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Techno-economic feasibility of distributed waste-to-hydrogen systems to support green transport in Glasgow

*Jade Lui, Manosh C. Paul, William Sloan, Siming You**

James Watt School of Engineering, University Glasgow, G12 8QQ, UK

HIGHLIGHTS

- Economic feasibility of waste-to-hydrogen technologies systematically presented.
- Steam methane reforming as a conventional hydrogen production method for comparison.
- Organic fraction municipal solid waste, wood waste and wet waste (sludge) considered.
- Levelized cost of hydrogen calculated as the main economic indicator.
- The most sensitive variables are the efficiency and the energy density of feedstock.

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ABSTRACT

Distributed waste-to-hydrogen (WtH) systems are a potential solution to tackle the dual challenges of sustainable waste management and zero emission transport. Here we propose a concept of distributed WtH systems based on gasification and fermentation to support hydrogen fuel cell buses in Glasgow. A variety of WtH scenarios were configured based on biomass waste feedstock, hydrogen production reactors, and upstream and downstream system components. A cost-benefit analysis (CBA) was conducted to compare the economic feasibility of the different WtH systems with that of the conventional steam methane reforming-based method. This required the curation of a database that included, *inter alia*, 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. The levelized cost of hydrogen (LCoH) was calculated to be 2.22 GB P/kg for municipal solid waste gasification and 2.02 GB P/kg for waste wood gasification. The LCoHs for dark fermentation and combined dark and photo fermentation systems were calculated to be 2.15 GB P/kg and 2.29 GB P/kg. Sensitivity analysis was conducted to identify the most significant influential factors of distributed WtH systems. It was indicated that hydrogen production rates and CAPEX had the largest impact for the biochemical and thermochemical technologies, respectively. 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 development.

* *Corresponding author.*
E-mail address: Siming.You@glasgow.ac.uk (S. You).
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Acronyms

CBA	Cost Benefit Analysis
WtH	Waste-to-Hydrogen
MSW	Municipal Solid Waste
WGS	Water Gas Shift
HTS	High Temperature Shift
LCA	Life Cycle Analysis
atm	Atmosphere (pressure)
CCS	Carbon Capture and Storage
LCoH	Levelized Cost of Hydrogen
O&M	Operation and Maintenance
NPV	Net Present Value
CAPEX	Capital Expenditure
CFB	Circulating Fluidised Bed (gasifier)
HHV	Higher Heating Value MJ/kg
RTFO	Renewable Transport Fuel Obligation
USD	United States Dollar ($)
EUR	Euro (€)
P_{H2}	Hydrogen production rate
MW	Megawatt
GHG	Greenhouse Gas
BEIS	UK Department for Business, Energy and Industrial Strategy
RDF	Refuel Derived Fuel
CO_2-eq	Carbon dioxide equivalent
LTS	Low Temperature Shift
PSA	Pressure Swing Adsorption
t	tonne
CHP	Combined Heat and Power
BCR	Benefit Cost Ratio
IRR	Internal Rate of Return
OPEX	Operational Expenditure
BFB	Bubbling Fluidised Bed (gasifier)
LHV	Lower Heating Value MJ/kg
RTFC	Renewable Transport Fuel Certificate
GBP	Great British Pound (£)
CF	Capacity Factor %
kWh	Kilowatt hour
MWh	Megawatt hour

Introduction

Hydrogen and WtH technology

Hydrogen is a zero-emission fuel when used in fuel cell electric vehicles. Traditional hydrogen production pathways (i.e., steam methane reforming from natural gas) have significant carbon footprints from the utilisation of fossil fuels. Relying on fossil fuels negatively effects the long-term sustainability due to finite reserves and fluctuating costs [1]. Methane reforming as the conventional technology has medium to high energy requirements from the high process temperatures, which adds to the environmental impact [2]. Alternative hydrogen production pathways are needed to facilitate the transition to the hydrogen-powered transport sector.

The waste-to-hydrogen (WtH) process is a dual-purpose method to manage waste whilst producing low-carbon hydrogen. Technologies available to convert waste to hydrogen include gasification (thermochemical) and fermentation (biochemical), both of which are immature in terms of scale and development for hydrogen production [3]. However, it has been demonstrated that the technologies have the potential for reasonable hydrogen production yields, the ability to be flexible with varying composition of feedstock, and the capacity to be carbon neutral [4]. In this case, WtH serves as a promising tool for tackling the challenges of climate change and renewable hydrogen production simultaneously.

Waste availability and management sustainability

In Scotland, 1.03 million tonnes of household waste were sent to landfill and 540,935 tonnes were incinerated in 2018 [5]. The carbon impact of household waste was estimated to be 5.76 million tonnes $CO_{2\text{-eq.}}$ a year [6]. The Scottish Government Zero Waste Plan, and Waste Regulations 2012 are designed to ensure the country moves towards improving waste management and sustainability. These policies aim to reduce the reliance on landfill and incineration as the main waste management methods and reduce the environmental impact of waste disposal [7]. A ban on biodegradable waste sent to landfill is to be introduced by 2025 [8]. Consequently, waste management alternatives such as the WtH-based ones are required to improve the utilisation of the waste diverted from the current systems. Glasgow City Council is implementing various projects and strategies to manage waste and reduce the associated carbon footprint. Part of the Waste Strategy for Glasgow focuses on viewing waste as a resource and to provide the technology to improve the potential of waste whilst improving sustainability [9].

Climate and transport policies in the UK and Scotland

Scotland declared a climate emergency in May 2019 [10] and committed to transition to clean energy generation and net zero emissions by 2045 [11]. Scottish policies, influenced by findings from Intergovernmental Panel on Climate Change (IPCC) [12] and Committee on Climate Change (CCC) recommendations aim to decarbonise the largest emission producers and energy intensive industries such as the energy and transport sectors [13]. In Scotland carbon emissions from transport were 14.9 million tonnes CO_2 equivalent ($CO_{2\text{-eq.}}$) or 37% of the total emissions in 2017 [14]. This makes the transport sector the largest contributor of greenhouse gas emissions in the UK [15]. The UK Department of Transport released the Decarbonising Transport report which states that the application of hydrogen in the transport sector is one of main methods for carbon abatement [16]. The publication of the UK Hydrogen Strategy in 2021 also sets out the plan for hydrogen to replace fossil fuels for transport applications [17]. Diesel-based vehicles are a significant contributor to carbon emissions and replacing these with fuel cell vehicles using renewable sources of hydrogen could reduce CO_2 emissions by 93% [18]. Glasgow City Council has shown a desire to invest and supply greener public vehicles as demonstrated by the plans to purchase hydrogen fuel cell electric refuse trucks and gritters [19]. This would go towards mitigating the 12.0 million tonnes $CO_{2\text{-eq.}}$ emitted in Scotland from domestic transport [20]. Glasgow City Council has implemented policies including "the Fleet Strategy (2020–2030)" with aims for a zero emission fleet by the end of 2029 [21]. The transition to greener, zero emission vehicles would be a positive step towards the widespread use of renewable hydrogen as derived from waste.

Techno-economic studies on hydrogen production

The research into thermochemical and biochemical technologies for electricity generation is extensive but there has been very less focus on waste for hydrogen production. Indeed, the few studies that do exist consider biomass (non-waste) as the feedstock for the analysis. The techno-economic study by Salkuyeh et al. [22] focussed on comparing two types of gasification for hydrogen production from biomass: fluidised bed and entrained flow. The resultant economic assessment determined a minimum hydrogen selling price for fluidised bed to be less than entrained flow by between 0.07 and 0.33USD per kg/H_2. Sathyaprakasan and Kannan [23] studied hydrogen production in the UAE comparing the cost of different biochemical methods using algae as the substrate. The results indicate that the cost for dark fermentation is 68.7 AED per kg/H_2 and 13.6AED per kg/H_2 for photo fermentation (1 GB P = 5.04AED). Studies comparing biomass or waste gasification with conventional hydrogen production methods provide insight on the current costs of the main competition for WtH technologies. Valente [24] considered biomass gasification and SMR using a levelized cost metric resulting in 3.59 and 2.17 USD per kg/H_2 respectively. Whereas Wang et al. [25] compared biomass gasification and coal gasification and observed that the production costs were higher for coal than biomass at 0.75 CNY/Nm^3 H_2 and 0.62 CNY/Nm^3 H_2, respectively. Fernández-González et al. studied the medium to low scale of energy generation from municipal solid waste (MSW) in Spain [26]. They found the revenues for energy generation from incineration to be 32.64 EURO/t as compared to 25.68 EURO/t for gasification (1 GB P = 1.18EURO). Sun et al. [27] compared the economics of different MSW-to-hydrogen conversion routes in China. They found hydrogen from MSW had a minimum hydrogen selling price of 14 CNY per kg/H_2 as compared to SMR at 7.4 CNY per kg/H_2 (1 GB P = 8.77CNY). Coal to hydrogen and biomass to hydrogen have the highest value at 22.9 and 20.5 CNY/kg H_2, respectively. Hence, it is important to analyse the economics of WtH development in terms of specific economic factors on a case-by-case basis.

