation.

Heterogeneity in waste causes low volumetric energy density and inconsistent size causes technical problems that reduce the energy efficiency and therefore profitability as suggested by Ramos et al. (2018). Without treatment biomass waste has a low energy value and hence low conversion efficiencies (Chen et al., 2015). Therefore, waste treatment before thermochemical processes to reduce moisture content, ideally below 20%, and increase homogeneity (consistency and size) is essential (Iribarren et al., 2012). This consequently will reduce storage requirements and transportation in the supply chain (Dong et al., 2018). Methods of pre-treatment to improve the composition and characteristics of waste feedstock are discussed further in Chapter 2.2.1.

2.2.1. Pre-treatment of waste

In general waste obtained from multiple sources is heterogenous in character with a mixed composition and inconsistent size. Pre-treatment is required before conversion processes to improve the energy density and morphology of feedstock (Dutta, 2014). Treating the waste also leads to more certainty in the operating conditions (Dong et al., 2018a). A low moisture content (below 15%) is assumed to aid thermochemical processes due to moisture effecting gasifier and reaction temperatures (Ramos et al., 2018).

Treating feedstock usually involves drying to lower the moisture content and grinding and homogenise the particle size and composition (Molino et al., 2016). Drying leads to lower moisture content and increases the energy efficiency, syngas quality and lowers process emissions (Pang and Mujumdar, 2010). The energy required for drying is approximately 2242kJ/kg moisture (Basu, 2013). Ramos et al., (2018) also discuss the reduction in unwanted gases such as carbon monoxide. However Dominguez et al. (2006) who studied sewage sludge pyrolysis and Hu et al., (2015) who studied gasification of wet MSW, discuss the improved hydrogen yield from syngas caused by the high moisture content of 40 wt.% during gasification reactions and reduced tar formation. The results from their studies suggest the moisture in the biomass aided steam reforming of volatile compounds and partial gasification during conditions of long residence times and high heating rate.

Lower heating temperature (LHV) can be used for comparison of fuels of MSW is approximately 6-18 MJ/kg while the biomass average is 15-20 MJ/kg (Arena, 2013). The

Inconsistent size of feedstock and the heterogeneity of MSW is one of the main technical problems associated with utilising waste (Dong et al., 2018). Compaction is a mechanical treatment to produce uniform shape and size of feedstock into pellets or briquettes. Pelletization would improve the operational ability, raising density and lowering moisture content and feedstock has higher calorific value and lower ash content (Ramos et al, 2018).

Torrefaction is a process involving the partial decomposition of biomass to reduce moisture content and increase fixed carbon (Verma et al., 2012). Torrefaction can increase the energy density of HHV, create a more uniform feedstock, lower H/C values and improve grindability (Chen et al., 2015). Torrefaction can improve the thermal efficiency of gasification up to 4 MJ/kg. Removing impurities could improve the overall process efficiency and reduce emissions per kg of hydrogen produced.

LHV is a measure of amount of heat generated from feedstock combustion not including the heat in the water vapour or combustion products that is not recovered. With pre-treatment and additional processing such a solid recovered fuel (SRF) from MSW, the LHV of waste can be increased to 18.6-21.3 MJ/kg (Arena and Di Gregorio, 2014). This compares to fossil fuels such as natural gas (mostly methane) which has LHV of 50 MJ/kg, diesel of 42.5 MJ/kg and gasoline (petrol) of 44.5 MJ/kg (Dincer and Acar, 2015).

Hognert and Nilsson (2016) discus the higher heating value of waste and found untreated MSW had a HHV of 11.3MJ/kg which increased to 19.9MJ/kg after drying and ash removal. Though Hu et al., (2015) show a high hydrogen yield and volumetric concentration at 40% moisture content, using CO_2 sorbent and catalyst. This suggests an optimal moisture content for specific temperatures occurs within a reactor to promote hydrogen formation reactions (steam reforming and water gas shift reaction) enhancing hydrogen production. The implications are that using the moisture in the waste without drying would reduce the energy requirements of pre-processing increasing the efficiency of the process.

2.2.2. Gas and solid by-products from thermochemical and biochemical conversion of waste

Thermochemical and biochemical waste conversion processes can produce a variety of solid, liquid and gas products. Gasification, pyrolysis and combustion, can produce solids such as biochar and tar, gases such as nitrogen, carbon monoxide, hydrogen, carbon dioxide and liquids such as oils. Biochemical conversion processes also produce gases such as biogas and hydrogen, and liquids such as ethanol, acetone and organic acids.

Synthetic gas (syngas), or producer gas, is an intermediate product in the thermochemical waste conversion process, produced directly from gasification or pyrolysis. The composition of the syngas is determined by waste type and operational conditions and usually consists of carbon dioxide, carbon monoxide, hydrogen, methane and nitrogen plus trace gases. Obtaining the highest LHV of waste feedstock, through measures such as pre-treatment, can increase the hydrogen content of the syngas. The operational conditions such as temperature, gasifying agent and use of a catalyst, also effect the hydrogen content in syngas and must be considered (Pinto et al., 2016).

Tar is a condensable organic compound produced during gasification and can become entrained in syngas (Jordan and Akay, 2012). Biochar is a carbon rich, highly porous solid residue produced during pyrolysis (temperature below 700°C) of carbonaceous biomass material (Lee et al., 2017). The type of feedstock and the thermochemical conditions effect the properties of biochar (Dissanayake et al., 2020). The porous feature of biochar means it can be used as an adsorbent for contaminants in soil and water which is of benefit to the environment (Lee et al., 2017). It can remain in the soil for more than 100 years and can be applied to soil to increase crop yield and reduce loss of nutrients. This has led to studies into the use of biochar for carbon dioxide adsorption as a carbon sink for carbon capture and storage (CCS) (Wang et al., 2018). Though further progress, such as advancements in engineered biochar enhancing the adsorption properties is needed for large scale implementation that is sustainable and cost effective (Dissanayake et al., 2020). In biochemical technologies biochar can increase hydrogen production and inhibit ammonia formation from organic waste as studied by Sharma and Melkania (2017) who found biochar facilitates biofilm formation and colonisation of microbes on the surface. Pyrolysis of biomass can also produce liquid products such as light and heavy oils, condensable liquids at temperatures between 375 and 550°C (Nikolaidis and Poullikkas, 2017). Beyond 600°C the liquid yield decreases due to cracking and more gas is generated.

2.3. Hydrogen properties and global production rates

In 2021 global hydrogen production rates reached 94 million tonnes with the IEA predicting demand could reach 115 million tonnes by 2030 (IEA, 2022). The main hydrogen consumers and industrial customers are chemical (for ammonia production), refining, pharmaceutical, power generation and space exploration (Ju et al., 2018). Conventional methods of hydrogen production centre around the conversion of fossil fuels and includes stream reforming of natural gas and petroleum, gasification of coal or coke, catalytic decomposition of natural gas and partial oxidation of heavy hydrocarbons (Arregi et al., 2018). The representation of hydrogen production types is shown in Fig 2-2 highlighting the natural gas reforming is currently the dominant production method.

Hydrogen acts as an energy carrier and has high energy content per mass compared to petroleum but with a low energy density (141.8 MJ kg^{-1}) and low heating value (LHV) of ~120MJ/kg^{-1} (Dutta, 2014). The net calorific value of 1kg of hydrogen is equivalent to 2.75kg of gasoline and 6kg of methanol (Łukajtis et al., 2018). Due to its properties of low boiling point gas hydrogen storage consists of insulated pressure vessels such as high pressure compression or low temperature cryogenic liquefaction (Sikarwar et al., 2017). 1kg hydrogen has a volume of 11m^3 (Dutta, 2014). Solid hydrogen storage solutions include combinations with materials such as metal hydride and carbon materials (Łukajtis et al., 2018). The energy is required to compress the hydrogen in the range of 35-70 MPa, is an extra consideration. The specific conditions impacts systems design and energy requirements can effect industrial applications and large-scale implementation (Dutta, 2014). While Dincer and Acar (2015) discuss the sustainability issues connected to renewable and non-renewable sources of hydrogen production and the importance of considering the social impact. Mohanty et al., (2015) reviewed the process of hydrogen from biomass with the challenges faced as well as the opportunities available in terms of the economic upside and benefits for the environment. While they do not specifically mention waste as feedstock is can be assumed similar issues will arise there is little mention of the other aspects of hydrogen production such as wastewater and water management.

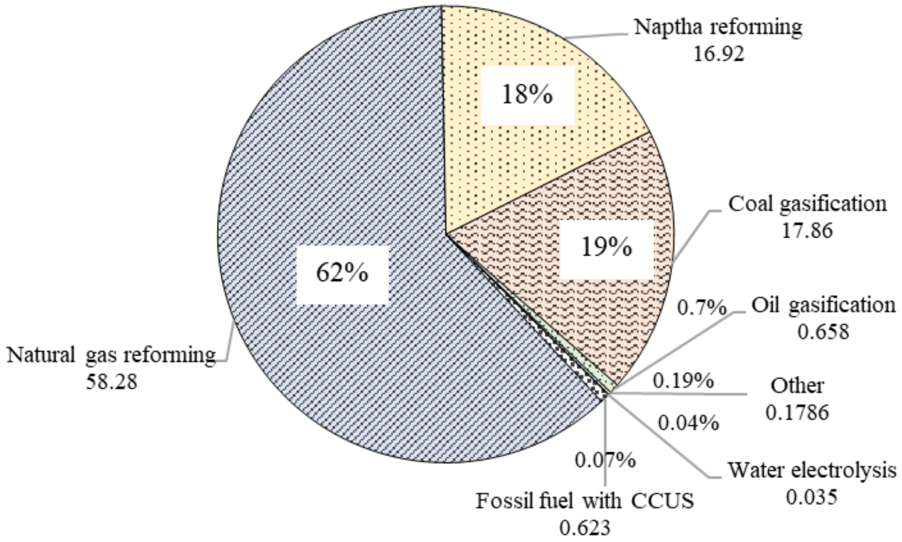

Fig. 2-2. A global matrix of hydrogen production. The values are in million tonnes of hydrogen. All production types are operated without CCUS unless stated. The data is supplied by IEA Global Hydrogen Review 2022.

Approximately 62% of hydrogen is produced though SMR worldwide (IEA, 2022) The efficiencies range from 70-75% for natural gas reforming to coal gasification at 45-65% (Ju et al., 2018). The processes are energy intensive requiring high temperatures in the range 600-1000°C and generate high CO_2 emissions (Salkuyeh et al., 2018). Processes using fossil fuels also contribute emissions of oxides of carbon, sulphur and nitrogen, ash containing radioactive substances and heavy metals to the environment. Using hydrogen produced by fossil fuels for the transport sector has a carbon footprint in the range of 67-112 kg CO_2-eq/GJ furthering the need to find alternative sources for hydrogen production (Fernández-Dacosta et al., 2019). Hydrogen production from waste is currently not at large industrial scales and does not produce enough to be registered in global metrics. However, gasification using mixed feedstock waste can produce hydrogen yields of up to 33.6 mol/kg and hydrogen concentrations of 82%. Whilst biochemical methods including fermentation techniques can produce hydrogen up to 418.6 mL/g.

2.4. Thermochemical WtH production methods

The technologies available for hydrogen production are based on two categories of thermochemical with the use of heat for conversion and biochemical using biological methods for conversion. Thermochemical technologies include gasification, pyrolysis and plasma gasification. Biochemical technologies include dark fermentation, photo fermentation and photolysis. The main differences are operating conditions of temperature and pressure, use of microorganisms, catalysts, process efficiencies, reaction time and final yield. Table 2-1 shows possible process efficiencies, obtained from literature for gasification, fermentation and SMR the conventional hydrogen production technique. Choosing the most suitable conversion system for the feedstock is important along with appropriate operation conditions such as gas cleaning system to avoid large volumes of emissions including nitrogen oxides (Koroneos et al., 2008).

Thermochemical processes, especially gasification, tend to be energy intensive because of the exothermic reactions, higher temperatures (breakdown waste feedstock) and pressure optimisation leading to larger environmental impacts compared to biological process of hydrogen (Nikolaidis and Poullikkas, 2017). However, gasification technology produces higher yields and rates of production of product gas with shorter reaction times than biological technologies (Huang et al, 2018). It also has an ability to adapt to feedstock type and this flexibility is an important aspect of gasification technology, which can improve the economics of the conversion facilities. The ability to use a variety of feedstock makes thermochemical processes more applicable for unsorted residual waste and MSW (Arena, 2010). A major advantage to thermochemical technology is the high reduction in waste mass of 70-80% and waste volume of 80-90% (Lombardi et al., 2015). Lombardi et al. (2015) also reviewed thermochemical treatments considering waste type and appropriate facility size and identified preserving landfill space as an important benefit. This combined with a reduction in associated emissions make gasification an attractive technology and a major future energy contributor and waste management strategy.

Thermochemical processing has also been found to reduce the generation of LFG before disposal in landfill sites. The high temperatures involved in thermochemical processes destroy organic contaminants such as halogenated hydrocarbons, by increasing the concentration and immobilization of inorganic contaminants which leads to safe or useful disposal (Wilson et al., 2013). Using the solid residues such as bottom ash and slag from thermochemical processes further reduces space required in landfill and increases the cost effectiveness of the processes (Arena, 2013).

Energy requirements are an important factor when considering the environmental impact of assessing either technology. The advantages or disadvantages of high verses low energy requirements discussed in the LCA results (Chapter 4.6).

Table 2-1. Efficiencies from selected WtH technologies

Technology	Feedstock	Process efficiency %	Reference
Gasification	MSW	35-50	(Nikolaidis and Poullikkas, 2017)
Gasification	Waste wood	39-48	(Navas-Anguita et al., 2020)
Dark Fermentation	Wet waste	60-80	(Abdalla et al., 2018)
Dark and Photo Fermentation	Wet waste	6.6-86	(Abdalla et al., 2018)
SMR	Natural gas	70-75	(Ju et al., 2018)

The WtH technologies are discussed in further in Chapters 2.4 and 2.5 and include justifications for matching feedstock type with conversion technology. For example, the technologies chosen can be used for both drier and wetter fractions of available waste to be utilised for conversion. Using the appropriate technology for waste type will avoid excess pre-treatment i.e., drier wastes used in thermochemical and the wetter waste for biochemical methods.

2.4.1. Pyrolysis

Pyrolysis is a thermochemical process that can convert organic material through thermal destruction into value-added products such as bio-oil, biochar, and product gas (Das et al., 2019). Pyrolysis is endothermic and occurs in the absence of oxygen, air or steam at temperatures of 350-550°C, and pressures of 0.1-0.5 MPa (Jahirul et al., 2012). Product gases include hydrogen, carbon monoxide, carbon dioxide, methane, and nitrogen. The presence air or water in the reactor through insufficient pre-treatment of feedstock from drying can produce carbon monoxide and carbon dioxide emissions (Holladay et al., 2009). The lack of air also mitigates the formation of dioxins (Bičáková and Straka, 2012).

Pyrolysis can either be a standalone process to produce chemical compounds or as the initial stage of gasification or combustion processes. As the initial stage of gasification, pyrolysis can generate biochar to improve the energy content of gasification feedstock. Eq. 1 displays the pyrolysis reaction with waste (modified from Bičáková and Straka, 2012).

$$\text{Waste or biomass} + \text{heat} \rightarrow H_2 + CO + CH_4 + \text{char} \qquad (1)$$

The yield of gas from pyrolysis is dependent on the feedstock type, heating rate, catalyst, temperature, and residence time of pyrolysis reaction (Hosseini and Wahid, 2016). The product gas is transformed further via steam reforming and water gas shift reaction to produce more hydrogen (Wu and Williams, 2014). Pyrolysis can be sped up by using catalysts based on inorganic salts such as chloride, carbonates and chromates (Bičáková and Straka, 2012). Lu et al., (2020) looked at the use of co-pyrolysis for a range of MSW wastes including biomass and food waste and found mixing can improve the end product though more research is needed to find the mix for the preferred end product and the process is in the early stages of development.

A summary of hydrogen production (percentage of hydrogen produced or the hydrogen yield) from gasification and pyrolysis with a variety of process conditions from various research papers is in Table 2-2.

2.4.2. Gasification

The gasification process converts carbon-based materials through partial oxidation into synthesis gas (syngas) in an endothermic reaction (Arregi et al., 2018). The gasification temperature range is 750-900°C and requires constant pressure generally at atmospheric pressure (1atm) (Cao et al., 2019). Autothermal gasification uses partial oxidation of waste within the reactor, in the presence of an oxidant at an amount lower than that required for stoichiometric combustion, to provide the required heat for the reaction (Rauch et al., 2014). A portion of the feedstock is combusted in exothermic reactions, which provides heat to gasify the remaining products (Chang et al., 2011). A gasifying agent, optimal steam-biomass ratio, sorbent for carbon dioxide adsorption and catalyst is also required for the reactions (Parthasarathy and Narayanan, 2014). The reactions involved in the gasification reaction of waste conversion, are waste gas shift, steam reforming, tar reforming, are shown in Eq. 2- Eq.5 respectively. An example of a process flow for fluidised bed gasification is in Fig. 2-3.

The temperature is important for gasification reactions because they are endothermic and the effect it has on the hydrogen yield (Ramos et al., 2018). Operating temperature has a large influence on the gasification kinetic rate, and enhances endothermic equilibrium reactions (Erkiaga et al., 2014). Increasing the temperature towards the optimum level will increase the hydrogen yield due to an enhancement in reactions such as the Boudouard, water-gas shift (WGS) and reforming reactions (Chutichai et al., 2013). The energy required for reactions can be provided by combustion of part of the fuel or by an external source (Arena, 2012). A study from Sirirermrux and Kerdsuwan (2019) highlight the influence of temperature by increasing the reaction temperature from 700°C to 800°C then further to 900°C, the energy output (kJ/kg of feedstock) was increased by 1.5 and 2 times.

The yield and composition of the produced syngas is dependent on feedstock type and size, reactor temperature, catalyst type and residence time (Nikolaidis and Poullikkas, 2017). Higher moisture content in the feedstock leads to steam generation for water gas shift reaction leading to conversion of carbon monoxide into carbon dioxide and hydrogen (Ong et al., 2015). The CO/H_2 ratio decreased 0.26 points after adding 20 wt.% sewage sludge to the woodchip feedstock in the gasifier. They also found the temperature decreased leading to further conversion of carbon monoxide in the water gas shift reaction. Though the increased moisture content requires energy for the vaporisation of moisture, lowering the efficiency of the gasifier.

The syngas product is mainly composed of carbon monoxide, methane and hydrogen (Huang et al., 2018). Gasification requires specific feedstock characteristics such as low heating value, ash and moisture content to be efficient and produce the desired syngas composition. Further processing of the syngas can increase the quality and quantity of hydrogen, while reducing the unwanted components. Generally, the aim is to produce syngas with a high yield and purity of hydrogen though this depends on the design of the system, operational conditions and therefore dictates which type of gasifier is used.

Sikarwar et al. (2017) used a range of biofuels for biomass gasification detailing operation conditions and highlighting the importance of processing and syngas cleaning though no details on hydrogen from waste. Syngas requires cleaning (particulate removal) and cooling, before passing through the waster-gas shift (WGS) reaction. The WGS reactions produces more hydrogen from the reaction of carbon monoxide and water (Abdalla et al., 2018).Varying the mixture of the waste could improve the quality of the syngas and the efficiency of the processes by changing the carbon and moisture content (European Commission, 2016). Ramos et al., (2018) also found the quality of syngas may improve when adding biomass to other waste to add moisture and carbon content.

In general, the efficiency of gasification is measured by the volume of syngas produced, the hydrogen yield or carbon conversion rate (Arena, 2012). Nikolaidis and Poullikkas, (2017) report the gasification of biomass for hydrogen production to have a thermal efficiency of 35-50% and up to 52% with steam gasification. While a study from Salkuyeh et al. (2018) suggested that fluidised bed gasification could have a thermal efficiency of 45% LHV and entrained flow gasification achieve 56% LHV.

$$\text{waste} + \text{steam} = H_2 + CO + CO_2 + CH_4 + N_2 + \text{tar} + \text{char} \quad (2)$$

$$\text{Water Gas Shift: } H_2O + CO \rightarrow CO_2 + H_2 \quad (3)$$

$$\text{Steam reforming: } C_nH_m + nH_2O \rightarrow nCO + (n + m/2)H_2 \quad (4)$$

$$\text{Tar reforming : tar} + H_2O \rightarrow CO + CO_2 + H_2 + HC \quad (5)$$

The main gasification reactor options available for the gasification of waste feedstock are bubbling fluidised bed, circulating fluidised bed, updraft fixed bed, downdraft fixed bed, entrained flow and plasma types (Watson et al, 2017).

Solid waste feedstock is best suited to fluidised bed gasification because of its capacity to handle the varying compositions in the feedstock (Molino et al., 2016). Fixed bed and fluidized bed gasification reactors are also used commercially due to being easier to use to the other types and the low capital investment costs. While fluidised bed reactors had the added advantage of load flexibility and scalability and is therefore able to adapt to the seasonal variations in waste generation (Molino et al., 2016).

Gasification reactor type and advantages are associated with certain gasification agents (Farzad et al., 2016). The gasifying agents typically used are air, pure oxygen, oxygen enriched air or steam, which enhance the reactions and the choice of gasifying agent will depend on the desired composition of the syngas. Air gasification uses air (contains approximately 78% nitrogen, 21% oxygen, 1% argon) as the gasifying agent and has a heating of value of 3.5-7.8 MJ/m^3, which is low compared to steam and oxygen gasifying agents (Watson et al., 2017). Air as the gasifying agent increases the concentration of nitrogen which dilutes the syngas concentration and increases the cost of separation as well as lowering the heating value (Sikarwar et al., 2017). Yet, air gasification is common as can be sourced from the atmosphere and therefore is the cheapest form of gasifying agent. Chang et al. (2011) suggested that using air as the gasifying agent can reduce the cost of extra energy requirements due to the partial oxidation reaction being exothermic. Oxygen enriched air gasifying agent is used as a compromise as the reduction in nitrogen content would increase the HHV value of syngas whilst being abundant and lower cost (Arena, 2012).

Equivalence ratio (ER) is the ratio of actual oxygen flow rate to stoichiometric oxygen flow rate. The ER effects the gas yield and reactor temperature in a gasifier with a low ER favoured. Increasing the ER beyond the optimal range (towards the combustion zone ~1) occurs with a reduction in hydrogen and carbon monoxide yields reducing the heating value of syngas and producing a low-quality gas product (Sikarwar et al., 2017).. An ER of 0.25-0.35 is required for char conversion. Beheshti et al., (2015) showed during the biomass gasification process increases in carbon dioxide (45.2 mol%) and hydrogen (12.1 mol%), as carbon monoxide decreased (12.9 mol%) when ER increased from 0.3 to 0.7. At a higher ER a decrease in tar content is also observed because of the increase in thermal cracking. The ER can also increase in the presence of volatile material and moisture (up to 15%) within the feedstock, while more than 15% causes temperatures to change (Sikarwar et al., 2017).

Gasification with steam as the gasifying agent is comparable in terms of quality to the other oxidation agents, is endothermic and requires energy to produce syngas (Erkiaga et al., 2014). The reaction temperature influences the steam flow rate and when the optimum temperature is passed, the hydrogen yield decreases. This is because high temperatures accelerate the reactions and reduce the ability of cracking and reforming reactions (Chutichai et al., 2013). Steam is the preferred agent for hydrogen production as it results in a higher H_2/CO ratio of 1.6 compared to air (ratio of 0.75) or oxygen (ratio of 1) agents and to increase the average hydrogen content (Lepage et al., 2021). The Steam to Biomass ratio (S/B) is important for steam gasification as the main reaction producing hydrogen is steam reforming (Parthasarathy and Naraynan, 2014). Generally, larger fractions of steam introduced to the gasifier cause the S/B ratio to increase, methane and carbon monoxide to decrease, while carbon dioxide and hydrogen increase, and a reduction in tar formation (Chutichai et al., 2013). Hydrogen yield will initially increase after a certain S/B level, followed by excess steam causing a decrease in hydrogen production and increase in tar formation. Steam gasification produces syngas with an HHV of 9.2-16.5 MJ/m^3 at standard temperature (25°C) and pressure (1 atm) (Iribarren et al., 2014). The equation for steam gasification is shown in Eq. 6 and air gasification is shown in Eq. 7.

$$\text{waste} + \text{steam} + \text{O2} \rightarrow H_2 + CO + CO_2 + CH_4 + \text{CHs} + \text{tar} + \text{char} \quad (6)$$

$$\text{waste} + O_2 \rightarrow H_2 + CO + CO_2 + CH_4 + N_2 + \text{tar} + \text{char} + H_2O \quad (7)$$

Gasification also produces biochar, tar, particulate matter, heavy metals, other pollutants and residues that require disposal. Tar (condensable organics) formation during gasification can damage equipment, effect performance, efficiency of the process and reduce syngas quality requiring clean-up from the gasifier or from the produced syngas (Ramos et al., 2018). For gasification using MSW as feedstock the content of tar should be no more than 1 mg/m^3 in the product gas or syngas (Watson et al., 2018). For high-purity hydrogen production (required by FCEVs) downstream upgrading processes and feedstock treatments are needed to reduce these by-products. This includes reducing carbon monoxide concentration which Chutichai et al., (2013) found was reduced by flowing the product gas through high and low water gas shift reactors and an oxidation reactor. This led to 33 mol% hydrogen in the final product gas and a decreased carbon monoxide concentration (<10 ppm) at a process efficiency of 57%.

Catalysts are used to improve the gasification efficiency and gasification rate of reaction, increase hydrogen selectivity and hydrogen production rate. Catalysts also promote tar cracking and steam reforming reactions in the gasification reactions (Inayat et al., 2014). In particular, catalysts can lower the activation energy required for the reactions and improve the carbon conversion efficiency, leading to higher gas yields (He et al., 2009). The reduction in temperature consequently leads to a decrease in energy requirements (Parthasarathy and Narayanan, 2014).

Catalysts traditionally consist of nickel based (Ni/Al_2O_3), alkali based, olivine and dolomite materials (Basu, 2013). Nickel-supported catalysts can reduce the formation of tar, char (recalcitrant by-products) and CO_2 in gasification (He et al., 2009). Dolomite and olivine are the most commonly used catalysts due to availability and sourcing from nature which causes them to be cost effective (Sikarwar et al., 2017).

An important operational issue related to catalyst use comes from the susceptibility to poisoning, plugging, loss of activity and deactivation including from carbon deposition (Al-Rahbi and Williams, 2017). Some feedstocks such as waste and sewage sludge often contain sulphur compounds, particulates and trace metals which negatively affect the performance of the catalyst (Watson et al., 2018). Further studies are needed to improve the longevity of catalyst to reduce the cost of frequent replacements and the environmental impact of spent catalyst waste.

Biochar as a carbon based catalyst has seen increased use and research to aid tar decomposition in the gasification process due to the porous characteristics as well as low costs (You et al., 2017). Biochar has a high surface area and a porous structure which aids physical adsorption, thermochemical reforming (Shen, 2015). The availability of biochar from processes such as gasification or pyrolysis of waste improve the ease of use and accessibility (Xiong et al., 2017, Chen et al, 2018). Ma et al. (2017) enhanced steam reforming of bio-oil by using biochar as a catalyst to produce a maximum hydrogen yield of 89.13% and concentration of 75.97%.

Calcium oxide (CaO) catalysts also have a high carbon absorbing capability with the ability to increase the concentration of hydrogen and reduce gasification equilibrium (Xiong et al., 2020). It is a low cost and abundant catalyst for reducing tar and carbon dioxide from the WGS reaction. However, CaO suffers from deactivation after the carbonation reaction and is a challenge which requires further research. Udomsirichakorn and Salam (2014) suggest CaO based chemical looping gasification as an option to improve continuous hydrogen production capabilities by reducing the fouling and blockages in pipelines caused by tars and control carbon dioxide capture. By improving hydrogen production rates, the economics for hydrogen production are improved, a hurdle for large scale gasification projects.

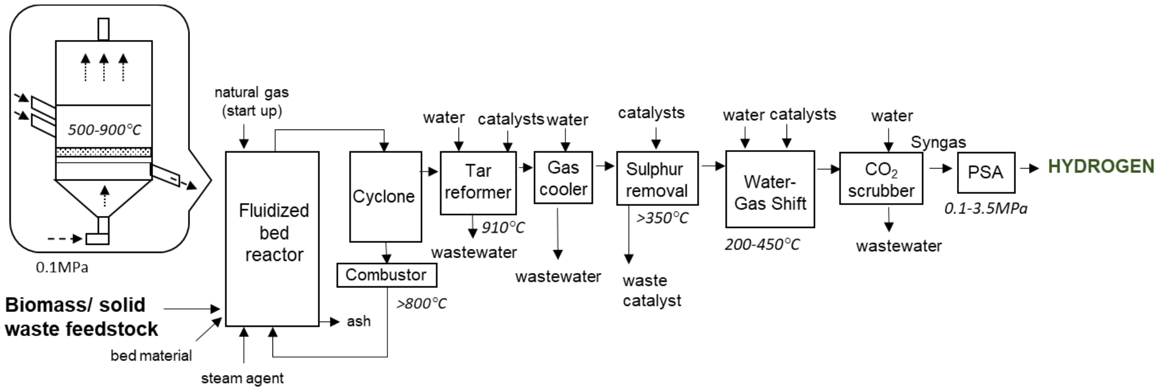

Fig. 2-3. CFB gasification process flow based on the process diagram in Lui et al., (2020)

Gasification has the highest commercial and competitive potential for producing syngas, and therefore hydrogen, from waste as well as biomass (Ramos et al., 2018). Gasification is a good candidate for waste conversion due to the high conversion efficiencies for hydrogen recovery compared to other thermochemical processes such as pyrolysis (Yao et al., 2018). However, there are challenges associated with waste gasification and the further development of technology. Irregular physical properties of waste can affect the operational efficiency of the gasifier and creates instabilities (Ramos et al 2018). These include increasing conversion efficiencies, low energy requirements for pre-treatment, and increasing the hydrogen fraction within the syngas. Potential technologies to improve the benefits and advantages of using gasification for waste conversion are discussed in Chapter 7.

A summary of gasification and pyrolysis studies from various research papers are listed in Table 2-1. Hydrogen production as hydrogen yield or percentage of hydrogen produced or the hydrogen yield is included. They show the range of feedstock used, operating conditions and the hydrogen produced. The hydrogen concentrations in the product gas range from 29.5% to 82.01% these are generally associated with biochar or bio-oil feedstock. The temperature is not necessarily related to the hydrogen production volume from a specific feedstock, for example higher temperatures do not always produce higher hydrogen concentrations. It can be observed that MSW corresponds to lower yields and hydrogen concentrations compared with biomass feedstock types such as agriculture-based corn stalk or straw. The reported range in feedstocks implies waste is flexible as a feedstock as are the thermochemical processes available for WtH.

Table 2-2. Summary of thermochemical hydrogen production (percentage of hydrogen produced or the hydrogen yield) of gasification and pyrolysis under different process conditions (MSW= municipal solid waste).

Author	Feed-stock	Main Reaction	Agent / Catalyst	Reactor	Ops Temp °C	% H_2 conc	H_2 yield
Chen et al. (2018)	Biochar from rice husk for bio-oil	Steam reforming of bio-oil	Ni/BC4 catalyst (biochar activated by KOH alkalisation coupled with HNO_2 reflux)	Fixed bed reactor	700	71.20 %	-
Chutichai et al. (2013)	Saw-dust	Water-gas shift reactor and oxidation reactor to purify syngas	-	Fluidised bed gasifier	600-650	-	33 mol.%
Al-Rahbi and Williams (2017)	Sawdust wood pellets	Steam gasification	Tyre char	Two stage fixed bed reactor	900	56 vol%	39.20 mmol g-1
			Acid treated tyre pyrolysis	Two stage fixed bed reactor	900	-	30.4 mmol g-1
Xin et al. (2017)	Cattle manure	Two step gasification: pyrolysis-carbonisation, steam gasification	-	Fixed bed reactor	850 (500 pyrolysis)	57.58 % conc	0.93 m3/kg
Yao. D et al. (2016)	Wheat straw (biochar from fast pyrolysis of wheat straw, rice husks and cotton stalk	Two step steam gasification	Ni/cotton char catalyst	Two stage fixed bed reactor	800 (550 pyrolysis)	64.02 vol% conc	92.08 mg g-1 biomass, gas yield about 90wt%

Li et al. (2017)	Corn stalk	Steam gasification	CaO	Fluidised bed gasifier	650	61.23 vol%	493.91 ml/g biomass
Chang et al. (2011)	Commercial α-cellulose and agricultural waste	Gasification	-	Fluidised bed gasifier	1000	29.50 %	-
Hu et al. (2015)	MSW	In situ steam gasification	-	Fixed bed reactor	750	49.42 vol% conc	277.67 ml/g MSW
Sirirermrux and Kerdsuwan (2019)	MSW (food waste, plastic, paper, textile, biomass)	Steam gasification	Steam agent	Drop tube fixed bed reactor	800	-	34.34 gH_2/kg MSW
Wu and Williams (2014)	Plastic (polypropylene)	Pyrolysis and catalytic gasification	Ni-Mg-Al catalyst	Screw kiln and Fixed bed gasifier	500 (pyrolysis) and 900 (gasif)	41.65 %	17.87 g/100g plastic
Klaas et al.(2015)	Hemp seeds	Pyrolysis	Steam reform-ing/ no catalyst	Fluidised bed pyrolysis reactor	700	-	2wt % origin biomass convert to H2

Combining two or more different feedstocks with a range of properties in thermochemical processes such as co-pyrolysis or co-gasification can produce a product gas with a more desired chemical composition and reduce energy requirements. Co-gasification can reduce the carbon dioxide emissions of gasification found when using separate feedstocks, which is due to increased efficiency and reduced energy requirement (Ramachandran et al., 2017). Feedstocks with a high moisture content, for example sewage sludge, can be co-gasified with torrefied biomass, which recovers the moisture content and can be fed back into the system as an agent (Huang et al., 2018). The appropriate ratio of each feedstock for co-gasification or co-pyrolysis is important to determine to be able to control to the syngas composition.

