

Hy₂Market

Market research and thermochemical techniques for waste- to-hydrogen

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Executive Summary

This report delves into the potential and challenges of converting bio-degradable waste into hydrogen (WtH) through examining various thermochemical methods (e.g., gasification and pyrolysis) and their various established technologies. Furthermore, the hydrogen production potential of waste-to-hydrogen is examined in the Netherlands by looking in to bio-degradable municipal waste stream data for various years (2020, 2030) in order to broadly outline theoretical hydrogen production values and identify where potential use cases of such hydrogen could be. The derived bio-organic waste stream volumes are also compared to an existing waste stream database from the S2Biom project in order to check for validity and accuracy.

Spanning from the introduction to detailed analysis in Chapters 1 to 4, the objective is to provide a comprehensive examination of the processes, expected waste volumes, and the associated opportunities and obstacles regarding the implementation of waste-to-hydrogen methods and techniques. The introduction sets the stage by outlining the report's objectives, highlighting the significance of hydrogen fuel in achieving net-zero emissions, and comparing various hydrogen production technologies. The focus is on waste-to-hydrogen (WtH) as a promising method due to its environmental benefits and the utilization of otherwise discarded materials.

An in-depth overview in Chapter 2 is provided for examining established thermochemical techniques such as gasification and pyrolysis used in the WtH process. It details the stages from waste sourcing and preparation to the thermochemical treatment involving syngas generation, cleanup, and hydrogen separation. Specific emphasis is given to gasification, including types of reactors and the variety of steam gasification reactions, emphasizing their role in transforming waste into syngas, followed by a detailed review of the hydrogen purification process.

Discussed in Chapter 3 is the expected volumes of biodegradable waste available for hydrogen production, focusing on bio-organic waste data from the Netherlands. Calculations reference bio-organic waste data from the European Union's S2Biom project, which provided historical and projected waste generation volumes and were compared to independent calculations regarding waste generation volumes. Based on the independent calculations, in 2020 a total of ≈ 2700 kton of biowaste¹ was generated from household waste in the Netherlands which is

¹ This is strictly referring to the organic fraction from mixed household waste (i.e., unseparated organic household waste) and organic, kitchen and garden waste (i.e., separately collected household waste).

composed of 1022 kton of unseparated biowaste and 1682 kton of separated waste. This total amount is equivalent to a theoretical maximum of 155kton of hydrogen based on a high-heating value and 183.5kton based on a low-heating value. From an energy equivalent perspective there is a potential to generate a theoretical maximum of 22 PJ. A projection was also made for 2030 based on expected population data. The information is summarized in the table below.

Year	Total biowaste (kton)	kton H2 based on HHV	kton H2 based on LHV	Energy equivalent (PJ)
2020 - unseparated	1022.39	58.61	69.36	8.32
2020 - separated	1682.17	96.44	114.12	13.7
2020 - total	2704.56	155.05	183.48	22.02
2030 - unseparated	956.74	54.85	64.1	7.79
2030 - separated	1622.58	93.02	110.01	13.21
2030 - total	2579.32	147.87	174.9	21

Chapter 4 analyzes the opportunities and challenges in the WtH sector through a SWOT analysis. It identifies strengths of WtH in its significant decarbonization potential and competitive levelized costs of hydrogen (LCOH) compared to other methods of hydrogen production (i.e., renewable/non-renewable). Conducting an in-depth calculation of the LCOH was outside the scope of this study but an in-depth study for the Department for Business, Energy & Industrial Strategy – UK (see source [1]) gives a very good indication in the table below.

	100,000 tpa	500,000 tpa
LCOH without CCS	£7.53 ≈ €8.79	£3.52 ≈ €4.10
LCOH with CCS	£7.79 ≈ €9.10	£3.81 ≈ €4.48

Chapter 4 also highlights weaknesses, including technological bottlenecks and legal barriers. Opportunities like advances in waste collection routing, economies of scale, and environmental benefits from CO₂ capture are contrasted with threats such as fluctuating waste volumes and economic viability.

The report concludes that while WtH presents a viable and environmentally beneficial method for hydrogen production, several challenges must be addressed. These include improving technological processes, ensuring consistent waste supply, and navigating regulatory landscapes. The findings suggest a promising future for WtH, contingent on strategic advancements and supportive policies.

1. Introduction

Topics covered in this chapter:

- Introduction of the aims and goals of the report
- Relevance of hydrogen fuel as a contributor to net-zero goals
- Types of technologies for the production of hydrogen
- Advantages of waste-to-hydrogen compared to other hydrogen production methods

The role of hydrogen as an alternative fuel source compared to fossil fuels has gained significant momentum in order to achieve climate neutrality targets and decarbonize various sectors of the global economy. While electrification² is an effective net zero strategy, certain processes within energetically intense industries (e.g., steel production, ceramics, metallurgy, glass manufacturing etc.) and long-distance air travel require heat and energy demands that electrification is currently not capable of fulfilling. Here, hydrogen can step in to provide a foundation for a potentially long-term solution and provide sustainable decarbonization opportunities.

Currently hydrogen has an important role as a feedstock for many industrial applications such as in refining operations where hydrogen is used across a spectrum of operations, all aiming at obtaining better product qualities. The main processes include hydrotreating of various refinery streams and hydrocracking of heavy products [2]. Other examples include the fertilizer industry where hydrogen is majorly used in the synthesis of ammonia [3] and also the metallurgical industry where it boasts excellent refining agent capabilities [4]. To give a better overview, **Figure 1** exhibits the global consumption sources of hydrogen.