The novelty of this study originates from the utilisation of actual waste data for economic assessment of WtH development in the UK and being one of the first studies systematically comparing the economics of three methods for hydrogen production: gasification and fermentation using waste as feedstock, and SMR using natural gas. The SMR system is included for comparison as it is the leading hydrogen production method currently used in the UK. The economic feasibility is evaluated using cost benefit analysis (CBA). A sensitivity analysis is conducted to determine the influences of different parameters on the economics. The study demonstrates how implementing a WtH system in Glasgow could provide an alternative waste management option and implies the influences of policy support, potential limitations, and the possible outlook for WtH.

Methodology

Glasgow waste generation

Glasgow covers an area of 176 square kilometres and is the largest city in Scotland with a population of 613,130 within the city in 2020 [28]. In 2018, the city produced 2.41 million tonnes of household waste [14]. Under the categories defined by SEPA, MSW/household waste includes plastics, packaging, textiles, and some hazardous materials. The wet waste and sludge category includes common sludges, dredging spoils, sorting residues, food waste, and vegetal waste. Wood waste includes agricultural woody-based plant material, non-recyclable paper and cardboard, and other wood wastes. Each category contains a range of energy content, particle size, moisture content and contaminants dealt with during the appropriate pre-treatment stage.

The data in Table 1 displays the volumes of waste from Glasgow 2018 annual reports sent to landfill or incineration from 21 original categories (details in Appendix A). They have been grouped into three categories, *i.e.* MSW, wet waste/sludge and waste wood for this study with waste destined for recycling (25% MSW) or inappropriate for conversion excluded. The carbon fraction of MSW or household waste portion is considered for gasification whilst the wet waste, sludge and food waste are for the fermentation processes.

Waste-to-hydrogen and steam methane reforming

Three WtH technologies (*i.e.*, gasification, dark-fermentation, and dark and photo fermentation) and steam methane reforming (SMR) are considered in this work. Process flow simulation diagrams were created in Aspen Plus V10 software to illustrate the sub-processes covering pre-treatment, waste conversion to *e.g.*, syngas, gas cleaning and hydrogen separation, and hydrogen compression and storage (Figs. 1–3).

Gasification

There are various reactor designs for gasification, *e.g.*, fixed bed (updraft and downdraft), fluidised bed (bubbling and circulating), and entrained flow. Fluidised bed (FB) gasification is receiving increasing attention for its ability to treat MSW efficiently and high scalability and flexibility [29]. FB gasification normally occurs at temperatures of 850–1000 °C and atmospheric pressure (1 atm) [30]. Gasification produces synthetic

Table 1 – Glasgow waste data for 2018 with recycling and inappropriate types of waste (inorganic, non-carbon based) for the gasification and fermentation processes excluded.

	MSW/household waste	Wet waste/ Sludge	Waste wood
Available waste tonnes/year	184,970	217,146	48,747
Percentage of total	34%	54%	12%

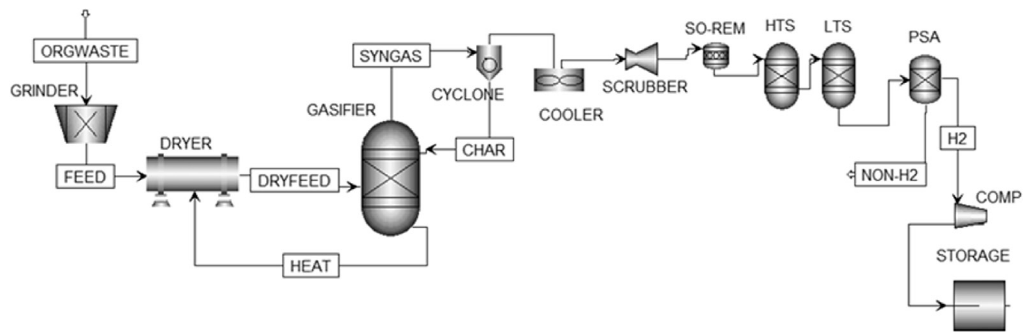

Fig. 1 – Process flow diagram of gasification. (HTS represents High Temperature Shift, LTS represents Low Temperature Shift, ORGWASTE represents organic waste, SO-REM represents sulphur removal process, PSA represents pressure swing adsorption, and COMP represents compression).

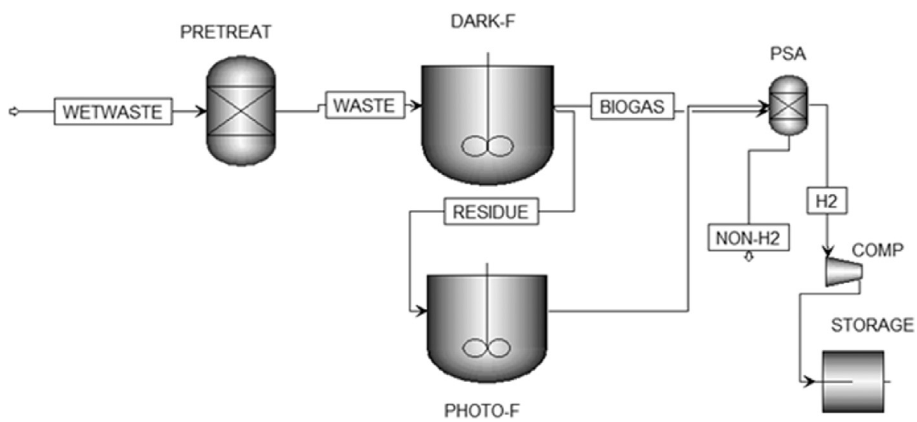

Fig. 2 – Process flow diagram of dark fermentation and combined dark and photo fermentation technology (adapted from Xia [47]) (DARK-F represents dark fermentation process, PHOTO-F represent photo fermentation, and COMP represents compression).

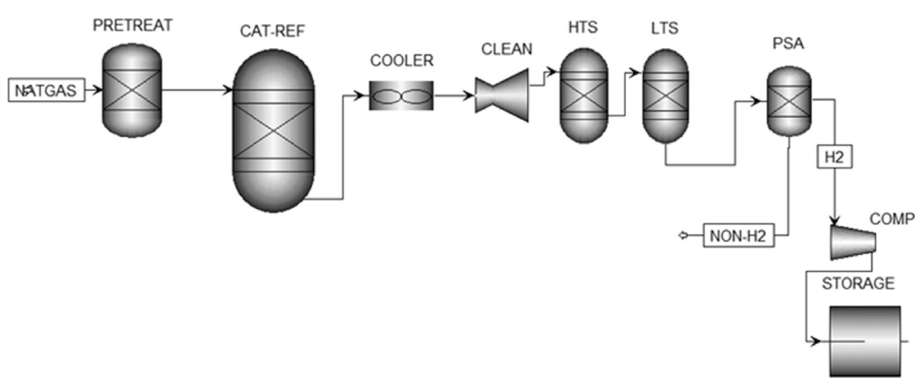

Fig. 3 – Process flow diagram of steam methane reforming (adapted from Taji et al. [55]) (NATGAS represents natural gas feedstock, CAT-REF represents catalytic steam reforming, HTS represents High Temperature Shift, LTS represents Low Temperature Shift, PSA represents pressure swing adsorption, and COMP represents compression).

gas (syngas) whose main components are carbon monoxide, hydrogen, and methane [31]. Water gas shift (WGS) is a further reforming process to increase the H_2/CO ratio in clean syngas [1]. The hydrogen could be separated from the syngas through pressure swing adsorption (PSA) or membrane technologies.

A range of carbon-based feedstocks can be gasified making it ideal for MSW from various sources such as households, and commercial and industrial sectors. Hognert and Nilsson [32] found MSW waste from Sweden had a HHV of 19.9 MJ/kg and Tang et al. [33] found untreated wet MSW had a LHV 9.8 MJ/kg. This demonstrates the similarity of MSW to forest waste biomass in terms of HHV (the HHV of dry forest residual biomass was reported to be 20.72 [34]) after drying and support the use of gasification. This first treatment step of drying involves reducing the waste from a moisture content of 50 wt % to 10 wt% for MSW [35] and from 30 wt% to 10 wt% for waste wood [36].

The gasification of MSW requires extra pre-treatment compared to that of waste agricultural biomass, usually in the form of drying and grinding/shredding due to the heterogenous nature (mixed compositions), and relatively high moisture contents of the waste. MSW and refuse derived fuel (RDF) is considered as the example feedstock for the gasification process [37]. RDF consists of domestic and business biodegradable waste and plastics and goes through extra pre-treatment (*i.e.*, drying and shredding) to achieve a higher energy density 15–25 MJ/kg [38]. The second example feedstock is wood waste for its suitability for hydrogen recovery via gasification. The diagram of the FB gasification process is illustrated in Fig. 1 showing the individual sub-processes. The volume of waste feedstock available determines the capacity of the gasification system and how the data in referenced papers were converted for the analysis in this work.

Dark and photo fermentation

Dark fermentation and combined dark and photo fermentation are considered for wet waste or sludge fraction such as food and animal waste generated in Glasgow. Food waste has high biodegradability and carbohydrate content, and therefore ideal for hydrogen production via fermentation [39]. The fermentation processes provide a biological option for wet waste conversion that would be less efficient in thermochemical techniques due to higher moisture contents [40]. Fig. 2 illustrates the simplified process steps for two potential paths of dark fermentation and combined dark and photo fermentation.