An example of combining moisture content feedstock is shown by Ong et al., (2015) who found the optimum mix of woody biomass and dried sewage sludge feedstock to produce the desired product gas composition, in this case less carbon monoxide and more hydrogen and carbon dioxide. A mix of feedstock can also reduce the blockage and formation of unwanted biproducts such as agglomerated ash. In this case the optimum amount to increase the amount of hydrogen in the product gas was 20 wt % dried sewage sludge and 80 wt% woody biomass. You et al. (2016) studied syngas production of the co-gasification of food waste and woodchips with sewage sludge and woodchips and found food waste and woodchips co-gasification produced 32.9% of syngas (observing total gas composition) with the volume of hydrogen at 16.5% compared to 32.4% syngas from sewage sludge and woodchips co-gasification with a volume of hydrogen at 16.8%. This is because sewage sludge contains a higher moisture and ash content, while food waste has a higher energy potential and a lower ash content.

Ramos et al. (2018) discuss the use of biomass as a fuel using co-gasification with waste and found combining the feedstock can improve the product quality and yield, energy content of produce syngas. Huang et al. (2018) studied the co-gasification of wet sewage sludge and forestry waste, using steam as the gasifying agent. They found the gas yield decreased as the ratio of wet sewage sludge increased with the hydrogen and carbon monoxide concentrations highest when the ratio of wet sewage sludge was 50%. The type of forestry waste had an impact with spruce producing the maximum hydrogen yield of 33.6 mol/kg at 827°C. Increasing the ratio of sewage sludge beyond the optimum temperature did not increase the yield of hydrogen due to the excess moisture and reduced organic matter. Fang et al., (2015) studied co-pyrolysis of MSW and paper sludge and found the optimum ratio of feedstock to be 50% paper sludge. This is possibly due to the large amount of ash in the paper sludge impeding the pyrolysis of the MSW.

2.4.3. Plasma Gasification

Plasma gasification is a type of gasification technology that generates plasma to be used as the heat source to gasify waste (e.g., MSW) for syngas production (Dincer and Acar, 2015). Plasma is generated by using an electric arc to ionize an inert gas. In general, the plasma gasification reactor consists of one or more plasma arc torches operating at approximately 13,000°C at atmospheric pressure. High temperatures of between 2,000 to

5,000°C are generated and the plasma reacts with the fuel or feedstock when steam is injected, to produce the syngas (Favas et al., 2017). The typical composition of the syngas is 55% nitrogen, 24% carbon monoxide, 15% hydrogen, and 6% carbon dioxide (Tavares et al., 2011). Increasing the moisture and inorganic matter within the reactor increases the hydrogen and decreases the carbon monoxide (Tavares et al., 2011). An increase in temperature produced a higher net energy content with higher combustion enthalpy to reduce the tar in the syngas (less than 10 mg/Nm^3) (Munir et al., 2019). The flow rates of plasma gas, oxidant and steam streams, residence times and reaction temperature affect the quality and mass of the resultant product gas (Munir et al., 2019).

Plasma gasification allows for flexibility in feedstock choice and is suitable for mixed waste and biomass feedstocks, as well as hazardous waste, of differing particle size, composition and moisture content with limited pre-treatment. Due to the high temperatures tar and ash are melted to form slag and therefore little tar remains in the product gas (Watson et al., 2018). The slag is then removed separately from the product gas out of the reactor.

The byproducts of plasma gasification include small volumes of vitrified slag, particulate matter, mercury, nitrogen oxide, sulphur dioxide and metals. These components require procedures to reduce the pollution such as scrubbers for syngas cleaning, cyclones and water quenchers which therefore reduce the emissions (Ramos et al., 2019). Favas et al., (2017) commented on the success of these pollution reduction methods in enabling plasma gasification to have the lowest emissions related to gasification. The assessment by Ramos et al in the LCA study of MSW plasma gasification agreed that the process has low environmental impact and high sustainability.

However, the limitations of the technology include the lack of large-scale industrial application and it is not proven (Panepinto et al., 2014). Plasma technology is also limited due to the high temperature and consequent high energy intensity which requires to a low carbon electricity source to shore up the sustainability.

2.4.4. Steam methane reforming

SMR is the main conventional hydrogen production method used in the UK and globally (Valente et al., 2019a). The SMR process contains natural gas pre-treatment, reforming reaction, cooling, water gas shift reaction (WGS combined as HTS and LTS) and hydrogen separation. The SMR flow diagram is shown on Fig.2-4 with the system inputs and outputs.

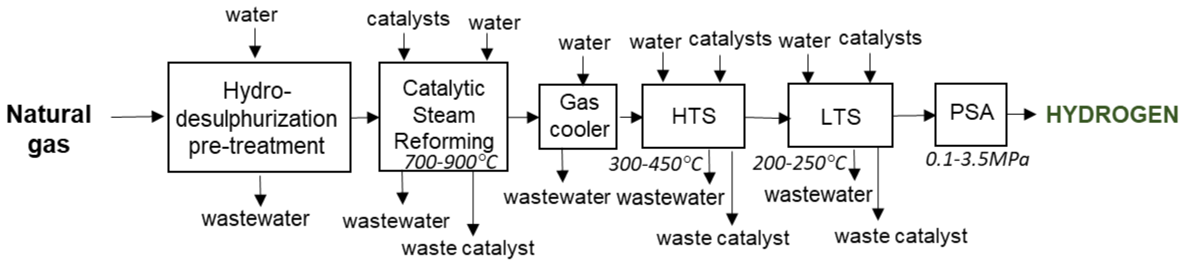

Fig. 2-4. SMR process flow diagram, including inputs and outputs.

The SMR process is strongly endothermic and uses natural gas (CH_4) as the feedstock in a reaction with steam and a catalyst to produce carbon dioxide and hydrogen, plus smaller fractions of other gases (Amran et al., 2017). Pre-treatment is necessary to remove sulphur then followed by steam reforming in the main reactor typically using nickel-based catalyst (Taji et al., 2018). SMR requires temperatures of 700-900°C and a catalyst (Carapellucci and Giordano, 2020). After steam reforming the syngas is cooled before the carbon monoxide and H_2O fractions are converted in the water-gas shift (WGS) reaction to increase the hydrogen and carbon dioxide (Carapellucci and Giordano, 2020). The WGS reaction converts carbon monoxide further to increase the volume of hydrogen. Eq. 8 displays the reaction for the methane reforming and Eq. 9 shows the reaction for the WGS reaction.

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad (8)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (9)$$

The WGS reaction is typically comprised of two temperature steps, the high temperature shift (HTS) reactor at 300-450°C and low temperature shift (LTS) reactors at 200-250°C. HTS and LTS are included as separate steps as they use different catalysts and due to the differences in temperature have different energy requirements. The thermal efficiency of steam reforming is between 70 and 85% (Bičáková and Straka, 2012). The hydrogen in the product gas is then separated from the carbon dioxide and remaining gases in a process such as PSA to deliver hydrogen at a high purity of 99.99% (Nikolaidis and Poullikkas, 2017).

A novelty of the study is to show the potential reduction in environmental impact through carbon emissions of WtH technologies compared to the most used hydrogen production method. SMR has high operational temperatures and medium to high energy requirements with a large impact on the environmental and is therefore important to consider further (Carapellucci and Giordano, 2020). Therefore it is discussed in this study as the conventional hydrogen production method to show the benefits or drawbacks on environmental impact or economic effect from using WtH.

2.5. Biochemical WtH production methods

Biochemical conversion of waste involves the use of microorganisms such as bacteria and algae through fermentation (dark or photo), photolysis or microbial electrolysis cells to decompose carbohydrate rich waste and wastewater to produce biohydrogen along with organic acids and alcohols (Tian et al., 2019). Other processes that utilise waste or organic matter with the action of microorganisms to produce a biogas, such as anaerobic digestion, produce a majority methane and carbon dioxide with hydrogen only at trace amount (Rasheed et al., 2021). AD is therefore not discussed further in this study.

Biochemical processes generally have lower energy requirements than thermochemical processes as they occur at ambient temperatures and pressures. However, biochemical processes have low hydrogen yields (mol H_2/mol feedstock) and low reaction rates. A summary of the hydrogen yield data from various biochemical research is in Table 2-3.

In the fermentation process carbohydrate-rich and biodegradable biomass is broken down to form organic acids, alcohols, acetone and then CO_2 and hydrogen (Wang et al., 2018). The fermentation process is affected by temperature, hydraulic retention time for continuous processes, partial pressure of hydrogen, and types of microorganisms (Bičáková and Straka, 2012). A enzymatic pre-treatment is often used to breakdown the waste by using enzymes to hydrolyse the lignocellulose (Bu et al., 2021). The pre-treatment also suppresses non-hydrogen producing microorganisms through inhibiting methanogenesis which may interfere with the hydrogen producing microorganisms (Florio et al., 2018). The pre-treatment stage therefore improves the efficiency of fermentation and gas yield. The raw gas product from fermentation contains mainly hydrogen and carbon dioxide (Tian et al., 2019). The hydrogen yield of fermentation depends on specific inoculants, cultures, substrates, and trace elements. The hydrogen is separated from the other component sin biogas using techniques such as PSA.

2.5.1. Dark fermentation

Dark fermentation is a well-established biochemical technology and can be utilised for wet waste considered with a high moisture content, above 40% moisture, which is less suitable for thermochemical technology (Liu et al., 2019). Dark fermentation has the capability to treat a variety of feedstocks such as food waste, paper waste, waste activated sludge whilst having low energy requirements (Pu et al., 2019; D. Wang et al., 2019). An illustration of the dark fermentation process in Fig. 2-5.

Dark fermentation is able to integrate with other processes such as methane production processes (Eker and Sarp, 2017). Xia et al., (2014) also suggested combining different waste types in fermentation to improve the hydrogen yield and lead to higher efficiencies. Recent advances in bioreactor design and optimizations for operational conditions have increased hydrogen production rates and yield (Ghimire et al., 2015). The general reaction of dark fermentation using organic waste as the feed is displayed in Eq. 10, modified from Bičáková and Straka (2012). The products are carbon dioxide, hydrogen, and acetates such as acetic acid.

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2 \tag{10}$$

Bioreactor design for dark fermentation are typically arranged in an array of cyclonical bioreactors allowing the culture to move through the fermenters (Sathyaprakasan and Kannan, 2015). Removal of the hydrogen produced during fermentation is important for continual production (Łukajtis et al., 2018). This also prevents significant pressure increase which would negatively affects the rate of hydrogen production because the partial pressure of hydrogen is negatively proportional to hydrogen synthesis and other products (lactic acid and ethanol) will increase in concentration (Nikolaidis and Poullikkas, 2017).

The operating conditions of dark fermentation are catered toward the metabolism of the specific microorganisms used as they are affected by temperature, partial pressure of hydrogen, pure or mixed bacterial cultures, method of preparation, and composition of medium. Low temperatures of between 25°C and <80°C and an ideal pH 5 – 6 is used

(Litti et al., 2021). Unfavourable system conditions affect the hydrogen production by inhibiting the microorganisms and the use of substances or buffers is required to keep the system in equilibrium. Higher substrate concentrations tend to lead to lower hydrogen yields, because of the thermodynamic limitations imposed by microbial fermentation (Kumar et al., 2018). Other influential factors of hydrogen yield include mode and reaction conditions such as microorganism type.

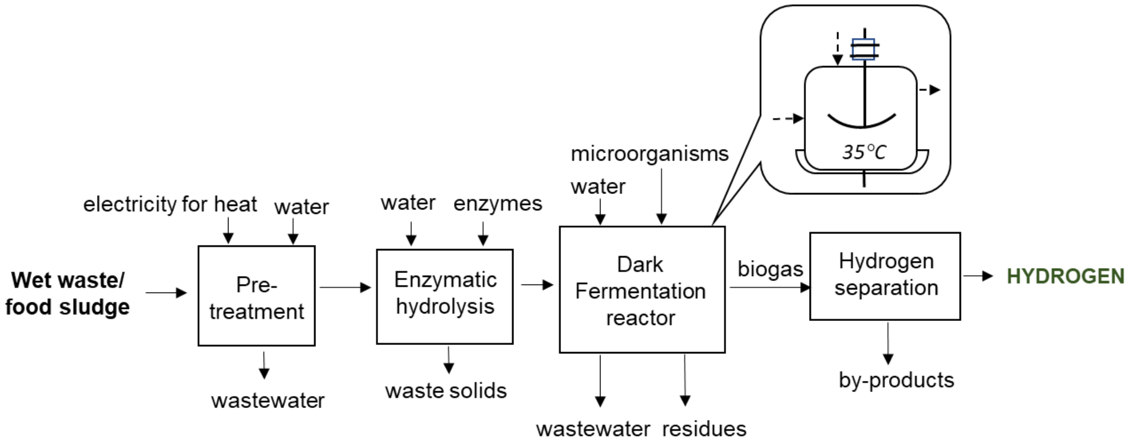

Fig. 2-5 Dark fermentation process diagram based on the process diagram in Lui et al., (2020)

For fermentation processes, an averaged hydrogen concentration of 34 vol.% is expected from the biogas generated, based on reported hydrogen concentrations of 10-60 vol. % for food waste dark fermentation by Nguyen et al., (2021), and 32 vol.% for sewage sludge fermentation Lin and Cheng (2006).

2.5.2. Photo fermentation

Photo fermentation uses light as an energy source for photosynthetic bacteria to synthesise hydrogen in anaerobic conditions at an optimum temperature of 30-35°C with pH 7 (Bičáková and Straka, 2012). The hydrogen yield increases as temperature increases when the pH of 4.5-6.5 remains stable for fermentation (Nikolaidis and Poullikkas, 2017). Production rate and yield are also affected by low light conversion efficiency, microbial strain and carbon source. Photo heterotrophic bacteria such as purple non sulphur bacteria are ideal as they are able to utilise a range of light and have a high biohydrogen yield (Ghimire et al., 2015). Rai and Singh, (2016) also discuss the use of purple non sulphur bacteria which light intensity in the range of approx. 3000-15000 lux or lumens/m^2 and led to a high substrate conversion efficiency for organic-rich wastewaters and waste. Wu et al., (2012) suggest the use of wastewater as feedstock would require pre-processing because of the colour limiting light penetration, possible contaminants and toxic compounds found in wastewater. The general reaction of photo fermentation using organic waste as the feed is displayed in Eq. 11, modified from Bičáková and Straka (2012). The photo fermentation microorganisms utilise simple organic acids to produce carbon dioxide and hydrogen.

$$\text{Photo fermentation: } CH_3COOH + 2H_2O \rightarrow 4H_2 + 2CO_2 \quad (11)$$

Combining dark fermentation with photo fermentation have been proposed to increase the potential for higher overall hydrogen yield and reduce light requirements from photo only fermentation (Fig. 2-6). However, the combined process increases the energy use of the system because of the wide spectral light requirements and extra supply of phototrophic microorganisms. Rai and Singh (2016) conducted sequential dark/photo-fermentation with anaerobic bacteria positioned in dark conditions to produce hydrogen and organic acids, which became sources for photosynthetic bacteria to produce extra hydrogen. However Pandey et al., (2021) shows that as the fermentation process reduces waste residues the environmental impact is also reduced. It is therefore considered as a beneficial WtH process to be included in the study for the purpose of comparison.

Lin et al. (2012) studied the increase of bioenergy production efficiency from two-stage fermentation processing of wastewater and indicated that combined dark and photo fermentation had a theoretical hydrogen yield of 12 mol per mole glucose. Wang et al., (2018) found that adding biochar could improve the maximum hydrogen production rate and shortened fermentation lag time. Their analysis suggested the biochar had a strong pH buffering capacity and stabilising effect during hydrogen production. While Sharma and Melkania (2017) found adding biochar to anaerobic fermentation of organic MSW using a co-culture, shortened the lag time by 4.4 ±0.5 hr and increased the hydrogen production. Sun et al. (2019) added biochar and metal co-factor nanoparticle Ni^0 to dark fermentation and observed an increase in hydrogen yield. Partly due to increasing the pH buffer stability as partly because of an enhanced electron/photon transfer plus the facilitation of biofilm formation during initial fermentation.

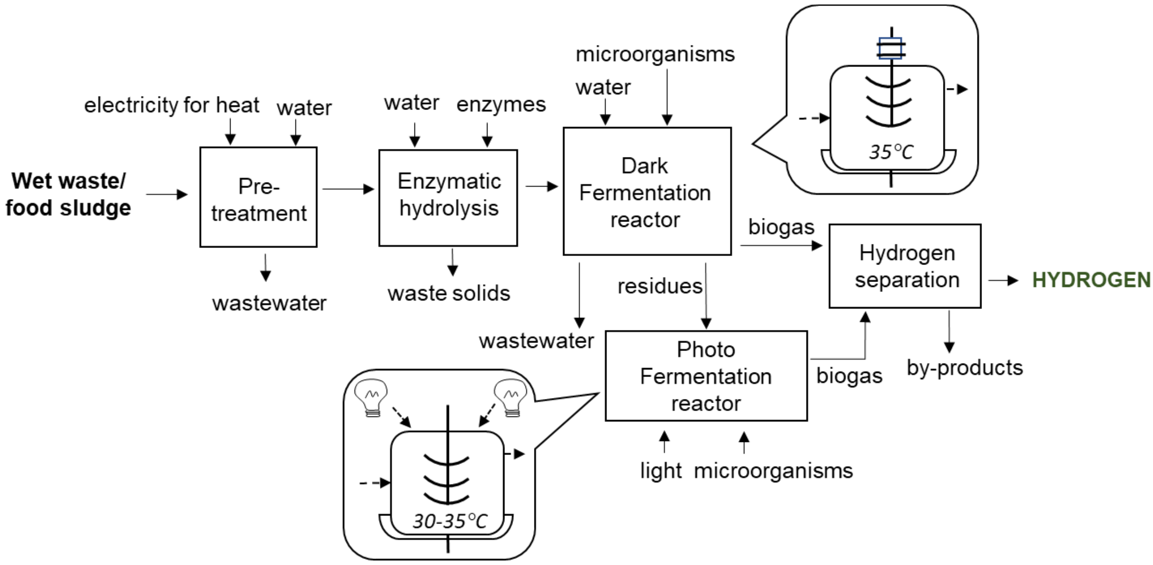

Fig. 2-6. Dark and photo fermentation process diagram based on the process diagram in Lui et al., (2020)

Comparison of biochemical WtH hydrogen production methods are displayed in Table 2-3. The results are represented by hydrogen yield, with VSS representing volatile suspended solids, VS representing volatile solids, and FW representing food waste.

Table 2-3. Summary of hydrogen production of biochemical methods using waste or waste derived sources.

Author	Main Reaction	Feedstock / Substrate	Bacteria/ Inoculum	Hydrogen yield
Eker and Sarp (2017)	Anaerobic dark fermentation	Glucose from acid hydrolyzed wastepaper	-	140 ml H_2 /g total sugar at 3.84g/l total sugar conc
Liu et al. (2013)(2013)	Two stage mesophilic fermentation	Activated sludge and food waste	Hydrogen producing bacteria	1.4 kJ/g-VS at food waste of 100%
Cheng et al. (2015)	Combined dark- and photo-fermentation	Alanine and Serine amino acids from waste biomass	Clostridium butyricum and Rhodopseudo-monas palustris	418.6 and 270.2 mL/g
Wang et al. (2018)	Effect of biochar on fermentation	Dewatered activated sludge and food waste	H_2 production bacteria	47.2-83.6 mL/day
Wang et al. (2019)	Adding calcium peroxide (CaO_2	Waste activated sludge	Hydrolytic microbes	10.55mL/g VSS

	accelerates breakage and death of sludge cells and biodegradability) increases max H_2 yield			
Pu et al. (2019)	Varying substrate concentrations on H_2 production during fermentation	Heat treated and fresh food waste	Untreated inoculums	75.3mL/g-VS at 15 g-VS/L heat treated FW
Sharma and Melkania (2017)	Anaerobic fermentation-add biochar to improve hydrogen production	Organic MSW	Enterobacter aerogenes and E. coli	96.63 ±2.8 mlH^2/g Carbon $_{initial}$

2.5.3. Microbial fuel cells

Microbial electrolysis cells (MECs), also called bioelectrochemically assisted microbial reactors (BEAMR), are a technology that can convert waste organic material into hydrogen (Ziara et al., 2018). MECs are a type of Microbial fuel cells (MFCs) which generate energy by using electrogenic microorganisms with a variety different substrates including waste and sludge (Rasheed et al., 2021).

MECs produce an electric current (electrochemical hydrogenation) from the microbial decomposition of organic and degradable material in an anaerobic environment into hydrogen (Bičáková and Straka, 2012). Whereas the cathode in an MFC is exposed to air (Rasheed et al., 2021). MECs partially reverse the MFC process by applying an additional voltage to the cell due to the redox potential of the anodic and cathodic reactions not being high enough for to produce hydrogen. Methane, acetate, and ethanol can also be produced depending on the microorganisms at the cathode. They have a low total energy efficiency of approximately 78%.

In a MEC the exoelectrogenic bacteria, attached to the anode, consume waste and discharge electrons to the anode with electrons and protons are produced on the anode, the electrons pass though the circuit to the electrode and protons through the electrolyte through proton membrane to the cathode (Ziara et al., 2018). The anode can be carbon based (paper or cloth) and graphite (felt or granules). Electrotrophs in the cathode receive and transfer electrons to the cathode via an external circuit and generate methane (Mallick et al., 2022). Electrons, protons and carbon dioxide are created in the MFC and by combining the voltage, in the MEC the protons are reduced, and hydrogen is produced.

Catalysts such as platinum or stainless steel can be used to reduce the overpotential or voltage required. The type of electrogenic microorganism and substrate used influences the products and efficiency of the MEC (Mallick et al., 2022). More research and advancements are required for MEC reactor design for use with organic materials due to the complex and heterogeneous nature of waste.

2.6. Hydrogen production methods from other technologies

Hydrogen production methods utilising renewable sources though not related to waste are included for comparison purposes. SMR is the conventional method for hydrogen production whilst water electrolysis is arguably the greenest production method and is gaining interest due to requiring only water and electricity.

2.6.1. Water splitting technologies for hydrogen production

Water splitting technologies include electrolysis, photoelectrolysis and thermolysis and whilst they do not involve the conversion of solid feedstocks such as waste, they will be a major future competitor to WtH when considering green or low carbon hydrogen production.

Thermolysis is the thermochemical cracking of water which relies on heat or electrical energy to decompose water into hydrogen and oxygen (Nikolaidis and Poullikkas, 2017). High temperatures, over 2500°C are required and whilst chemical reagents can be added to reduce the temperature requirements, a higher pressure is the trade-off as is the increased corrosion (Bičáková and Straka, 2012). Therefore, the process has a high cost and a need for further technological advancements before becoming competitive.

Electrolysis of water is the cracking of the chemical bond of water into hydrogen and oxygen which occurs when a direct current passes through two electrodes in a water solution (Bičáková and Straka, 2012). It is energy intensive with high electricity demand. When the electricity is provided by renewable sources such as solar power or wind turbines water electrolysis is truly zero carbon and provides green hydrogen. It is therefore the focus of many hydrogen strategies however according to Ju et al., (2018) they will not be truly competitive with fossil fuel reforming methods until there are changes in subsides, carbon credits and further development of technology.

Carbon assisted water electrolysis is a low carbon potential technology, a combination of electrochemical oxidation and water electrolysis, for hydrogen production. Ju et al., (2018) suggest a process with water or steam electrolysis using energy supplied by chemical energy, traditionally from coal, to reduce the electrical energy requirements. Other carbon sources are feasible instead of coal such as biomass, alcohols or potentially waste. The carbon dioxide would be sequestered so separation technology would not be needed.

Water splitting technologies are not included for further study as SMR is preferred to provide a better compassion technology for WtH technologies. SMR and WtH technologies both require a fuel source, with similar processes of pretreatment, conversion and hydrogen separation from product gas.

2.7. Hydrogen separation technologies of pressure swing adsorption and membranes

The hydrogen component of syngas or biogas is separated through conventional techniques such as pressure swing adsorption (PSA) and membrane separation. In thermochemical technologies after the conversion process the syngas requires cleaning, reforming and gas shift reaction processes before the hydrogen can be separated from the remaining gases. Similar processes apply to biochemical technologies for separating the hydrogen fraction from the other gases that make up biogas.

PSA uses an adsorbent bed at high pressure to capture impurities in the syngas, then releases the gases at low pressures (Nikolaidis and Poullikkas, 2017). The PSA method requires a minimum of 70 mol% hydrogen in the input gas stream (Koroneos et al., 2008). The efficiency of PSA for separating hydrogen from syngas or biogas generally at 99% and can be as high as 99.99% (Iribarren et al., 2014). PSA systems can differ according to adsorption size, velocity, regeneration and adsorbent material (Salam et al., 2018). The PSA unit operates at 85% efficiency at 40°C and 22 bar (Susmozas et al., 2013).

Membrane technologies can also be used to separate out and adjust the gas composition in syngas (Rauch et al., 2015). Membranes operate by allowing molecules of hydrogen through a surface whilst larger molecules such as carbon, oxygen and nitrogen remain unseparated. This process relies on partial pressure of hydrogen feed streams to force permeation and as the gases move through it balances with the product stream.

Zeolitic frameworks, porous materials with metal nodes linked by imidazole ligands, can be used to isolate selected gases in syngas (Yin et al., 2016). This can lead to increases in the H_2/CO ration and H_2/CO_2 ratio. Disadvantages of zeolitic framework arise from the thermal stability of at high temperatures (above 230°C) which is poor. Though Yang and Chung, (2013) have shown demonstrated a method of improving the thermal and separation stability and H_2/CO_2 selectivity using a zeolitic imidazolate frameworks-8 nano polymer as the composite material. Another method to improve the separation success is to use a sweep gas, such as nitrogen, which can be used on the other side of the membrane. This lowers the partial pressure and encourages more hydrogen to pass through the membrane (Nikolaidis and Poullikkas, 2017).

Membrane separation materials can be expensive and prone to contamination from trace metals, sulphur and ammonia depending on the feedstock even after cleaning-up processing (Salam et al., 2018). Other separation methods include cryogenic processes which require extremely low temperatures and temperature swing adsorption and electrical swing adsorption. However, these methods are currently not commercially viable and are either experimental or expensive to run (EERC, 2010).

After the hydrogen separation stage, it is compressed to 200 bar from an original post gasification pressure of 20 bar in a booster compressor unit (Lozanovski et al., 2018). The compressed hydrogen is stored in tanks onsite before being transferred to the hydrogen refuelling station (HRS). Hydrogen compression is required due to the low volumetric energy density of 0.01079 MJ/L at standard pressure and temperature. The theoretical energy to compress hydrogen isothermally from 20 bar to 350 bar is 1.05 kWh/kg H_2. Depending on the type of compressor used 2–4 kWh/kg H_2 are the generally accepted values to compress hydrogen to 350 bar (Platzer and Sarigul-Klijn, 2021).

2.8. Hydrogen as a fuel for transport applications

The applications for hydrogen for transport and the energy industry have been widely discussed by many governments and the energy industry as having a major role in the low carbon future. Development of WtH technology is occurring in conjunction with the rise in popularity of hydrogen as a fuel. Reducing reliance on fossil fuels to increase the long-term sustainability of energy production systems due to finite fossil fuel reserves with fluctuations in cost (Susmozas et al., 2013). Innovative applications with designs for alternative energy sources are occuring with hydrogen power amongst them. Alternative hydrogen pathways are needed to facilitate the move towards hydrogen powered transport and other energy-based sectors. The hydrogen economy is the international partnership for hydrogen and fuel cells in the economy interested in promoting and encouraging use and research for companies, industries and governments into viewing hydrogen as a future global fuel.

The hydrogen distribution network is relatively immature and underdeveloped for widespread applications. The main delivery methods for hydrogen include road for gas and liquid forms of hydrogen and railway with storage using containers and vessels (Zheng et al., 2012). However, these methods face limitations of volume and space (low density of gas) and contribute to high costs which effect the development of hydrogen as a fuel on a large scale (Abdalla et al., 2018). Adapting natural gas pipelines to hydrogen pipelines could enable additional delivery methods and therefore reach more locations and areas (Nikolaidis and Poullikkas, 2017). However, pipeline use is limited by the lack of availability, loses, inconsistent networks and capacity, requiring extra development as well as maintenance (Reiter and Lindorfer, 2015).

The characteristics of hydrogen cause it to be good as a storage medium with many advantages for transport and fuel cell (Ju et al., 2018). Hydrogen storage options consist mainly of gas compression (at 35-70 MPa and 27°C, ambient temperature) requiring 5-20% LHV energy requirement (Zheng et al., 2012). Other choices are liquid hydrogen storage, and solid-state storage. Liquid storage requires cryogenic tanks involve compression and cooling (Nikolaidis and Poullikkas, 2017). Solid state hydrogen storage involves the physical storage of molecular or di-hydrogen in nano-porous materials for example activated carbons (Dissanayake et al., 2020). According to Abe et al., (2019) solid state storage based on metal hydrides have potential as they are compact, secure, repeatedly reversible and capable for holding large quantities of hydrogen.

Other storage possibilities that are being researched are chemical storage options including complex hydrides such as magnesium borohydride $Mg(Bh_4)_2$ and sodium borohydride which was found by Santos and Sequeira, (2011), to exhibit the highest gravimetric densities for hydrogen storage of 1.074 specific gravity. Storage within fuel cells is also possible for fuel cells containing borohydride (Santos and Sequiera, 2011). Research challenges for chemical storage involves capacity improvements, the kinetics of uptake and release of hydrogen, as the kinetics for bulk materials often require high temperatures of approximately ~127°C (Stockford et al., 2015). Current hydrogen storage alloys have a low capacity typically less than 2% mass of hydrogen (Lai et al., 2019).

The development of hydrogen technology is in part driven by the demand for end use applications such as fuel cells electricity generation or for vehicles. The number of electric vehicle sales reached over 1.2 million in 2018 (IEA, 2019) showing the interest in alternatives to petrol and diesel vehicles is present. Hydrogen fuel cell vehicles have the potential to provide another option other than fossil fuels and an alternative to battery electric vehicles as they provide onboard electricity generation and the benefit of refilling at hydrogen refuelling stations (HRS) which are similar in design to petrol stations. Battery electric cars suffer from short to limited driving range, relatively long recharging time (hours), limited recycling options for used batteries, enhancement in green credentials (Łukajtis et al., 2018). Electrification is also inadequate for heavy goods vehicles (HGV) due to the current status of battery technology and the charging time would limit the continuous use of such vehicles negatively effecting the economics (Materazzi et al., 2019). Further advantages of hydrogen vehicles are discussed in Chapter 2.8.1.

2.8.1. Fuel cell electric vehicles

Hydrogen is a zero-emission fuel when used is fuel cell electric vehicles (FCEV) producing only water and oxygen without direct CO_2 or NOx emissions or particulate matter (Navas-Anguita et al., 2020).

Fuel cells are electrochemical devices that convert the chemical energy of gas such as hydrogen or solids such as coal into electrical energy through an electrochemical process (Hua et al., 2014). A fuel cell consists of an anode, where hydrogen splits into ions (H^+) and negatively charged electrons (e^-). The ions pass through the electrolyte and the electrons are forced around the outer circuit towards the cathode forming an electric current (Bala et al., 2019). The ions combine with oxygen from air forming water as green by-product with no other emissions. For fuel cells to operate efficiently in vehicles a high purity hydrogen above 99% is required.

Types vary according to different parameters such as hydrogen production rate, power density, energy consumption system leading to generated power output (Chisholm and

Cronin, Leroy, 2016). The main types of fuel cells are Proton Exchange Membrane Fuel Cell (PEMFC), alkaline, Solid oxide fuel cell (SOFC). They differ according to power densities, hydrogen production rates, and specific energy consumption (kWh). Fuels cells can be compact in size and therefore portable. This makes them ideal for vehicles and stationary power generation units (Bala et al., 2019). They operate at lower temperatures of between 80-100°C and at lower pressures, while having high-power density light in weight and with low maintenance requirements (Kwan et al., 2018). However, PEMFC require pure hydrogen and use electrodes made of precious metals (Chutichai et al., 2013). This has implications for the source and variation of potential feedstocks and impurities present within the hydrogen produced from waste. PEMFC are at a mature stage of development for commercial use (Tanç et al., 2019). They are the most commonly used fuel cell in buses (Burheim, 2017).