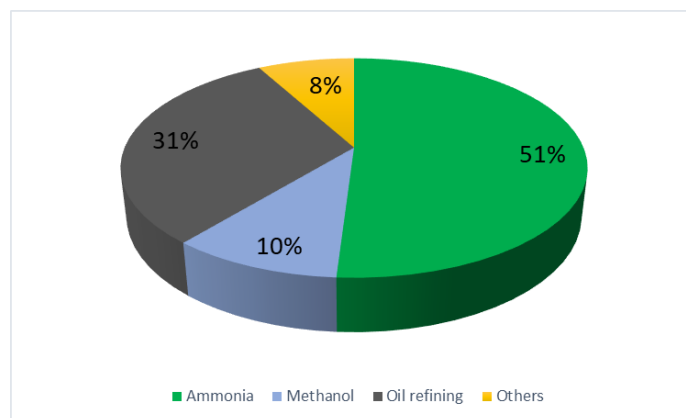


Figure 1: Global Consumption of Hydrogen [5]

² The replacement of technologies or processes, like internal combustion engines and gas boilers, with electrically powered equivalents, such as electric vehicles or heat pumps [123].

Conventional forms of producing hydrogen are done through the reforming of methane, recovery from refinery off-gases and coal/coke gasification³ [6]. Fossil-fuel based hydrogen production processes are 48% sourced from natural gas, 30% from oil and 18% from coal gasification [7]. In total, 96% of hydrogen production techniques are sourced from fossil fuels with only 4% sourced from water electrolysis (**Figure 2**).

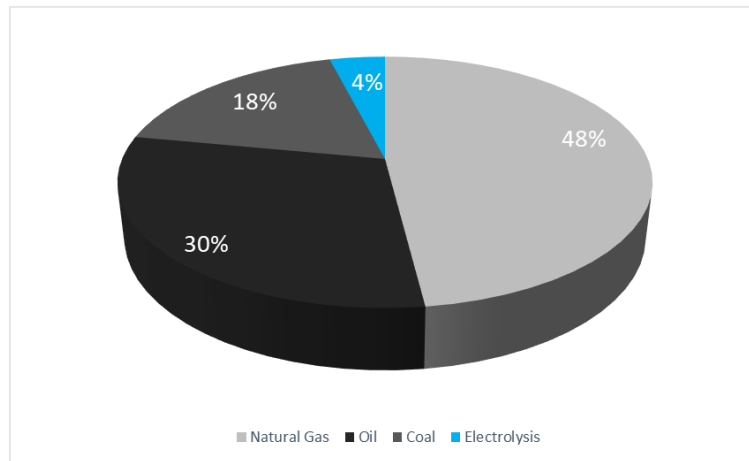


Figure 2: Sources of hydrogen production [7]

As seen in **Figure 2**, hydrogen is primarily sourced from natural gas which is commonly dubbed as 'grey hydrogen'. Steam Methane Reforming (SMR) is the most widespread technology for hydrogen production from natural gas at a large scale, although Autothermal Reforming (ATR) is also in use [8]. SMR and ATR techniques involve reacting natural gas with steam or limited amount of oxygen, at high temperatures over a catalyst to produce syngas (a mixture of hydrogen and carbon monoxide). This is then processed to maximize H₂ generation (via water gas shift reaction) and separate H₂ product from a CO₂-rich stream [9]. The main issue involved in these methods are the high amounts of carbon dioxide that are released into the atmosphere during production. Sources attribute SMR with a global warming potential of 11.2 kg CO₂ eq [10] and 11.43 kg CO₂ eq [11] which accounts for upstream and downstream emissions respectively. For ATR, total GHG emissions of 11.01 kg CO₂ eq have been reported [12].

Current production of hydrogen for these applications emits 1100 – 1300 MtCO₂ equivalent worldwide (including upstream and midstream emissions from fossil fuel supply) [13]. Replacement of carbon intensive modes of hydrogen production with low-emission hydrogen will be an important short-term step to take since low-carbon hydrogen can be substituted with carbon-intensive form with limited technical challenges and utilized in existing applications.

Emerging low-carbon methods of producing hydrogen consist of:

- Utilization of renewable electricity to produce hydrogen via water electrolysis e.g., 'green hydrogen'.
- Combining carbon capture and storage (CCS) with SMR or ATR e.g., 'blue hydrogen'.
- Thermochemical conversion of biomass.
- Biochemical methods such as fermentation and anaerobic digestion.

³ This is also known as the 'partial oxidation' of heavy cuts of hydrocarbons.

Of topical importance to this report is the thermochemical conversion of lignocellulosic biomass in which solid organic materials undergo thermal conversion through pyrolysis/gasification in order to produce biofuels such as methanol, ethanol, dimethyl ether, synthetic natural gas and biohydrogen⁴. **Figure 3** represents a schematic trail of these processes; these processes will be further described and analyzed in section 2 of the report.