There is likely to be solid organic material present in the waste stream (food and sludge) which are required to be broken down to aid utilisation by the microorganisms [41]. Enzymatic pre-treatment was considered as a simple bioreaction with low energy requirement which used enzymes to hydrolyse lignocellulosic biomass to degrade its structure [42]. The breakdown of the cellulose and hemicellulose fraction of the waste aids the subsequent fermentation process [43]. Pre-treatment is also required to suppress non-hydrogen producing microorganisms (methanogens) within the waste stream [39]. For example, food waste contains native microorganisms that may affect hydrogen production and interfere with the environment within the reactor [44]. The mass of feedstock is reduced by 55% post pre-treatment [45]. Bundoo et al. [46], suggested that combining pre-treatment technologies would enhance the hydrogen yield by maximising the conversion of the different organic compounds within the waste.

The hydrogen yield of fermentation depends on inoculant, cultures, substrates, and trace elements [48]. Batch operations are preferable over continuous reactors as they achieve higher product concentrations [49]. The maximum fermentation time according to NREL (National Renewable Energy Laboratory) data is 74 h, after which the hydrogen production rate would decrease [50]. The product gas mixture contains hydrogen and carbon dioxide which are vented and separated using PSA [43].

To improve and maximise the rates of hydrogen production via dark fermentation, a further photo fermentation step can be added to utilise the carbon rich effluents and residual waste from the dark fermentation reactor [51]. This reduces the final waste residue volume and the environmental impact of the system [30]. Additional requirements for hydrogen conversion in photo fermentation are wide spectral light energy and phototrophic microorganisms in neutral or alkaline pH conditions [4].

Steam methane reforming

The steam methane reforming process involves catalytically reforming methane with steam for hydrogen rich [52]. The process is represented in Fig. 3. It is assumed that the natural gas feedstock contains 96.5% methane [53]. During the reforming process, a temperature condition of 850–900 °C is reached at pressures of between 20 and 40 bar [1]. The system requires 63.3 kJ/mol H_2 of energy [54]. Pre-treatment is required to remove the sulphur content and pre-reformed with steam before reforming takes place in the main reforming reactor over a catalyst, typically using a nickel-based catalyst [55]. In the next stage, 94% of carbon monoxide from the raw syngas reacts with water over a high temperature catalyst in the high temperature shift (HTS) and low temperature shift (LTS) reactors (combined as the water gas shift reaction) [56]. This generates hydrogen and carbon dioxide which is then separate in PSA process to produce hydrogen at a high purity of 99.99% [54].

Critical process data

The scale of the technology used is determined by the volume and composition of waste produced in Glasgow. The technology procedures, energy requirements and efficiencies were established using the specifications of the technologies reported in the literature [36,37] as illustrated in Figs. 1–3. The process efficiency values are stated in Table 2 for each technology. The syngas yield from gasification was calculated using the observation by Mustafa et al. [57], that 2.4 kg of syngas is generated per kilogram of biomass or waste treated. Arena [35] observed the volume of hydrogen within the syngas derived from waste varied from 7 to 10 vol% (dry basis) and it varied between 10 and 15 vol % (dry basis) for the syngas derived from dry woody biomass when using a CFB gasifier. For the fermentation processes, an averaged hydrogen concentration of 34 vol% was considered for the biogas generated, based on the reported hydrogen concentration of 10–60 vol % for food waste dark fermentation [58], and 32 vol% for sewage sludge fermentation [59].

Table 2 – A summary of the efficiencies for the chosen WtH technologies and SMR.

Technology	Process efficiency %	Reference
Gasification-MSW	35–50	[53]
Gasification-Waste wood	39–48	[60]
Dark Fermentation	60–80	[30]
Dark and Photo Fermentation	6.6–86	[30]
SMR	70–75	[61]

The ultimate hydrogen yield (quantity of hydrogen generated per unit mass of feedstock) is calculated by multiplying the hydrogen process efficiency with the syngas or biogas yield. The hydrogen production rate (quantity of hydrogen generated per unit time and mass of feedstock) is calculated by dividing the hydrogen yield by the duration of system operation.

Data have been adapted using scaling ratios according to feedstock volumes or hydrogen production volumes. As SMR does not use waste as the feedstock, the volume of natural gas required was determined by back calculating from the volume of hydrogen produced by waste wood gasification. This is based on the consideration of 3.18 kg of natural gas to produce 1 kg of hydrogen [1].

Five scenarios were considered based on the main types of waste in Glasgow and the technologies analysed (Table 3): MSW and wood waste treated by gasification, wet waste/sludge treated by dark fermentation or dark and photo fermentation, and SMR-based hydrogen production. The scenario design is based on the consideration of the general suitability of the technologies in treating waste. For example, a feature of wet waste/sludge is a relatively high moisture content and thus is more suitable to be treated using the biochemical technologies from an energy efficiency perspective.

The mass balances for WtH gasification and fermentation technologies and SMR based on a waste feedstock input of 1 tonne are shown in Fig. 4. The feedstock rate is determined by considering the waste available, collected and transported to waste management facilities in Glasgow, estimated from 2019 data records [8]. The mass balances highlight the difference in hydrogen yields as the main energy output, along with variations in waste emissions (exhaust) and residues (ash, tar).

The rated capacity of the WtH plant (MW) is calculated using the hydrogen production rate (P_{H2}), capacity factor (CF), energy density value of hydrogen (LHV = 120 MJ/kg) and MJ/h to MW conversion factor (Eq. (1)). The capacity factor is set at 90% which corresponds to 7884 h a year for the gasification and SMR technologies and 7469 h/year for dark fermentation, 7629 h/year for combined dark and photo fermentation.

$$MW = P_{H2} \times CF \times LHV \quad (1)$$

As part of the CBA 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 consumption processes for the different scenarios are listed in Table 4 and their electricity requirements corresponding to the feeding rate (Table 3) were calculated using GaBi software (gabi.sphera.com).

Economic data collection

The cost and benefit information for all the modelled scenarios are sourced from researched papers, published articles, available industrial online resources, UK and Scottish government reports (*e.g.*, BEIS [62]). This includes cost data (CAPEX, OPEX and tax), technical data for the gasification and fermentation process flows (yield, inputs, outputs, and energy requirements), and technical diagrams (system performance and efficiency).

The cost data for the gasification technology is based on an ARUP report from 2015 under which gasification is classified as an Advanced Conversion Technology (ACT) [63]. In the standard subcategory within the 2020 cost prediction, it encompasses technologies that produce syngas used for combustion or to generate electricity or heat. The feedstock is comprised of MSW, RDF and biomass, though the report does not provide details on the quantities or exact composition, therefore these are assumed. The report uses MW of the technology to calculate the cost of CAPEX and OPEX and therefore can be adapted to fit gasification technologies using biomass and waste for hydrogen production (Table 5). The costs are calculated in GBP per MWh or MW and applied to each technology. 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 [64].

Costs for the fermentation scenarios (dark fermentation and combined dark and photo fermentation, respectively) are modified from Randolph and Studer [43] (Table 5). 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 as well as the hydrogen production proportion (*i.e.*, 50,000 kg/day for the original study is 9.12 times that of the current work). The costs of the SMR technology were calculated based on the International Energy Agency Greenhouse Gas R&D Programme (IEAGHG) [53] report (EURO converted to GBP). The base case cost values in the report were adapted based on the feedstock conversion rate (*i.e.*, 26.23 tonnes/hour for the original study, 13.66 times the current work) and calculated as cost per MW or MWh (Table 5).

As part of the strategy to reduce carbon emissions, the UK applies a tax to industries that produce CO_2 through their activities. The UK Carbon Emissions Tax (UK ETS) is set at £16 per tonne of $CO_{2\text{-eq}}$ [65]. The UK ETS is designed to be a net zero carbon cap and market trade measure to control and limit carbon credits, implemented after Brexit in January 2021 [66]. The scheme is similar to the EU Emissions tax which controls the supply of carbon credits to energy intensive industries and power generation sectors with significant carbon emissions. The Carbon Price Support (CPS) is set at £18 per

Table 3 – Scenarios with corresponding feedstock used in the study.