Fuel cells in buses have been implemented to support green transport policies within cities. Fuel cells have the potential for use in public transport particularly in urban and high population areas due to producing zero emissions when in operation (Fuel Cell and Hydrogen Joint Undertaking, 2017). They could be part of the solution to tackle air population within city centres associated with diesel buses. FCEBs also have the capability to achieve a travel distance of up to 500km, complete refuelling in a short time in the region of 3 minutes (Edwards et al., 2021). Fuels cell electric buses (FCEB) have been successfully demonstrated in cities through Europe such as Aberdeen in Scotland, Wuppertal in Germany, Slagelse in Denmark have been (Eurotransport, 2017). Comparisons of diesel buses with hydrogen FCEV have shown a reduction of 85% in CO_2 emissions over a buses life cycle (Eurotransport, 2017).

Further work on fuel cell technology and processes are beyond the scope of this study and will not be included beyond reference to the relevance in the chapter on recommendations and conclusions.

2.9. Hydrogen refuelling stations

The HRS provides the connection from hydrogen storage container to FCEV or FCEB and contains equipment for further compression, temporary storage, and dispensing the hydrogen to a vehicle. The extra compression step is required due to the low volumetric energy density of hydrogen at 0.0898 kg/m^3. Further compression also reduces storage space within the facility or plant. Refuelling a vehicle relies on pressure differential between the storage container and the onboard vehicle tank. Therefore, hydrogen is further compressed to 800 bar which allows for positive displacement through the dispenser to the vehicle onboard storage usually set at 700 bar onboard storage for passenger cars. For FCEBs hydrogen is compressed to 440 bar for 350 bar onboard storage (Fuel Cell and Hydrogen Joint Undertaking, 2017). Compression produces the highest carbon dioxide emissions from the HRS due to the electricity requirements to reach the required pressures (Wulf and Kaltschmitt, 2012). Using renewable sources of electricity could go some way to decreasing the carbon footprint of the HRS.

High pressure gaseous hydrogen (HPGH2) storage is the widely used method for refuelling station due to the technical simplicity and fast filling-releasing rate (Zheng et al., 2012). Refuelling station specifications vary according to the type and model of the FCEV, due to varying pressure, temperature requirements and filling rate.

2.10. Environmental and economic impact review of WtH

The WtH and conventional technologies have been compared in literature using LCA and CBA analyses to highlight the advantages or disadvantages to the environmental and economics. They emphasise which technologies provide the greatest cost savings or highest reduction in carbon dioxide emissions. Multi-objective optimisation studies have been conducted to optimise thermochemical or biochemical systems with a range of variables, usually concerned with minimising cost. WtH has the potential to save carbon from both waste management and hydrogen production processes when compared with traditional methods of landfill and incineration and SMR. Conventional SMR from natural gas and coal gasification are the most cost-effective forms of syngas production (Nikolaidis and Poullikkas, 2017). However, commercial hydrogen plants produce the highest emissions at a range of 9-11 kg CO_2 per kg H_2 in typical natural gas plants (Salkuyeh et al., 2018).

Materazzi et al., (2019) discusses the potential of biohydrogen from waste gasification by designing a commercial plant. The main challenges identified are associated with the MSW feedstock and the high treatment costs associated. However they found savings of 243 kgCO_2-eq could be achieved compared to a natural gas plant.

When considering the current research for this study the aspects of the environmental impact and economics viability, on both waste management with certain feedstocks and hydrogen production. There is limited available research on the whole process of waste conversion technologies producing hydrogen as the main product.

The environmental impact of organic feedstock for energy conversion is evaluated using global warming potential (GWP) which are usually supplied as results from LCA studies. GWP measures how much a greenhouse gas is estimated to contribute to global warming. It is a relative scale which compares the strength of each gas to CO_2. A positive GWP value suggests an environmental impact whilst a negative value shows environmental avoidance and therefore a benefit through a removal of CO_2-eq (Kourkoumpas et al., 2015). Pandey et al., (2019) stated that biomass feedstock for hydrogen production has the potential to reduce CO_2 emissions compared to using SMR. A study by Valente et al., (2019) supported this idea with research on eco-efficiency finding hydrogen from biomass gasification was 5-38 times higher than SMR produced hydrogen when using GWP as an indicator. Fujii et al., (2019) conducted an LCA proposing the use of waste in energy production methods including upgrading of EfW to increase CO_2 emission reduction from 0.28kg-CO_2/kg of waste to 0.67 kg-CO_2/kg of waste as well as improving the exergy efficiency.

The study by Hajjaji et al., (2016) showed that hydrogen production from biogas reforming of 5.59 kg CO_2-eq per kg of hydrogen, is approximately half the GHG emissions compared to SMR of 13.7 kg CO_2-eq per kg of hydrogen. The study includes biogas production from anaerobic digestion using of a range of organic wastes to produce synthesis gas from which the hydrogen is separated.

Comparing the conversion technologies available with different feedstocks and the GWP they emit provides an insight into the environmental impact of current technologies and where WtH could fit in. Valente et al., (2019b) found biomass gasification had a GWP of 0.18 kg CO_2-eq, which is in the order of 65 times less than SMR which has a GWP of 11.43 kg CO_2-eq based on a functional unit of 1kg H_2 (at 200 bar and 25°C). These results supported the suitability of biomass gasification for hydrogen production. For the treatment of waste Panepinto et al., (2015) compared gasification and pyrolysis with incineration for MSW. They found gasification to be a competitive when syngas production is the aim with results measured in energetic valorisation (fuel utilisation, thermal energy generation) and flexibility of design. A study by Sun et al., (2021) found using MSW in gasification to produce hydrogen had the low GWP of 897.3 kg CO_2-eq/hr when compared to 1245.9 kg CO_2-eq/hr for MSW conversion to synthetic natural gas. Valente et al., (2018) discussed the eco-efficiency of hydrogen from biomass gasification (not waste). WtH as a decentralised approach could led to further reductions in cost and reduce transport related emissions.

Existing economic analyses cover a wide range of conversion technologies and feedstocks including MSW and biomass and were based on a variety of locations. Determining the total costs associated with a technology and the available waste in each location plays a role in the economic feasibility and the development of WtH. The techno-economic study by Salkuyeh et al. (2018) focussed on comparing two types of gasification process; fluidised bed and entrained flow for hydrogen production from biomass. The resulting economic assessment determined a minimum hydrogen selling price for fluidised bed to be less than entrained flow by between £0.05 and £0.25 per kg/H_2 (0.07 and 0.33USD) (price conversion using an average rate for 2018 of 0.7501 GBP= 1 USD). Sathyaprakasan and Kannan (2015) studied hydrogen production in the UAE and compared the cost of different biochemical methods using algae as the substrate. The results show the cost for hydrogen production from dark fermentation is £12.07 (68.7 AED) per kg/H_2 while photo fermentation costs are £2.42 (13.6 AED) per kg/H_2 (price conversion using an average rate for 2015 of 0.1783 GBP = 1AED).

The success of hydrogen-power transport projects is largely influenced by the economic feasibility, and for new concepts such as WtH it is important to demonstrate profitability with reliable technology to obtain investment. This is especially important when compared with conventional energy production methods. Studies comparing biomass or waste gasification with conventional hydrogen production methods provide an understanding on the current costs of the main competition for WtH technologies. Levelized cost is the preferred method for energy systems for comparison purposes. Salkuyeh et al. (2018) showed that for hydrogen production from biomass gasification to be competitive with SMR with a minimum biomass price of £75 per tonne ($100 per tonne), £86 CO_2-eq ($115 tonne CO_2-eq)., or minimum natural gas price of £3.75/GJ ($5/GJ) is needed (price conversion using an average rate for 2018 of 0.7501 GBP= 1 USD). Valente et al., (2019b) performed a cost assessment comparing SMR against biomass gasification and used the levelized cost metric of hydrogen and found biomass gasification had a cost of £3.15 (3.59€) compared to £1.90 (2.17€) for SMR (price conversion using an average rate for

2019 of 0.8771 GBP= 1 Euro). This covers the economic lifetime of the plant and the amount of energy produced from the plant.

SMR is the most cost-effective method due to the high conversion efficiency of 74-85% and mature technology (Nikolaidis and Poullikkas, 2017). However fossil fuel price fluctuations can lead to some reliability issues and uncertainty in supply. Comparing low carbon and conventional fossil fuel technology can be challenging due to the different stages of development with variations in investment and support. Future fuel options are likely to consider carbon emission targets and environmental sustainability into account.

The economic evaluation from Yao et al. (2017) discussed how optimising the operational condition of equivalence ratio (ER) for maximising the economic benefits of gasification. Their study demonstrated that as ER increased from 0.1 to 0.6, the HHV decreased from 6.15 to 3.60 MJ/Nm^3. Their model predicted a maximum economic benefit at £0.08 /kg ($0.11/kg at 2017 USD to GBP average conversion rate of 0.7765) biomass feedstock and an optimum ER of 0.25.

Wang et al.(2019) compared biomass gasification with coal gasification and calculated production costs of 0.75 CNY/Nm^3 H_2 for coal which were higher than 0.62 CNY/Nm^3 H_2 for biomass. Fernández-González et al., (2017) studied medium to low volumes of MSW for energy generation in Spain and compared the revenues for incineration ang gasification found £28.61/t (32.64 EURO/t) and £22.51 (25.68 EURO/t) respectively (price conversion using an average rate for 2017 of 0.8766 GBP= 1Euro). Han et al., (2016) conducted a techno-economic evaluation on fermentative hydrogen production on food waste found the process was feasible with a return on investment of 26.75%. Sun et al. (2021) compared the economics of different MSW conversion routes including MSW to hydrogen using data from China. They found hydrogen from SMR has a minimum hydrogen selling price of £0.83 per kg/H_2 (7.4 CNY per kg/H_2) compared to MSW at £1.58 per kg/H_2 (14 CNY per kg/H_2) (price conversion using an average rate for 2021 of 8.77 CNY = 1GBP). Coal to hydrogen and biomass to hydrogen have the highest value at £2.58/kg H_2 and £2.31/kg H_2, respectively (22.9 and 20.5 CNY/kg H_2) respectively. Therefore, it is important to analyse the economics of WtH development on a case-by-case basis in terms of the specific economic factors for each project.

2.11. Optimisation of economic and environmental aspects

Multi-objective optimisation studies involving the cost and environmental impact of WtH technologies are few. Studies such as Arora et al., (2017) who used multi-objective optimisation to minimize the effects of the biomass to ammonia process on cost and GWP in three countries provide an indication of the implication of optimisation. They found diversifying the production of the conversion technology in this case using syngas from gasification for electricity production. You et al., (2012) studied cellulosic biofuel supply chains with economic and environmental criteria for optimisation in the United States. They found when total annualised cost reduced by 600 million USD, the GHG emissions increased by 700k ton. Buddadee et al., (2008) used multi-objective optimisation for minimising the GWP of excess bagasse from the Thailand sugar cane industry for either onsite electricity production or offsite ethanol production. They found the GWP became negative with the production of ethanol by 106.19% compared to the typical situation as the ethanol replaces gasoline fuel used in vehicles reducing GHG emissions.

The key findings from this literature review highlight the potential for thermochemical (gasification and pyrolysis) and biochemical technologies (fermentation) to use carbon-based waste as the feedstock to produce hydrogen at a scale to support the introduction of FCEBs. The literature suggests that while thermochemical technologies are high cost relative to the conventional hydrogen production methods such as SMR there is merit in investigating the carbon emissions related to a WtH plant based in a city like Glasgow. Biochemical technologies for WtH also have challenges which include low hydrogen yields and production rates, however the benefits of providing alternative waste management strategy and hydrogen production method suggest further investigation is worth the inclusion in this work. By showing the environmental impact, potential carbon savings and economics of WtH, this work would add to the weight to support the progression of alternative energy conversion technologies.

The research studies considered for this work support the hydrogen and transport Scottish and UK policies making pathways available to low carbon technologies like WtH. The expected expansion of the hydrogen economy is presented in literature as reasonable justification for extended research into technologies such as WtH and finding ways to fully utilise all resources especially when conversion can lead to a product such as hydrogen which is seen as a clean, low carbon fuel of the future. The literature predicts the demand for hydrogen to increase due to global zero emission targets and the decarbonisation efforts with policies such as Paris climate agreement (2015), Climate Change Act (2008) and COP 26 targets.

The research into thermochemical and biochemical technologies for waste for hydrogen production is limited when compared to energy generation for electricity. Therefore, the few studies that do exist on using biomass provide important cost and performance data.

Chapter 3 Critical process data and methodology for calculating waste available for WtH and hydrogen production in Glasgow

To assess the environmental and economic feasibility of WtH technologies in Glasgow the methods of LCA and CBA and multi-objective optimisation were utilised. The methodology, results, discussion, and conclusion of each analysis are detailed in the following chapters. This chapter introduces the input data types, parameters and methodologies used in the LCA, CBA and multi-objective optimisation.

3.1. Introduction

Three WtH technologies of gasification, dark-fermentation, and dark and photo fermentation plus the hydrogen production technology SMR are considered in this study. To assess the feasibility of WtH in Glasgow five scenario were designed with different technology and feedstock choices used. Gasification as a fuel conversion thermochemical technology is popular due to the easier handling of gas over solids in terms of storage space required. It also produces a high fraction of hydrogen in the product gas and fewer solid by-products and has higher conversion efficiencies when compared to the other thermochemical conversion processes of pyrolysis, combustion and liquefaction (Yao et al., 2018). Dark and photo fermentation is the chosen biochemical technology for this study as it is assumed to be more appropriate for waste with higher moisture contents (above 20%) and to represent technologies with lower energy requirements. Fermentation also favours hydrogen in the product gas rather than methane such as in anaerobic digestion.

3.2. Glasgow, Scotland

Glasgow is the largest city in Scotland with a population of 613,130 in 2020 and provides the location for the study. Glasgow is 176 km sq. in size and the city produced 2.41 million tonnes of household waste in 2018 (National Statistics Publication for Scotland, 2019). Traditionally the carbon-based waste is sent to landfill or incineration facilities within Glasgow city as is done in the rest of Scotland. For this study the carbon-based waste is divided into three groups: MSW, waste wood and wet waste, and are the feedstocks for WtH generation. Recycled material, metals, glass, compostable waste and waste inappropriate for conversion are excluded from the study. The MSW or household waste portion is considered for gasification whilst high moisture content waste such as wet waste, sludge and food waste is intended for the fermentation processes.

The waste generation statistics for Scotland were obtained from data publicly available from SEPA (2018) and modified to estimate the quantity of waste generation in Glasgow. Inferred volumes of MSW waste were 21.12 tonnes/hr, waste wood at 5.56 tonnes/hr and wet waste ate 24.79 tonnes/hr. A detailed list of waste type and volume for Glasgow in 2018 is in Appendix B. The scale of the technology used is determined by the volume and composition of waste produced in Glasgow. The energy requirements and efficiencies were determined from technology specifications reported in published literature (Saleh et al., 2020; Wilson et al., 2013).

3.3. Data for WtH systems

The data used in this study have been provided by academic research, UK and Scottish government reports. Data have been adapted using scaling ratios according to feedstock volumes or hydrogen production volumes form that provided in the sources.

Five scenarios were designed to represent the available conversion technologies and waste feedstocks (Table 3-1). These are gasification with MSW (Scenario 1), gasification with waste wood (Scenario 2), dark fermentation with wet waste (Scenario 3), dark and photo fermentation with wet waste combined (Scenario 4) and SMR (Scenario 5). SMR and is the most widely used and well-known technologies for hydrogen production, the technology is therefore included for comparison of the thermochemical and biochemical technologies.

The infrastructure of a WtH system comprises of plant/reactor sites, storage facilities, delivery and transport options, refuelling stations, conversion and end-use applications The scenario design considers the individual processes and the general suitability of the technologies for treating the different wastes. For example, wet waste consisting of sludge and food waste has a relatively high moisture content and therefore is most suitable for treatment using the biochemical technologies from an energy efficiency perspective. Table 3-1 displays the Scenarios with the corresponding feedstock type and feed rate with waste data from Glasgow. The biochemical technologies included in this study are dark fermentation and photo fermentation, chosen for the low energy requirements and the emphasis on hydrogen production from organic waste rather than biomethane as in AD.

Table 3-1. Scenarios 1-5 with paired feedstock, conversion technology and feed rate (tonnes per hour) determined by waste availability in Glasgow.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Conversion Technology	Gasification	Gasification	Dark Fermentation	Dark and Photo Fermentation	SMR
Feedstock	MSW	Wood waste	Wet waste	Wet waste	Natural gas
Feed rate (t/hr)	21.12	5.56	24.79	24.79	5.56

The electricity requirements (kWh) for the Scenario systems are listed in Table 3-2. The values correspond to the requirements for each operational stage based on the feeding rate per hour from Table 3-1.

Table 3-2. Electricity requirements per hour of plant operation (kWh/hr) determined by the hydrogen produced which is further determined by the waste available in Glasgow for the conversion processes. Data for Scenarios 1 and 2 are listed under the gasification process, Scenarios 3 and 4 are listed under fermentation and Scenario 5 is in under SMR.

Gasification			Fermentation			SMR	
Process	Electricity consumption (kWh)		Process	Electricity consumption (kWh)		Process	Electricity consumptio n (kWh)
	S1	S2		S3	S4		S5
Drying	1,626	428	Enzymatic hydrolysis pre-treatment	4,95 8	4,958	Hydro-desulphurizatio n pre treatment	834
Shredding/ Grinding	2,323	450	-	-	-	-	-
FB gasification	4,625	1,351	Dark fermentation	1,02 9	1,028	Catalytic Steam Reforming	1,885
Gas solid cyclone	902	262	Photo fermentation	-	1,983	-	-
Syngas cooling	691	201	-	-	-	Syngas cooling	101
Syngas cleaning	1,271	370	-	-	-	-	-

Syngas sulphur removal	731	213	-	-	-	-	-
Water gas shift (HTS and LTS)	657	191	-	-	-	Water Gas Shift (HTS and LTS)	118
PSA-syngas to H_2 at 12%	4,921	1,151	PSA- syngas to H_2 at 15%	535	867	PSA- syngas to H_2 at 45%	1,062
Compression of H_2	2,260	795	Compression of H_2	930	748	Compression of H_2	1,829
Hydrogen gas storage (700 bar tanks)	3,949	1,379	Hydrogen gas storage (700 bar tanks)	462	1,301	Hydrogen gas storage (700 bar tanks)	3,180
HRS (compression, cooling, dispensing)	7,878	2,758	HRS (compression, cooling, dispensing)	1,859	2,603	HRS (compression, cooling, dispensing)	6,361
Total (kWh/hr)	31,834	9,550	Total kWh/hr	9,931	13,490	Total kWh/hr	15,370

3.4. Calculations of hydrogen production

The hydrogen production values with information on a theoretical plant containing the chosen WtH technologies (Scenarios 1-5) are listed in Table 3-3. The quantity of syngas produced after conversion is calculated by using the value of 2.4 kg of syngas produced for each kilogram of biomass or waste (Mustafa et al., 2017). The yield of hydrogen (H_2 kg) is the quantity of hydrogen generated per unit mass of feedstock, calculated by multiplying the hydrogen process efficiency with the syngas or biogas yield. The hydrogen production rate (H_2 kg/hr) is the quantity of hydrogen generated per unit time and mass of feedstock) calculated by dividing the hydrogen yield by the duration of system operation.

For the gasification process in Scenarios 1 and 2 the first step is to dry the waste from an assumed value of 50% to 10% for MSW while and waste wood has a lower moisture content of 30%. For the dark and phot fermentation processes the volume of feedstock is reduced by 50% after pre-treatment, whilst natural gas is reduced by 2% for the SMR process. The associated technical principles were detailed in Chapter 2.

Combining the process efficiencies at each stage (cleaning, sulphur removal and WGS) generates the total efficiency of 42% for gasification, 50%-52% for fermentation and 70% for SMR (corresponding to the published values in Table 2-2). The conversion rates are calculated from the difference in starting volume of feedstock of 1 tonne (1000kg) to the final yield of hydrogen (H_2kg). The rate is then scaled up and is applied to the actual value of waste available an hour provided by Glasgow waste data (Table 3-1).

Scenario 5 uses natural gas as feedstock for SMR and therefore the volume of natural gas was determined by back calculating from the volume of hydrogen produced by waste wood gasification. This is based on the value from Susmozas et al., (2013) that states 3.18 kg of natural gas feedstock (8.12MJ) was used in the SMR for hydrogen production system to produce 1kg of hydrogen.

The rated MW of the plant is used to calculate the total system costs as part of the CBA and illustrates the differences in potential size of facilities using the waste available from Glasgow. The rated capacity of the WtH plant (MW) is calculated using the hydrogen production rate, capacity factor (CF) as a percent (%), energy density value of hydrogen (LHV=120 MJ/kg) and MJ/h to MW conversion factor (Eq. 12) (Lui et al., 2022a). The CF represents the amount of time the plant is operational and generating product gas, averaged over the time period of one year. Limited by technical constraints and plant availability such as down time for maintenance. The CF is assumed to be 90% which corresponds to 7884 hours a year for the gasification and SMR technologies and 7469 hours/year for dark fermentation, 7629 hours a year for combined dark and photo fermentation. The fermentation bioreactor is assumed to be 100,000 litres or 100 tonnes in size. With the available wet feedstock at 24.79 tonnes an hour it is calculated that a single 100 tonne reactor would fill every four hours and six would be needed a day. To fill bioreactors with wet waste continuously, enough reactors are needed for three days. It is assumed the cleaning of a reactor takes 4 hours for every 72 hours it is in operation (5% of time cleaning) and at 90% there are 7469 hours a year of operational time. For combined dark and photo fermentation the study by Rezaeitavabe et al., (2020) was used a guide, they used a single reactor for both dark and photo fermentation reactions in a hybrid cocultured system with an added light source beside the reactors. It requires an extra 48 hours for the photo fermentation reactions added to the dark fermentation reaction of 3 days.

$$MW = \frac{H_2\ kg/hr * (H_2\ 120\ MJ\ kg * CF\ \%)}{3600} \quad (12)$$

Where H_2 kg /hr is he hydrogen production rate per hour, MJ kg are megajoules per kg, CF is the capacity factor and the conversion factor for MJ to MWh.

Table 3-3 displays the yield of hydrogen calculated per tonne of feedstock and the rate (tonnes/hour) of hydrogen production for each scenario. The highest yield of hydrogen per kg of feedstock is observed from Scenario 5 (SMR) at 286 kg, which is three times that of Scenario 1 (gasification with MSW) at 93.4 kg H_2. This is in part due to the high process efficiency and the quality of the feedstock. When calculated on an annual basis hydrogen production is the highest for MSW gasification (Scenario 1) at 6,469 tonnes compared to gasification of waste wood (Scenario 2) of 2,262 tonnes/year and SMR (Scenario 5) of 3,361 tonnes/year. This is partly due to the large feedstock availability of MSW in Glasgow compared to waste wood gasification (Scenario 2).

The hydrogen production calculations give an indication to the differences between the chose technologies and indicate where the main benefits or disadvantages will be for the economic and environmental analysis.

Table 3-3. Hydrogen production rates for Scenarios 1-5, using feedstock volumes (tonnes/hour), process efficiency and rated plant MW.

Parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Feedstock input tonnes/hour	21.12	5.56	24.79	24.79	2.13
Efficiency of plant	42%	42%	52%	52%	70%
Yield H_2 kg per tonne feedstock	93.4	124	18.75	26.25	286
H_2 production kg/hour (at 90% CF)	738.58	258.25	228.98	304.55	383.78
Electricity requirement kWh per kg H_2	1,507.3	529.9	400.6	544.2	2,764.3
Plant rated capacity in MW	24.62	8.61	7.23	10.12	12.79
H_2 tonnes/year	6,469.98	2,262.27	2,005.94	2,667.81	3,361.91

The fermentation technology in Scenarios 3 and 4 produce the lowest hydrogen yields, approximately four times less than MSW gasification and six times less than gasification with waste wood even though the feedstock quantity is 15% higher. The operational input time for the fermentation scenarios (3 and 4) are based on the reactor size which is a limiting factor for the operational time due to the batch process.

Mass balance analysis was completed for each of the WtH technologies and SMR (Fig. 3-1 to 3-5). A waste feedstock input value of 1 tonne is used and the feedstock rate is determined by the waste available, calculated from 2018 data records (SEPA, 2018). Hydrogen is the main product of interest; the other components of syngas are termed other gases. The mass balance highlights the differences in hydrogen yields from the different WtH technologies along with variations in waste emissions (exhaust) and process residues such as bottom ash and tar.

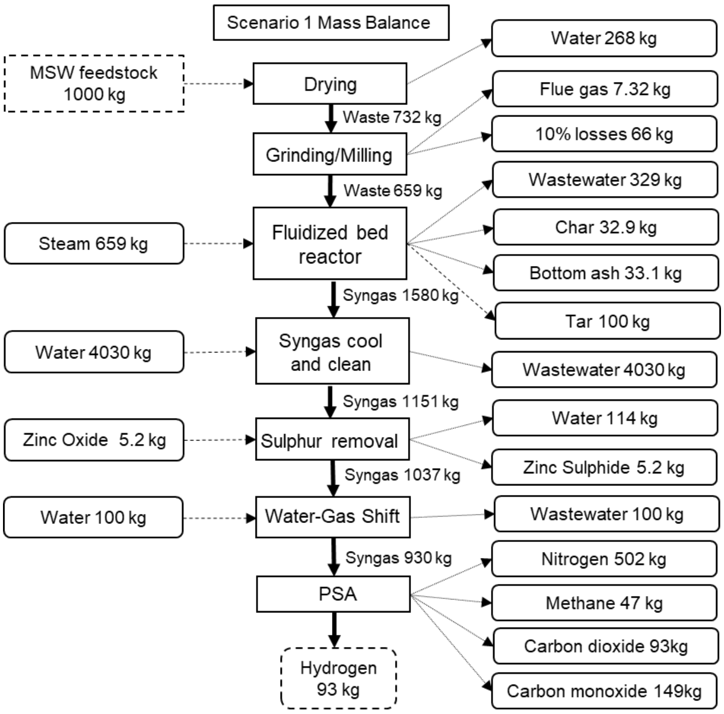

Fig. 3-1. Mass balance diagram for Scenario 1 gasification system using MSW as feedstock and hydrogen as the main product.

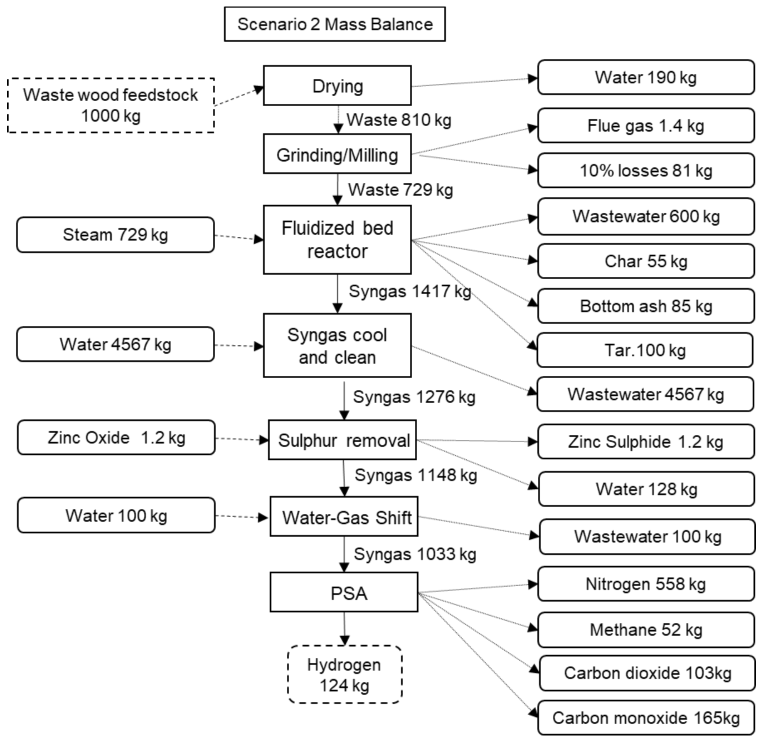

Fig. 3-2. Mass balance diagram for Scenario 2 gasification system using waste wood as feedstock and hydrogen as the main product.

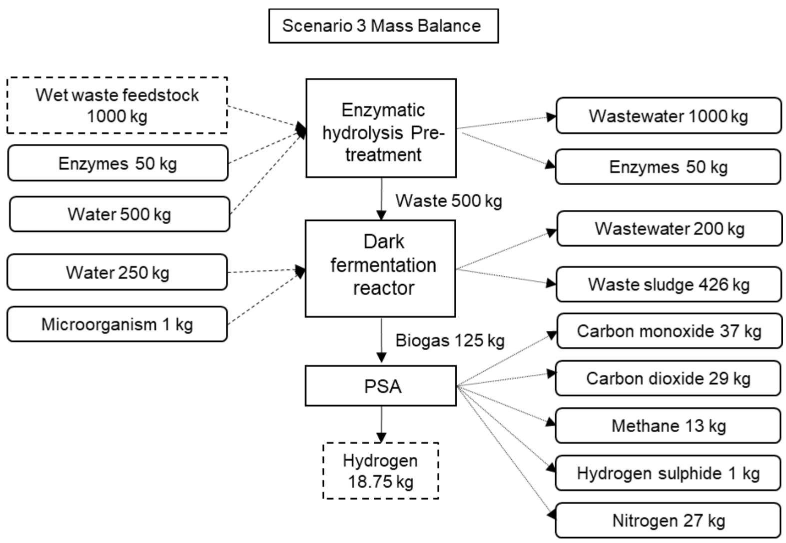

Fig. 3-3. Mass balance diagram for Scenario 3 dark fermentation system using wet waste as feedstock and hydrogen as the main product.

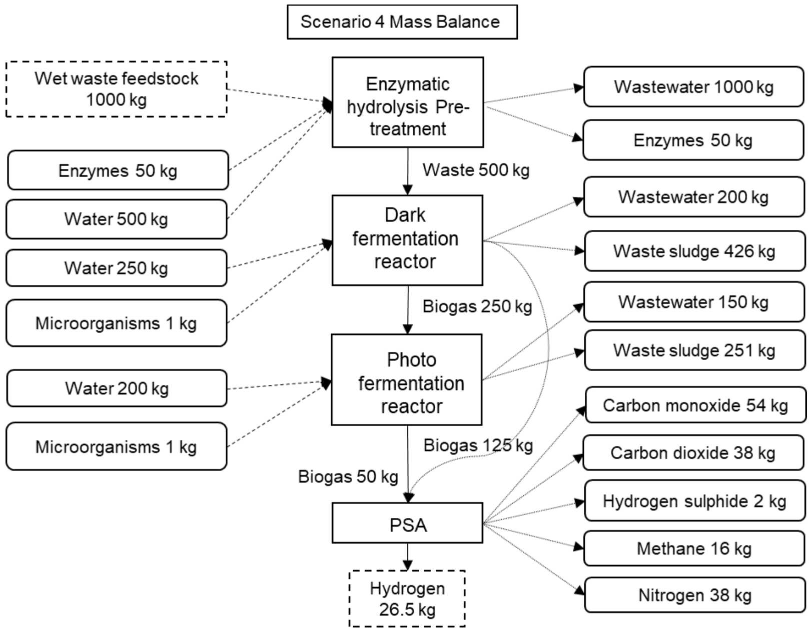

Fig. 3-4. Mass balance diagram for Scenario 4 dark and photo fermentation system using wet waste as feedstock and hydrogen as the main product.

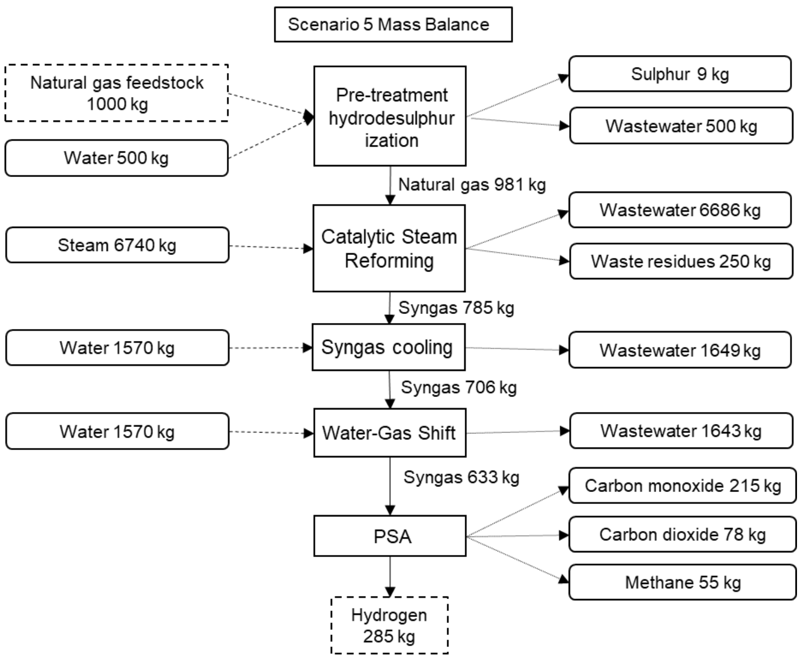

Fig. 3-5. Mass balance diagram for Scenario 5 SMR system using natural gas as feedstock and hydrogen as the main product.

To summarise the data for this study has been calculated using the waste data of MSW, woody waste and wet waste for Glasgow. Five scenarios were designed with yearly waste type and volume data supplied by SEPA was used in calculations to provide hydrogen production values, MW of a WtH plant and electricity requirements. The differences in hydrogen yield are reflected in the waste available for conversion and the associated plant technology efficiencies. The data calculated in this chapter will provide values for the LCA (Chapter 4) and CBA (Chapter 5).