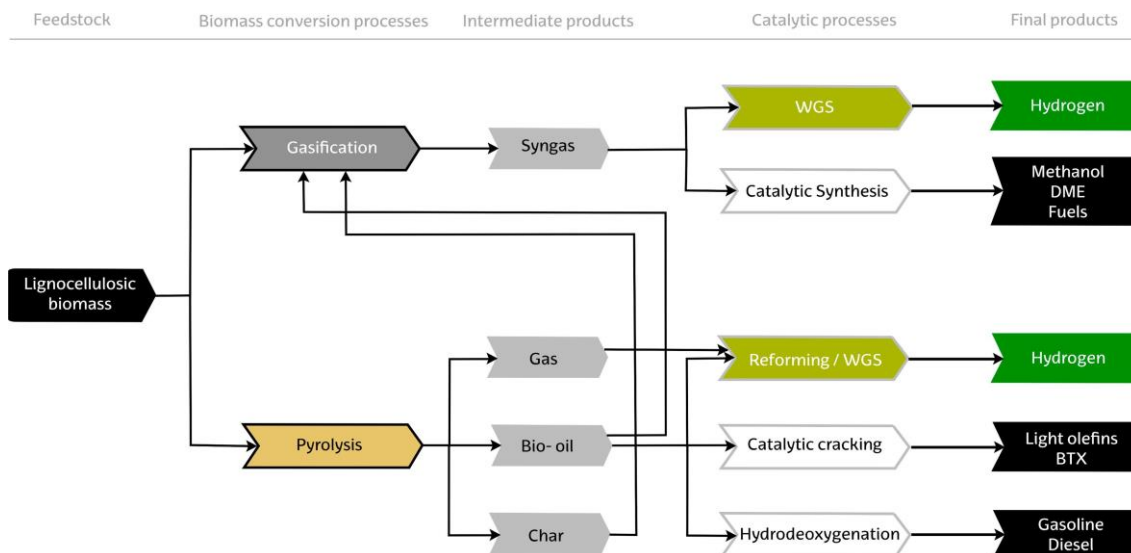


Figure 3: Schematic representation of the main processes involved in a lignocellulosic thermochemical bio-refinery [14].

Biomass feedstock can be used to produce two broad categories of biofuels:

- first-generation biofuels
- second-generation biofuels

First-generation biofuels (e.g., ethanol or biodiesel) are produced from types of biomasses that are often used for food such as grains and starch crops (e.g., corn, sugar cane, sugar beets) and vegetable oils (e.g., soy, canola, palm) [15]. Second-generation biofuels (e.g., cellulosic ethanol, bio-butanol etc.) are produced from non-food biomass, such as perennial grasses (e.g., switchgrass, miscanthus), fast growing trees (e.g., hybrid poplar, willow) and byproducts & waste (e.g., corn stover, wheat straw, forest residue, municipal waste, used cooking oil) [15].

Countless studies have looked into the production of biofuels from first-generation biomass. However, the challenge of using first-generation biomass for the production of any biofuel is disputed by the ‘food vs. fuel’ debate where energy crops encroach into the production of food crops. Consequently, land and fresh water normally utilized for food production is displaced by energy crops. There are also environmental concerns due to this substitution, specifically on the over-usage of water and fertilizer for the production of energy crops.

Second generation biomass offers more opportunities for energy production since it does not compete with food production⁵ and is not limited by the issue of security of supply due to its

⁴ The term ‘Biohydrogen’ is used in this report to refer to hydrogen produced from biomass

⁵ It is difficult to draw a hard line between food and fuel uses for agricultural crops. For example, switchgrass, which is considered a second-generation crop, can also be fed to cattle to produce beef [15].

abundance but is challenging to utilize due to the complexity introduced by pre-treatment of the biomass. Specifically, municipal solid waste (MSW) as a feedstock is deemed as a complex and technically challenging type of feedstock to process due to the abundance of contaminants. Nonetheless, utilizing waste for the production of energy falls into the category of producing energy-from-waste (EfW) and is an important step in the hierarchy of European strategy for waste management mentioned in Directive 2008/98/EC.

This emphasizes the high level of importance that needs to be placed on improving waste management techniques since global waste production is expected to reach more than 6Mt of solid waste daily [16] and solid-waste management accounts for one of the greatest costs attributed to municipal budgets [16]. Additionally, conventional waste management techniques relying on landfilling⁶ and incineration have adverse environmental impacts and limited energy efficiencies [17]. Hence, sustainable waste management can play a prominent role in curbing these challenges and in contributing to the sustainable cities and communities' goal among the UN's 17 sustainable development goals (SDG's) [18].

Figure 4 represents an integrated waste management approach based on EU Directive 2008/98/EC (see **Box 1** for definition). Material recovery (via re-use and recycling) has the highest value, if for certain waste streams material recovery is not possible then energy recovery is pursued; landfilling with proper treatment is advised only as a last step.

Directive 2008/98/EC

Member States shall take measures to encourage the options that deliver the best overall environmental outcome. This may require specific waste streams departing from the hierarchy where this is justified by life-cycle thinking on the overall impacts of the generation and management of such waste" [93].

Box 1: Definition of EU Directive 2008/98/EC



Figure 4: Waste hierarchy as determined in Directive 2008/98/EC of the European Union

Among this hierarchy, energy recovery is the focal point of this study. Producing energy from waste contributes to primary energy savings in conventional utility systems [19]. By and large, production of energy commodities such as electricity and heat via the thermal treatment of waste is nothing new and has existed for decades however additional attractiveness toward waste thermal treatment is given by the possibility of making significant energy recovery, thanks to technological developments [20] but also due to changes in consumer habits and increases in upstream separate collection [21].