Scenario (S)	Technology	Feedstock	Feeding rate (tonnes/hr)
1	Gasification (FB)	MSW	19.01
2	Gasification (FB)	Waste wood	5.00
3	Dark Fermentation	Wet waste/Sludge	22.31
4	Dark and Photo Fermentation	Wet waste/Sludge	22.31
5	SMR	Natural gas	1.92

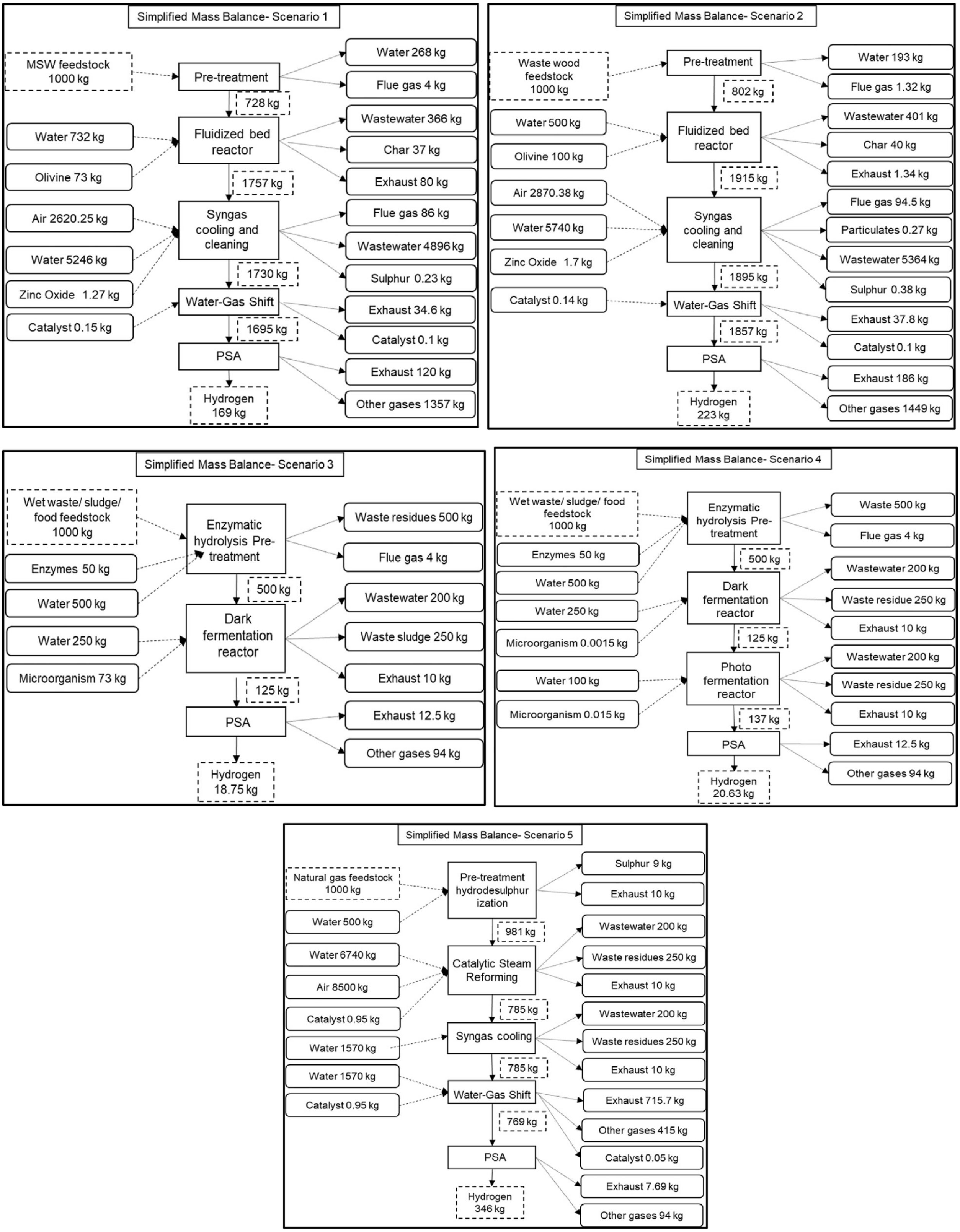

Fig. 4 – Simplified mass balance flow diagrams for Scenarios 1–5. (The data is estimated based on [36] (for Scenario 1) [1,31], (for Scenario 2) [45], (for Scenario 3) [47], (for Scenario 4) and [22] (for Scenario 5)).

Table 4 – Electricity requirements in kWh for S1–S5. The values correspond to the requirements for the stages assessed using the starting feedstock value stated.

Gasification			Fermentation			SMR	
Process	Electricity consumption (kWh)		Process	Electricity consumption (kWh)		Process	Electricity consumption (kWh)
	S1	S2		S3	S4		S5
Drying	1464	84	Enzymatic hydrolysis pre-treatment	3347	3347	Hydro-desulphurization pre treatment	288
Grinding/shredding	2851	500	–	–	–	–	–
FB gasification	6335	1668	Dark fermentation	1852	1852	Catalytic Steam Reforming	663
Gas solid cyclone	513	135	Photo fermentation	–	3570	–	–
Syngas cooling	437	65	–	–	–	Syngas cooling	25
Syngas cleaning	893	135	–	–	–	–	–
Syngas sulphur removal	570	150	–	–	–	–	–
Water gas shift (HTS and LTS)	570	150	–	–	–	Water Gas Shift (HTS and LTS)	58
PSA-syngas to H_2 at 12%	4752	1001	PSA- syngas to H_2 at 15%	5355	5355	PSA- syngas to H_2 at 45%	289
Compression of H_2	1159	403	Compression of H_2	1339	1339	Compression of H_2	115
Hydrogen gas storage (440 bar tanks)	393	83	Hydrogen gas storage (440 bar tanks)	462	462	Hydrogen gas storage (440 bar tanks)	40
Total (kWh/hr)	19,939	4373	Total kWh/hr	12,360	15,930	Total kWh/hr	1478

tonne CO_2 as a carbon price floor and is designed to tax the power sector in addition to the UK ETS [67]. It is worth noting that UK government subsidies (*e.g.*, Renewable Transport Fuel Obligation) are important to consider when discussing the potential profit of WtH technology, but they currently apply to the energy supplier not hydrogen production [68]. Therefore, they are excluded from this assessment.

Cost-benefit analysis

The economic feasibility of the WtH technologies was assessed using CBA, and the benefits and costs of the different technological options were compared [69]. The economic variables include costs (capital and fixed and variable operating), income from the sale of hydrogen, and carbon emissions taxes. The capital expenditure (CAPEX) comprises of the total installed plant cost including materials, utility connections, project design procurement and construction, as well as total capital requirement which includes interest during construction, spare parts cost, working capital, and start-up costs. The operational expenditure (OPEX) includes the fixed operations costs of labour, admin, general overhead, utilities, maintenance, insurance local taxes and fees. The costs are calculated using the MW classification of the facility, which was determined by the volume of waste, efficiency of the technologies involved and LHV of hydrogen (120 MJ/kg) [63]. The project operational lifetime is set at 25 years, and plant availability is determined by using the capacity factor as plant availability over a certain period of time, here assumed to be 90%. Calculations are based on a single unit (one of a kind), and it is expected bulk manufacture would bring costs down in a non-linear trend (not included).

This work does not consider the sale of the by-products from gasification and fermentation such as biochar and digestate for agricultural use as a soil enhancer. Instead, it is considered that they are disposed of by landfilling and the associated costs are part of the OPEX listed in Table 5. The data for the SMR scenario is adapted from the IEA GHG report [53] and the cost of natural gas feedstock is 0.465p/kWh [70]. Gate fees are not included as a source of income due to the variability in price given to them in the UK. The use of gate fees is uncertain with the current trend in decreasing prices as the value of waste is predicted to increase with competition and waste technology implementation [63]. It also suggests that current analysis focuses on WtH development which the waste collection and transport services are separated from, and it is assumed that the cost of waste and gate fees cancel each other out in terms of income and expenses. This makes the analysis of the current work conservative.

Similarly, the analysis does not include the cost of transport to and from the facility or fuel cells, vehicle conversion, waste disposal after conversion, refuelling stations, long-term hydrogen storage, manufacture markup, or warranty. Results are stated in Great British Pounds (GBP £) and have been converted where necessary and inflation rates have been incorporated.

The selling price is set at a higher value than the LCoH for each scenario and given a base value of £2 with an increase of 20% for the maximum price (£2.40) and a decrease of 20% for the minimum price (£1.60). As the actual selling price of

Table 5 – Economic parameters for gasification [63], fermentation [43], and SMR [53].

CBA	Unit	Gasification	Fermentation	SMR
Total CAPEX	GBP mill/MW	6.5	3.853	1.152
Pre-Development	GBP mill/MW	0.18	–	–
Construction	GBP mill/MW	6.2	–	–
Infrastructure	GBP mill/MW	0.12	–	–
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
Balancing Services Use of System	GBP/MWh	1.9	1.9	1.9
Insurance	GBP mill/MW	0.055	31,407	31,407
Use of System	GBP mill/MW	0.013	12,921	12,921

hydrogen is at the discretion of each individual production company, there are difficulties in determining potential profit. Consequently, a general trend for profit is suggested with the NPV and BCR results used as additional support data. The feasibility of each scenario is discussed by comparing the CBA results firstly with S5 SMR technology, as the leading hydrogen production technology, but also with other published results.

Calculations of LCoH, Benefit Cost Ratio (BCR), Net Present value (NPV), and Internal Rate of Return (IRR) are listed below (Equations (2), (5) and (34) respectively). A summary of the variables used are listed in Table 6. Together these calculated values provide the basis for the assessment on the economic feasibility of each scenario, 1 to 5. LCoH is the average annual cost of hydrogen production calculated as GBP per kg and is a summation of investment and manufacturing cost. It is therefore an estimation of the price of the product [71]. The calculation is adapted from the levelized cost of energy from IRENA [72] and assumes constant prices for costs such as fuel and constant operating capacity for the plant lifetime. LCoH is used as a comparison analysis tool for the different technologies, shown in Eq. (2)

$$LCoH = \frac{\sum_{t=1}^{n} \frac{I_{t+} M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{2}$$

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 [73].