Chapter 4 Life Cycle Assessment of four WtH systems plus a conventional hydrogen production method

This chapter assesses the environmental impact of the WtH systems designed in Chapter 3 (Scenario 1- MSW gasification, Scenario 2- waste wood gasification, Scenario 3– wet waste dark fermentation, Scenario 4 – wet waste dark and photo fermentation, and Scenario 5- natural gas for SMR) to determine the carbon savings or carbon deficit when compared with each other, the conventional SMR system and other research.

The focus is to use the LCA is to calculate the carbon emissions related to each process in the Scenarios and generate a total. The goal and scope are described in more detail in Chapter 4.2. The content from this chapter has been published Lui et al., (2022b).

4.1. Introduction

The LCA assesses the environmental impact of a technology or process using a standardised method. The LCA methodology and framework follows the International Organisation for Standardisation (ISO) guidelines ISO 14040 and ISO 14044 (2006). ISO 14040 describes the principles and framework for conducting a LCA and includes the four main phases of goal and scope, inventory (LCI), impact assessment (LCIA), and interpretation and was last reviewed in 2022. ISO 14044 sets out the specific requirements and guidelines for the LCA. Each phase of the LCA is described in the following sections and related to the WtH scenarios.

4.2. LCA Goal and Scope

The goal of the LCA is to evaluate the GWP of the different WtH technologies treating three types of feedstocks and a conventional SMR method. The GWP is one of the impact categories in an LCA and indicates the amount of greenhouse gas (kg CO_2 equivalent) emitted throughout the life cycle of a technology, process or system (Dincer and Acar, 2015). Energy production technologies such as those used in WtH, are evaluated for sustainability from the carbon emissions and impact on the environment. Comparisons of the environmental impact of current fossil fuel-based waste management and hydrogen production technologies will go towards demonstrating the advantages or disadvantages of WtH as a low carbon alternative.

The functional unit (FU) defines the quantification of the identified functions, with performance characteristics, of the product (Curran, 2012). It is important to select an FU that represents the main variable or variables involved in the assessment, and as a reference point from which the results can be assessed. In this study two functional units were deemed important and provided two perspectives when assessing from either waste management (waste as a feedstock) and or from hydrogen production for transport (hydrogen as the main product). The functional units are 1 tonne of waste feedstock and 1 kg of hydrogen produced. The functional units represent how the calculated carbon emissions (GWP) are related back to the technology and used for comparison purposes. By calculating two different functional units it will be possible to highlight the two objectives of waste management and hydrogen production and how it effects the way the results are viewed in terms of policy decisions.

The results generated from the LCA are in GWP because the focus of the project is determining the environmental impact of WtH systems. The overall aim of the LCA is to show if WtH can help with the decarbonisation effort of both hydrogen production and waste management through alternative methods, therefore only GWP is required. The other impact factors generated by the LCA software including eutrophication, blue water and acidification are discussed as further work in Chapter 8.2.

The scope determines the system processes involved in the thermochemical (gasification), biochemical (dark and photo fermentation) and SMR technologies. The system boundary includes all the processes and parameters for the analysis and will be the same for each scenario. Process flow diagrams with the system boundaries for the different technology systems (gasification, fermentation and methane reforming) are in Figs. 4-1 to 4-3. For all the technologies the process starts at the pre-treatment stage at a processing facility, followed by waste conversion technology, syngas cleaning and cooling, hydrogen separation, hydrogen compression and storage, and an onsite refuelling station. The HRS parameters such as hydrogen storage and compression have been chosen to be compatible with FCEB vehicles for use in fuel cells such as PEMFC. The design is geared towards heavy vehicles including buses (for public transport) as the main consumers of the hydrogen.

The WtH facility design includes a refuelling station to allow the site to act as a central transport hub for Glasgow city. Therefore, compressed hydrogen transport (trucks, pipelines) has not been considered and hydrogen infrastructure and networks beyond the facility or plant are not discussed further. By providing a refuelling station on the site of the waste conversion facility, a major obstacle to the uptake of hydrogen vehicles or FCEBs could be lessened. Removing delivery of hydrogen from the system will also reduce the carbon footprint of WtH production.

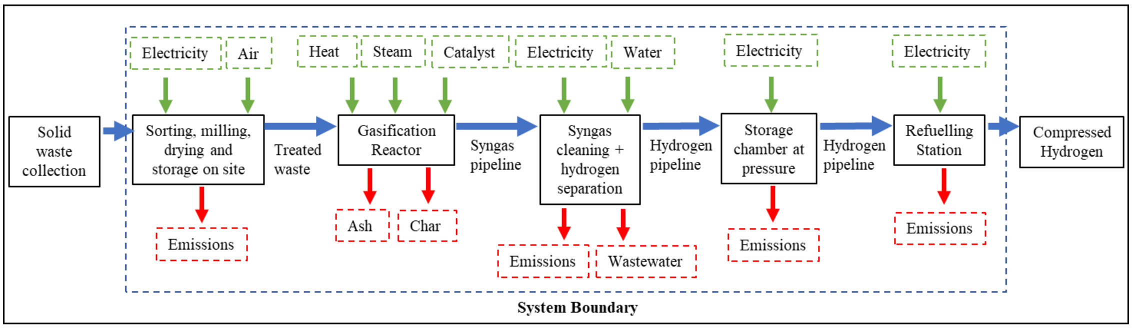

Fig. 4-1. Process flow diagram for the gasification technologies (Scenarios 1 and 2) including the system boundary. Modified from Lui et al., (2020).

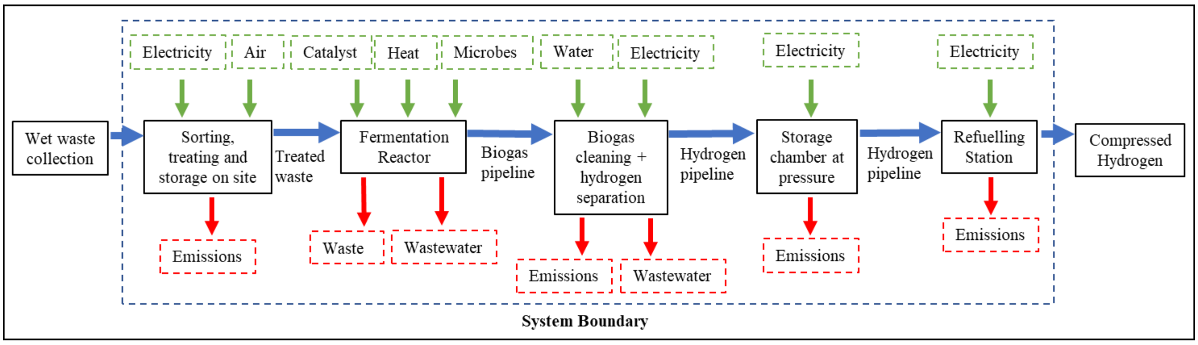

Fig. 4-2. Process flow diagram for the fermentation technologies (Scenarios 3 and 4) including the system boundary. Modified from Lui et al., (2020).

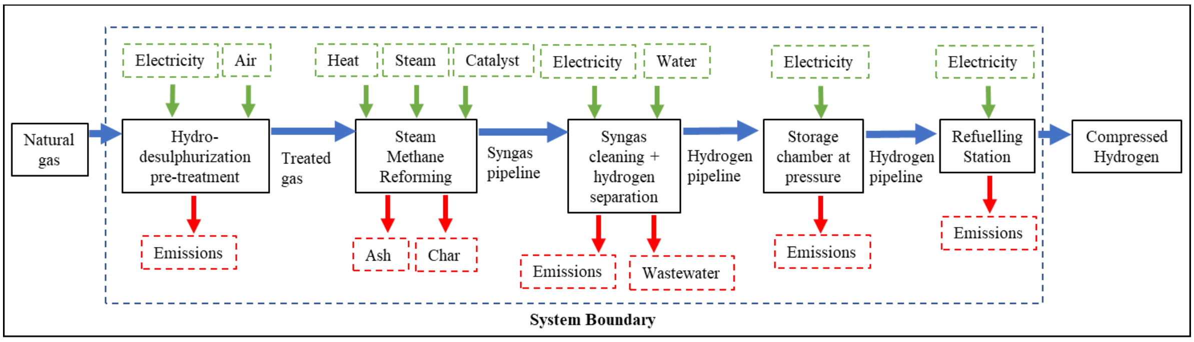

Fig. 4-3. Process flow diagram for the SMR system (Scenario 5) including the system boundary. Modified from Lui et al., (2020).

4.3. Life Cycle Inventory

The life cycle inventory (LCI) contains all the input and output data for the LCA are included within the system boundary of each LCA mode. Tables 4-1 and 4-2 display Scenarios 1 and 2, and Scenarios 3, 4 and 5 respectively. The references for the parameters are provided and each has been modified for the specific conditions or feedstock for each scenario.

Waste data and emission statistics were collected from the Scottish Environment Agency (SEPA) and Glasgow City Council online resources. Other technical, environmental and policy data is sourced from UK government data, BEIS reports, Scottish government, and academic papers. The energy requirements use kWh or MW units, water in litres and materials such catalysts in kg. Electricity inputs in the process models are supplied by the UK electricity grid including a mix of generation methods (nuclear, natural gas, renewable sources etc.). The electricity used for all models is the average annual country specific "GB electricity grid mix" and is based on primary industry data and secondary literature data. It is composed of different energy carries involved in the conversion to electricity including nuclear, coal, natural gas, heavy fuel oil, wind power, hydro power, photovoltaics as well as imports from neighbouring countries.

The LCA was modelled using GaBi software owned by Sphera (gabi.sphera.com), an extensive product containing life cycle modelling, balances and reporting capabilities plus global industry life cycle inventory databases. It is used to assess the environmental impact of all stages of products and systems. Individual modules can be managed within the process chains and then combined during the calculation of the system. The databases contain life cycle inventory obtained by long term research from the University of Stuttgart and thinkstep AG (a Sphera company focusing on software, data services).

The CML 2001 method is used with the unit kgCO_2-eq. CML is a database used worldwide that contains characterisation factors all baseline and non-baseline characterisation methods for LCIA (Curran, 2012). The aim of CML is to operationalise the ISO 14040 standards and provide best practice for midpoint indicators. In GaBi, plans are the location to gather and connect individual processes of the products life cycle and the inputs and outputs in the balance are called flows. Processes are determined using the associated flows (can have different units) which are defined using quantities which are the properties of the flow.

The professional database was accessed within GaBi to provide data for input and output processes such as materials, products and energy sources for different location including the EU and UK. Gaps in the GaBi database exist in niche research or operational areas including some WtH processes. These gaps in data were filled in using operational and process data collected from academic papers and publicly available UK government reports and UK energy industry reports. All data is referenced and shown with the inputs, using 1 tonne of waste feedstock as the starting value, and outputs for Scenarios 1 and 2 in Table 4-1, and Scenarios 3, 4 and 5 in Table 4-2. The inputs and outputs of each process stage include pre-treatment, thermochemical or biological waste conversion, syngas cleaning and cooling, hydrogen separation, compression, and storage, and HRS.

Table 4-1. Input and output parameters for Scenarios 1 and 2. The starting value for the process is 1000kg of waste feedstock.

Process stages		Scenario 1	Scenario 2	References
Input				
Pre-treatment	Waste feedstock kg	1000	1000	Kourkoumpas (2015), GaBi database
	Electricity kWh	183	85.6	
Waste conversion technology	Electricity kWh	219	243	Khoo (2009)
	Heat (Steam) kWh	3	3	Hamedani et al., (2018)
	Waste feedstock kg	659	729	Susmozas et al., (2013),
	Water kg	732	500	Dwivedi et al., (2020), Ghimire et
	Catalyst kg	73	100	

				al., (2015), GaBi database
Gas solid cyclone (particulates removal)	Electricity kWh	42.7	47.2	Hamedani et al., (2018),
	Syngas kg	1581	1750	Susmozas et al., (2013)
	Air kg	2620	2870	Spath et al. (2005)
Syngas cooling and cleaning	Electricity kWh	127.5	141.1	Hamedani et al., (2018)
	Syngas kg	1423	1575	Susmozas et al., (2013)
	Water kg	5246	5740	
	Air kg	0.25	0.25	
	Zinc oxide kg	1.27	1.7	
Water Gas Shift	Electricity kWh	31.1	34.4	Susmozas et al., (2013)
	Catalyst kg	0.15	0.14	
	Syngas kg	1037	1148	
PSA	Electricity kWh	233	207	Valente et al., (2017)
	Syngas/ Biogas kg	934	1033	
Hydrogen compression	Hydraulic oil kg	0.14	0.18	GaBi database, Gardiner (2009) Li et al., (2020)
	Electricity kWh	107	143	
	Hydrogen kg	93	124	
Hydrogen storage	Electricity kWh	187	248	Hua et al., (2011)(2011)
	Hydrogen kg	93	124	
Hydrogen refuelling station	Electricity kWh	374	496	Elgowainy et al., (2016)
	Hydrogen kg	93	124	
Output				
Pre-treatment	Waste feedstock kg	732	810	Khoo (2009), Salkuyeh et al., (2018) GaBi database
	Wastewater kg	268	193	
	Flue gas kg	7.32	1.32	
	Sulphur kg	0.23	0.26	
Waste conversion technology	Biochar kg	36.6	40	Susmozas et al., (2013), Hamedani et al., (2018), Ghimire et al. (2015), Elgowainy et al., (2016)
	Exhaust kg	1.22	1.34	GaBi database
	Bottom ash kg	36.7	10.4	
	Wastewater kg	366	401	
	Syngas kg	1581	1750	
	waste residue/ catalyst kg	0.007	0.008	
Gas solid cyclone	Water kg	4896	5364	Susmozas et al., (2013),
	Particulates kg	0.25	0.27	GaBi database
	Flue gas kg	86.8	94.5	

	Syngas kg	1423	1575	
Syngas cooling & cleaning	Sulphur kg	0.23	0.38	Susmozas et al., (2013),
	Syngas kg	1037	1148	Dong et al., (2018b)
	Water kg	5246	5740	
Water-Gas Shift	Exhaust kg	34.6	37.8	Susmozas et al., (2013)
	Catalyst kg	0.1	0.1	
	Syngas kg	934	1033	
PSA	Exhaust kg	170	186	Susmozas et al., (2013),
	Other gases kg	1357	1449	Valente et al., (2017)
	Hydrogen kg	93	124	
Hydrogen compression	Used oil kg	0.14	0.18	GaBi database, Gardiner (2009)
	Waste heat MJ	1	1.4	
	Hydrogen kg	93	124	

Table 4-2. Input and output parameters for Scenarios 3, 4 and 5. The starting value for the process is 1000kg of waste feedstock.

Process stages		Scenario 3	Scenario 4	Scenario 5	References (modified)
Input					
Pre-treatment	Waste feedstock kg	1000	1000	1000	Kourkoumpas (2015), GaBi database
	Electricity kWh	62	62	150	
	Enzymes kg	50	50	-	
	Water kg	500	500	-	
Waste conversion technology	Electricity kWh	12.8	37.5	339	Khoo (2009),
	Waste feedstock kg	500	500	981	Susmozas et al., (2013),
	Water kg	250	350	6740	Dwivedi et al., (2020), Ghimire et al., (2015), GaBi database
	Catalyst kg	-	-	0.95	
	Microorganisms kg	0.0015	0.0165	-	
	Air kg	-	-	8500	
Syngas cooling and cleaning	Electricity kWh	-	-	18.1	Hamedani et al., (2018)
	Syngas kg	-	-	785	Susmozas et al., (2013)
	Water kg	-	-	1570	
Water Gas Shift	Electricity kWh	-	-	21.2	Susmozas et al., (2013)
	Catalyst kg	-	-	0.05	
	Syngas kg	-	-	706	
PSA	Electricity kWh	25	35	191	Valente et al., (2017)
	Syngas/ Biogas kg	125	137	636	

Hydrogen compression	Hydraulic oil kg	0.18	0.18	0.29	GaBi database, Gardiner (2009) Li et al., (2020)
	Electricity kWh	21.6	30.2	329	
	Hydrogen kg	18.75	26.25	286	
Hydrogen storage	Electricity kWh	37.5	52.5	572	Hua et al., (2011)
	Hydrogen kg	18.75	26.25	286	
Hydrogen refuelling station	Electricity kWh	75	105	1144	Elgowainy et al., (2016)
	Hydrogen kg	18.75	26.25	286	
Output					
Pre-treatment	Waste feedstock kg	500	500	981	Khoo (2009), Salkuyeh et al., (2018) GaBi database
	Wastewater kg	500	500	-	
	Flue gas kg	10	10	10	
	Sulphur kg	-	-	9	
Waste conversion technology	Wastewater kg	200	200	2940	GaBi database
	Syngas kg	125	137	785	Susmozas et al., (2013), Hamedani et al., (2018), Ghimire et al. (2015), Elgowainy et al., (2016)
	waste residue/ catalyst kg	250	250	0.0012	
	Other gases kg	-	-	415	
Syngas cooling and cleaning	Syngas kg	-	-	706	Dong et al., (2018)
	Water kg	-	-	1410	
Water-Gas Shift	Exhaust kg	-	-	15.7	Susmozas et al., (2013)
	Catalyst kg	-	-	0.05	
	Syngas kg	-	-	636	
PSA	Exhaust kg	12.5	17.5	346	Susmozas et al., (2013),
	Other gases kg	106	131	415	Valente et al., (2017)
	Hydrogen kg	18.75	26.25	286	
Hydrogen compression	Used oil kg	0.18	0.18	0.29	GaBi database, Gardiner (2009)
	Waste heat MJ	0.2	0.3	3.1	
	Hydrogen kg	18.75	26.25	286	

The main product of the three conversion systems in Scenarios 1-5 is hydrogen gas. The solid by-products of the gasification process are tar, biochar, and ash. Biochar as a by-product has potential to be valuable as an additive for agricultural use, however that path is not included in this study and therefore its environmental impact is not considered further. The other output products such as wastewater are regarded as waste from the system to be disposed of via landfill or incineration and are not considered for further use. The allocation of environmental impact is directed towards the gas waste constituents of syngas that include carbon monoxide, carbon dioxide and methane. For modelling purposes carbon dioxide and carbon monoxide are categorised as inorganic emissions not currently utilized, whilst the methane is viewed as a valuable by-product and captured for further use (specified in GaBi).

The data from the GaBi database is consistent and references are provided in the database adding some reliability to the software. However, the basis of the LCA has been criticised for user bias and the large amount of data without a system to aid interpretation (Curran, 2012). Decision makers therefore have to manage and interpret data and results often provided as a single figure leading to variations to the outcome and conclusions of a study. As assumptions are made for various parameters this will affect the reliability and reproducibility of results if performed by different studies. These factors are taken into consideration in this work and comparative research is used to provide some validation.

4.4. Life Cycle Impact Assessment

LCA results calculate the impact of various environmental indicators such as global warming potential (GWP), as well as eutrophication, acidification water use and land use. The Life Cycle Impact Assessment (LCIA) category used in this study is GWP as a measure of climate change impact of process of waste conversion to produce hydrogen throughout its life cycle using gasification or fermentation, by estimating the GWP using the unit of kg CO_2-eq (equivalent carbon dioxide emissions). The GWP is a measure of the radiative forcing (thermal radiation absorption) of the atmosphere, the effects are seen in the emissions of greenhouse gases, such as methane and nitrous oxide, relative to an equal amount of carbon dioxide emissions, over a specific time period usually years. GWP is therefore a measure of the impact of humans, leading to climate change, the effects of which can be seen in the ecosystem and on human health (Curran, 2012).

The LCA results estimate the downstream emission created by each system and allow for comparison between Scenarios 1-5. The GWP results as a general unit can also be compared with other research studies.

4.5. Life Cycle Interpretation

The last phase of the LCA is the interpretation of results in this case those produced by the GaBi LCA software and includes a completeness and consistency check. The results are compared to other scenarios in the study as well as other LCA based studies. Recommendations made from the results will identify the significant input and output variables and understanding the systems in which they are based. Advantages and disadvantages are also proposed for each scenario (1-5) in regard to the functional unit with GWP.

A sensitivity analysis was conducted to find the influences effecting the uncertainty in the LCA parameters using a Monte Carlo simulation in MS Excel. The Monte Carlo simulation is a probability simulation that uses repeated random sampling to obtain statistical results. A deterministic computation performed on the inputs in a black box system and the results are collected and displayed on a histogram.

The uncertainty variables used are waste feedstock (kg), feedstock conversion rate (waste to hydrogen %), kg CO_2-eq per 1kg H_2, capacity factor (CF%), and operation time in hours. Some uncertainties parameters for waste generation (both MSW and wood waste) are affected by seasonal (e.g., holidays and festivals), local and weather conditions which need to be taken into account. For the Monte Carlo simulation 1000 iterations were performed with operational input data (electricity requirement, water, etc.) modified according to the specifics of each process with 20% variation for waste volume and 10% variation added to the other outputs to account for losses and uncertainty. The number of iterations represents the sweet spot to produce meaningful results without excess runs using unnecessary computer power.

The results are displayed in a triangular distribution. Whilst difficult to cover all aspects of the complex systems with limited and wide set of available data, any uncertainties can lead to biased conclusions which are recognised and discussed in the results section. The impact of the sensitivity analysis will be to show how the performance of the WtH systems vary with key parameters. It highlights where the most significant changes can be made to improve the system and large differences are expected to be seen between the thermochemical and biochemical technologies.

4.6. LCA Results

The GWP results for Scenarios 1-5 based on the functional unit of one tonne waste feedstock treated are shown in Fig. 4-4. The GWP results for the functional unit of one kg H_2 are shown in Fig. 4-5. A further breakdown of the GWP and functional unit is presented in Figs. 4-6 to 4-10 as pie charts showing the percentage of the total kg CO_2-eq for each scenario. This highlights the relative contributions to the GWP of each process and emphasises the largest contributors.

Scenarios 1 and 2 have the highest GWP for WtH technologies, at 466 and 530 kg CO_2-eq respectively, when considering the functional unit of 1 tonne feedstock. Scenarios 3 and 4 have the lowest GWP of 124 and 168 kg CO_2-eq and the lowest hydrogen yields of 18.75 and 26.25 kg respectively (Fig. 4-4). The high GWP of Scenarios 1 and 2 is due to the higher electricity requirements of the gasification process and the higher process emissions compared to the biochemical technologies. Scenario 2 has slightly higher GWP of approximately 12% which is related to the higher yield of hydrogen a difference of 30kg H_2.

Scenario 5 (SMR) has the highest hydrogen yield of 286 kg H_2 although also the highest GWP of 3,811 kg CO_2-eq. A general trend of a high GWP with a high hydrogen yield can be seen for the different technologies.

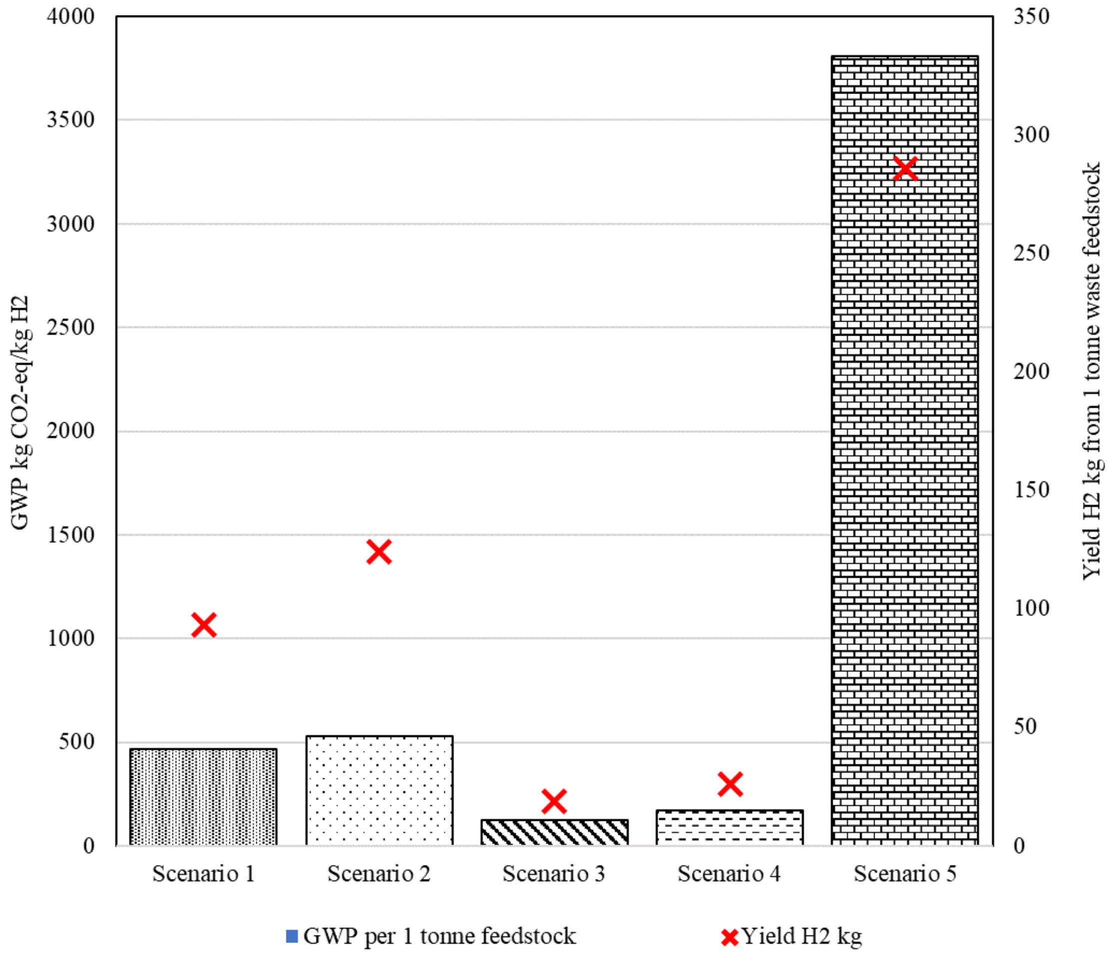

Fig. 4-4. The graph displays the calculated GWP using the functional unit of 1 tonne waste feedstock. The yield of hydrogen H_2/kg is displayed as a red cross (data from Chapter 3).

The results for the functional unit of kg H_2 produced, the fermentation technologies (Scenario 3 and 4) have higher (~25% higher) GWPs than the gasification scenarios (1 and 2) (Fig. 4-5). The relatively high carbon cost of the fermentation technologies along with lower hydrogen production values reduces the benefits associated with the lower energy requirements, when compared to the other scenarios, specifically gasification.

Scenario 5 has the highest GWP of 13.32 kg CO_2-eq, which is 2.6 times and 2 times greater than Scenario 1 and 3, respectively. When considering both functional units Scenario 5 has a markedly higher GWP, and hydrogen yield as expected.

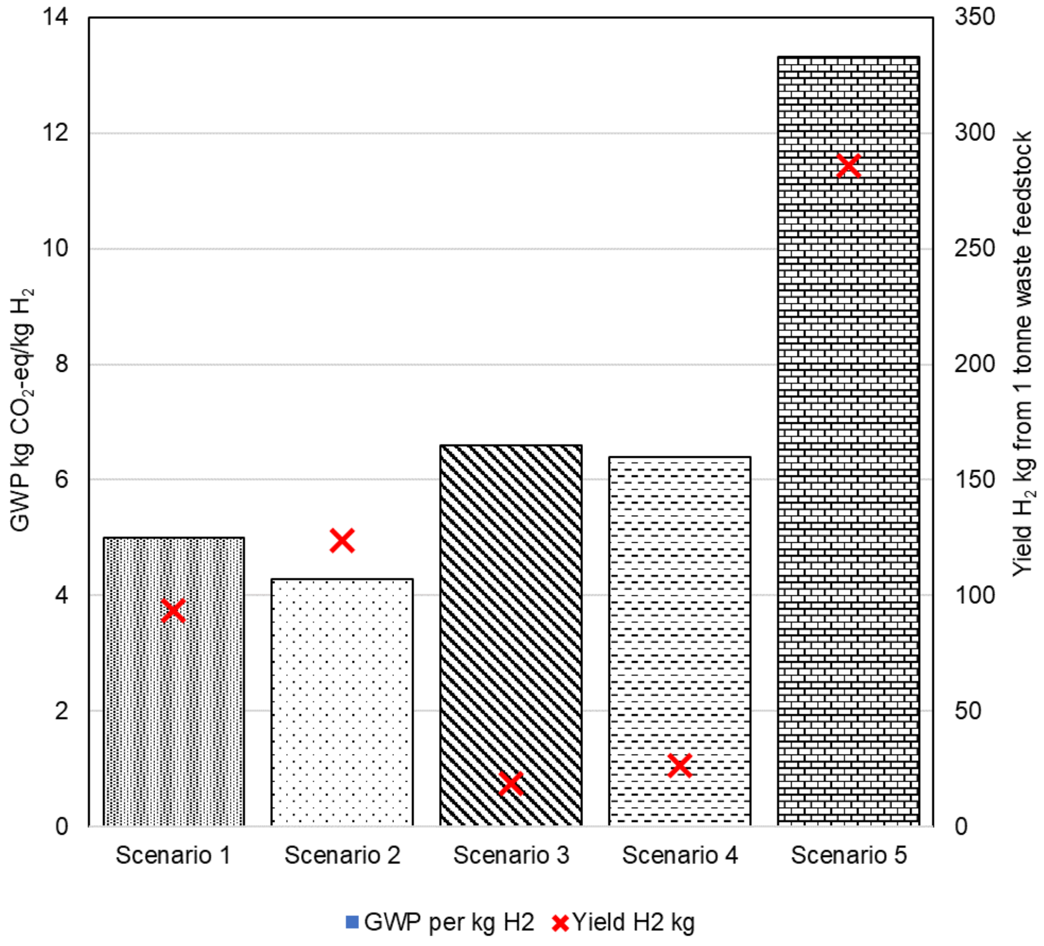

Fig. 4-5. Graph with calculated GWP using the functional unit of 1 kg hydrogen produced. The yield of hydrogen H_2/kg is also displayed.

Comparing the WtH technologies using both functional units show how the gasification technologies appear to have a lower environmental impact when considering waste feedstock but higher environmental impact when using hydrogen yield. Viewing them in isolation may affect decision makers and how potential projects are chosen. This highlights the importance of assessing both functional units to get a full view of WtH technologies and the associated GWP.

A breakdown of the GWP calculated for each individual process are shown in Figs. 4-6 to 4-10 for Scenarios 1-5. The pie charts show the contributions from HRS, storage and compression are high for all WtH scenarios, providing the most for Scenarios 1 (44%) and Scenario 2 (54%) of 2.2 kg CO_2-eq. This is associated with the higher hydrogen production quantities leading to higher compression and storage requirements. The pre-treatment requirements for Scenarios 3 and 4 contributes most to the GWP for the fermentation technologies at 3.3 and 2.4 kg CO_2-eq, respectively, whilst the catalytic steam reforming process contributes 11.3 kg CO_2-eq for SMR in Scenario 5.

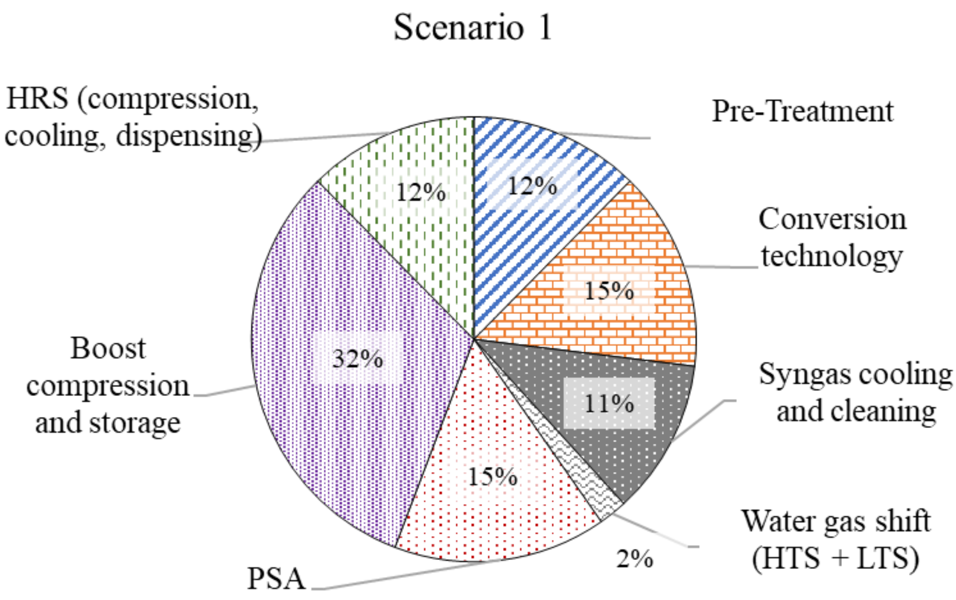

Fig. 4-6. Pie chart displaying the percentage GWP for each process stage for Scenario 1. The total GWP is 466 kgCO_2-eq/ tonne waste feedstock.