The production of hydrogen from waste falls under the Waste-to-Energy (WtE)/Energy-from-Waste (EfW) paradigm. MSW and waste in general, represent an ideal source because of their large availability and low cost [22]. From a climate change perspective, the use of waste as feedstock not only ensures large and economical availability for consistent hydrogen supply, but

⁶ Landfilling is known to emit very large amounts of methane: solid waste landfills account for about 14% of global methane emissions [90].

also avoids use of current disposal technologies, which are known to contribute enormously to GHG emissions and water and land pollution [23].

Waste suitable for waste-to-hydrogen (WtH) consists of biomass wood waste (e.g., timber or paper industry waste), municipal solid waste (MSW), sewage sludge, packaging and plastics, solid recovered fuel (SRF) and refuse derived fuel (RDF) derived from MSW [17]. MSW normally includes biodegradable waste, recyclable material, inert waste, electronic waste, hazardous and toxic waste which is discarded by the public [24]. Among these, food waste represents a significant fraction of MSW (globally anywhere between 24-66% [25] and 30-37% for Europe); **Table 1** represents MSW composition for the Europe, of specific interest for 'biohydrogen' production are the compositions of food waste, paper/cardboard, and wood.

Table 1: MSW Composition Data by Percent (adapted from [25])

European Region	Food Waste	Garden Waste	Paper/cardboard	Wood	Textiles	Nappies	Rubber/Leather	Plastic	Metal	Glass	Other
Eastern Europe	31.8	2.4	17.1	2.5	3.1	0.1	0.5	4.6	0.7	1.8	35.3
Northern Europe	30.3	5.2	13.8	1.8	3.2	1.2	0.0	4.9	1.4	4.3	34.0
Southern Europe	37.1	2.2	19.2	1.4	3.2	1.1	0.2	11.8	1.9	3.6	18.3
Western Europe	33.2	2.7	17.2	2.3	5.9	3.0	0.0	20.5	1.5	1.4	12.3

Biological and thermochemical technologies (e.g., incineration, pyrolysis, gasification and hydrothermal oxidation) have been used for the production of energy and are therefore considered appropriate for food waste recycling/valorization though the potentially high moisture content affects the practical use and leads to energy losses [26]. Sources mention the average lower-heating-value (LHV – also see **Box 2**) of MSW around 10 GJ/Mg in the EU which is low compared to fossil fuels, though it can be higher (~25 GJ/Mg) with pre-treatment of the feedstock [27]. Thermochemical processes such as gasification and pyrolysis will be further analyzed and discussed in detail in **Chapter 2: Overview of Thermochemical Technologies** but an overview of food-to-waste energy technologies/pathways is shown in **Figure 5**.

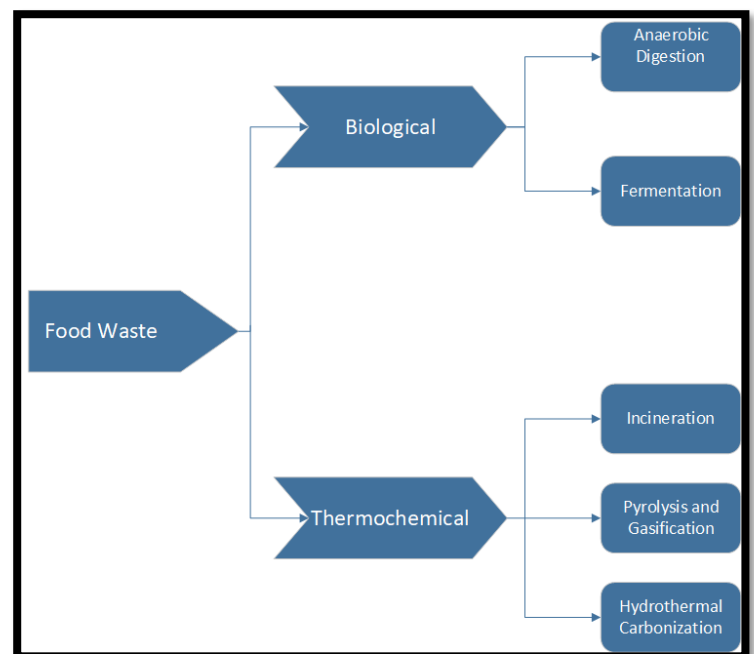


Figure 5: Summary of food-to-waste energy technologies (adapted from [26])

Pre-treatment is an important step since hydrogen from household or commercial waste is only partially renewable due to the presence of plastics-based carbon, and only the energy contribution for the biogenic portion is typically counted towards renewable energy targets [22]. Hence, the waste has to be re-treated for the separation of the biogenic fraction. This is normally done by taking the untreated waste and mechanically processing it in a material recycling facility where it is homogenized, de-moisturized, rid of other components such as metals, glass, and heavy plastics for further processing. The next chapter will take a more detailed look into this separation process.

Heating Value: the heating value of a substance (usually a food or fuel) is the amount of heat released during the combustion of a specified amount of it. It is expressed as energy/mole or energy/mass or energy/volume [125].

During combustion, water vapor is produced as a byproduct when the hydrogen in the fuel combines with oxygen from the air. This water vapor is initially in a gaseous state.

The water vapor may condense back into a liquid under certain conditions, typically when the combustion gases cool down to a point where the water vapor reaches its dew point. This can happen in applications such as power generation, where combustion gases are often cooled to recover waste heat or to increase the efficiency of the process. However, in most practical applications, such as home heating or industrial processes, the water vapor remains in its gaseous form as it is released into the atmosphere without condensing back into liquid.