The benefit to cost ratio (BCR) indicates the value for money of the project by assessing the relationship between the assigned cost and benefit shown in Eq. (3). A BCR result greater than 1 indicates a positive net present value while a result of less than 1 suggests the costs will exceed by the benefits costs.

$$BCR = \frac{Income}{CAPEX + OPEX + TAX} \tag{3}$$

The NPV determines the projects worth over the lifetime, given as 25 years, which is discounted to the present and the required investment using Eq. (4)

$$NPV = \sum_{N=0}^{N=final} \frac{R_t}{(1+i)^N} \tag{4}$$

where R_t is the net cash flow inflows-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 2%, 5% and 10%.

The IRR estimate the profitability of projects or investments with a higher IRR value suggesting a more desirable the investment. It can be used as a comparison tool when making investment decisions. The IRR is determined using Eq. (5).

Table 6 – Summary of the variables with low, mid, and 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	Lower	2.22×10^8	1.21×10^8	3.01×10^7	16.90	1.195	8295	21.8	1.60
	Mode	2.77×10^8	1.52×10^8	3.76×10^7	21.12	1.494	8710	22.9	2.00
	Upper	3.33×10^8	1.82×10^8	4.51×10^7	25.34	1.793	9125	24.0	2.40
S2	Lower	8.77×10^7	2.99×10^7	8.19×10^6	4.45	0.412	8295	21.8	1.60
	Mode	1.10×10^8	3.75×10^7	1.02×10^7	5.56	0.515	8710	22.9	2.00
	Upper	1.31×10^8	4.50×10^7	1.23×10^7	6.67	0.618	9125	24.0	2.40
S3	Lower	2.23×10^7	2.790×10^7	1.23×10^7	19.83	0.192	8213	21.8	1.60
	Mode	2.79×10^7	3.49×10^7	1.54×10^7	24.79	0.241	8645	22.9	2.00
	Upper	3.34×10^7	4.19×10^7	1.85×10^7	29.75	0.289	9125	24.0	2.40
S4	Lower	2.71×10^7	3.52×10^7	1.54×10^7	19.83	0.212	8389	21.8	1.60
	Mode	3.30×10^7	4.40×10^7	1.92×10^7	24.79	0.265	8830	22.9	2.00
	Upper	4.06×10^7	5.28×10^7	2.31×10^7	29.75	0.318	9125	24.0	2.40
S5	Lower	1.35×10^7	6.18×10^7	3.72×10^7	1.7	0.412	8295	21.8	1.60
	Mode	1.69×10^7	7.72×10^7	4.64×10^7	2.13	0.515	8710	22.9	2.00
	Upper	2.02×10^7	9.27×10^7	5.57×10^7	2.56	0.618	9125	24.0	2.40

$$0 = NPV = \sum_{t=1}^{T} \frac{C_t}{(1 + IRR)t} - C_0 \quad (5)$$

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

A sensitivity analysis was conducted using Monte Carlo simulation to account for the influences of parameter uncertainties in the results of CBA. Each simulation was run 1000 times with the values of the parameters randomly selected from triangular distributions whose modes correspond to nominala values and lower and upper bounds correspond to ±20% of the nominal values as displayed in Table 6.

Results and discussion

Hydrogen production

The results demonstrate the variations in the yield of hydrogen according to the production technology and type and energy density of the feedstock. Table 7 displays the rate (tonnes/hour) and yield of hydrogen calculated per tonne of feedstock for each scenario. The highest yield of hydrogen per kg of feedstock is observed from S5 (SMR) at 242 kg, which is 3.4 times that of S1 (MSW gasification) at 71 kg H_2. This is partly due to the high process efficiency and waste conversion efficiency of S1 compared to S5, an increase of 28% and 18% respectively. S3 and S4 have the lowest hydrogen yields, approximately one sixth of that of the MSW gasification scenario, even though the feedstock quantity is 15% higher. Hydrogen production per year is the highest for MSW gasification (S1) at 13,089 tonnes due to the large feedstock availability compared to waste wood gasification (S2) of 4,514 tonnes/year and SMR (S5) of 4,506 tonnes/year.

Cost benefit analysis

The CBA results detailing the range of costs associated with each technology for the five scenarios are shown in Fig. 5 and Table 8. MSW gasification (S1) shows a total lifetime cost of approximately £486 million whilst the conventional SMR (S5) has a total cost of over £145 million (Table 8). This indicates a significant difference of £341 million. The lowest total cost scenario corresponds to the dark fermentation of wet waste/sludge and is approximately £78 million. Combining photo fermentation with dark fermentation (S4) increases the technology cost by 15% compared to dark fermentation (S3) whilst only increasing the hydrogen yield by 4.7% (Table 8).

There is no direct correlation between the total cost and LCoH, as seen in Fig. 4, where a low total cost does not imply a low LCoH. The highest LCoH value applies to combined dark and photo fermentation (S4), as the low hydrogen yield may not provide a high enough benefit to counter the high cost of production. The WtH technologies (S1, S2, S3, and S4) have a narrow range of mean LCoH values, 2.02 GB P to 2.29 GB P, while S5 has the lowest LCoH value of 1.06 GB P (Table 9). These results are comparable with the findings from Shahabuddin et al. [73] who found LCoH from biomass varies from 1.79 GB P to 4.1 GB P (2.3–5.2 USD/kg using conversion rate of 0.78 GB P) (Table 10).

The price of hydrogen is primarily dependent on the yield and efficiency of the technology, though other factors such as tax also affect it. This is shown in S5 which has a high level of tax applied to SMR and thus a significant effect on the total cost. CAPEX is the highest expenditure for all scenarios apart from S5 (SMR), where equipment and infrastructure costs are lower for the mature, standard production technology. SMR has a high OPEX cost due to the cost of natural gas feedstock, whereas utilising waste avoids this.

The NPV for all scenarios (S1–S5) are positive. This indicates that all scenarios will make a profit based on these parameters (Table 9). The IRR results are above 20% for all scenarios, indicating they are attractive investment projects. The BCR for the fermentation-based technologies of S3 and S4 have the highest ratios due to the lowest total cost and therefore the benefits outweigh the costs. The BCR for S5, given the changing view of natural gas for hydrogen production (grey hydrogen), may be least reliable given the potential for further tax increases on carbon emissions from fossil fuel sources. When comparing these results with other studies on gasification, fermentation and SMR technologies, similarities have emerged for the production cost and/or LCoH, where data is available (Table 10). For S1 the LCoH of 2.22 GB P/kg H_2 fits within the range stated by Shahabuddin et al. [73] of 1.02–3.50 GB P/kg H_2. The production cost of 2.23 GB P/H_2 kg for S2 also sits within the range of 0.75–2.06 GB P/H_2 kg for biomass gasification as stated by Bui et al. [74]. Comparison of dark fermentation data by Nikolaidis and Poullikkas [54] with S3 shows a difference in production cost of 0.13 GB P/kg H_2. While there is a difference of 0.22 GB P/kg H_2 between dark and photo fermentation and S4 [54]. No comparisons could be made for the LCoH of S3 and S4 due to the lack of data. The production cost for S5 is similar to the findings for SMR from IEAGHG [53] of 1.44 to 1.5–1.6 kg/H_2, though the LCoH of 1.06 is much lower than 1.72 from Valente et al. [24].

The plot of the profit against the hydrogen production cost (H_2 GBP/kg) indicates a profit increase potential, as shown in Fig. 6 for S1–S5. The WtH technologies have higher breakeven points than the SMR technology. S1 (MSW gasification) has the steepest gradient indicating a sharp profit rise of 3227 GB P per 10 p, greater than the SMR technology at 1112 GB P per 10 p (S4). The fermentation technologies (S3 and S4) have the smallest profit increase rates (548 GB P and 572 GB P per 10p, respectively), most likely due to their low hydrogen production rates.

Table 7 – Hydrogen production rates for S1–S5, using feedstock volumes (tonnes/hour), process efficiency and plant MW.