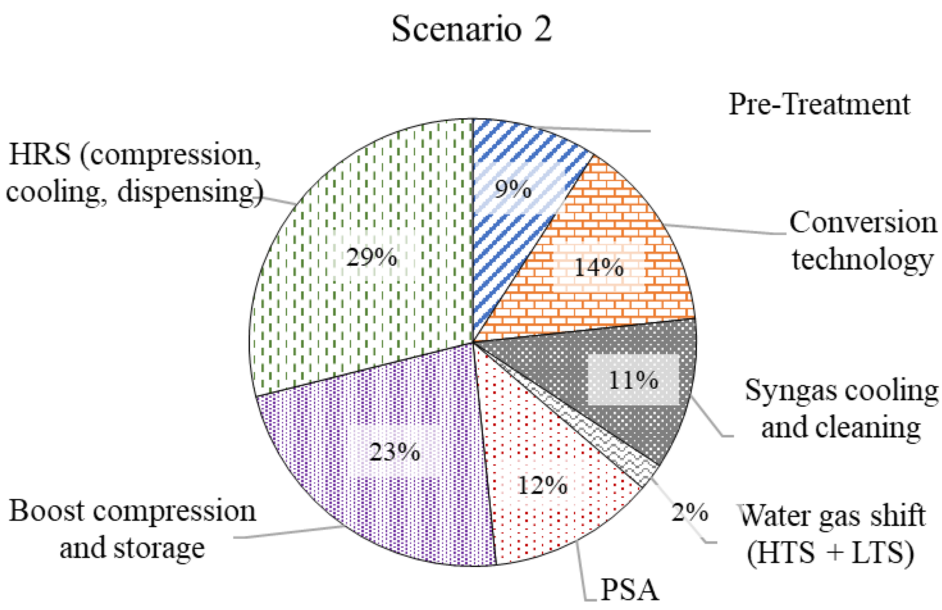

Fig. 4-7. Pie chart displaying the percentage GWP for each process stage for Scenario 2. The total GWP is 529 kgCO_2-eq/ tonne waste feedstock.

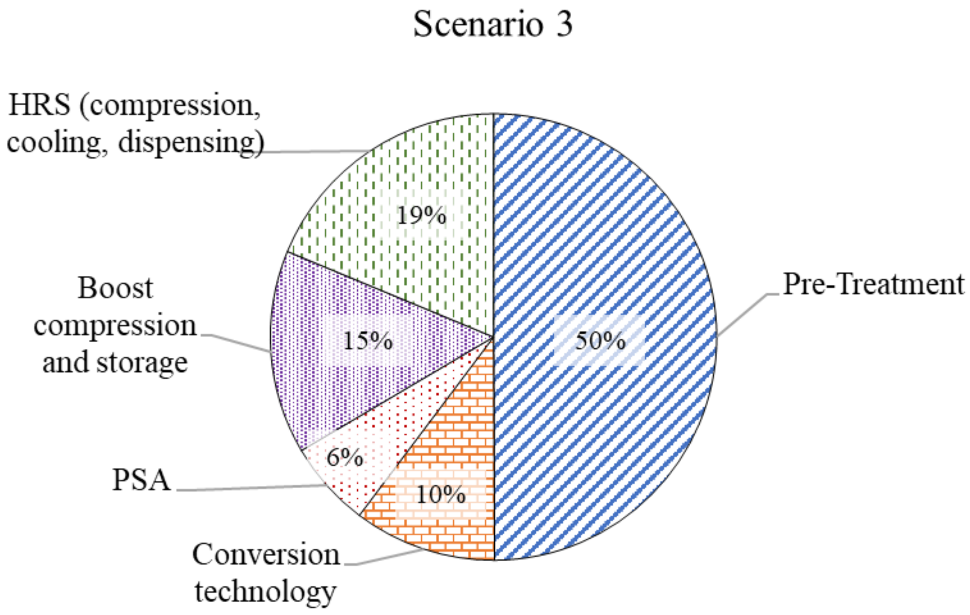

Fig. 4-8. Pie chart displaying the percentage GWP for each process stage for Scenario 3. The total GWP is 124 kgCO_2-eq/ tonne waste feedstock.

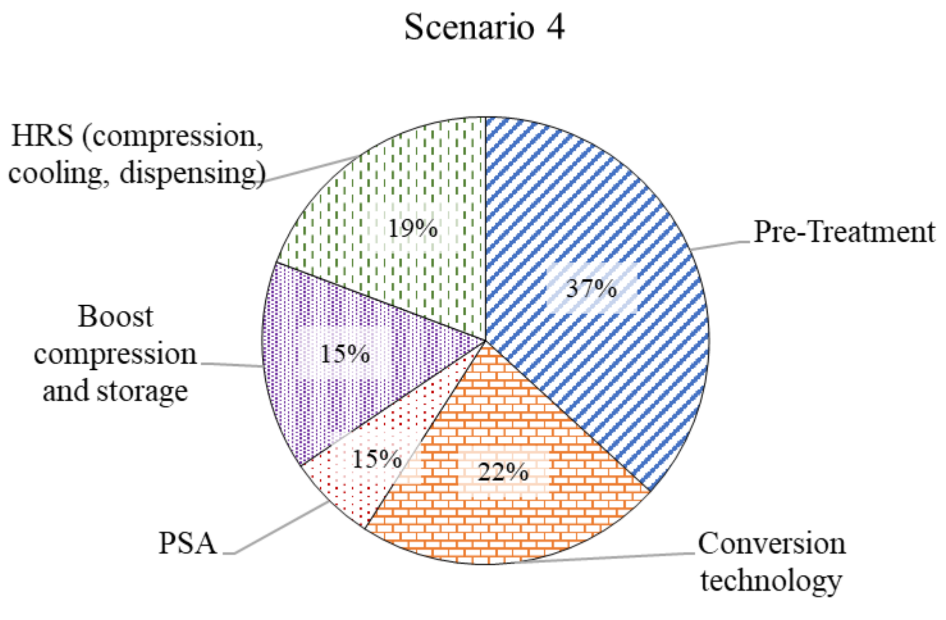

Fig. 4-9 Pie chart displaying the percentage GWP for each process stage for Scenario 4. The total GWP is 168 kgCO_2-eq/ tonne waste feedstock.

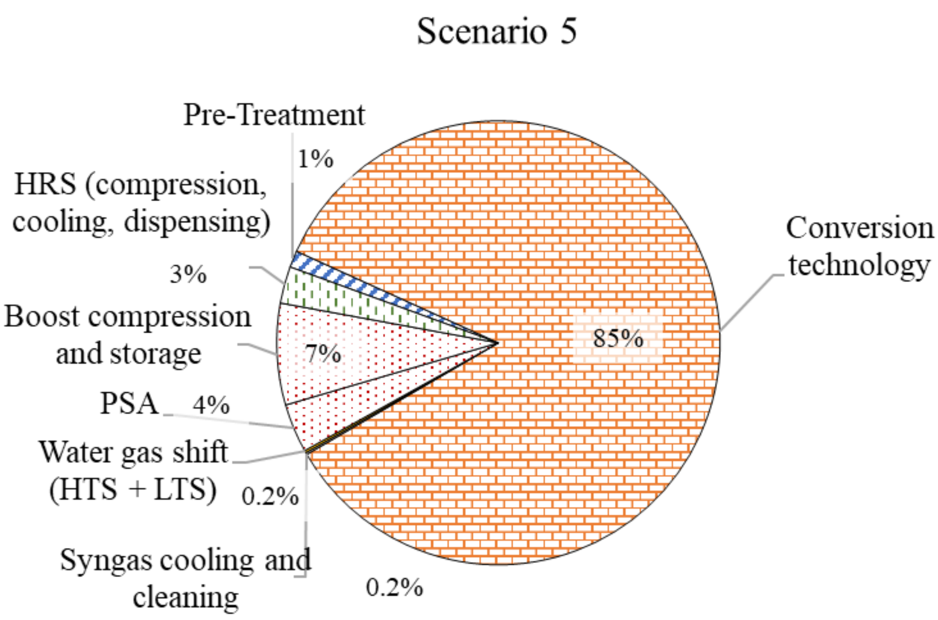

Fig. 4-10. Pie chart displaying the percentage GWP for each process stage for Scenario 5. The total GWP is 3811 kgCO_2-eq/ tonne waste feedstock.

By evaluating the results of this study with similar studies on thermochemical and biochemical technologies comparisons can be made. The wide variation in WtH system configurations leads to a wide range of GWP results as seen in Table 4-3. There are few studies on the environmental impact of waste-based feedstocks (such as MSW) for comparison though biomass purposely grown for energy production provides reasonable alternatives.

Table 4-3. Comparison of results from this study with similar academic research.

Process	Feedstock	kg CO_2-eq/ kg H_2	Reference
Fluidised gasification	MSW	4.98	This study (Scenario 1)
Gasification	MSW	-	-
Fluidised Gasification	Waste wood	4.27	This study (Scenario 2)
Indirect Gasification	Biomass	0.385	(Susmozas et al., 2013))
Entrained Fluidized Bed Gasification	Biomass	3.26	(Li et al., 2020)
Gasification	Biomass (corn stover)	4.2	(Siddiqui and Dincer, 2019)
Dark fermentation	Wet waste	6.6	This study (Scenario 3)

Dark Fermentation	Biomass (corn stover)	9.6	(Elgowainy et al., 2016)
Dark and Photo Fermentation	Wet waste	6.4	This study (Scenario 4)
Dark and Photo Fermentation	Wheat straw	5.60	(Djomo and Blumberga, 2011)
SMR	Natural gas	13.32	This study (Scenario 5)
SMR	Methane	5.18	(Amran et al., 2017)
SMR	Natural gas	9.0 - 11.0	(Spath and Mann, 2000)
SMR	Natural gas	11.43	Valente et al., (2019a)

The results of this study are within a satisfactory range compared to other studies. The exception is wet waste with dark fermentation (Scenario 4) results which are ~ 30% lower in this study.

The results of this study were compared with existing studies based on gasification, fermentation, or SMR (Table 4-3). There is a large variation in the WtH system configurations using biomass as feedstock studied in literature leading to a wide range of GWP results, while the study of the environmental impact of MSW-based WtH is limited. It is shown that GWP results for gasification tend to be similar and within 0.72 kg CO_2-eq/kg H_2 whereas the variation for SMR shows a larger range up to 7 kg CO_2-eq/kg H_2. Dark fermentation technologies have a higher range up to 9.4 kg CO_2-eq/kg H_2. This implies the importance of waste composition, waste feedstock types, and operational parameters (energy requirements) on GWP.

The energy requirements of Scenarios 1-5 were supplied by electricity from the UK grid because of the reliability, existing electricity infrastructure and inner-city location far from large scale renewable sources. The UK electricity grid is composed of ~55% fossil fuel-based, ~33% renewable energy and ~12% low carbon sources. The carbon intensity of the grid evidently effects the carbon footprint of the systems and therefore impacts the GWP results. As energy generation sources are predicted to change in line with global decarbonisation targets and increases in green energy options, towards renewable energy (wind or solar), it is expected that CO_2-eq emissions related to grid electricity will decrease in future.

4.7. Sensitivity analysis

The results of sensitivity analysis are shown in Fig. 4-11 with the standard deviation and mean values displayed. The results as GWP kg CO_2-eq/hr. The values for all WtH scenarios are observed to be positively skewed with Scenario 1 and 2 having the largest skewed curves and standard deviations higher than Scenarios 3 and 4. Scenario 5 has the highest standard deviations of 1.41×10^4 of all the scenarios. The skewed distribution that tapers gently to the right of the graph indicating high or extreme values with a larger uncertainty, particularly for Scenario 2 and Scenario 4.

Scenarios 3 and 4 have the smallest mean values at 2.73×10^3 and 3.69×10^3, respectively. They also have the smallest standard deviation values implying the variations in input parameters have the least influence on GWP compared to the other scenarios. The mean is highest for the SMR technology (Scenario 5), and it displays the most symmetrical shape indicating fewer extreme values even with the highest standard deviation suggesting there is more certainty in the data. This supports the development status of SMR and its wide use as the conventional hydrogen production technology.

The most sensitive variable for the WtH technologies is this study is the availability and volume of waste feedstock because it affects the energy input required for all the conversion processes. It also affects the amount of hydrogen produced and thus the GWP results based on the functional unit of 1kg H_2. The variability and fluctuations in waste supply due to the seasonal changes in waste generation could be a concern and this is expressed in the results.

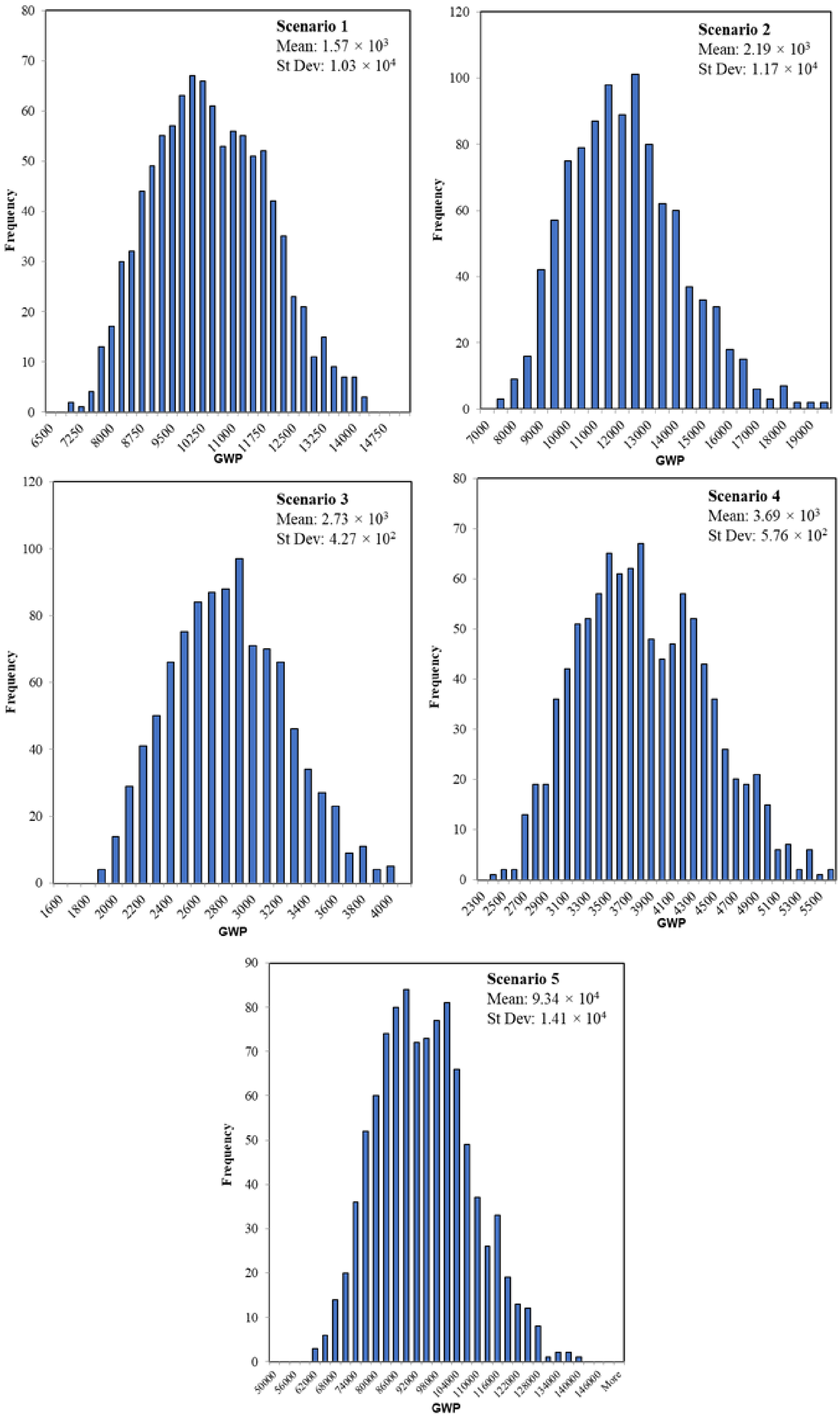

Fig. 4-11. Sensitivity analysis graphs for Scenarios 1-5 with mean and standard deviation values included.

4.8. Discussion

4.8.1. Implications for decarbonisation

The process of using waste for resource recovery has been shown to have an additional environmental benefit of GHG emission reduction in studies such as Arafat et al., (2015). The displacement of fossil fuel use whether it is through hydrogen or electricity, generates a useful product which adds further value to the process.

From this study the GWP is shown to be adversely affected by the lower efficiency of hydrogen production technologies. Reaching and maintaining a low GWP would help support WtH technologies while development and infrastructure becomes more competitive with other methods. The GWP of hydrogen production can be reduced if renewable resources are used at all stages and all products created are utilised (Reiter and Lindorfer, 2015).

This study demonstrates that WtH technologies have relatively low GWP values, which strengthens the apparent benefits when viewed as a dual-purpose system to dispose of waste and produce clean hydrogen. An example to highlight the benefits of WtH is to calculate the disposal of a years' worth of waste and producing hydrogen from SMR, with the combined emissions of 407,000 tonnes CO_2-eq (248,000 tonnes CO_2-eq a year from landfill and incineration plus 158,000 tonnes CO_2-eq from SMR for 5,336 tonnes H_2). Compared to the production of the same amount of hydrogen via MSW gasification (5,336 tonnes) and dispose of the yearly waste that would have gone to landfill or incineration the CO_2 footprint would be almost half at 86,211 tonnes.

The advantages of offering a variety of hydrogen sources improves the viability of the hydrogen economy and industry. This adds confidence to supply channels and goes towards limiting bottlenecks for consumers which should eventually lead to confidence in alternative energy technologies increasing decarbonisation efforts and strengthening environmental objectives.

4.8.2. Implications for public transport

To gain an insight into the possible carbon emissions saved by producing hydrogen using the WtH technologies the kg CO_2-eq of kilometres travelled by a conventional diesel bus and a FCEB were compared.

The GWP results (kg CO_2-eq / kg H_2) from this study for Scenarios 1 to 5 were matched with a double decker FCEB. The Wright bus (StreetDeck Hydroliner, Wrightbus.com) was chosen as the example with a hydrogen tank capacity of 27 kg and an operating range of 402km (250 miles). For Scenarios 1-4, the unit distance emissions are 0.33-0.44 kg CO_2-eq/km when the whole bus is considered, and for Scenario 5, it is 0.89 kg CO_2-eq/km This is compared to 1.62 kg CO_2-eq/km for an average local diesel bus (BEIS, 2021a).

To allow for comparison with other modes of transport, emissions are often measured based on the occupancy for passenger vehicles in the form of kg CO_2-eq passenger-km (or -mile). The average bus carries 13 passengers based on the local bus data from the UK Government (BEIS, 2021a). In this case, for Scenarios 1-4, the emissions are 0.022 to 0.035 kg CO_2-eq per passenger-km, whilst it was 0.13 kg CO_2-eq per passenger-km for an average local diesel bus (fig. 4-12). When considering a single decker FCEB such as the Van Hool A330, with a range of 350 km and a hydrogen storage tank of 38.2 kg is in the range of 0.043 to 0.056 kg CO_2-eq per passenger-km (Vanhool.be). This is on average 63% less than a conventional diesel fuel local bus. This result has implication for public transport which is currently one of the highest emitters in Scotland and could help reach the zero emissions target set by the Scottish government for 2045.

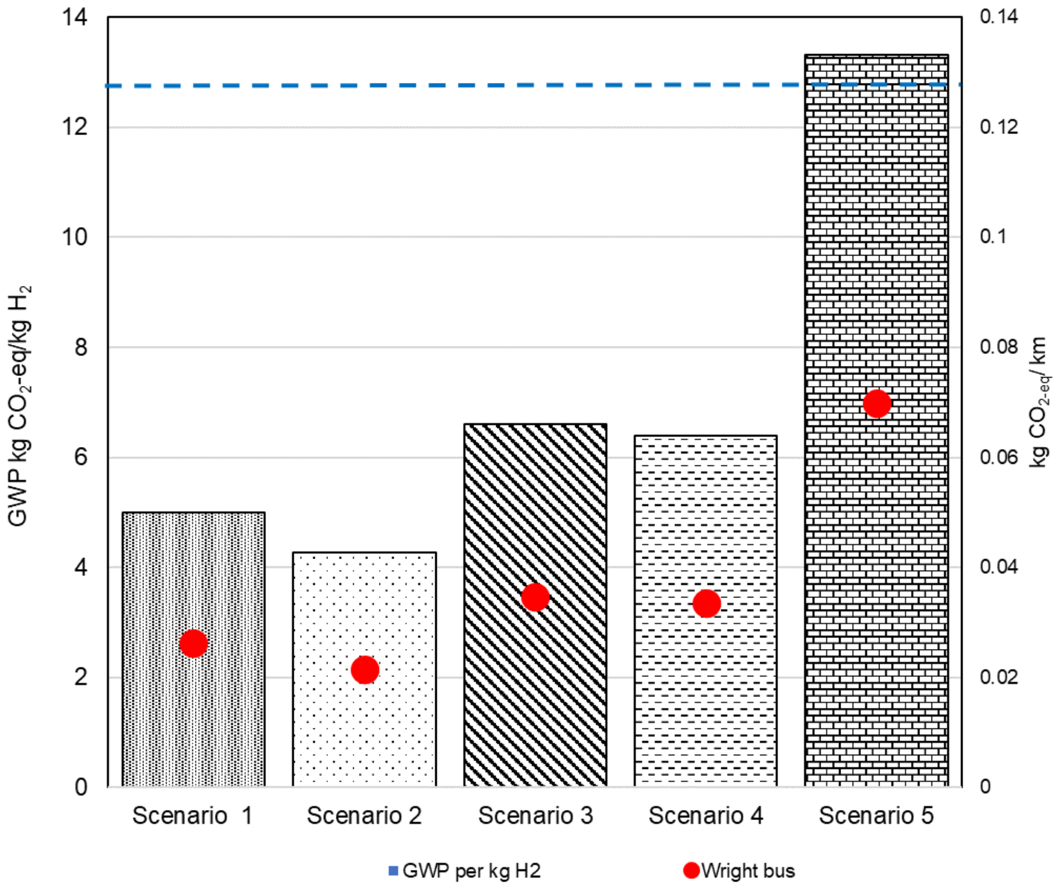

Fig. 4-12. Graph of kg CO_2-eq/km for passenger occupancy, comparing Scenarios 1-5 to a diesel bus.

Providing an option for hydrogen supply in a central location with high population density and high public transport use could benefit the communities in terms of improving health and convenience. A transport hub located in a large city in the central belt of Scotland would provide strategic advantage for the implementation of hydrogen in Scotland. The demand for hydrogen systems could be met by a fleet of FCEBs. FCEB projects already exist in UK cities such as Aberdeen, London, and Birmingham.

Whilst a FCEB is zero emission and does not produce air pollutants when operating, a WtH facility would be located within the city (to reduce travel distance of waste and product) and would still impact the environment for the local population.

Systems like those proposed in Scenarios 1-5 could help establish Glasgow as a hub for fuel cell vehicles and zero emission vehicles by providing HRS along with onsite production. The results suggest that the HRS could add 0.68-1.24 kg CO_2-eq per kg H_2 (Scenarios 1-4) at 3-30% of the total CO_2-eq emissions. This does not account for the landfill and incineration emissions saved, the benefit to the consumer would still present. Similarly Shayegan et al.,(2009) discussed the lack of hydrogen refuelling infrastructure causing limitations to growth of the hydrogen industry. Therefore, a refuelling hub could encourage support and further investment for WtH projects.

There is a reliance on support from policies to increase interest from industries and communities, and an expectation for system cost reductions with hydrogen infrastructure developing at larger scales (commercial/industrial). Technological advancements and further research to improve novel technologies such as WtH will provide additional opportunities and situation specific alternatives.

4.9. Conclusions

The results of this work indicate the carbon saving potential of WtH technologies; gasification and dark fermentation and photo fermentation technologies with GWPs of 4.3 to 4.9 kg CO_2-eq/kg H_2 and 6.4 to 6.6 kg CO_2-eq/kg H_2, respectively. When considering public transport, the WtH scenarios were 0.33-0.44 kg CO_2-eq/km as compared to 0.89 kg CO_2-eq/km for SMR-based scenario for unit distance emissions.

The carbon footprints of hydrogen production for MSW gasification and dark fermentation were about 30% to 50% less than that for SMR. WtH for sustainable waste management increases the carbon savings potential as an alternative to landfill and incineration. When decarbonisation is the focus of hydrogen production and waste disposal, WtH provides an interesting option for consideration.

Further progress on WtH processes relies on investment, recognition, and support for the transition from fossil fuel-based technology to a low carbon alternative, as well as the double benefit of utilising waste and converting it to a valuable resource. Decarbonising the transportation system and finding a zero-emissions fuel replacement for petrol, diesel and natural gas has been discussed as has the potential role of WtH.

Chapter 5 Cost Benefit Analysis of WtH systems

This chapter details the economic analysis method for the five scenarios (gasification, fermentation and SMR) to assess potential feasibility, profit and project success. Some of content from this chapter has been published Lui et al., (2022a).

5.1. Introduction

The aim of this work is to evaluate the techno-economic feasibility of select WtH systems with waste data from Glasgow. The analysis compares three systems for utilising waste and hydrogen production: gasification and fermentation using waste as feedstock, and SMR using natural gas. The SMR system is the leading hydrogen production method currently used in the UK and is included as a means for comparison. The economic feasibility is determined using cost benefit analysis (CBA) with a sensitivity analysis to identify the most significant factors. This study, as the first to publish research on utilising waste data from Glasgow for an economic assessment of WtH technology, provides an insight into the potential untapped cost benefits of waste. It also demonstrates how implementing a WtH system within Glasgow could provide an alternative waste management option with potential to reduce the economic burden to the city. The influences of policy support, potential limitations, and the outlook for WtH related to the economic feasibility are discussed in Chapter 1 as well as in the Chapter 8.

5.2. Methodology

The economic variables associated to each system were gathered and categorised into the main classifications. The variables include costs such as capital, fixed and variable operating costs, carbon emissions taxes and income from the sale of hydrogen. Capital expenditure (CAPEX) consists of the total installed plant cost including materials, utility connections, project design procurement and construction (Eq. 13). CAPEX also includes the total capital requirement which consists of interest during construction, start-up costs, working capital, spare parts cost, feedstock storage and hydrogen storage, feedstock conversion system, gas cleaning system and gas separation system. Operational expenditure (OPEX) includes the fixed operations costs of labour, admin, maintenance, overheads, utilities, insurance, local taxes and fees (Eq. 14). Variable operations costs include energy requirements such as electricity and other operation and maintenance costs include feedstock collection and handling, pre-treatment, handling operating costs, material transportation, chemicals, bed materials, catalysts, and processing of the syngas. Costs for externalities such as those for climate change and human health, pollution and emissions costs are not included (Valente et al., 2019a).

Capital and operation costs of a gasification plant vary depending on the size (MW) and processing requirements of feedstock, the syngas composition required and consequently the complexity of the plant and the individual components. Capital costs include machinery, equipment and buildings.

The UK and Scotland apply a tax as part of the approach to encourage reductions in carbon emissions, to energy intensive industries that produce CO_2 through their activities. The UK ETS is an emissions trading scheme intended to set a cap for net zero carbon cap and market trade measure to control and limit carbon credits, implemented after Brexit in January 2021 (BEIS, 2021b). The UK Carbon Emissions Tax (UK ETS) is set at £16 per tonne of CO_2-eq (Scottish Government, 2020b). The scheme has replaced the EUs emissions tax which controlled the supply of carbon credit to energy intensive industries and power generation sectors with significant carbon emissions. The Carbon Price Support (CPS) has been implemented to tax the power sector in addition to the UK ETS. The CPS is set to £18 per tonne CO_2 as a carbon price floor (HM Customs and Revenue, 2016). Both types of tax have been included in this study and are shown in Eq. 15.

It has been noted that UK government subsidies (*e.g.*, Renewable Transport Fuel Obligation) are currently available for energy suppliers, though unfortunately do not apply to not hydrogen production (Department for Transport, 2021b). These subsidies may become applicable in future and will worth including in future studies when discussing the potential profit of WtH technology. As they do not currently apply, they are excluded from this study.

The data for the system costs and benefits for the modelled scenarios were sourced from researched papers, published articles, available industrial online resources, UK and Scottish government reports. This includes the costs (CAPEX, OPEX and tax), as well as technical data for the gasification and fermentation process flows (yield, inputs, outputs, energy requirements), and technical diagrams (system performance and efficiency).

Hydrogen production yields (kg H_2) and rate (kg H_2/hr) calculated for profit prediction are in Table 3-3.

$$\text{CAPEX} = PDev + \ Con + Inf \tag{13}$$

Where PDev are predevelopment costs such as planning, Con is the construction cost and Inf is the infrastructure cost over the lifetime of the project.

$$\text{OPEX} = OMF + OMV + OMO \tag{14}$$

Where OMF are the fixed operational and maintenance costs, OMV are the variable operational and maintenance costs and OMO are the other operation and maintenance costs associated with the project such as insurance and systems costs over the lifetime of the project.

$$\text{Total TAX} = \ \text{UK ETS} + \text{CPS} \tag{15}$$

Where UK ETS is the UK carbon emissions tax and CPS is the carbon support price, over the lifetime of the project.

The source of the cost calculations for the gasification technology are taken from ARUP (2016) report in which classified as an Advanced Conversion Technology (ACT). ACT is in the standard subcategory within 2020s cost prediction, which encompasses technologies that produce syngas used for combustion or to generate electricity or heat. Calculations are based on a single, one-of-a-kind unit. The feedstock for ACT is comprised of MSW, SRF, RDF and biomass, though the report does not provide details on the quantities or exact composition, therefore these are assumed and edited according to the scenarios in this study.

The ARUP report uses MW of the technology to calculate the cost of CAPEX and OPEX for a facility and therefore can be adapted to fit gasification technologies using waste and biomass feedstocks for hydrogen production. The MW was calculated using factors such as the volume of waste, efficiency of the technologies involved and LHV of hydrogen (120 MJ/kg). The costs are in GB pound per MWh or MW and applied to each technology. The BSUoS (Balancing System Use of System) is a cost charged to the generator. The UoS

(Use of System) are the costs for connecting to and using the transmission network, which are averaged for UK generation (ARUP, 2016).

Costs for the fermentation scenarios (dark fermentation and combined dark and photo fermentation, respectively) are modified from Randolph and Studer (2017) (Table 5-1). The cost data were based on hydrogen production (kg) per day in USD and then adapted to GBP considering the effect of inflation from year 2007. The data was also modified to account for hydrogen production yield as the report stated a value of 50,000 kg/day for the original study which is approximately 9 times that of the current work. The costs for the SMR technology were calculated based on the IEAGHG (2017) report and a currency conversion was applied to convert EURO to GBP. The report stated a base case cost value based on feedstock conversion rate of 26.23 tonnes/hour which is 13 times that of this study and calculated as cost per MW or MWh (Eq. 12).

The data for the SMR scenario is adapted from the IEA GHG technical report on SMR-hydrogen plant (2017). The cost of natural gas feedstock is 0.465p/kWh (UK Government, 2020).

The costs of electricity consumption, included in the variable O&M costs, were calculated using the current cost of electricity sourced from the UK grid and the electricity consumption for the scenarios. The electricity price was obtained separately, sourced from the UK Government non-domestic fuel price list for the industrial sector, is stated as 0.775p/kWh (BEIS, 2020). The electricity consumption processes for the different scenarios are listed in Table 3-2 and their electricity requirements corresponding to the feeding rate (Table 3-3) were calculated using GaBi software (gabi.sphera.com).

Table 5-1. Economic parameters for gasification, fermentation and SMR modified from ARUP (2016), Randolph and Studer (2017) and IEAGHG (2017) respectively.

CBA	Unit	Gasification	Fermentation	SMR
Total CAPEX	GBP mill/MW	6.5	3.853	1.152
Pre-Development	GBP mill/MW	0.18	N/A	N/A
Construction	GBP mill/MW	6.2	N/A	N/A
Infrastructure	GBP mill/MW	0.12	N/A	N/A
Total OPEX	GBP mill/MW	3.506	4.394	0.231
Fixed O&M	GBP mill/MW	0.227	0.73	0.022
Variable O&M	GBP mill/MWh	2.795	3.663	0.209
BSUoS	GBP/MWh	1.9	1.9	1.9

Insurance	GBP mill/MW	0.055	31,407	31,407
UoS	GBP mill/MW	0.013	12,921	12,921

A project operational lifetime of 25 years (plus 2 years construction) is used in this study. Plant availability is determined by using the capacity factor as plant availability over a certain period of time, here assumed to be 90%. The calculations and results use Great British Pounds (GBP £) and have been converted where necessary and inflation rates have been incorporated.

The focus of WtH processes for this study is the production and sale of hydrogen therefore the by-products from gasification and fermentation are not included and it is assumed they are disposed of in landfill. The costs of this disposal are part of the OPEX listed in Table 5-1. By-products include biochar and digestate which has potential for use in agriculture for use as a soil enhancer. The potential of the by-products is discussed further in Chapter 8.

Gate fees are the cost or charge given to waste when accepted to the processing site determined by the developer. The gate fees are not included as a source of income in this project due to the variability in price in the UK with the predicted trend in decreasing prices as demand for waste increases. Increased plant projects and competition for waste Other waste to energy processes (such as combustion for electricity generation) is increasing competition for waste as a resource (ARUP, 2016). The analysis also does not include waste disposal after conversion, the cost of transport to and from the facility or fuel cells, refuelling stations, vehicle conversion (installing fuel cells into vehicles), long-term hydrogen storage, manufacture markup, or warranty.