The distinction between higher heating value (HHV) and lower heating value (LHV) accounts for this difference in treatment of the water vapor produced during combustion—whether it is assumed to remain as vapor (LHV) or to condense into liquid (HHV).

Higher Heating Value (HHV):

- HHV considers the total amount of heat released when a fuel is completely burned
- It includes the heat released when the water vapor formed during combustion is condensed back into liquid water.
- HHV assumes that the water vapor produced during combustion is in its liquid form.

Lower Heating Value (LHV):

- LHV considers the heat released when a fuel is burned but does not include the heat released by condensing water vapor back into liquid.
- It excludes the heat from the condensation of water vapor.
- LHV assumes that the water vapor produced during combustion remains in the form of vapor

Box 2: Definitions of heating value

2. Overview of Thermochemical Technologies

Topics covered in this chapter:

- Looking into the WtH process chain: Waste → Technology → Products → Downstream Processing.
- Thermochemical Technologies within Gasification and Pyrolysis:

This chapter will provide an overview of the main transformation steps involved in the production of hydrogen from waste. depicts a simple flow diagram of this process and can be broken down into two main activities:

- Sourcing of the waste and preparation of the waste
- Thermochemical treatment of the waste, such as syngas generation, cleaning, reforming, separation and purification processes.

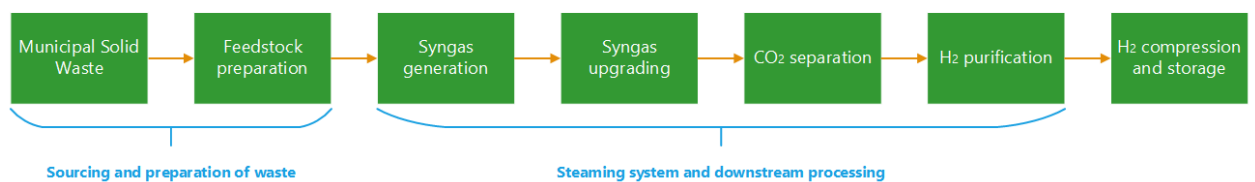


Figure 6: Schematic diagram of the main stages of a WtH process flow

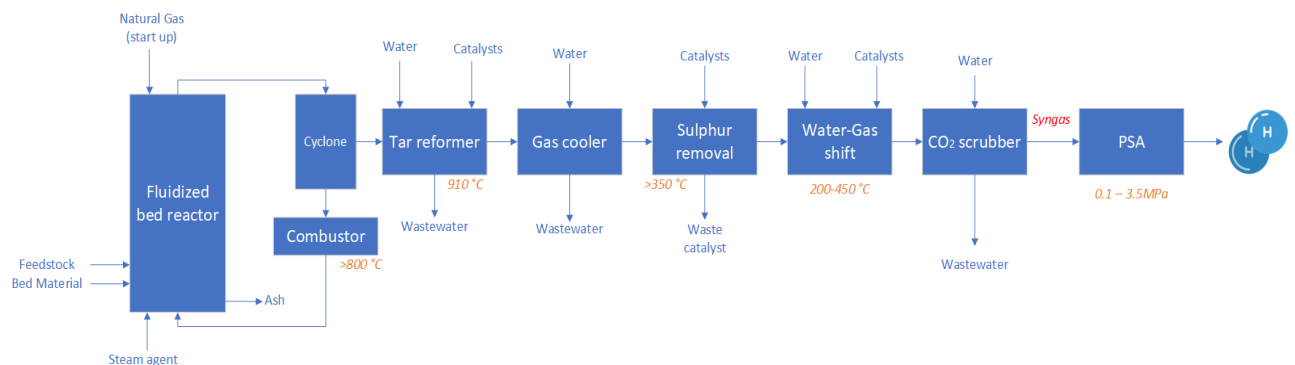


Figure 7: Flow diagram of gasification process using circulating fluidized bed reactors [17]

Figure 7 provides a schematic overview of all the steps involved in the thermochemical treatment of waste. These steps can be summarized into three main activities: 1) the gasification of waste in a specific kind of reactor, 2) treatment of the produced fumes in order to remove impurities, increase the ratio of H₂:CO and reduce tar formation and 3) the separation of hydrogen via pressure-swing absorption. We will take a closer look at each of the components and steps in detail.

2.1 Sourcing and preparation of waste

Waste suitable for waste-to-hydrogen (WtH) production consists of biomass wood waste (e.g., timber or paper industry waste), municipal solid waste (MSW), sewage sludge, packaging and plastics, solid recovered fuel (SRF) and refuse derived fuel (RDF) derived from MSW [16]. However, waste for the purpose of energy recovery cannot be directly utilized as a feedstock and needs to undergo pre-treatment. The untreated municipal or commercial waste is first mechanically and biologically treated in a material recycling facility (MRF) and is aimed at improving the combustible quality of the waste via reducing the moisture and ash content and the technical and environmental parameters via reduction of pollutants [28] in order to produce solid recovered fuel (SRF) and refuse derived fuel (RDF) (see [Figure 8](#)). RDF and SRF are both waste-derived fuels, but SRF is typically of higher quality with more extensive processing to remove impurities and attain a higher fuel calorific value, making it suitable for a wider range of industrial applications (see [Table 2](#) for comparison). The choice between RDF and SRF lies in the specific needs of the end-user and the available waste streams and processing capabilities but RDF is a completely viable feedstock for hydrogen production.