Parameter	S1	S2	S3	S4	S5
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	71	93	10	11	242
H_2 production kg/hour (at 90% CF)	1345	464	228	239	464
Plant rated capacity in MW	44.83	15.46	7.23	7.95	15.44
H_2 tonnes/year	13,089	4514	2111	2322	4508

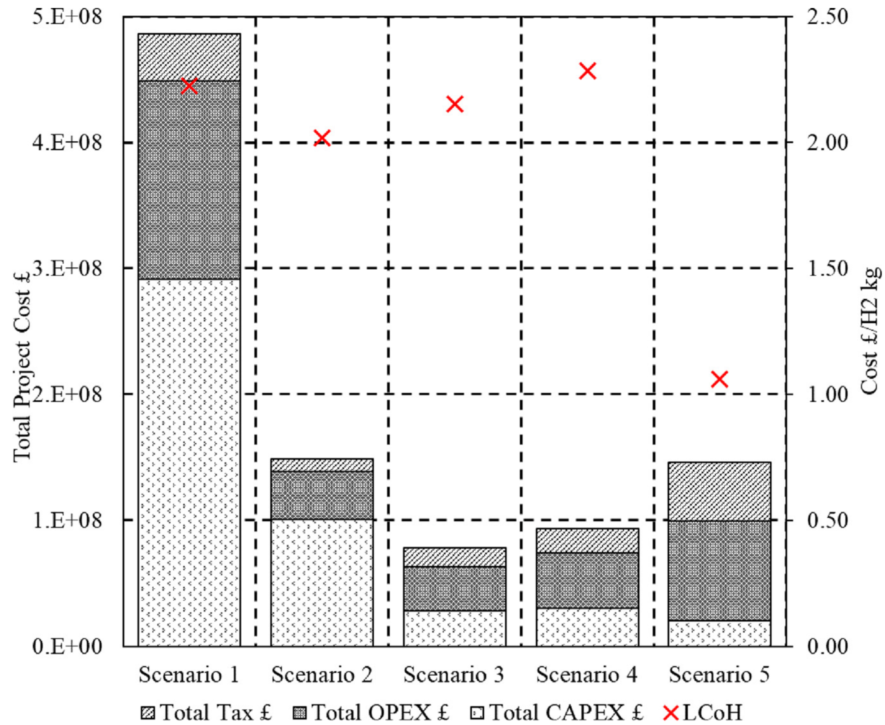

Fig. 5 – Comparison of CAPEX, OPEX, tax in GBP and LCoH as GBP/H_2kg for S1–S5.

Table 8 – Summary of costs in GBP for S1 to S5. CAPEX is divided into pre-development costs, construction, and infrastructure costs. OPEX is divided into fixed, variable, Balance of Systems use of systems (BSuS), Use of Systems (UoS) and insurance costs as defined by ARUP [63].

Stage	S1	S2	S3	S4	S5
Total CAPEX	291,395,000	100,490,000	27,857,992	30,398,677	20,611,666
Pre-Development	8,069,000	2,782,800	–	–	–
Construction	277,946,000	95,852,000	–	–	–
Infrastructure	4,379,600	1,855,200	–	–	–
Total OPEX	157,201,329	37,977,381	35,097,879	43,560,987	78,674,909
Fixed O&M	10,179,503	3,510,487	9,056,390	5,762,599	340,762
Variable O&M	125,313,167	26,980,482	26,488,016	34,137,985	70,857,420
BSUS	18,653,763	6,432,906	3,008,403	3,307,995	6,424,584
Insurance	2,482,237	856,020	227,073	249,686	854,913
UoS	572,658	197,486	93,419	102,722	197,231
UK ETS	17,694,219	4,818,175	7,253,946	9,053,460	21,853,222
CPS	19,905,996	5,420,447	8,160,689	10,185,143	24,584,874
Total Cost lifetime	486,196,544	148,706,004	78,370,505	93,198,266	145,724,671

Table 9 – Results of the CBA presented as average values for NPV, BCR, IRR and LCoH.

	S1	S2	S3	S4	S5
BCR	0.38	0.28	0.66	0.71	0.51
NPV	3.07×10^9	6.66×10^8	5.05×10^8	5.50×10^8	1.11×10^9
IRR	21.45%	20.27%	22.97%	22.4%	26.56%
LCoH	2.22	2.02	2.15	2.29	1.06

The analysis suggest S1-5 are economically feasible with positive CBA results. The scenarios rely on acquiring the appropriate start up investment (CAPEX) 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. SMR with carbon capture and storage systems may become more favourable due to the reduced tax implications, though it is still reliant on the low cost of natural gas.

Sensitivity analysis

The results of the sensitivity analysis are shown as histograms for LCoH and BCR and NPV in Figs. 7–9, respectively (the calculated means and standard deviations are also shown). The distributions show the significant effects of the variations in input parameters on each of the economic factors. It is observed that the values for all scenarios do not become negative and are fairly robust. The NPV for the gasification technologies are most sensitive to the changes in CAPEX and moderately sensitive to the effects of OPEX in all

Table 10 – LCoH comparison between this work and existing studies. (* denotes 1 USD = 0.73 GB P, and ″ denotes 1 EUR = 0.85 GB P.

Process	LCoH GBP/kg H_2	Production cost GBP/kg H_2	Conditions	Reference
S1	2.22	1.65	MSW	–
Waste Gasification	1.02–3.50*	–	MSW, residual	Shahabuddin et al. [73],
Waste Gasification	-	2.23	100 dry tonne/hr,	Ng and Phan [38]
S2	2.02	1.46	Waste wood	–
Biomass Gasification	–	4.19–5.74*	10t/day feed	Dowaki et al. [75],
Biomass Gasification	–	0.75–2.06*	–	Bui et al. [74],
Biomass Gasification	1.6–3.79*	–	10 MWth scale	Shahabuddin et al. [73],
Biomass Gasification	2.04–2.48*	–	250 MWth scale	Shahabuddin et al. [73],
Biomass Gasification	–	1.29–1.49*	Woody, steam	Nikolaidis and Poullikkas [54]
Biomass Gasification	–	8.07–10.83″	S/B ratio 1.5	Sara et al. [76],
Biomass Gasification	–	2.26*	FB reactor, 16.3 t/t H_2	Salkuyeh et al. [22],
S3	2.15	1.74	Wet waste/sludge	–
Dark Fermentation	–	1.87*	Organic biomass	Nikolaidis and Poullikkas [54]
S4	2.29	1.84	Wet waste/sludge	–
Photo Fermentation	–	2.06*	Solar source	Nikolaidis and Poullikkas [54]
Photo Fermentation	–	<1.46*		Dincer and Acar [77]
S5	1.06	1.44	Natural gas	–
SMR	1.72*	–	–	Valente et al. [24],
SMR	–	1.5–1.6	–	IEAGHG [53],

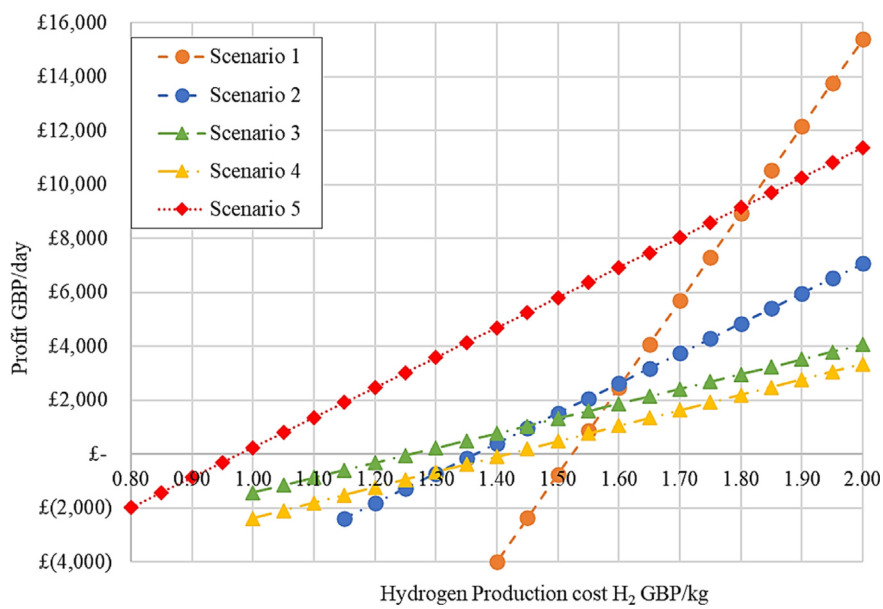

Fig. 6 – Profit trend for Scenarios 1–5. The zero profit GBP/day point represents the hydrogen production cost (GBP/kg).

scenarios. The lower hydrogen yield of the MSW gasification compared to waste wood gasification is an indication of the impact of higher energy density feedstock, and the sensitivity of MSW to a decreased conversion efficiency. Analysis suggests that the dark and photo fermentation technology (S3 and S4) are moderately sensitive to hydrogen production rates, shown by the low peak in LCoH (Fig. 7). The analysis does not account for the impact of the demand for hydrogen.

Limitations

WtH technologies are currently immature for large-scale deployment, and there are limitations associated with the analysis of thermochemical and biochemical processes. For example, the use of MSW as the feedstock for gasification-based hydrogen production is not widespread and therefore a lack of data or research for use at larger industrial scale projects exists [78]. There is also uncertainty related to the exact composition of MSW, as it is highly variable and affected by seasonal changes and external factors. The waste volumes used in this study are averaged over one year whilst a WtH facility would be affected by daily or weekly variations, which would impact the hydrogen yield, income and revenue of the development. The other main assumption stems from the use of basic scaling methods for the data collected from pilot, small-scale or academic research laboratories which do not account for economies of scale.