A sensitivity analysis was conducted as part of the cost assessment using a Monte Carlo simulation to identify the uncertainty of key parameters. The results allow the identification of the parameters involved in reducing the overall costs for the scenarios. The simulations were run 1000 times, using random number calculations with the maximum and minimum boundaries stated in Table 5-2. Eight input variables were analysed with high, mean and low values representing the variations set at ±20%.

Table 5-2. Summary of the variables with low, mid, high values involved in calculating the LCoH, NPV and BCR.

Variables		CAPEX (GBP)	OPEX (GBP)	TAX (GBP)	Waste input tonnes/hr	H_2 production rate tonnes/hr	Operational days (lifetime)	Operational hr/day	Selling price (GBP)
S1	Low	1.28×10^8	1.58×10^8	2.44×10^7	16.90	1.418	8295	21.8	2.40
	Mean	1.60×10^8	1.97×10^8	3.05×10^7	21.12	1.772	8710	22.9	3.00
	High	1.92×10^8	2.37×10^8	3.66×10^7	25.34	2.127	9125	24.0	3.60
S2	Low	4.47×10^7	4.81×10^7	1.00×10^8	4.45	0.206	8295	21.8	2.40
	Mean	5.59×10^7	6.02×10^7	1.25×10^8	5.56	0.258	8710	22.9	3.00
	High	6.71×10^7	7.72×10^7	1.50×10^8	6.67	0.309	9125	24.0	3.60
S3	Low	2.24×10^7	1.84×10^7	1.12×10^6	19.83	0.183	8295	21.8	2.40
	Mean	2.80×10^7	2.30×10^7	9.00×10^7	24.79	0.229	8645	22.9	3.00
	High	3.36×10^7	2.76×10^7	1.35×10^7	29.75	0.274	9125	24.0	3.60
S4	Low	3.30×10^7	1.17×10^7	1.16×10^7	19.83	0.243	8295	21.8	2.40
	Mean	4.13×10^7	1.47×10^7	1.45×10^7	24.79	0.305	8477	22.9	3.00
	High	4.95×10^7	1.76×10^7	1.74×10^7	29.75	0.365	9125	24.0	3.60
S5	Low	1.36×10^7	6.55×10^7	3.38×10^7	1.70	0.341	8295	21.8	2.40
	Mean	1.70×10^7	8.19×10^7	4.22×10^7	2.13	0.426	8710	22.9	3.00
	High	2.05×10^7	9.83×10^7	50.7×10^7	2.56	0.511	9125	24.0	3.60

The actual selling price of hydrogen is at the discretion of each individual energy production company and therefore there are difficulties in determining potential profit. For this study the selling price has been set at a base value of £3 with an increase of 20% for maximum (£3.60) and decrease of 20% to a minimum price (£2.40). The selling price value chosen ensures a positive Levelised Cost of Hydrogen (LCoH) for each scenario. Consequently, a general trend for profit is presented with additional data support from the NPV and BCR results.

The yield of hydrogen is included as the source of revenue and used to calculate potential profit. The kg/H_2 is shown in Chapter 3, Table 3-3 and varies according to the production technology and type and energy density of the feedstock.

5.3. CBA Equations

The following equations of Benefit Cost Ratio (BCR), Net Present Value (NPV), Internal Rate of Return (IRR) and Levelized Cost of Hydrogen (LCoH), are used in the CBA to determine the profitability and economic benefit of each scenario. The results can be used as a comparison tool between different scenarios and with other studies.

The BCR is the ratio between the assigned costs and benefits from a project and indicates the value for money by assessing this relationship, shown by Eq. 16. Benefit of a project is considered as income and costs are the expenses associated with the project.

$$\text{BCR}=\frac{\text{Income}}{\text{CAPEX}+\text{OPEX}+\text{TAX}} \tag{16}$$

The NPV is a widely used economic valuation technique (Žižlavský, 2014). It determines the worth of a project over the lifetime including a construction phase, usually given in years, which is discounted to the present and the required investment. This is displayed in Eq. 17.

$$\text{NPV}=\sum_{N=0}^{N=final}\frac{R_t}{(1+i)^N} \tag{17}$$

Where R_t is the net cash flow inflows minus outflows during the time period, i is the discount rate or return earned in alternative investment, t is the number of time periods and N is the discount rate in percent. The discount rates used are in the range of 2%, 5% and 10%.

The IRR estimate the profitability of a project or investment with a higher IRR value indicating a more desirable the investment. It can be used as a comparison tool when making investment decisions. The IRR is determined using Eq. 18.

$$0=NPV=\sum_{t=1}^{T}\frac{C_t}{(1+IRR)t}-C_0 \qquad (18)$$

Where C_t is the net cash inflow during a time period t, C_0 are the total initial investment costs.

The LCoH is an estimation of the price of the product, in this case kilogram of hydrogen, calculated from the annual cost of hydrogen production, summation of investment and manufacturing cost (Shahabuddin et al., 2020). The LCoH calculation is based on the levelized cost of energy (LCoE) from IRENA (2012) and uses constant prices for costs such as maintenance and a constant operating capacity for the plant lifetime. In this study LCoH is used as a comparison analysis tool between the different technologies, shown in Eq. 19.

$$LCoH=\frac{\sum_{t=1}^{n}\frac{I_{t+}M_t}{(1+r)^t}}{\sum_{t=1}^{n}\frac{E_t}{(1+r)^t}} \qquad (19)$$

Where I_t is the investment cost for year t, M_t is the maintenance cost for year t, E_t is the energy generation in the form of kg hydrogen for year t, r is the discount rate, set at 5% and n is the lifetime of the plant (Bui et al., 2021).

A list of variables and variables used to calculate the economic indicators provide the basis for the assessment on the economic viability of each Scenario (1 to 5) are in Table 5-2.

The economic feasibility of each scenario is considered by comparing the CBA results firstly with Scenario 5 SMR technology, as the leading hydrogen production technology, but also with other published results.

5.4. Results and Discussion

The CBA results show total costs with the range of costs associated with each technology and for the five scenarios, in Fig. 5-1 and Table 5-3. CAPEX is divided into pre-development costs, construction, and infrastructure costs. OPEX is divided into fixed, variable, BSuS, UoS and insurance costs as defined by ARUP (2015). Parameters with the most impact on the total cost can be identified.

Gasification with MSW feedstock (Scenario 1) shows a total lifetime cost of approximately 388 million GBP which is significantly more (2.7 times) compared to the conventional SMR (Scenario 5) total cost of over £141 million (Table 5-3). The lowest total cost scenario when not considering hydrogen yield, is from dark fermentation of wet waste at approximately £62 million. Scenario 3 is 55% of the cost of combining photo fermentation with dark fermentation (Scenario 4) whilst producing 78% the hydrogen yield.

CAPEX is the highest expenditure for fermentation scenarios while OPEX is the highest expenditure for gasification technologies and SMR. High OPEX costs are related to energy requirements and in the case of SMR the cost of natural gas feedstock. Utilising waste avoids this extra cost until the value of waste changes. High CAPEX costs are associated with expensive or extensive equipment requirements and infrastructure which are higher for immature technologies.

Table 5-3. Summary table of costs (CAPEX, OPEX and TAX) in GBP for Scenarios 1 (MSW gasification), 2 (waste wood gasification), 3 (wet waste dark fermentation), 4 (wet waste dark and photo fermentation) and 5 (natural gas SMR). A breakdown into subcategories is included in italics under each main category with the overall scenario calculated total cost at the bottom of the table.

Stage	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Total CAPEX	160,095,000	55,965,000	28,020,057	49,564,679	17,074,042
Pre-Development	*4,433,400*	*1,549,800*	-	-	-
Construction	*152,706,000*	*53,382,000*	-	-	-
Infra-structure	*2,955,600*	*1,033,200*	-	-	-
Total OPEX	197,581,161	60,211,299	23,012,963	48,193,365	81,924,318
Fixed O&M	*5,592,709*	*1,955,064*	*5,311,690*	*9,395,849*	*282,276*
Variable O&M	*180,061,522*	*54,086,895*	*14,372,379*	*34,137,985*	*75,488,561*
BSoS	*10,248,543*	*3,582,621*	*3,008,403*	*4,210,932*	*5,321,919*
Insurance	*1,363,763*	*476,736*	*227,073*	*317,839*	*708,182*
UoS	*314,624*	*109,984*	*93,419*	*130,761*	*163,379*

Total TAX	30,504,698	9,123,091	11,252,850	14,512,766	42,291,634
UK ETS	*14,355,152*	*4,293,219*	*5,295,459*	*6,829,537*	*19,902,887*
CPS	*16,149,546*	*4,829,871*	*5,957,391*	*7,683,229*	*22,390,748*
Total Cost lifetime	388,180,859	125,299,390	62,285,870	112,270,811	141,291,955

The current high cost of gasification has been well documented compared to the relatively low cost of fermentation technologies (Nikolaidis and Poullikkas, 2017). These results suggest the same range of costs for WtH technologies applies when using Glasgow to supply the volume and composition of waste.

The cost of hydrogen production is dependent on yield and efficiency of the technology. However, when other factors such as tax are extremely high this has a significant effect on the total cost. With the expected tax increase in line with the toughening of climate change targets the factors will become more important for the economic viability of fossil fuel-based production systems, such as grey hydrogen.

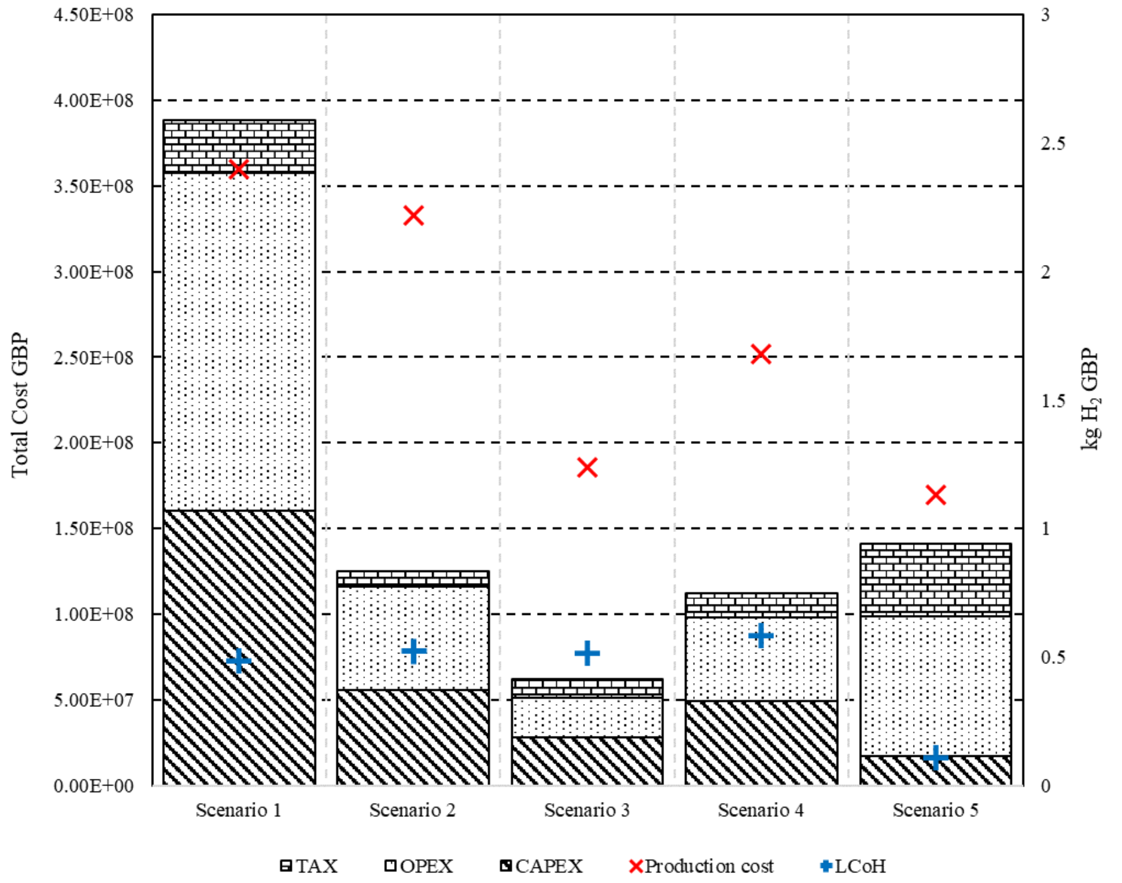

Fig. 5-1. Total project cost with CAPEX, OPEX, and Tax for Scenarios 1-5 are displayed for comparison.

Results comparing the economic indicators as average values for BCR, NPV, IRR and LCoH (Eq. 16-19 respectively) of Scenarios 1- 5 are in Table 5-4. There is no direct correlation between the total cost and LCoH, as seen in Fig. 5-1, where a low total cost does not imply a low LCoH.

The gasification scenarios have the highest production cost values of 2.4 GBP and 2.3 GBP for Scenarios 1 and 2 respectively. Scenario 1 has the lowest value of WtH technologies at 0.92 GBP because of the high total cost of the system. The LCoH values of the fermentation Scenarios (3 and 4) are impacted by the low hydrogen production yield even with the lowest total costs of the WtH systems. The total cost of SMR (Scenario 5) is higher than the fermentation scenarios mainly due to the large tax (UK ETS and CPS) imposed on the production method.

Table 5-5 compares these results with other studies. The gasification scenarios when compared with Shahabuddin et al., (2020) who calculated LCoH from biomass with a range of 1.02-3.50 GBP/kg H_2. (2.3-5.2 USD/kg using conversion rate of 0.78 GBP) are just below this. No comparisons could be made for the LCoH of Scenario 3 and Scenario 4 due to the lack of data. The production cost of 2.22 GBP/H_2 kg for Scenario 2 is sightly higher than the range of 0.75-2.06 GBP/H_2 kg for biomass gasification identified by Bui et al. (2020). Comparison of dark fermentation data by Nikolaidis and Poullikkas with Scenario 3 shows a difference in production cost of 0.13 GBP/kg H_2 and a difference of 0.22 GBP/kg H_2 between dark and photo fermentation and Scenario 4 (Nikolaidis and Poullikkas, 2017). The production cost for S5 is similar to the findings for SMR from IEAGHG (2017) of 1.68 to 1.5-1.6 kg/H_2, though the LCoH of 0.23 is much lower than 1.72 from Valente et al.,(2019b).

Table 5-4. Summary table of economic indicators averaged for Scenario 1-5.

Economic indicator	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
BCR	1.25	1.35	2.29	3.45	1.98
NPV (£)	2.22×10^9	7.87×10^8	7.47×10^8	1.02×10^9	1.36×10^9
IRR	19.25	20.67	27.34	32.71	24.19
LCoH (£)	0.49	0.52	0.52	0.59	0.11

The NPV for all Scenarios (1-5) are positive which indicates that all scenarios will make a profit using these input parameters (Table 5-4). The IRR results are above 19% for all scenarios, indicating attractive investment projects. The BCR values are above 1 for all scenarios. The fermentation-based technologies (Scenarios 3 and 4) have the highest BCR values due to the lowest total cost and demonstrating that the benefits strongly outweigh the costs.

Fig. 5-2 show a plot of profit using a range of selling prices in 25 pence increments. The hydrogen production price per kg (H_2 £/kg) shows the potential economic benefit from WtH hydrogen production using Scenarios 1-5. The plot also shows differences in the gradients of the trend lines for each scenario and indicates which technologies have potential for highest profit. The thermochemical WtH technologies (Scenario 1 and 2) have the highest breakeven points whilst the biochemical technologies (Scenarios 3 and 4) have the lowest breakeven point as expected. Scenario 1 (gasification of MSW) has the steepest gradient indicating the sharpest increase in profit of 4,900 GBP per 25p price rise, greater than the next steepest WtH technology of Scenario 4 (dark and photo fermentation) at 1,827 GBP per 25p. The SMR technology (Scenario 5) has a rise of 2,300 GBP per 25p, the second highest of the five scenarios, with the second lowest breakeven point. Scenario 3 has the least capacity for increases in profit, most likely due to low hydrogen production rates (1,500 GBP per 25p price rise).

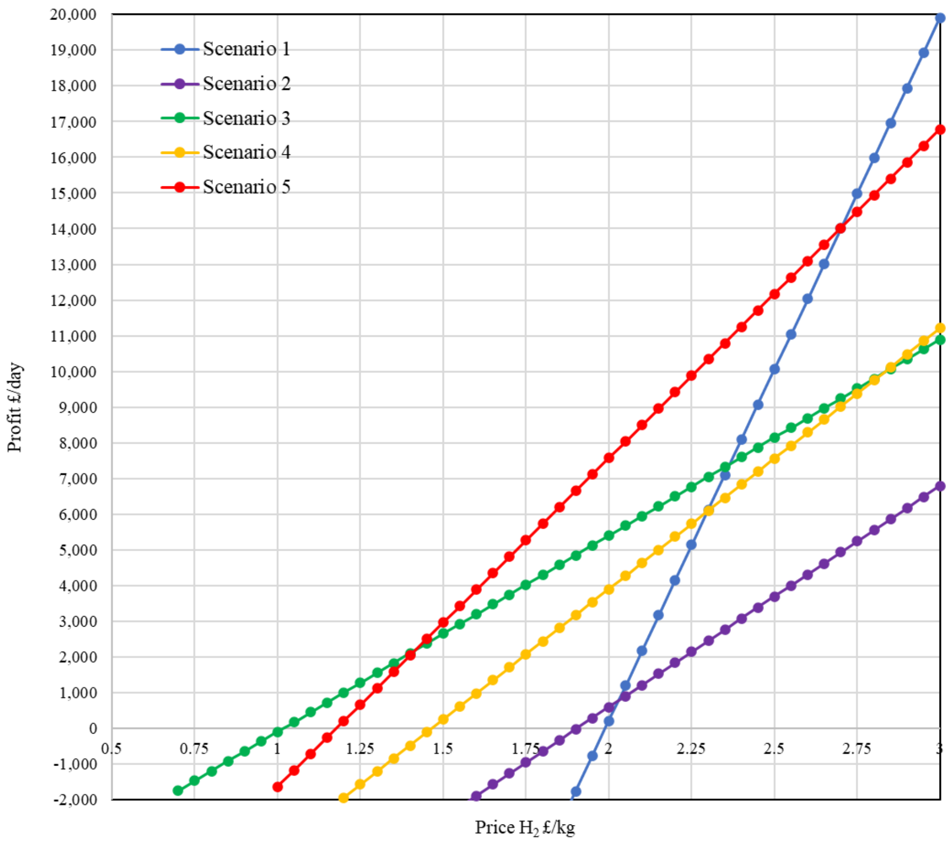

Fig. 5-2. Potential profit trends for Scenarios 1-5 at a range of hydrogen selling prices. The zero profit GBP/day point represents the breakeven point.

Table 5-5. Cost comparison table with results of cost analysis from Scenarios 1-5 with other research studies. Currency conversion symbol * is 1 USD to 0.73 GBP, and “ is 1 EUR to 0.85 GBP.

Process	LCoH £/ kg H_2	Production cost £/kg H_2	Conditions	Reference
Scenario 1	*0.49*	*2.40*	*MSW*	*This study*
Waste Gasification	1.02-3.50*	-	MSW, residual	Shahabuddin et al., (2020)
Waste Gasification	-	2.23	100 dry t/hr,	Ng and Phan (2021)
Scenario 2	*0.52*	*2.22*	*Waste wood*	*This study*
Biomass Gasification	-	4.19-5.74*	10t/day feed	Dowaki et al., (2007)
Biomass Gasification	1.6-3.79*	-	10MWth scale	Shahabuddin et al., (2020)
Biomass Gasification	2.04-2.48*	-	250MWth scale	Shahabuddin et al., (2020)
Biomass Gasification	-	1.29-1.49*	Woody, steam	Nikolaidis and Poullikkas (2017)
Biomass Gasification	-	8.07-10.83"	S/B ratio 1.5	Sara et al., (2016)
Biomass Gasification	-	2.26*	FB reactor, 16.3 t/t H_2	Salkuyeh et al., (2018)
Scenario 3	*0.52*	*1.24*	*Wet waste/ sludge*	*This study*
Dark Fermentation	-	1.87*	Organic biomas	Nikolaidis and Poullikkas (2017)
Scenario 4	*0.59*	*1.68*	*Wet waste/ sludge*	*This study*
Photo Fermentation	-	2.06*	Solar source	Nikolaidis and Poullikkas (2017)
Photo Fermentation	-	<1.46*	-	Dincer and Acar (2015)
Scenario 5	*0.11*	*1.68*	*Natural gas*	*This study*
SMR	1.72*	-	Natural gas	Valente et al., (2019)
SMR	-	1.5-1.6	Natural gas	IEAGHG, 2017
Fossil fuel reforming	-	0.54*	Natural gas	Dincer and Acar (2015)

5.5. Sensitivity Analysis results

The results of the sensitivity analysis using Monte Carlo simulation for the CBA are displayed as triangular distributions for BCR, NPV and LCoH in Figs. 5-3, 5-4 and 5-5 respectively with the calculated mean and standard deviation. The distributions show the significance of the input variables to each of the economic factors. It is observed that the values for all scenarios did not become negative and are robust.

The NPV for gasification technologies (Scenarios 1 and 2) are most sensitive to changes in CAPEX and moderately sensitive to the effects of OPEX. This is associated with less developed, immature, high-cost systems. The lower hydrogen yield of MSW gasification compared to waste wood gasification shows the impact of higher energy density feedstock, and the sensitivity of MSW to conversion rates.

The sensitivity analysis suggests that dark and photo fermentation technologies (Scenarios 3 and 4) are moderately sensitive to low hydrogen production rates, shown by the low peak in LCoH (Fig. 5-5). The analysis does not account for the demand for hydrogen and therefore the potential profit that could be expected in a competitive market.

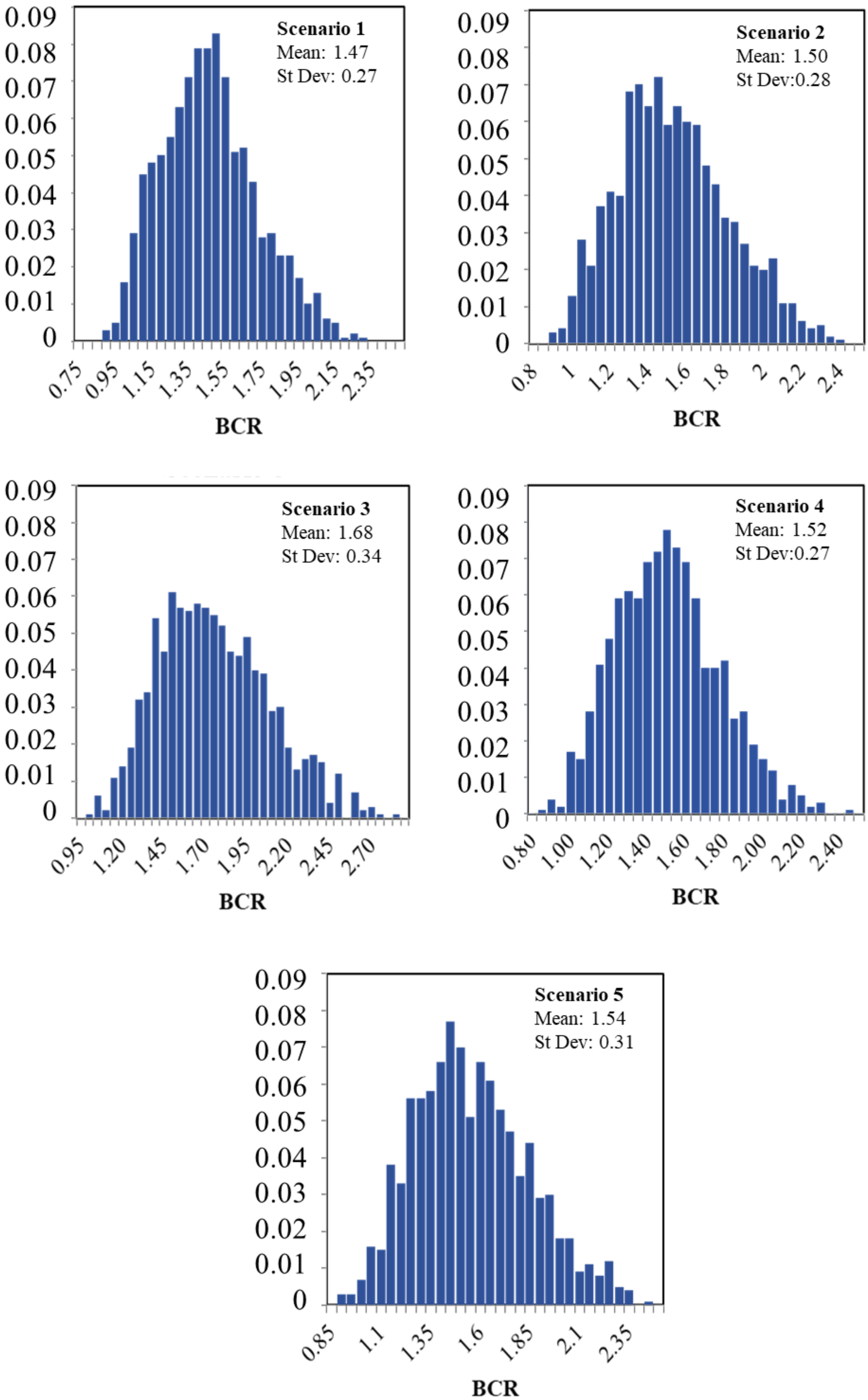

Fig. 5-3. The distributions of BCR from Monte Carlo Simulations for Scenarios 1 to 5

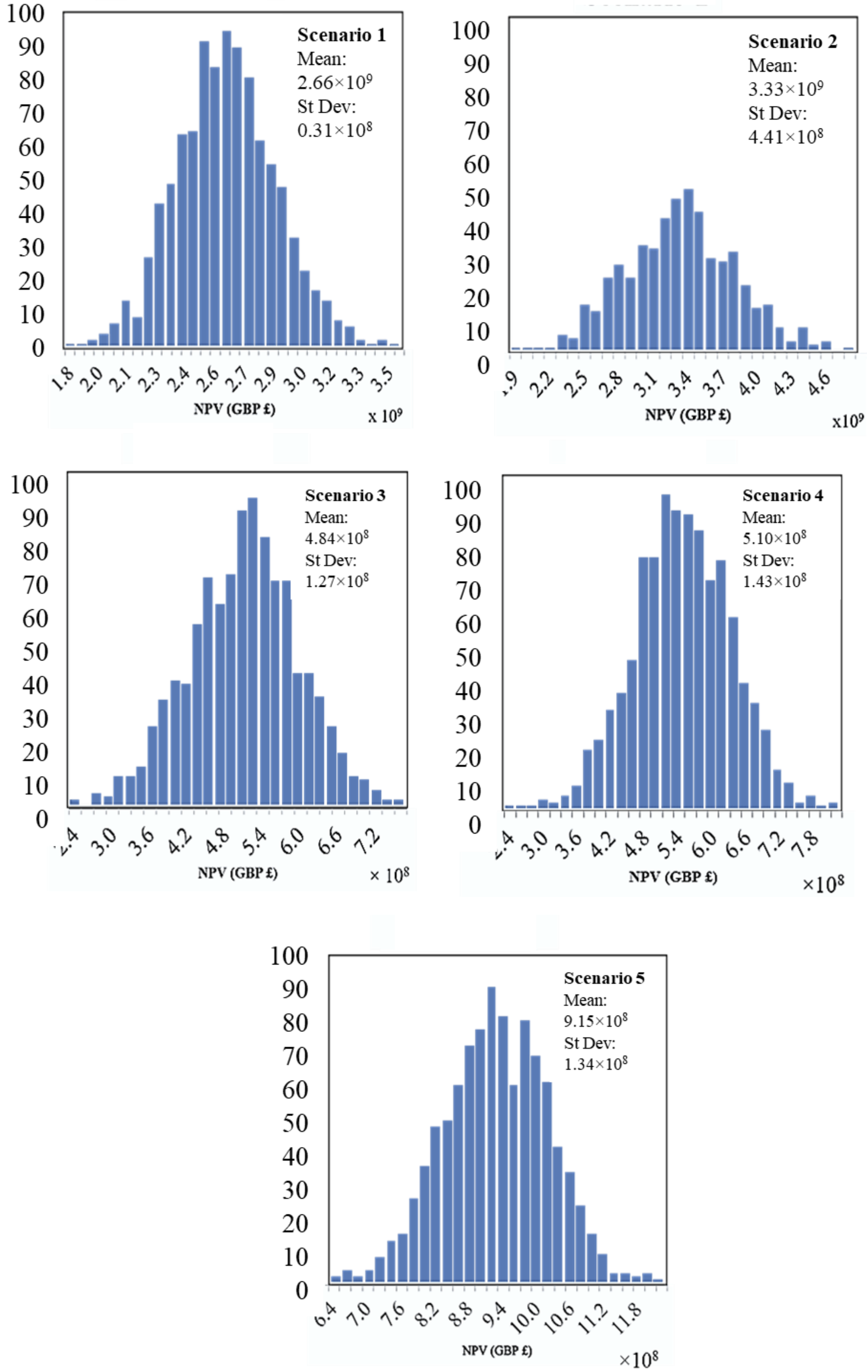

Fig. 5-4. The distributions of NPV from Monte Carlo simulations for Scenarios 1 to 5.

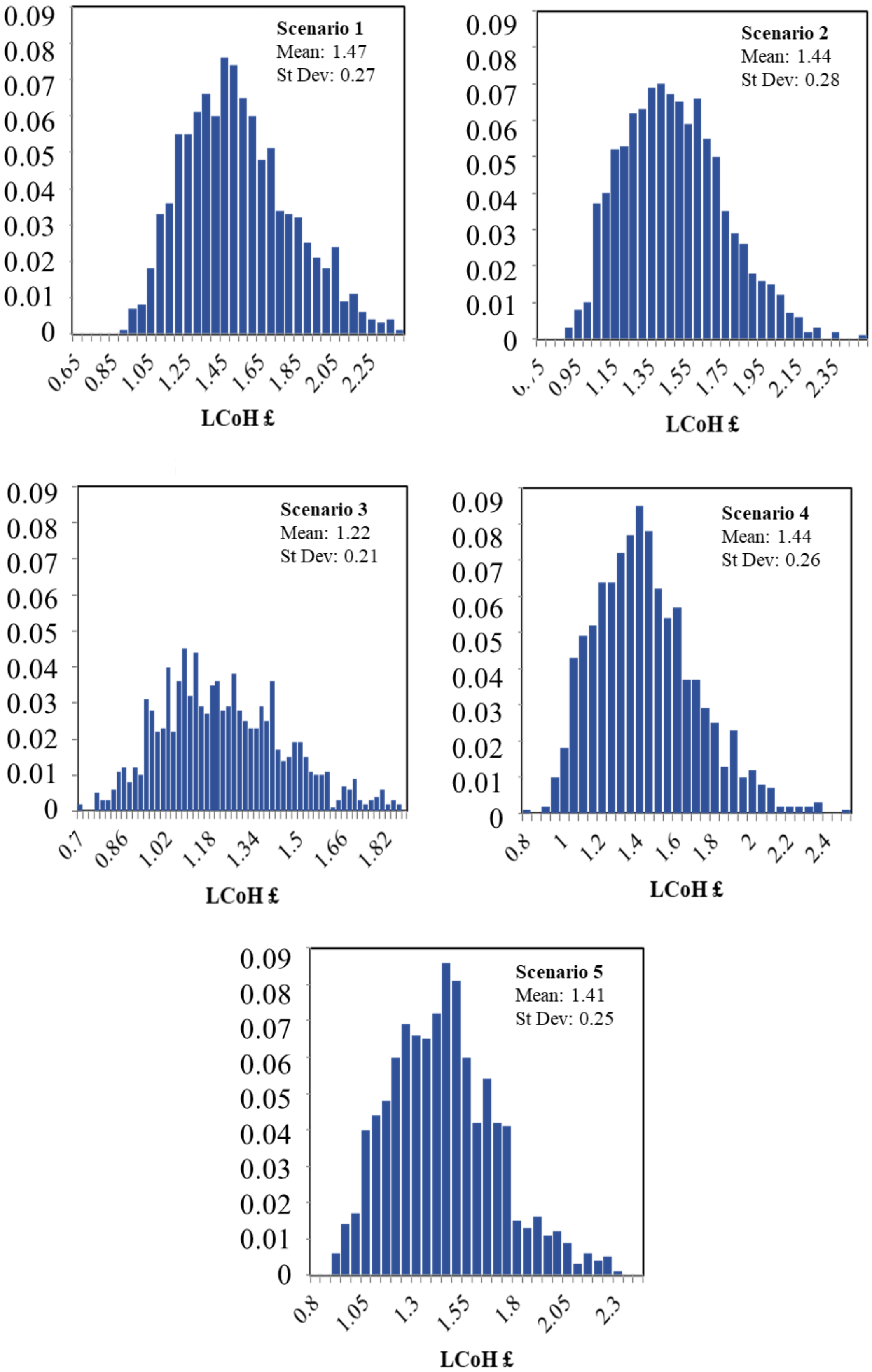

Fig. 5-5. The distributions of LCoH from Monte Carlo Simulations for Scenarios 1 to 5.

5.6. Discussion

The cost analysis suggests all thermochemical and biochemical Scenarios (1-5) would be economically feasible with positive economic indicators based on the input data. The projects represented by the scenarios would rely on securing the start-up investment (CAPEX) for the feasibility to be possible, otherwise the economic potential for the WtH technology is limited. Implementation of the carbon tax supports the WtH projects and penalises the fossil fuel technologies such as SMR. Combining the SMR technology with carbon capture and storage systems may become more favourable due to the reduced tax implications, though is reliant on consistently the low cost of natural gas.