Figure 8: Loose RDF material (left) [29] RDF/SRF in a pelletized format (right) [30]

Techniques implemented in an MRF facility involve Mechanical-Biological treatment (MBT) in order to homogenize the waste and remove parts of the moisture, recyclables (e.g., metals and dense plastics) and reject materials [22]. This is because MSW includes inert waste such as glass, sand and rocks, electronic waste and batteries and an assortment of hazardous waste that is not deemed usable. The mechanical phase of MBT, generally consisting of shredding and sieving units, sometimes followed by density separation (e.g., air classification or ballistic separation), produce a waste flow, namely refuse derived fuel (RDF) [28]. Shredding is achieved by using a tearing motion to achieve a rough shred of waste residues, with a homogenous, predetermined particle size between 1 and 50mm depending on the gasification reactor requirements⁷ [22]. The biological phase of MBT involves aerobic or anaerobic degradation of the organic fractions that are mechanically separated [28]. This step is done to improve the quality of RDF by reducing the organic fraction of the waste leading to waste that has a lower moisture content and increasing the energy content or the calorific value of the fuel. This ultimately results in a more efficient combustion process. A similar step to the biological treatment step in order to increase the energy content of the feedstock is torrefaction: a thermochemical process which is carried out at a temperature between 200 and 300 °C in the

⁷ The size of the fuel particles affects the time required for their combustion [27]

absence of oxygen. At these temperatures some chemical reactions take place; the biomass loses both the rigid fibrous structure and moisture content, with a consequent increase in the energy content [31].

Typically, a 100,000 tons MSW feed produces an output of ca. 60,000 to 80,000 tons of RDF with a moisture content of 10-17%, 10-20% ash content and 15-25 MJ/kg calorific value (CV) [22]. **Table 2** shows overall energy and content specifications of RDF/SRF, it's clear that SRF has higher performance in terms net calorific value, reduced moisture and ash content compared to RDF, but one has to be mindful that SRFs are very complex and heterogeneous materials, and the fraction of each component can vary significantly depending on the waste origin, the season, the waste separation plant, and the SRF production technique [32].

Table 2: General composition of waste derived fuel (Source: [33])

Measure	Units	Residual Waste ^[1]	RDF	SRF
Net Calorific Value	MJ/kg (as received)	9 - 15	10 - 15	>18.5
Moisture	wt% (dry basis)	10 - 40	<25	<15
Biomass Content	wt% (dry basis)	>45	>65	>65
Ash Content	wt% (dry basis)	10 - 30	<20	<15
Sulphur	wt% (dry basis)	< 0.85	<0.5	<0.5
Nitrogen	wt% (dry basis)	<1.5	<0.8	<0.8
Lead	mg/kg	<200	<100	<80
Chlorine Cl	wt% (dry basis)	<1.2	<0.1	<0.6
Zinc	wt% (dry basis)	<0.1		
Sodium and Potassium	wt% (dry basis)	<0.8		
Mercury	mg/kg	<2	<1	<0.6
Nickel	mg/kg	<200	<100	<100
Thallium	mg/kg	<20	<10	<10
Ferrous and non-ferrous metals	wt% (dry basis)	<7	<3	<1
Non-combustible material	wt% (dry basis)	<15	<10	<5
Glass	wt% (dry basis)	<5	<2	<1
Dust <1mm	wt% (dry basis)	<5	<5	<5
Bulk Density (loose)	kg/m ³	100 - 275	100 - 175	185
Particle Size (max dimension)	mm	500	300	<40

After the waste is converted into RDF/SRF it can undergo the gasification process in order to produce syngas.

2.2 Gasification

Gasification is a process aimed at converting a solid fuel – solid waste in this specific case – to a gaseous fuel, called “producer gas” or “syngas”, through a partial oxidation of the solid fuel in the presence of an oxidant amount lower than that required for the stoichiometric combustion. A solid product is generated, too, containing char (carbonaceous compounds) and ashes [27]. The conversion of solid material occurs between temperatures of 500 °C and 1200 °C in an oxygen deficient environment at atmospheric pressure (0.1 MPa) [14].

Gasification is one of the most efficient methods to extract energy from fuel sources and convert it into a usable form by partial or total transformation of solids to gases [34]. In the presence of an oxidizing agent at high temperature (such as steam, air (in partial oxidation) or CO₂), the large polymeric molecules of biomass decompose into lighter molecules and eventually to permanent gases (CO, H₂, CH₄ and lighter hydrocarbons), ash, char and tar, and minor contaminants [34] (see **Figure 9**).

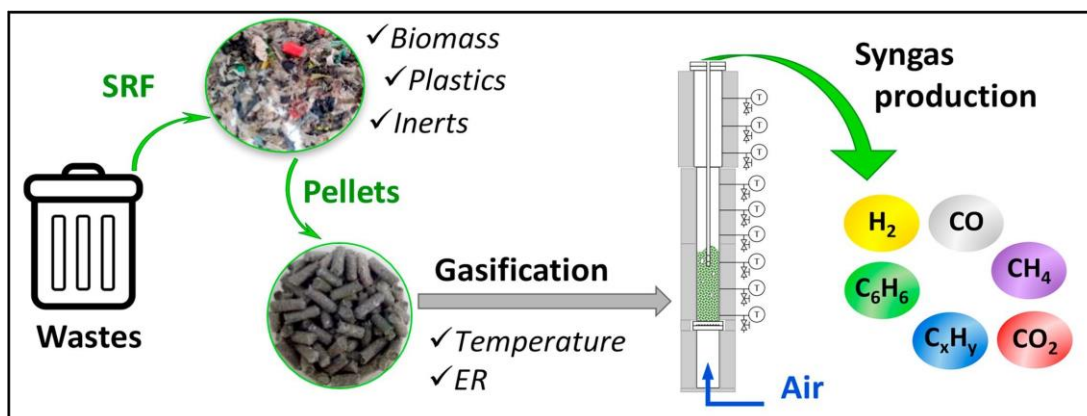


Figure 9: Gas composition of syngas derived from SRF/RDF [32]