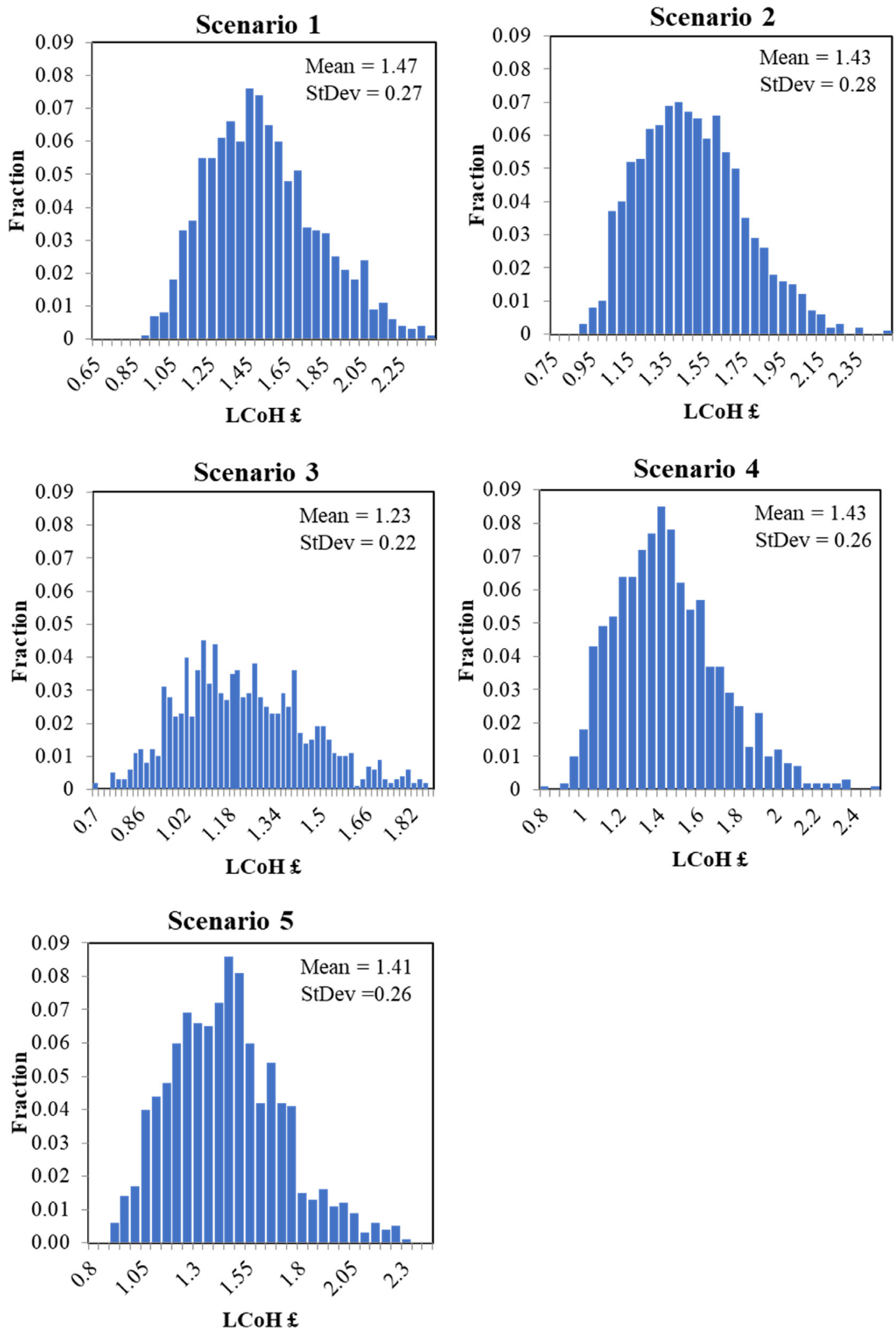

Fig. 7 – The histograms of LCoH from Monte Carlo Simulations for S1 to S5.

Consequently, there may be some under or overestimation when scaling to the large industrial size modelled here. Watson et al. [79], also recognized that the variations present in cost of gasification plants affected by the size (MW), complexity of the plant, feedstock and use of final product. This is in part due to the relatively immature technology leading to uncertainties in costs and the estimates that can be applied.

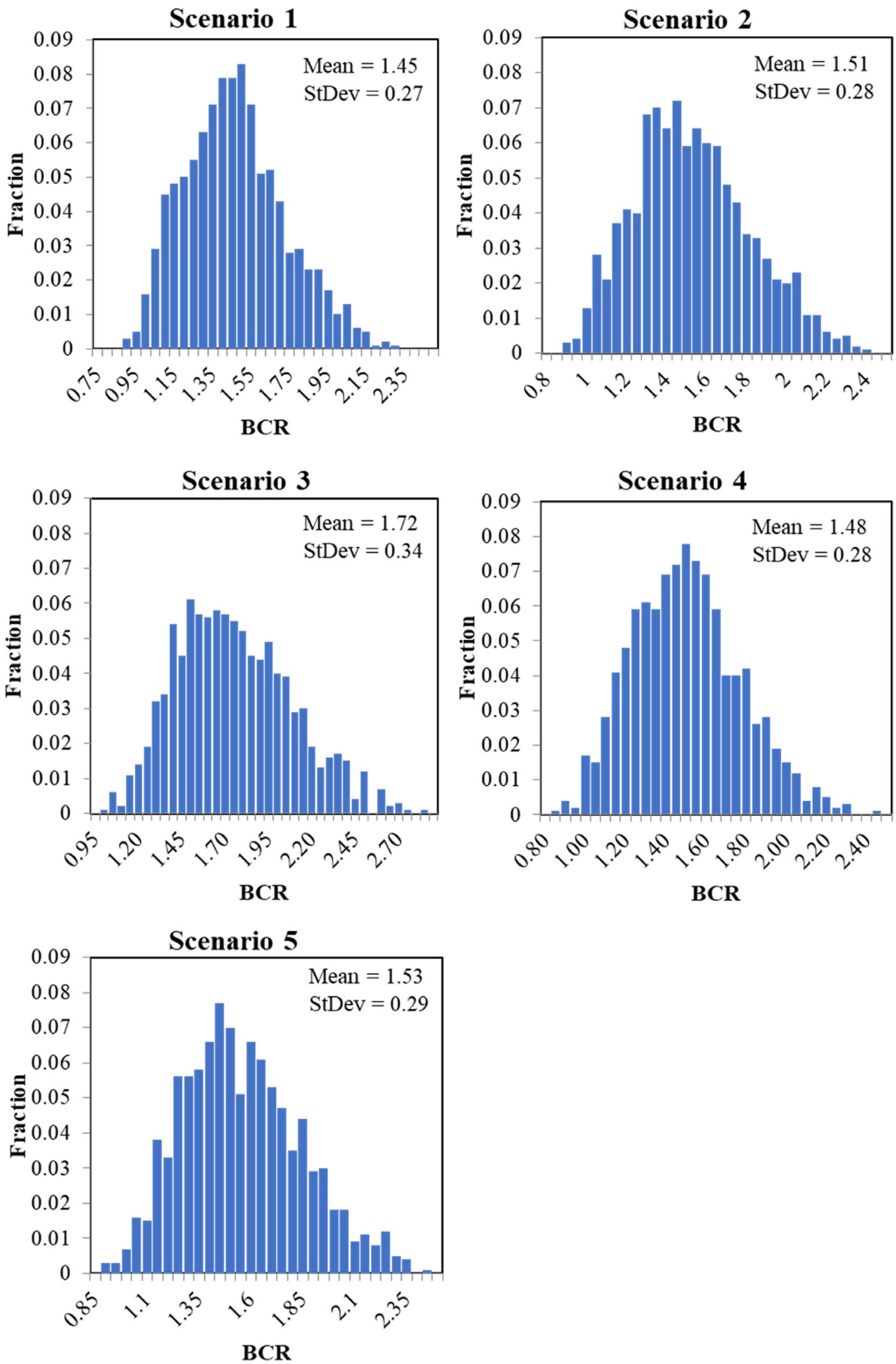

Fig. 8 – The histograms of BCR from Monte Carlo Simulations for S1 to S5.