5.6.1. Economic limitations

The limitations associated with WtH technologies arises from the immature status of this type of waste conversion method with hydrogen as the main product. Sikarwar et al., (2017) stated the main barrier to widespread uptake is the cost of hydrogen. The hydrogen industry, investors, stakeholders, and policy makers require a reduction in market uncertainty and benefit from a competitive hydrogen price, ideally from renewable sources. Baykara (2018) discusses the future of biomass as a fuel with hydrogen production in mind and concluded it is not cost competitive presently.

The use of MSW as feedstock for gasification hydrogen production is small scale at best and limited in use. Therefore, there is a lack of data or research for use at larger industrial scale projects like those suggested in this study. This has led to assumptions on scaling methods for the data collected from pilot, small-scale or academic research laboratories that do not account for economies of scale. Consequently, there may be over or under estimation for values when scaling to the large industrial size modelled here. Watson et al., (2018) also recognized that the differences in the cost of gasification plants is affected by size (MW), complexity of the plant, feedstock and use of final product. This is related to the immaturity of the technology leading to uncertainties in costs and the estimates that can be applied. Industrial scale operations rely on efficiency improvements and technology advancements for reducing energy losses through conversion, storage materials, compression equipment (Cimpan and Wenzel, 2013). Economic viability is linked to reduced capital costs, with process intensification or integration is required (Thomson et al., 2020).

Uncertainty also exists related to the exact composition of MSW, as it is highly variable and affected by seasonal changes and external factors which may affect hydrogen production yield and consequently income and revenue. The waste values used in this study are averaged over a year from annual reports, whereas a WtH facility would be affected by daily or weekly variations.

5.6.2. Economic opportunities

The profitability of WtH technologies could be increases and further revenue generated from the sale of by-products from syngas and solid residues that could open up alternative markets. Solid by-products from gasification would add value to the system and these include biochar utilized as agricultural additives. Dark fermentation by-products include organic acids and alcohols that can be utilized for recovery or further conversion to biofuels and platform chemicals. Hamedani et al., (2018) suggested the off gas produced could be sold for electricity production and sold the electricity grid, generating extra revenue.

Hydrogen demand is predicted to increase with investment in technological advancement and innovation expected to reduce costs and allow for faster commercial and industrial growth. Therefore, the potential for growth is high and the opportunities for companies to be involved in hydrogen production or equipment manufacturing increases with market demand. Although the Hydrogen Council, policy, support, and investment of around $70 billion up to 2030 is required to scale up (Hydrogen Council, 2021).

The rate of change and development has been slower than could be argued for the benefits WtH could provide. The slow-moving speed of cost reductions and competition from the petroleum industry may be part of the reason.

As the use of fossil fuels to produce hydrogen without the use of CCS is carbon intensive, hydrogen production methods such as SMR are disproportionally expensive in tax. Nikolaidis and Poullikkas (2017) also state the importance of carbon taxes and the direct influence they will have on hydrogen production cost. Alternative low carbon methods therefore have an opportunity to provide hydrogen which, as costs decrease with technology advancements, will become advantageous from a tax point of view.

5.7. Conclusions

Waste conversion technology as a sustainable management method provides an innovative approach to source hydrogen for fuel cell vehicles. The WtH concept can contribute to the energy transition by providing an alternative to reduce reliance on fossil fuel. The four WtH scenarios studied here encompassing gasification, dark and photo fermentation suggest WtH technology is economically feasible when using a cost benefit analysis with waste data from Glasgow. Total costs are relatively high, approximately 3 times higher for MSW gasification than conventional hydrogen production technologies (SMR). High capital costs for the MSW gasification (Scenario 1) and low hydrogen yield for dark and photo fermentation (Scenarios 3 and 4) are the main concerns. When considering taxes, subsidies, and predictions of increased demand for hydrogen, the economic outlook for WtH technology becomes more favourable and the economic feasibility increases.

WtH technology can be harnessed in Glasgow to aid the zero emission targets set by the Scottish government in 2020. Providing clean fuel in the form of hydrogen for transport in the city throughout the public transport system (heavy duty vehicles, such as buses, gritters and refuse trucks) has the ability to be part of the solution.

Chapter 6 Multi-objective optimization

This chapter describes the multi-objective optimisation designed to assess the conflicting aspects of environmental impact and economic viability for the WtH scenarios. The results influence the feasibility assessment of WtH projects.

6.1. Introduction

A multi-objective optimization study aims to provide optimal decisions when looking for a solution for conflicting objectives when considering more than one objective simultaneously. Multi-objective optimisation produces a set of non-dominated solutions as the Pareto Optimal Front from which decision making can provide an optimisation value which aims to satisfy both objective functions (Arora et al., 2017). Each pareto solution is a compromise the of the design functions depending on the objectives set. The solutions above the pareto curve are sub-optimal and can be improved by further optimization while solution below the pareto curve are infeasible (You et al., 2012). The optimized results are then used to assist decision making on the which solution best suits considering the input values and operating conditions. One point on the pareto front can be chosen as the optimal design point chosen by a decision maker. The ideal point or the closest point to it is where the objective functions simultaneously achieve the optimized value.

The solution is nondominated if neither objective function can be improved without degrading the values of the other objective function. The optimization problem has independent variables or design variables. Design variables provide the parameters that can be adjusted to produce the highest or lowest values for the objective function (Anvari et al., 2021).

Genetic algorithms (GA) can be used in multi-objective optimisations are based on an evolutionary theory where robust species have more opportunity for reproduction and passing on their genes to future generations (Chang, 2015). Populations are comprised of a collection of chromosomes. Initially the population is one, and as the process develops the population gets fitter and the solutions converge an optimal individual. If there is no fitness the GA makes a new population and uses two operators: crossover and mutation (Anvari et al., 2021). Offspring generated from crossover are expected to inherit good genes from the parents' chromosomes. Repetition of crossover leads to the good genes increasing in the population to produce an optimal solution. Selection chooses the parent points for the next generation based on scaled values from the function. Mutation occurs at gene level and makes small random changes to individuals in the population to provide genetic diversity. This allows the genetic algorithm to have a broader search space. The termination of the genetic algorithm is when the final population set of point determined.

The aim of the multi-objective optimization for the study is to minimize the total cost and to minimize the environmental impact of a WtH system. The results from the LCA in Chapter 4 provide the data for the environmental objective (GWP) while the CBA in Chapter 5 provides data for the economic objective (total cost in GBP). Both gasification technology Scenarios (1 and 2) and fermentation technology Scenarios (3 and 4) are optimised. As Scenario 5 is the SMR system and not a WtH technology, only included previously for comparison purposes, it will not be included in the multi-objective optimization. Different types of waste are the inputs into each system and hydrogen is the main product.

6.2. Methodology

The steps of the multi-objective optimization involve the design of the objective function, defining the decision variables, bounds and constraints. Different types of constraints that can be applied are bound, linear inequality, linear equality and nonlinear. The multi objective optimization in this study was conducted using MATLAB software and the Genetic Algorithm gamultiobj. The genetic algorithm is considered non dominated if none of the objective functions can be improved in value without degrading other objective function values. All points are considered equally good unless there is additional preference information.

Two objective functions were designed that best represent the main economic and environmental solution to the challenges of WtH systems. The first objective function to be minimized is the GWP of each system calculated using the LCA software GaBi (Chapter 4). The results from GaBi are in kg CO_2-eq units and were calculated using system input and output parameters such as electricity, materials and emissions. The GWP objective includes all WtH processes from pre-treatment to storage of the produced hydrogen and hydrogen refuelling stations (HRS) for the lifetime of the project.

The second objective function of minimizing total cost of the WtH system includes all the costs in the lifetime of the project (25 years) and split into the main categories of CAPEX, OPEX and TAX (Chapter 5, Table 5-2). The costs were calculated using the report by

ARUP (2015) which use the MW of a proposed plant to calculate the costs associated with operating the WtH facility. Total cost is the chosen to represent the economic objective as it does not rely on the selling price of hydrogen or profit unlike NPV and will therefore reduce the assumptions in the data. The decision variables, constraints with reasoning are in Tables 6-1, 6-2 and 6-3.

The study provides multiple solutions representing trade-offs between the objective functions and allows for any understanding into them. As it is possible to have various answers the objective function is developed to finds the relevant variables and selects the optimum ones.

For the first objective is in Eq. 20:

$$Min\ GWP = \sum i\ (a * Pelec * Peff) + (Whr * Peff * PH2)t \tag{20}$$

where a is a constant of 0.3048, Pelec is the electricity requirements (kWh) for all process i for 1 tonne of waste input, Peff is the efficiency for all processes, Whr is the waste available per hour, t is operation time for an expected plant lifetime of 25 years.

The second objective is represented by Eq. 21:

$$Min\ Total\ Cost = \sum i\ CAPEX_t + OPEX_t + TAX_t \tag{21}$$

Where CAPEX represents capital costs including construction, infrastructure, and pre-development, OPEX are the operation costs including fixed and variable costs and TAX includes the carbon taxes imposed on energy producers which generate carbon emissions (UK ETS and CPS).

The parameters were selected based on the conflicting impact on GWP and total cost (Tables 6-1 and 6-2). Temperature of the waste pre-treatment and gasification or fermentation increases the GWP because higher temperatures require more energy and increase the CO_2-eq emissions related to electricity use. This applies to electricity supplied by the UK electricity grid and may be different if considering different sources such as dominantly renewable generation. However, gasification or fermentation temperature deceases the cost of the system as it effects the composition of syngas and higher temperatures are linked to a higher yield of hydrogen in the syngas. The larger the yield of hydrogen the higher the revenue and profit made to recoup the cost of investment. A similar relationship is seen with the rate of hydrogen produced (kg H_2) which sees an increase in GWP with higher rates though also a decrease in total cost. The capacity factor (%) of the WtH facility is linked because the larger the utilization of the facility the more energy is required to operate it. However, a reduction in capacity factor means there is less opportunity for hydrogen to be produced and then sold. Process efficiency influences the electricity requirement with higher electricity use related to higher GWP though this leads to high higher production rates and therefore less total cost.

Table 6-1. Decision variables for the gasification-based scenarios used in the multi-objective optimisation.

Design parameters	**Scenario 1**	**Scenario 2**
	Range	**Range**
Gasification temperature °C	750 ≤ Tg ≤ 1000	750 ≤ Tg ≤ 1000
Pre-treatment temperature °C	100 ≤ Tpt ≤ 200	100 ≤ Tpt ≤ 200
Process efficiency %	30 ≤ Ef ≤ 50	30 ≤ Ef ≤ 50
Capacity factor %	70 ≤ CF ≤ 95	70 ≤ CF ≤ 95
Waste feed rate per hour	18 ≤ Wt/hr ≤ 24	3 ≤ Wt/hr ≤ 8
H2 production rate per hour	80 ≤ kg per Waste t ≤ 100	100 ≤ kg per Waste t ≤ 150

Table 6-2. Decision variables for the fermentation-based scenario used in the multi-objective optimisation.

Design parameters	**Scenario 3**	**Scenario 4**
	Range	**Range**
Fermentation temperature °C	15 ≤ Tf ≤ 35	15 ≤ Tf ≤ 35
Process efficiency %	30 ≤ Ef ≤ 70	30 ≤ Ef ≤ 70
Capacity factor %	70 ≤ CF ≤ 95	70 ≤ CF ≤ 95

Waste feed rate per hour	$20 \leq Wt/hr \leq 30$	$20 \leq Wt/hr \leq 30$
H2 production rate per hour	$15 \leq H_2$ kg/hr ≤ 22	$20 \leq H_2$ kg/hr ≤ 30

Table 6-3. Constraints values used in the multi-objective optimisation.

Constraints	
Wr i ≤	Amount available
Hr ≤	Calculated maximum
Hr ≤	Wr
Tg ≤	Maximum for syngas production
Tf ≤	Maximum for microorganisms
Tpt ≤	Maximum for optimum feedstock moisture content
CF ≤	Maximum according to operations

Constraints were applied to the decision variables to control the input parameters and prevent unreasonable relationships (Table 6-3). The total rate of waste per hour (Wr) is limited by the amount of waste available. This depends on the generating ability of the people in Glasgow over time period i which varies according to season and other factors causing fluctuations such as visiting tourists in holiday periods. The rate of hydrogen (Hr) produced is constrained by the maximum hydrogen volume in the waste and the composition of waste varies according to source. Maximum gasification temperature (Tg) is supplied by literature and the highest temperature before syngas yield drops significantly. The pre-treatment temperature (Tpt) is constrained by the feedstock moisture content reduction required for gasification. Maximum fermentation temperature (Tf) is also supplied from literature sources with the bounds limited by the conditions for optimum microorganism activity (Table 6-2). The capacity factor (CF) is limited by the operating hours available after procedures such as essential maintenance, and the maximum processing capability of the facility.

The parameters for the genetic algorithm which are sufficient to produce a Pareto front in Matlab are a population size of 200, maximum number of generations of 100, crossover probability of 0.8, constraint tolerance of 0.001 and mutation probability of 0.05.

Multi decision criteria making (MDCM) are used to assist decision making with different criteria and the best alternative chosen as a compromise from the best available solutions. It is determined to be the best compromise when compared to ideal solution (Dwivedi et al., 2018). An MDCM is tailor made for the specific situation and with different weighting factors and list of criteria used. The outcome will ultimately depend on the intention of the decision maker, whether policy maker, climate advisor or company investor.

To find the best solution on the pareto front for each Scenario's optimisation results, the criteria decision-making method called TOPSIS (technique for order preference by similarity to ideal solution) is used. The function is applied in Matlab and uses ranking and selecting a number of possible alternatives by measuring Euclidean distances (Sianaki, 2015). A range of data points from the optimisation results are selected as possible ideal solutions though all points are optimal (Alirahmi et al., 2021). The closeness coefficient, is measured from the distance or separation from negative ideal solution and proximity to the positive ideal solution (Dwivedi et al., 2018). They are then ranked to provide a value used as the best solution.

6.3. Results

The optimization results arise from the most acceptable solutions for the problem with the given constraints and conditions. The optimum values for objectives considered and operating conditions of the process for different configurations is compiled in Table 6-4. The Pareto optimal set of solutions for the objective functions shows the comparison of individual objective functions with the operating conditions. The optimal solutions generate the pareto curve and show the trade-off between environmental impact and economic feasibility. The points are non-dominated solutions of the objective functions 1 (Eq. 19) and 2 (Eq. 20). Each point on the pareto front can be chosen as a solution and is dependent on the optimisation target for the decision maker, in this study the optimisation point is selected to represent both the minimal total cost and minimal GWP over the lifetime of the project.

The results are displayed in the following Pareto plots (Fig. 6-1 to Fig. 6-5) with the full set of results in Appendix B. The effect of the decision variables will be discussed for each scenario with interpretation on the decision variable with the biggest impact.

The pareto front for Scenario 1 is in Fig. 6-1 and shows the range of optimal solutions available. The optimal total cost (Objective 2) reduces from 320 million GBP to 310 million GBP as the GWP (Objective 1) increases from 820,000 tonnes CO_2-eq to 850,000 tonnes CO_2-eq. Whilst for Scenario 2 (Fig. 6-2) the optimal total cost (Objective 2) reduces for 130 million GBP to 120 million GBP with an increase in GWP of 220,000 tonnes CO_2-eq to 270,000 tonnes CO_2-eq. Therefore, showing a significant reduction the GWP can be achieved with a small increase in total cost compared to Scenario 1.

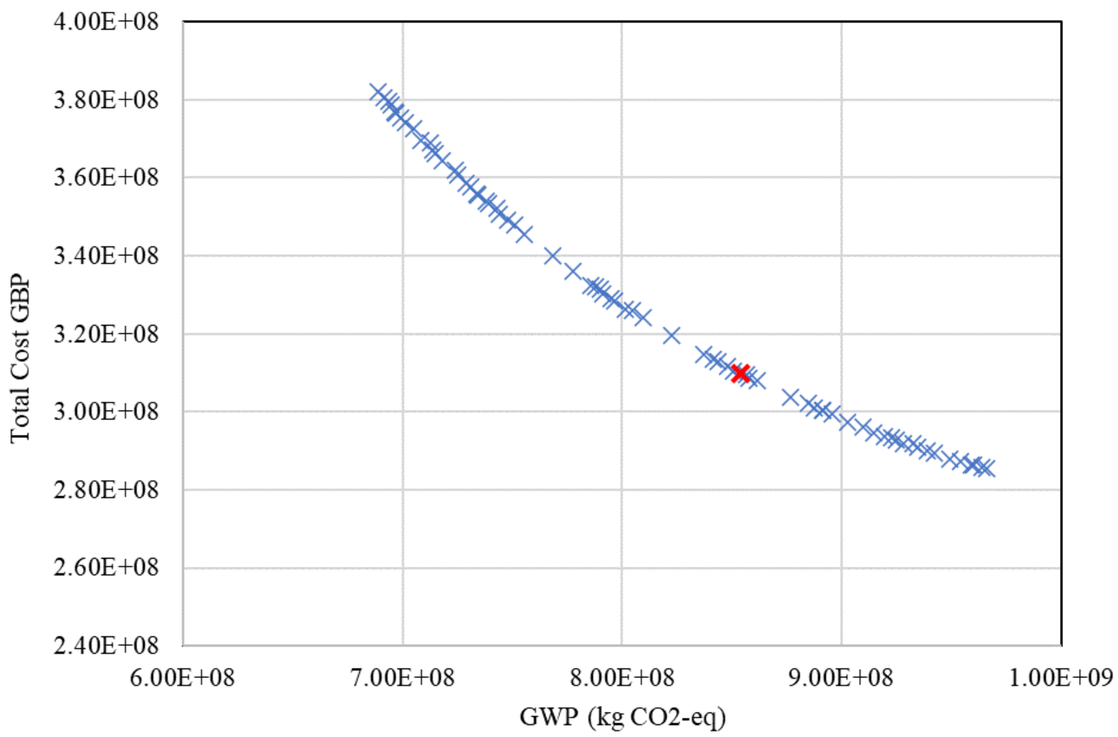

Fig. 6-1. Graph showing the Pareto front for Scenario 1. The ideal solution point, as a red cross, from the TOPSIS decision making tool.

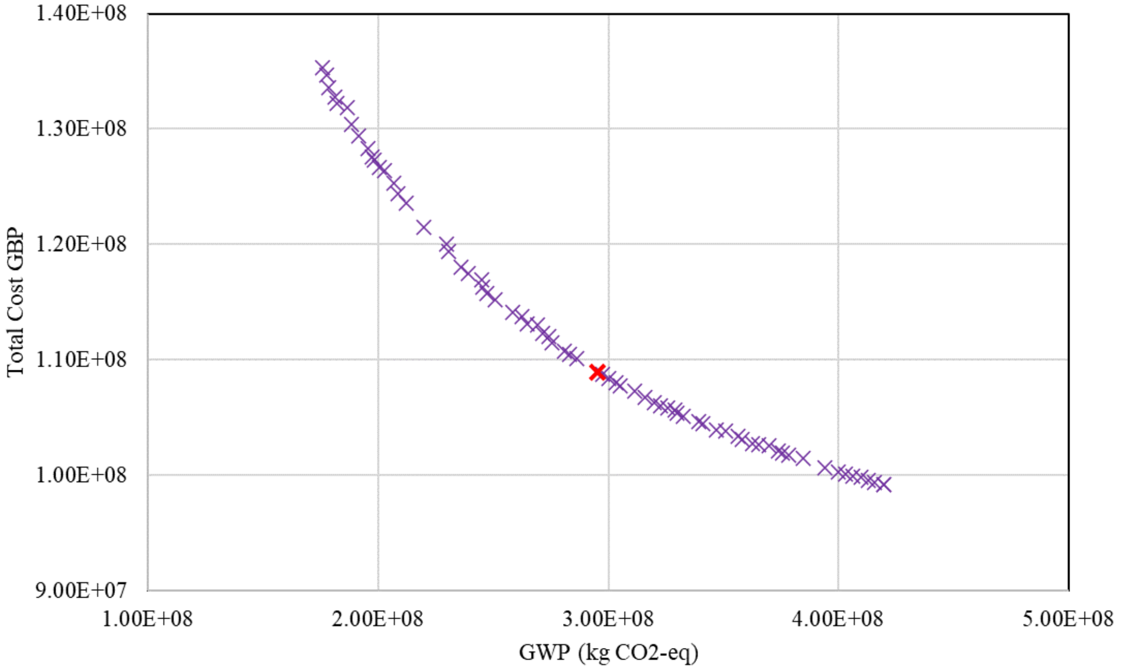

Fig. 6-2. Graph showing the Pareto front for Scenario 2. The ideal solution point, as a red cross, from the TOPSIS decision making tool.

For the fermentation scenarios, Scenario 3 (Fig. 6-3) shows the optimal total cost (Objective 2) reduces from 70 million GBP to 60 million GBP as the GWP (Objective 1) increases from 280,000 tonnes CO_2-eq to 320,000 tonnes CO_2-eq. Whilst for Scenario 4 (fig. 6-4) the optimal total cost (Objective 2) reduces for 170 million GBP to 150 million GBP with an increase in GWP of 310,000 tonnes CO_2-eq to 350,000 tonnes CO_2-eq. Scenario 4 has the smallest effect of total cost reduction influencing the GWP reduction amount. This could be due to the costs associated with containing the two technologies of dark and photo fermentation, thus requiring efficiency increase from two conversion processes effecting the ability for cost reduction. This compares to Scenarios 1-3 which contain one conversion process available for changes in process efficiency.

The hydrogen production rate is the lower for fermentation technology compared to thermochemical processes, as discussed in Chapter 3, and effects the total cost through the plant MW calculation (Eq. 9). The large amount of wet waste feedstock (24.79 tonnes/hour) is connected to high GWP, and the resulting small hydrogen yield prevents it from reducing the GWP significantly. Fermentation technologies are also affected by available operational hours and capacity factor (%) due to the slower nature of biological processes (reaction time of the microorganisms) compared to thermochemical processes.

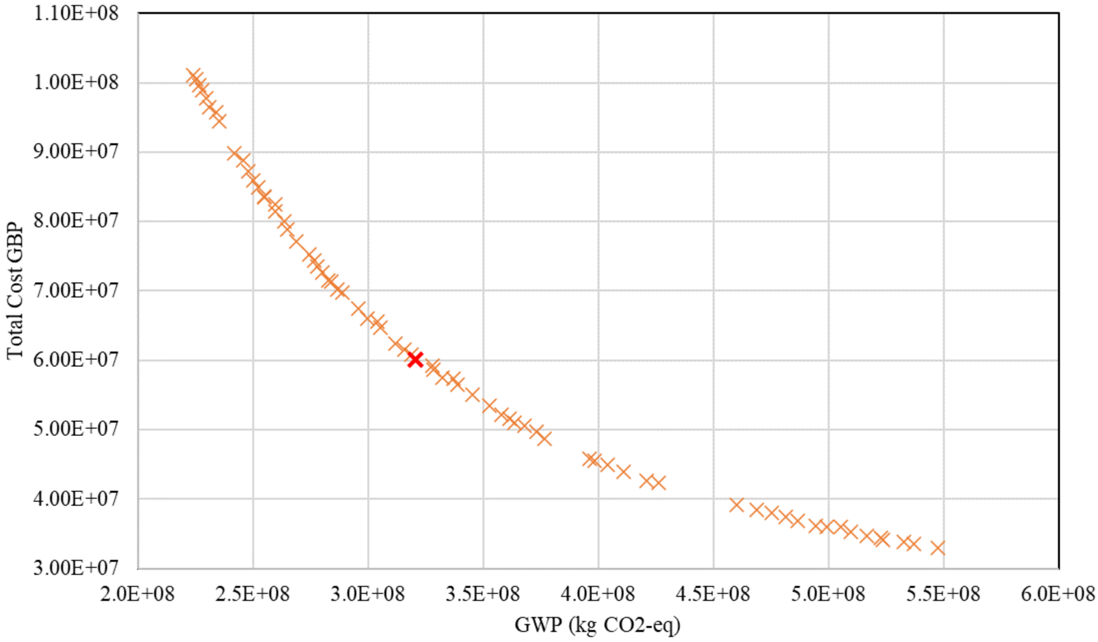

Fig. 6-3. Graph showing the Pareto front for Scenario 3. The ideal solution point, as a red cross, from the TOPSIS decision making tool.

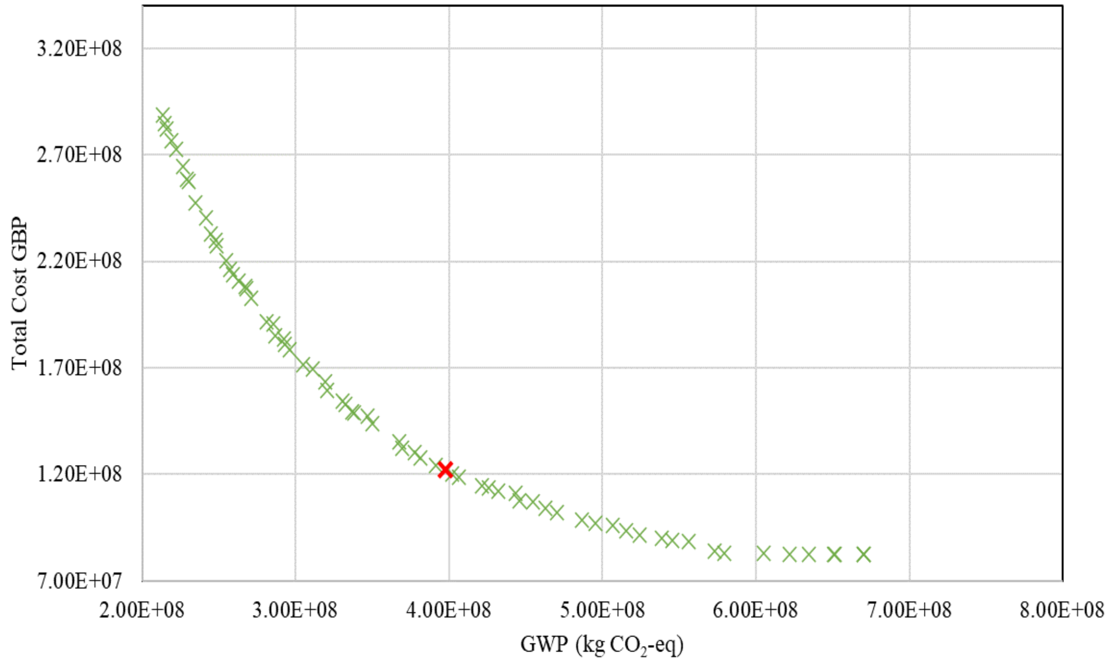

Fig. 6-4. Graph showing the Pareto front for Scenario 4. The ideal solution point, as a red cross, from the TOPSIS decision making tool.

The optimum solution from each Scenario selected using TOPSIS on data points from the Pareto front are displayed in Table 6-4.

Table 6-4. Best solution of minimised GWP and total cost for Scenarios 1-4

Scenario	GWP	Total Cost
1	853,969,045	309,859,376
2	295,223,094	108,870,692
3	320,841,185	60,096,668
4	397,983,227	121,929,124

Combining the pareto solutions for the different solutions allows for comparison of the WtH systems designed in this study (fig. 6-5). It highlights the high cost and high GWP for Scenario 1 compared to the other WtH scenarios. The wide pareto front for Scenario 4 suggests a large range of possible solutions are available. Scenario 3 offers the lowest total cost and lowest GWP option, though this coincides with the lowest hydrogen production rate.

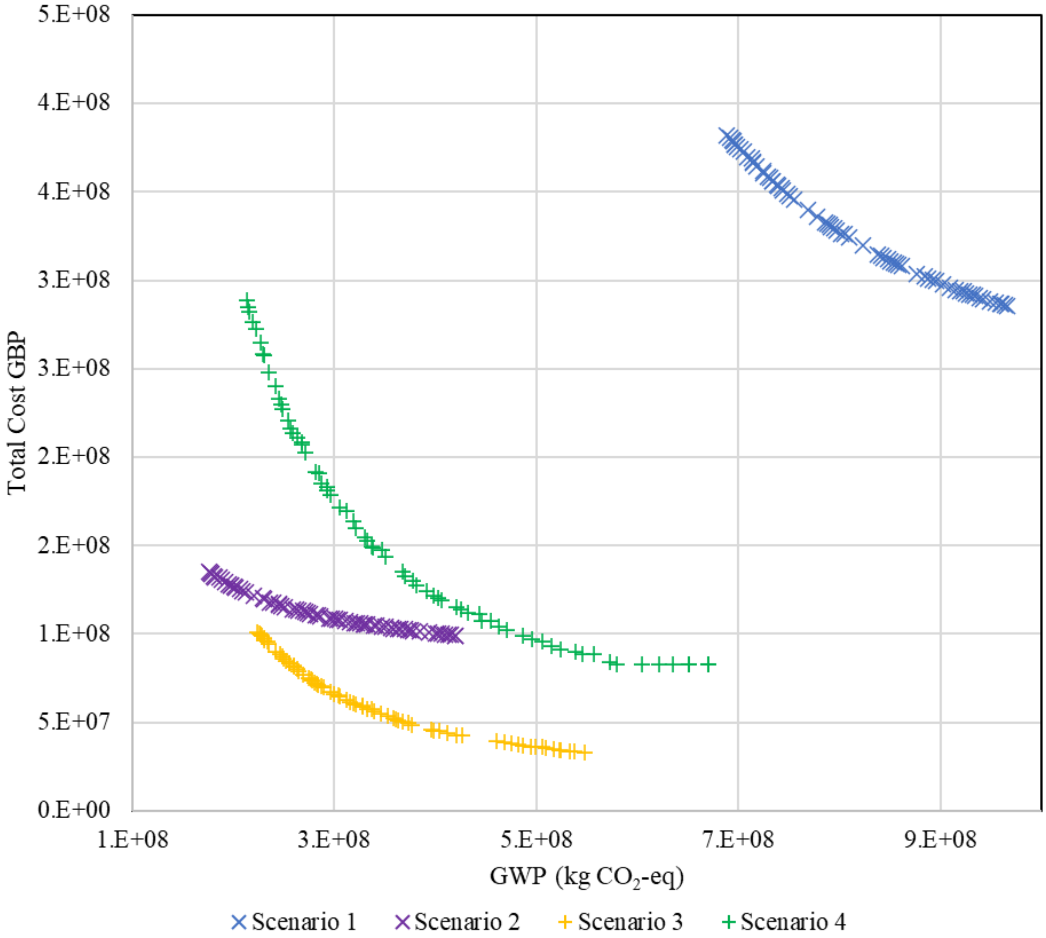

Fig. 6-5. Graph showing pareto solutions for Scenarios 1-4.

6.4. Conclusions

The results of the multi-objective optimisation performed on Scenarios 1-4 provide an indication of the optimal solutions that can be found for the designed WtH systems. Optimisation of the decision parameters in this study will have an effect on the total project cost and GWP of all scenarios. It is important to show that optimisation of WtH systems can be achieved due to the high total costs of systems like Scenario 1 (gasification with MSW) with costs approximately three times that of SMR (Scenario 5) (CBA, Chapter 5). High capital and operational costs are one of the biggest disadvantages and potential bottlenecks for solid waste management and large-scale gasification systems.

The solutions displayed as Pareto fronts can be compared against each other to highlight where the biggest savings can be made. For example, if only one WtH system was to be constructed in Glasgow, the scenario with the highest optimisation potential could influence the decision. If hydrogen production rates are not the main goal the Scenario 3 system using wet waste with dark fermentation provide the lowest cost and lowest GWP and may be ideal for wet waste management. The solution is which scenario best fits Glasgow and the waste volume and type available for the conversion technology.

Chapter 7 Discussions

This chapter will discuss WtH technology, WtH systems, and the hydrogen economy in terms of outlook, uptake of hydrogen and the bottlenecks faced by each. These factors all relate to the success of WtH as a concept, judged in terms minimal environmental impact and economic competitiveness, compared to other hydrogen production and waste management systems. The discussion therefore coincides with the environmental and economic assessment from Chapters 4 and 5.

7.1. Outlook for WtH

The outlook for WtH technologies and systems relies heavily on supportive hydrogen policies and the need to tackle waste sustainably. The advantages of moving to a hydrogen industry and economy have been stated in many reports and government policies globally and in the UK within the last few years (BEIS, 2021 and IEA, 2019). Such interest and support provide hydrogen production technologies with a high potential for future interest and investment. The lack of information for the broader public on zero carbon energy schemes needs to be addressed as it can affect the uptake and the involvement from the general public (da Silva Veras et al., 2017).

Figure. 7-1 illustrates the connection between investment, policy support, technology innovation, and a decrease in the cost of hydrogen with environmental variables of decreasing carbon emissions and improving air quality related to clean fuels.

As hydrogen production methods become more cost competitive, interest is likely to increase in large scale energy facilities to enhance the capacity for low carbon hydrogen. The trigger for economic investment has been determined to be changes in energy and transport policies from targets on carbon emission reductions. The climate emergency and energy production changes that need to take place to reach climate targets are changing the long-term outlook for the role of hydrogen and for fossil fuels. Despite this fossil fuels are likely to have an important place in the short to mid-term of the energy industry.