Gasification is divided into four steps: drying (endothermic step), pyrolysis (endothermic step), oxidation (exothermic stage), and reduction (endothermic stage). Tar-reforming can also be added as a step to produce light hydrocarbons from large tar molecules [35]. **Table 3** describes the main characteristics of these steps.

Table 3: Steps involved in the gasification process (based on information from [31])

Steps of Gasification	Description
Oxidation	Oxidation of biomass is necessary to obtain the thermal energy required for endothermic processes and to maintain the operative temperature at the required value [35]
Drying	Drying consists in the evaporation of the moisture contained in the feedstock, generally the heat required is derived from other stages of the process [31]
Pyrolysis	Pyrolysis consists of the thermochemical decomposition of the carbonaceous materials. By pyrolysis it is possible to obtain different fractions: a solid, a

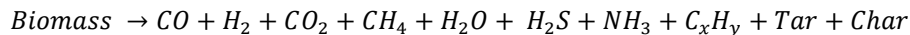
	liquid/condensate and a gaseous fraction [36] [37] [38]
Reduction	This step involves all the products from the stages of oxidation and pyrolysis (gases and char) to react with each other resulting in the formation of syngas [31]. As seen in Table 4 reduction is composed of both endothermic and exothermic reactions but globally, reduction is endothermic.

A few of the major reactions involved in this process are listed in **Table 4**:

Table 4: Major reactions involved in gasification [39]

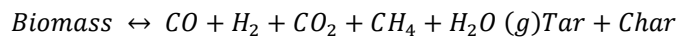
Reaction name	Chemical Reaction	Reaction type	Gasification Step
Char Combustion	{biomass volatiles/char} + O ₂ → CO ₂	Exothermic	Oxidation
Partial oxidation	{biomass volatiles/char} + ½O ₂ → CO	Exothermic	Oxidation
Methanation	{biomass volatiles/char} + 2H ₂ ↔ CH ₄	Exothermic	Reduction
Water-gas shift	CO + H ₂ O ↔ CO ₂ + H ₂	Exothermic	Reduction
CO methanation/steam reforming of methane	CO + 3H ₂ ↔ CH ₄ + H ₂ O	Exothermic	Reduction
Steam-carbon reaction	{biomass volatiles/char} + H ₂ O ↔ CO + H ₂	Endothermic	Reduction
Boudouard reaction	{biomass volatiles/char} + CO ₂ ↔ 2CO	Endothermic	Reduction
Thermal Cracking of Tar	C _n H _m ↔ C _{n-x} H _{m-y} + H ₂ + CH ₄ + C	Endothermic	Reduction

A simplified gasification process is shown below in **Equation 1**:



Equation 1: Chemical reaction of the gasification process [40]

The pyrolysis process is typified as an endothermic reaction:



Equation 2: Pyrolysis reaction [41]

Pyrolysis and gasification are sometimes misidentified, misrepresented or equated with each other but they are distinct processes. The main defining criteria that separate both is the presence of oxygen. While gasification occurs with restricted oxygen, pyrolysis occurs in the

absence of oxygen or steam [42]. **Table 5** provides a comparison between the two and a comparison to combustion as well.

Table 5: Comparison of Combustion, Gasification and Pyrolysis (Source: [42])

	Combustion	Gasification	Pyrolysis
Oxidizing Agent	Greater than the stoichiometric supply of oxygen	Less than the stoichiometric oxygen or steam as the oxidizing agent	Absence of oxygen or steam
Typical Temperature Range with Biomass Fuels	800 °C – 1200 °C	800 °C – 1200 °C	350 ° - 600 °
Principle Products	Heat	Heat and Combustible Gas	Heat, combustible liquid and combustible gas
Principle Components of Gas	CO ₂ and H ₂ O	CO and H ₂	CO and H ₂

However, pyrolysis is a sequential step within the gasification process. For gasification to proceed, pyrolysis must occur since the biomass has to undergo thermochemical decomposition. Gasification of biomass without the pyrolysis stage is meaningless. As the biomass is heated, it first undergoes pyrolysis, breaking down into char, bio-oil, and syngas. This initial breakdown is crucial for the subsequent gasification process. This is shown in effect where **Equation 2** is in essence embedded in **Equation 1** and contributes in bulk to the gasification process.

Figure 10 shows how the various chemical reactions involved in the gasification process cascade into each other in order to produce syngas. Based on the figure, it is clear that gasification involves numerous complex interactions.