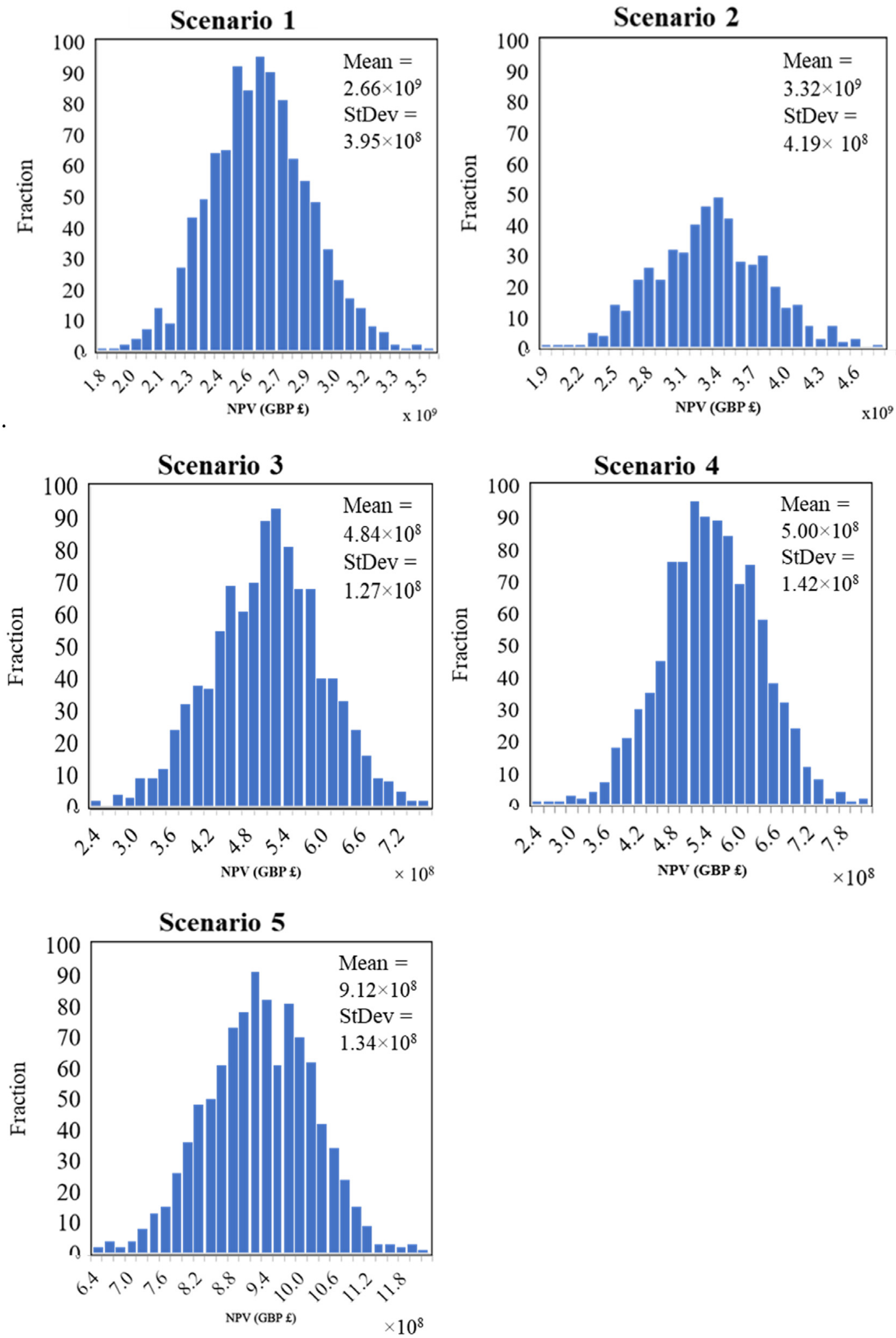

Fig. 9 – The histograms of NPV from Monte Carlo simulations for S1 to S5.

WtH outlook

The advantages of moving to a hydrogen industry and economy have been stated in many reports and government policies within the last few years [17,21]. This support places hydrogen production technologies in a good position for future interest and investment [80]. Though industrial scale operations will rely on efficiency improvements and technology

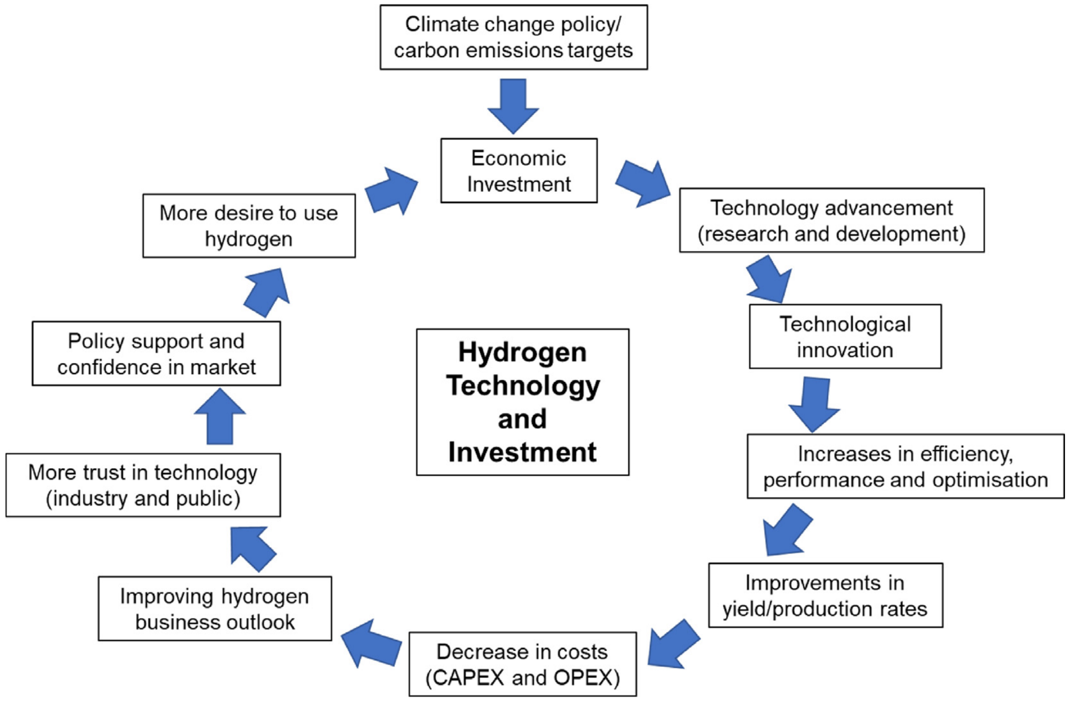

Fig. 10 – The relationship between policy, investment and advances in hydrogen technology development.

advancements for storage, compression and reducing energy losses through conversion [81]. For gasification technology to become economically viable and reduce capital costs, process intensification or integration is needed [82]. Fermentation currently modelled to be the lowest cost WtH technology analysed, also produces considerably lower hydrogen yields. Developments and optimisation of operating conditions, microorganisms, and inoculum to increase efficiency are needed to make it competitive with the other WtH systems [44].

The cost of hydrogen is a major barrier to widespread uptake [83]. The hydrogen industry, investors, stakeholders, and policy makers will benefit if the hydrogen price from renewable sources becomes competitive with other fuels, facilitating a reduction in market uncertainty. Fig. 10 illustrates the connection between investment, policy support, technology innovation, and a decrease in the cost of hydrogen. As production methods become more cost-competitive, the interest in large-scale energy facilities is likely to increase towards enhancing the capacity for low carbon hydrogen. The trigger for economic investment has been determined to be a change in policy regarding a reduction in carbon emissions and limiting climate change. Regular updating and revisions of cost parameters for modelling and commercial assessment is required to improve the reliability and analysis of future demand.

To improve the profitability of WtH technologies and generate further revenue, by-products from syngas and solid residues could be exploited and WtH projects would benefit from access to different markets. For example, Hamedani et al. [84] suggests the off-gas produced could be sold for electricity production and fed to the electricity grid, thereby generating extra revenue. Solid by-products from gasification can add profit to the process via *e.g.*, biochar sale and application as agricultural additives. Dark fermentation by-products including organic acids and alcohols can be utilized for recovery or further conversion to biofuels and platform chemicals [85].

As hydrogen demand is predicted to increase, investment in technological advancement and innovation is expected to bring costs down and allow faster commercial and industrial growth. According to the Hydrogen Council 2020 policy, support, and investment of around $70 billion up to 2030 is required to scale up [86]. However, the speed and scale of hydrogen production implementation is limited by challenges such as building of infrastructure and market economics [87]. Policy support and regulation is vital to encourage the acceptance of hydrogen technologies and use within energy, and transport industries. Favourable policy may have the added benefit of counteracting slow adoption and enhancing public opinion.

Conclusion

WtH technology can be harnessed in Glasgow to aid the zero emission targets set by the Scottish government in 2020. The WtH concept can contribute to the energy transition by providing an alternative to reduce reliance on fossil fuel-based hydrogen production. Providing a clean fuel in the form of hydrogen throughout the city's public transport system (heavy duty vehicles, such as buses, gritters and refuse trucks) has potential to promote low carbon transport. The results of the work support the concept of WtH in Glasgow and highlight the value of such innovative technologies in facilitating the transition towards a hydrogen economy. The four WtH scenarios in this study encompassing gasification, dark and photo fermentation suggest WtH technology could be economically feasible with the appropriate subsidies and policy support. 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 (S1) and low hydrogen yield for dark and photo fermentation (S3 and S4) are the main concerns. When considering taxes, subsidies, and predictions of increased demand for hydrogen, the economic outlook for WtH technology becomes more favourable, implying a promising route towards achieving hydrogen-powered transport and a hydrogen economy.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A1. Summary of waste types sent to landfill in 2018 in Scotland from SEPA [8].

Waste type	tonnes
Animal and mixed food waste	4352
Animal faeces, urine, and manure	27
Chemical wastes	1942
Combustion wastes	723
Common sludges	3192
Dredging spoils	2334
Health care and biological wastes	8549
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	3739
Soils	1,415,748
Sorting residues	745,403
Spent solvents	0
Textile wastes	996
Used oils	0
Vegetal wastes	5095
Waste containing PCB	0
Wood wastes	332
Total	3,445,727

Table A2. Summary of waste types sent for incineration in 2018 in Scotland from SEPA [17].

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	1314
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	2307
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

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