The trigger for changes in environmental impacts is the increase in performance of energy producing technology. Economic assessments and regular updates of cost parameters for modelling and commercial assessment are required to improve the reliability and analysis of future demand. As shown in Fig.7-1 the environmental aspects are linked to increases in technological performance for hydrogen systems which has been shown to decrease the associated GWP and in turn decrease costs such as the carbon taxes. The positive repercussions lead to environmental improvements and further commissioning of hydrogen project which in turn encourages more economic investment and a positive outlook for hydrogen productions systems such as WtH.

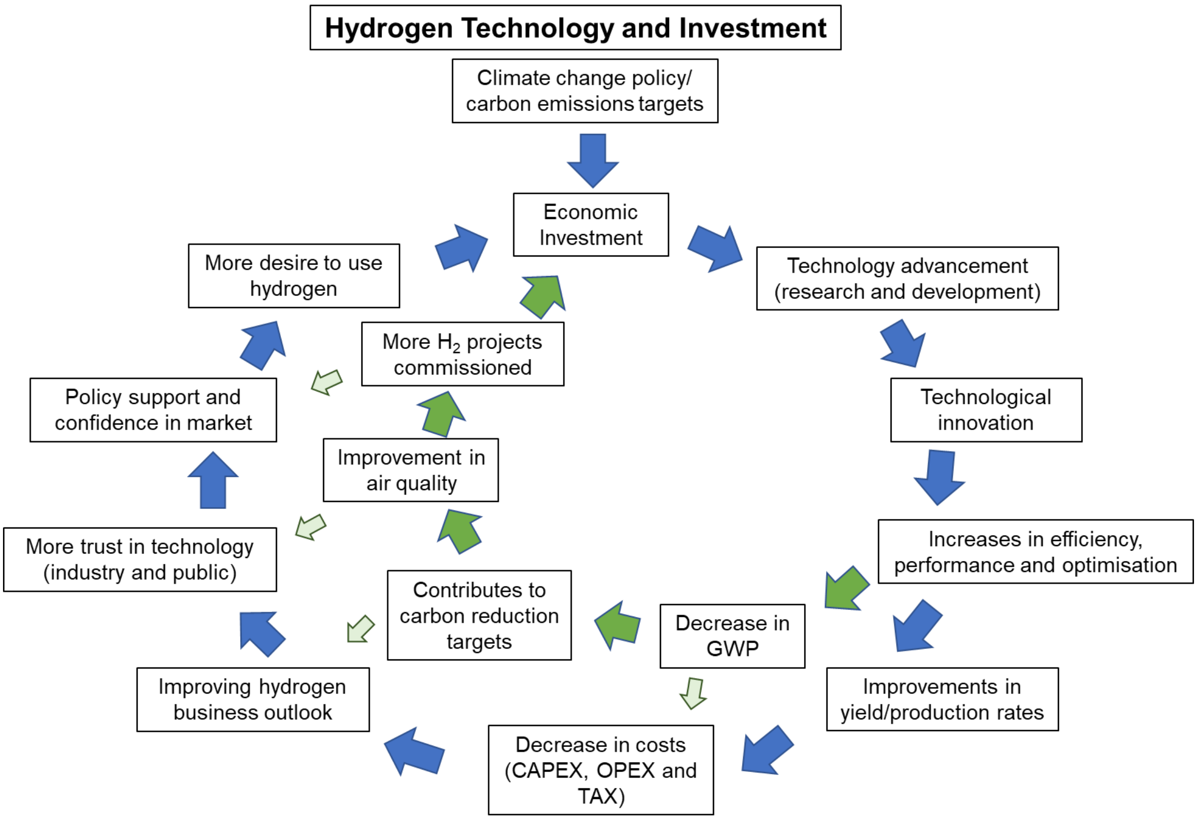

Fig. 7-1. A diagram with the link between economic (blue) and environmental (green) impact of hydrogen technologies in the transport sector. Modified from Lui et al., (2022a).

In the UK, the withdrawal from the EU in 2020 (Brexit) and the global Covid-19 pandemic (2020- 2021) will have had an impact on costs and expenses, such as cost and availability of materials and equipment linked in import and export costs, changes in tax, uncertainties in supply of energy due to changing regulations and the availability of employees (UK and EU, 2020). The full long-term impact is still to be determined.

7.2. WtH bottlenecks

Bottlenecks in all aspects of the delivery or production of a product hinder the development the system and chain, in this case for WtH. Supply bottlenecks are present throughout the hydrogen production system from waste supply to supply of materials and equipment due to the niche technology involved with hydrogen production such as storage and compression. Manufacture and supply chains require support and technological innovation to increase and encourage the growth of the hydrogen industry, as well as for waste recovery and waste management industries. Lane et al., (2021) also highlighted the challenges such as building of infrastructure and market economics impacting the speed and scale of hydrogen production. Policy support and regulation is vital to encourage the acceptance of hydrogen technologies and use within energy, and transport industries. It is essential to overcome the bottlenecks for hydrogen to be competitive as an energy carrier. Favourable energy and transport policies may have the added benefit of counteracting slow adoption and enhancing public opinion.

Key barriers according to the hydrogen council are the lack of demand visibility with developers waiting for regulations and funding to encourage off takers (customers purchasing hydrogen) to participant on long term project and contacts (Hydrogen Council, 2022). This particularly effects investment in infrastructure and the connection between supply and demand. An additional global investment of 700 billion USD by 2030 to help reach the global net zero target for 2050 (IEA, 2021).

The technical bottlenecks for thermochemical processes are generally low conversion efficiencies, low hydrogen yields and the generation of unwanted by-products such as tar (Watson et al., 2018). These incur additional cleaning effort and cost. Costs associated with syngas cleaning, necessary to achieve higher energy efficiencies and have great flexibility in meeting defined gas specifications, would benefit from reductions (Arena, 2012). The components of, alkali and earth alkali metals (mainly potassium), require removal and filtering to prevent fouling and agglomeration of the processing equipment (Mohanty et al., 2015). To reduce alkali tar and ash fouling, specific bed materials can be used such as alkali feldspar, olivine, and low iron bauxite (Thunman et al., 2018). The properties and amount of tar formed during gasification depend on fuel type, operating conditions, and secondary gas phase reactions (e.g., reactions of aromatics species, chain radical reactions, and molecular dehydration reactions) (Panepinto et al., 2014). Damage to equipment and operation issues can occur during the condensation of tar (200 and 600°C) including gas passage clogging, deactivation of sulphur removal systems, and damage to gas engines (Peng et al., 2017). Also if the tar is transferred to wastewater extra treatment and disposal is required through gas tar condensation, droplet filtration, or gas/liquid separation (Panepinto et al., 2015). Adaptations to reactor system technology and materials have improved the economics of the process and shown positive environmental effects (Sansaniwal et al., 2017).

For the biochemical processes, bottlenecks exist regarding efficiencies as generally, they are featured by low efficiency, low yield and slow rate of reactions the processes (Singh et al., 2015). Fermentation, whilst currently the lowest cost WtH technology analysed, also produces considerably lower hydrogen yield. Developments and optimisation of operating conditions, microorganisms, and inoculum to increase efficiency are needed to make it competitive with the other WtH systems. Additionally, species of microbes and hydrogen producing bacteria require specific conditions and light intensities for photo-fermentation, therefore variations in this may cause yields to become unreliable (Cheng et al., 2015; Rai and Singh, 2016). This would impact the source reliability with a knock-on effect on the hydrogen supply chain thus possibly reducing the uptake of hydrogen as a fuel. Genetic engineering of microorganisms is a practical option to improve metabolism and the yield of hydrogen (Łukajtis et al., 2018). There is steady progress in the research on utilising lignocellulosic for the production of biofuels such as bio-oil and bioethanol though efficient technology for the industrial production of hydrogen is slow coming (Iribarren et al., 2012).

7.3 Feasibility of WtH for waste management and hydrogen production

The WtH concept is proposed as a method to reduce the volume of waste sent to landfill and incineration and the environmental pollution associated. Psomopoulos et al., (2009) estimated that an EfW plant processing 1 Mt per year for 30 years required less than 100,000 m^2 of land compared to 300,000 m^2 for landfilling of 30 Mt of MSW. WtH technologies and recycling activities can form a cooperative relationship with both sectors aiming to reduce waste sent to landfill and incineration such as metals, glass, and inorganics. The continuous generation of usable waste from populated areas supports the use of WtH techniques for the long term. Though due to its physical properties of waste with low bulk density, it can be a relatively expensive resource to gather, handle, store, process, and transport (Hosseini and Wahid, 2016). The transport of MSW from households or businesses to processing plants for large towns and cities may involve large distances and can add significant costs depending on the delivery systems available (Abdalla et al., 2018). Factors such as transport distance related emissions support decentralised energy systems.

Innovative technology such as advancements in catalysts, microorganisms, feedstock pre-treatment, to produce higher hydrogen yields would see increases in the conversion efficiency of waste through and further decrease the carbon impact of WtH. Optimising the operational conditions could also lead to a reduction in waste residues and higher hydrogen yields through decreased duration, temperature and pressure of processes. Other goals for development to further decrease carbon emissions would be a reduction in waste residues produced from the WtH processes that would be sent to landfill. The waste residues could be utilising for different purposes such as biochar for agriculture or forestry industry as additives. Processing waste with different by-products in mind and discovering alternative uses, will add extra value to waste as a feedstock and improve the financially viability.

To improve the energy density of waste and determine the physical and chemical properties, pre-treatment such as drying, and contaminant removal are necessary processes before continuing onto the conversion step. Pre-treatment requires energy, time, space, separation facilities, equipment and chemicals which impacts the GWP (Iribarren et al., 2012). Processes to increase the energy density of biomass waste and improve the efficiency of thermochemical procedure include pyrolysis and torrefaction. These convert waste into carbon-rich material, a biochar with a higher carbon ratio compared to oxygen and energy density (Yao et al., 2018).

Solid waste management is has potential for substantial pollution for air, soil and water pollution (Brunner and Rechberger, 2015). The indirect cost of emissions on human health and climate are not always included in cost calculations (Lozanovski et al., 2018). Consequently, all management practices involving waste require monitoring avoid mishandling and excess pollution. High-end waste management technologies such as those centred on ultrasonic sensors, GIS, radio frequency identification, and international system for mobile or general radio packet service, have been suggested to improve waste collection and preparation (Das et al., 2019). The EU Research and Innovation group is an example of institutions looking into smart technologies and increased efficiency and sustainability.

When considering the ideal location for the development of a biochemical facility proximity to the source of the raw material is important and is dependent on the optimum feedstock identified. As the criteria for selecting raw material are availability, source location, and also cost, carbon content and biodegradability of waste (Bičáková and Straka, 2012). The system design can be altered for specific operational requirements to achieve the composition of syngas preferred. Constant issues for WtH gasification plants are the heterogeneous nature of waste feedstock especially for household waste (Ramos et al., 2018). Heterogeneity from ranges in density, form, and moisture content of waste effect both the economic and technical aspects through the cost of materials transport and energy requirements. All these aspects need to be considered in the early stages of plant design and reducing the uncertainty of feedstock characteristics will improve the outlook for plants and production projects.

The environmental benefits that WtH as an alternative hydrogen production method provides from the conventional conversion of fossil fuels such as natural gas, reforming of coal and other fossil fuels includes a reduction in process carbon footprint. The high cost of thermochemical technologies requiring large investment in part because of underdeveloped systems for waste conversion including hydrogen storage, and compression. Economic benefit of not as obvious due to large upfront costs and investment required with many successful examples to reduce risk. To decrease costs research on potential efficiency improvements have been highlighted throughout the different technology stages and within the fuel and equipment supply chain. Carbon capture and storage (CCS) has been promoted publicized as an option though is an expensive and energy intensive way to deal with CO_2 emissions from fossil fuel-derived hydrogen, with few large-scale projects and therefore may not always be feasible.

Large industrial scale operations will require phases of upscaling and trials to improve efficiency rates and encourage technology advancements to reduce energy losses throughout the processes. This increase in scale will rely heavily on the economies of scale concept to reduce costs. The options available for storage of hydrogen will have an impact on the scale of production achievable when considering future upscaling and large industrial application (Dutta, 2014). Lai et al., (2019) indicated that storage was one of the main obstacles to widespread hydrogen use, and required improved storage material design for transport and distribution purposes. Suggested material technology advancements are alloying, catalysis and milling plus lowering the temperatures involved and increasing rates of dehydration. Whilst Stockfield et al., (2015) suggested that improved practicality of storage options is critical to increase implementation capacity. Also improving the operating conditions such as pressure, temperature, and reactant concentrations would increase ease on application.

Other sources of renewable and green hydrogen, such as those using electrolysers and electrolyser systems sourced by renewable energy (wind, solar) also are expensive, requiring large investment. Whilst these systems are more advanced and mainstream, they show the potential of other hydrogen productions systems given the correct support.

Adding value to hydrogen produced by WtH and finding alternative uses, other than transport applications, will improve the appeal of a transition to the hydrogen economy (Pellegrino et al., 2017). Applications such as for heat generation, by adding a hydrogen fraction in the natural gas mix in the national gas grid and joining the energy grid to the natural gas network (Materazzi et al., 2019). If the fraction is delivered by renewable or sustainable sources the gas network will become greener and consequently decarbonisation of the energy sector.

7.4 Feasibility of WtH for transport

Transport is a large and important sector in most economies so finding an alternative clean fuel is important to reach the carbon emissions targets set by international organisations. As the WtH industry is expanding, hydrogen production projects in the transportation industry show that some governments and investors are willing to be early adopters to support technology innovation and the growing hydrogen economy. Though the initial cost of hydrogen production projects for transport remains elevated due to relatively limited infrastructure system, component manufacturers, and underdeveloped supply chain. The early stages of WtH development and enrolment depends on pioneer firms and innovative projects while costs are high. Research into the uptake of hydrogen state the main barrier to large scale uptake of hydrogen is that it is currently economically infeasible (Ajanovic and Haas, 2021). Hence hydrogen cost reduction is essential for developing hydrogen-based transportation for large scale implementation.

The demand for hydrogen in the transport sector is linked to the demand for fuel cells and accordingly the cost of fuel cells for FCEVs. The sale of the hydrogen to transport companies will create revenue for the generation processes. Influencing the price of hydrogen and stabilising the market value of hydrogen should encourage confidence in its continued use.

The issues with hydrogen from WtH arise from its purity when using waste as the source. Contamination can occur and requires significant cleaning and purification efforts. For example, the syngas generated from the gasification process can have a significant amount of CO which if not correctly filtered out can deteriorate PEMFC performance (Chutichai et al., 2013). The purification process is required to decrease the CO content (10 ppm or less) to avoid catalyst poisoning.

Fuel cell types that are better able to handle lower purity hydrogen are SOFCs so may be the ones recommended for the hydrogen produced from waste (Nikolaidis and Poullikkas, 2017). SOFC can operate using natural gas, biogas, shale gas and coal gas, thereby increasing the flexibility and resilience of fuel cell systems during the energy transition phase (Bala et al., 2019). However, they the current issues of high costs, low durability, difficulty in optimisation of interfaces with other technology, and limited performance and sustainability of materials is a large disadvantage (Stockford et al., 2015). SOFCs also use a large volume of lanthanides (metallic elements) and require rare earth elements and consequently the development of large scale SOFC manufacture may be restricted due uncertain long term availability (Stockford et al., 2015). They are an example of tech that would benefit from research into alternative cheaper and more sustainable materials.

Chapter 8 Conclusions and recommendations for future work

This section concludes the study with final remarks summarising the findings of the LCA, CBA and Multiobjective Optimisation sections. If the objectives of the study have been met and whether the original questions have been answered are considered. The main aim of this study being to determine the feasibility of WtH technologies, both thermochemical and biochemical, in the city of Glasgow. The WtH concept involves utilising waste as a sustainable management technique and producing hydrogen intended for use in FCEB for public transport. The WtH scenarios designed in this study need to satisfy both environmental and economic factors to be deemed feasible or with potential to be successful. The recommendations leading on from this study are in Chapter 8.2 and the recommendations in Chapter 8.3 provides suggestions on further work for WtH technology and systems.

8.1. Conclusions from this study

Assessing the economic viability and environmental impact of both thermochemical and biochemical systems provides a two-pronged look at the feasibility of a WtH project. Using the LCA for the environmental impact assessment and CBA for the economic assessment has provided results to justify a conclusion on the feasibility of such projects. A multi-objective optimisation has shown how each WtH system studied can be optimised to achieve the best performance in terms of minimising GWP and minimising total cost.

WtH technology has been shown how it has the potential to aid the zero emission targets in Glasgow set by the Scottish government in 2020. This is both for reducing the environmental impact of waste management and proving low carbon hydrogen production. WtH has an important role to play in the future of providing renewable energy and replacing CO_2 emission intensive fossil fuels. To prepare for the landfill ban introduction in 2025, the city will need to implement alternatives waste strategies, with studies like this highlighting the alternatives like WtH amongst the next generation of clean fuel providers. Providing low carbon fuel in the form of hydrogen for public transport in the city such as heavy-duty vehicles, (buses, gritters and refuse trucks) has the ability to be part of the solution.

The LCA results from this study show the CO_2-eq emissions savings from using gasification and dark and photo fermentation technologies compared to SMR were 30 to

50% less. The CBA results suggest the gasification and dark and photo fermentation systems proposed would be successful with positive NPV, BCR and IRR results. While the total project costs are high in comparison to SMR and high when considering the low hydrogen production rates for the biochemical technologies, revenue and a return on investment is possible. Some of the other bottlenecks discussed include high costs of production and operations, inconsistent feedstock, low efficiencies, inadequate management and logistics, and policy support are.

The multi-objective optimisation results offer a range of non-dominated solutions displayed as a pareto optimal front from which TOPSIS was applied to each scenario to provide a ‘best’ solution. The results suggest the four WtH technologies can be optimised to minimise both GWP and total lifetime cost. The implications should be encouraging for decision makers considering the economic and environmental consequences for low carbon hydrogen production and sustainable waste management.

Hydrogen is an ideal fuel to be involved in the decarbonising the transport sector and mitigating traffic related air pollution. As the interest in hydrogen grows due to approaching climate targets WtH is one of the options available. It is necessary for WtH technologies to be cost competitive to fossil fuels and offer high technical and operational reliability along with its environmental sustainability within the hydrogen production realm. WtH should be part of a combined solution for future energy needs, increases in energy demand and clean hydrogen production techniques. The research and analysis from this study have shown positive results for the future of WtH systems. This supports WtH systems and suggests it could be a feasible option for Glasgow when supplying hydrogen for public transport systems and FCEBs.

8.2. Recommendations for future work based on this study

This study has provided a starting point for the environmental and economic discussions on WtH for waste management and hydrogen production in Glasgow. Future work and the extension of some of the ideas are proposed here. They can be divided into economic studies and environmental work based on technology innovation and methods.

Developing the WtH system to encompass larger systems boundaries with transport of waste to a WtH facility and potential HRS being offsite. Including transport and delivery of the hydrogen produced from a WtH facility will impact the GWP and cost of the system.

It would be interesting to include variations on types of transport of the hydrogen around Glasgow for example to other refuelling sites. Expanding the LCA to include other impact factors from the LCA such as water use and land use to gain a broader understanding of the impact a WtH facility might have. Upscaling of WtH facilities to consider a larger volume of waste, perhaps assessing WtH in a larger city. Geographical analysis of the best sites for WtH facilities considering other environmental impacts such as land use and water use.

CBA of the other products produced from the gasification or fermentation of waste such as biochar and additives for food. It could be accompanied by market analysis to find demand or interest in such products or further processes available to conversion to something useful. This would reduce overall cost and reduce waste send for disposal such as landfill or incineration.

This study considers the current available technology therefore future predictions on the possible direction of WtH technologies given the advancements and innovations would add an element of longevity to it. Work on economic predictions for future costs for issues such as gate fees and the changing value of waste as a feedstock, and how that relates to WtH implementation and how important it is. The changing cost of natural gas will influence the price of grey hydrogen from SMR production methods therefore forecast into the evolving petroleum market world complement the establishment of the hydrogen economy. Production that does not rely on global energy markets and the price of gas imports will have a more stable cost forecast.

A social study on the implications of a WtH on the population within a city may highlight the benefits of a decentralised waste management system wo produce hydrogen to be used locally for zero caron transport. The thoughts of communities and the impact of living near a WtH facility would need to be assessed for the emissions related to transport of feedstock, materials, the workforce, and operational emissions. A comparison to an EfW incineration plant may further emphasise benefits but also highlight disadvantages and areas for improvement.

8.3. Recommendations for future work for WtH systems

In literature technology advancement studies are focussing on operational improvements including efficiency improvements, increasing energy recovery and reducing additional energy input requirements for the conversion technology and for producing hydrogen content in the syngas or biogas. This is important considering that the energy input for hydrogen production can be greater than energy available from hydrogen for secondary uses (Baykara, 2018). New materials for catalysts in the gasification process will have marked improvements of hydrogen yield. Catalytic reforming of tar will also increase hydrogen yields (Tan et al., 2020). Research is taking place on the operation conditions of gasification, for example CO_2 as an agent is being worked by Santasnachok and Nakyai (2022). Plasma gasification for waste is a highly efficient method of thermally treating waste requiring very high temperatures however is very expensive and has only been tested at lab or pilot scale and would benefit from a LCA and CBA. Optimising process integration and intensification would be expected to improve the GWP of a system, an LCA to show this would impact the feasibility. Catalytic microwave assisted pyrolysis (CMAP) is a thermochemical waste conversion technique adapted that would provide another technology for comparison of the WtH mentioned in this study.

Further research on dark and photo fermentation is required extend the knowledge on finding, isolating, and improving strains of bacteria for the conversion of lignocellulosic material to hydrogen. This would allow operational improvements though successful conversion with higher hydrogen yields. Integrating carbon capture and storage (CCS) or bioenergy carbon capture and storage (BECCS) may be necessary for WtH as the system produces carbon emissions and unlike biomass for bioenergy waste is not carbon negative in the initial phase of generation (Bui et al., 2020).

Reducing waste feedstock heterogeneity would improve the design of the reactor and allow for a more appropriate operational conditions to be selected. Therefore, further work on feedstock preparation for increasing the homogeneity for more efficient drying and grinding techniques of waste would add value to thermochemical techniques. Waste storage issues include large space required for both MSW and wet waste and the strictly environmental safeguards required to protect sanitary conditions for the workforce and the local area.

Opportunities to improve operational efficiencies for hydrogen storage as include sufficient infrastructure, volume density/mass density, safety ease of release, and overall costs. Research into different storage options focussing on supply chain effectiveness may allow for a more predictable and workable system. There is research into storage efficiencies with gas (simple but low density and expensive) compared to liquid (greater density but complicated) for long- and short-term use. Other work into storage options includes inorganic and organic compounds with hydrogen. Inorganic compounds have a good mass density but are awkward to release and recycle e.g., NH_3 with 17.6% Wt%H_2 stored as liquid at 8 bar, requires 400°C or a catalyst to remove, is toxic, flammable and poison to PEM. Organic compounds e.g., methylcyclohexane uses existing large scale chemical infrastructure but low density and slow storage or retrieval with a fair mass density and is acceptable for bulk shipment. Another option are metal hydrides in battery forms such as Ti2Ni, $MgZn_2$, $CeNi_3$ and $MgCu_2$, with electrochemical loading and discharge. reasonable mass density, and the technology is well established for battery applications, and is therefore safe and easy to use. Integrating these storage technologies into a WtH system would provide insight into other solutions to improve the outlook for WtH.

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Chapter 10 Appendix A

Table A1. Summary of Scottish waste sent to incineration for 2018 (SEPA)

Waste type	tonnes
Animal and mixed food waste	398
Animal faeces, urine, and manure	85,320
Chemical wastes	145
Combustion wastes	0
Common sludges	0
Dredging spoils	0
Health care and biological wastes	1,314
Household and similar wastes	142,946
Industrial effluent sludges	13,430
Mixed and undifferentiated materials	1
Paper and cardboard wastes	2
Plastic wastes	0
Rubber wastes	17,511
Sludges and liquid wastes from waste treatment	2,307
Soils	0
Sorting residues	31,858
Spent solvents	0
Textile wastes	0
Used oils	0
Vegetal wastes	0
Waste containing PCB	0
Wood wastes	416,272
Total	711,504

Table A2. Summary of Scottish waste sent to landfill for 2018 (SEPA)

Waste type	tonnes
Animal and mixed food waste	4,352
Animal faeces, urine, and manure	27
Chemical wastes	1,942
Combustion wastes	723
Common sludges	3,192
Dredging spoils	2,334
Health care and biological wastes	8,549
Household and similar wastes	1,187,185
Industrial effluent sludges	18,717
Mixed and undifferentiated materials	46,497
Paper and cardboard wastes	36
Plastic wastes	859
Sludges and liquid wastes from waste treatment	3,739
Soils	1,415,748
Sorting residues	745,403

Spent solvents	0
Textile wastes	996
Used oils	0
Vegetal wastes	5,095
Waste containing PCB	0
Wood wastes	332
Total	3,445,727

Chapter 11 Appendix B

Table B1. Complete list of multi objective optimisations results for Scenarios 1-4. Objective 1 are GWP results and Objective 2 is the total cost.

Scenario 1		Scenario 2		Scenario 3		Scenario 4	
Objective 1	Objective 2	Objective 1	Objective 2	Objective 1	Objective 2	Objective 1	Objective 2
693,568,447	379,652,267	419,688,775	99,183,873	547,723,163	32,960,441	670,212,749	82,759,820
688,529,451	382,045,602	419,688,775	99,183,873	537,194,425	33,574,732	446,077,144	107,562,742
965,824,682	285,436,724	332,556,145	105,124,300	224,025,885	101,111,241	670,212,749	82,759,820
696,294,613	376,954,608	177,591,502	134,682,458	499,078,156	35,971,588	213,145,849	288,538,252
751,097,898	347,883,430	175,512,453	135,327,888	363,476,903	50,986,908	650,784,153	82,759,820
928,005,375	292,045,042	181,831,647	132,181,353	284,204,867	71,374,776	579,538,993	82,959,552
714,581,019	366,104,151	369,670,764	102,603,725	274,689,280	75,200,735	621,876,041	82,760,296
694,937,242	378,616,217	180,966,210	132,793,138	420,846,828	42,628,696	214,394,736	284,952,963
789,778,837	331,567,188	197,347,749	127,622,494	278,101,312	73,522,236	336,976,517	149,258,915
958,617,089	286,557,039	275,412,150	111,463,555	242,054,793	89,864,518	669,996,006	82,759,820
791,090,136	330,230,893	178,638,272	133,624,187	481,559,253	37,496,162	296,327,496	178,562,570
934,568,635	290,964,177	415,533,489	99,403,385	509,634,428	35,226,801	219,323,340	276,667,912
861,311,735	308,093,494	412,636,062	99,587,868	225,509,164	100,520,652	470,486,975	102,082,845
919,129,975	293,870,237	247,311,792	115,797,852	332,291,101	57,441,637	350,209,574	143,783,726
954,182,390	287,314,533	347,023,861	103,945,250	263,610,200	80,080,985	254,469,340	220,531,945
777,454,762	336,135,220	188,406,316	130,400,122	255,004,385	83,616,704	369,489,180	132,547,718
744,148,838	350,831,507	325,640,949	105,864,622	320,841,185	60,096,668	604,752,830	82,804,653
730,792,880	357,815,000	409,626,470	99,820,154	279,965,589	72,656,094	256,974,240	216,260,386
959,916,691	286,458,447	245,145,234	116,309,958	234,005,588	95,728,621	524,305,636	91,468,114
914,418,904	294,725,410	328,851,038	105,661,848	235,252,542	94,399,128	244,686,074	233,141,893
701,285,636	374,076,287	229,474,556	120,053,710	259,664,153	81,507,520	248,592,665	227,358,362

755,471,722	345,476,393	230,369,277	119,396,232	505,382,213	35,938,732	651,172,198	82,759,820
942,331,569	289,518,503	358,187,414	103,075,180	373,193,432	49,741,226	431,792,512	112,200,329
724,776,878	360,737,356	258,222,542	114,135,585	252,454,735	84,873,573	486,731,083	98,749,420
724,096,790	361,928,128	403,107,142	100,104,510	337,257,279	57,351,762	332,450,178	152,979,124
837,307,598	314,741,604	211,913,980	123,559,195	361,260,258	51,542,179	285,335,194	190,615,003
822,578,951	319,634,630	399,895,824	100,298,730	468,872,953	38,449,151	402,140,444	120,305,324
963,736,596	285,793,986	219,745,516	121,479,463	286,567,792	70,190,994	262,700,151	211,014,073
691,563,681	380,430,611	362,537,640	102,764,958	305,426,003	64,773,882	221,981,215	272,505,828
809,460,971	324,277,948	250,577,824	115,236,313	398,583,507	45,503,970	381,058,560	127,670,077
794,607,009	329,218,666	200,362,103	126,695,215	338,972,922	56,422,530	267,657,229	207,243,795
742,939,823	352,173,120	329,830,367	105,372,827	303,979,795	65,533,889	495,512,149	97,108,124
713,904,058	367,147,093	304,912,242	107,783,244	227,869,625	98,916,129	234,673,183	247,590,779
728,669,009	358,640,671	311,203,843	107,254,860	282,659,066	71,566,694	280,822,264	191,508,919
932,260,198	291,953,187	235,687,161	118,015,713	229,851,502	97,727,384	506,285,846	95,927,515
717,941,044	364,454,569	281,022,703	110,792,432	516,649,580	34,654,130	397,983,227	121,929,124
924,931,675	292,892,898	393,941,705	100,626,377	486,723,863	36,814,474	271,025,042	202,759,148
949,347,284	288,020,936	297,327,191	108,754,346	315,628,199	61,610,334	391,183,667	124,132,317
708,504,856	369,612,296	208,536,190	124,427,900	264,732,571	78,799,299	293,169,873	180,911,817
796,750,794	328,417,296	356,234,155	103,386,684	523,833,669	34,170,094	634,632,231	82,760,067
887,553,269	301,059,475	406,033,562	99,938,423	358,132,525	52,190,499	226,863,539	264,693,790
734,110,353	355,711,609	378,239,905	101,785,132	255,036,662	83,448,055	443,413,628	111,306,784
801,494,215	326,481,241	350,712,913	103,853,832	245,923,164	88,864,812	215,939,179	282,323,717
733,678,157	355,892,377	384,713,988	101,469,149	522,606,302	34,459,456	311,457,048	169,659,791
843,652,296	312,888,287	197,972,962	127,291,996	396,215,597	45,837,065	545,211,470	88,910,646
848,166,356	311,799,256	300,191,594	108,365,719	288,830,316	69,821,754	367,536,949	135,303,224
853,969,045	309,859,376	339,044,880	104,693,539	230,814,834	96,499,465	292,155,709	183,389,822

738,842,190	353,376,470	271,222,036	112,293,288	259,549,784	82,417,556	229,087,540	258,327,882
884,534,202	302,370,493	365,439,688	102,619,541	276,601,676	74,356,555	230,235,413	257,718,073
891,695,787	300,195,782	195,311,249	128,297,510	247,973,013	87,202,860	320,508,402	159,520,320
804,616,881	326,153,915	206,662,325	125,266,428	250,022,981	85,960,550	319,220,242	163,606,265
705,029,439	372,612,980	245,087,785	116,957,030	352,905,640	53,440,754	346,600,031	147,502,017
785,844,725	332,541,768	283,088,554	110,455,881	494,587,236	36,204,012	454,767,288	107,059,608
737,767,279	354,061,704	269,039,866	113,065,593	295,943,078	67,449,349	337,799,951	148,874,353
747,727,298	349,087,335	295,223,094	108,870,692	426,147,925	42,363,272	572,732,629	84,047,309
909,438,281	296,053,040	238,894,296	117,468,514	226,618,698	99,646,232	421,269,524	114,911,560
850,771,858	310,566,236	264,705,411	113,121,955	368,003,094	50,562,161	267,335,935	208,376,817
939,084,819	290,110,444	341,001,037	104,506,846	318,932,247	60,843,790	463,004,862	104,229,852
768,503,677	339,978,830	186,444,288	131,896,754	268,754,119	77,080,651	241,623,109	240,228,438
841,452,066	313,673,743	286,231,490	110,127,240	328,238,819	58,586,090	377,416,762	130,121,747
895,732,191	299,422,221	262,188,568	113,787,453	312,078,895	62,455,229	286,835,453	185,070,256
712,660,400	369,016,230	202,482,670	126,434,155	460,335,397	39,169,730	425,732,277	113,908,828
787,933,888	332,060,952	303,351,457	107,991,450	404,133,376	44,889,044	305,142,220	171,662,136
902,533,107	297,430,986	322,720,850	106,060,669	299,881,574	66,070,467	247,601,938	229,648,606
856,469,487	309,482,628	315,831,569	106,767,547	327,754,583	59,165,126	406,391,692	118,727,425
922,501,641	293,547,123	375,608,850	101,913,891	345,449,290	55,002,247	515,152,097	93,422,717
857,741,797	308,518,848	373,603,092	102,151,267	532,747,407	33,851,772	259,283,611	213,890,643
698,917,960	375,467,118	191,307,039	129,415,141	475,441,074	38,016,630	538,810,754	89,917,505
876,502,953	303,861,764	274,009,375	111,991,077	376,857,260	48,701,708	556,258,081	88,438,297
696,630,570	376,743,423	319,922,797	106,323,794	411,143,564	43,948,129	330,296,542	154,569,415