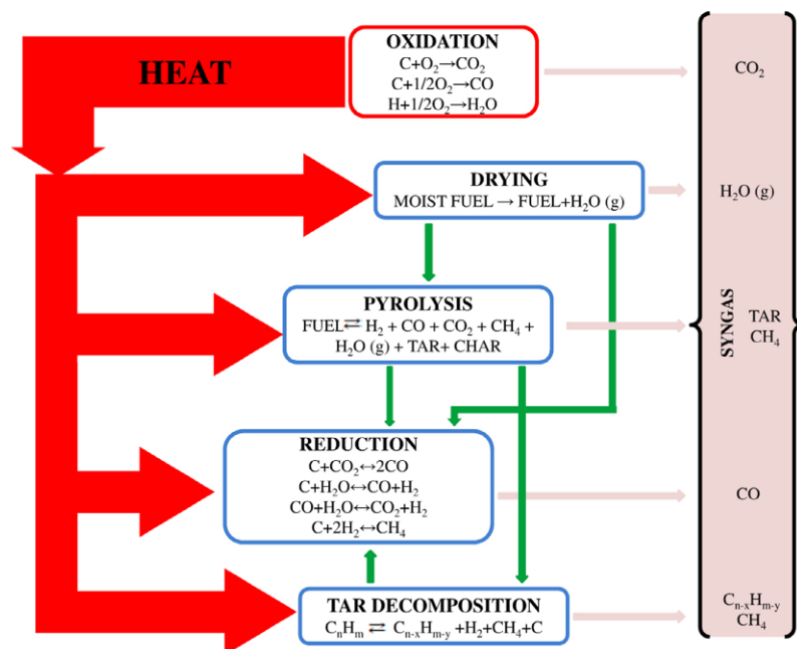


Figure 10: Main stages of the gasification process [31]

Figure 11 provides a general overview of the main stages involved in the gasification of biomass and the percentage volumes of components available in the syngas, tar and char.

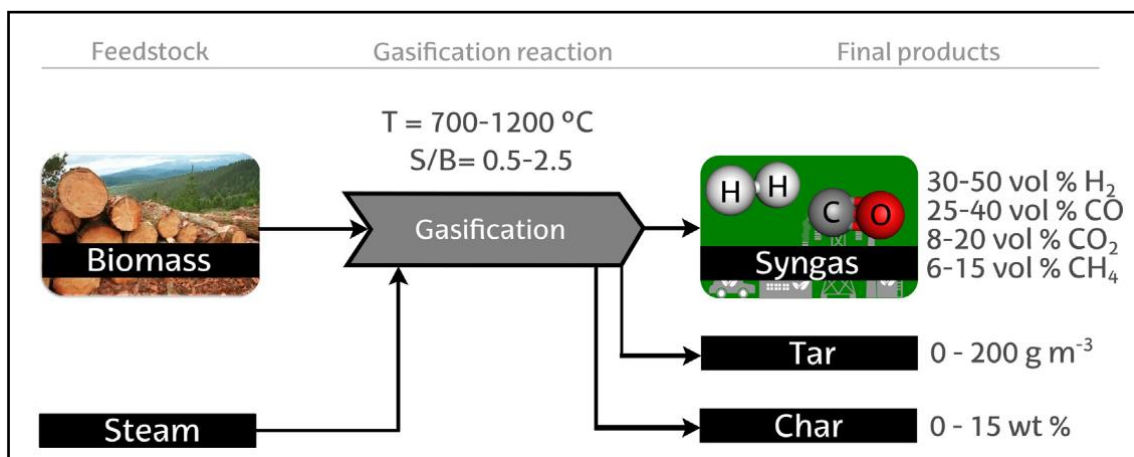


Figure 11: Representation of the biomass steam gasification process for hydrogen production (Derived from [14]).

2.2.1 Supplying heat to gasifiers

Gasification requires heat and the process could be either autothermal or allothermal, depending on how the heat is provided to the gasifier [34]. The difference between these methods lies in how heat is supplied to the gasification chamber for gasification. Each method has a highly determinant effect on what the composition of the syngas will be.

2.2.1.1 Autothermal Gasification

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 [43]. Part of the feedstock is combusted in exothermic reactions to provide heat to gasify the remaining products [44]. The reduced atmosphere of 0.1 MPa in the process limits the emissions of furans and dioxins that often link with the combustion of waste [45], while the oxygen deficient environment reduces heat losses and increases energy recovery efficiency. **Figure 12** depicts a flow diagram for autothermal gasification.

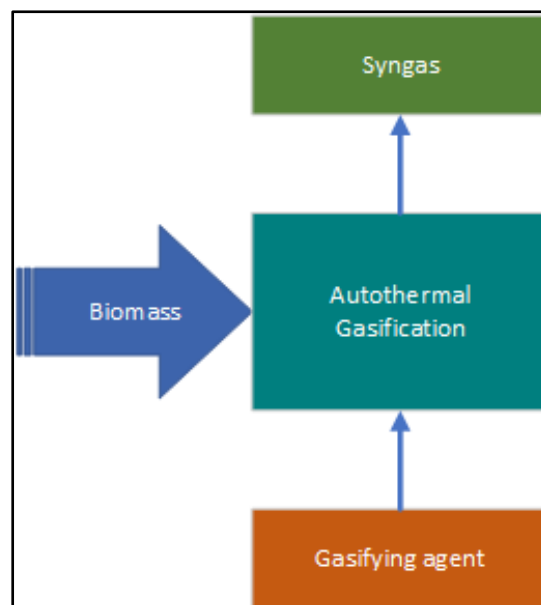


Figure 12: Autothermal gasification flow diagram (adapted from [46])

2.2.1.2 Allothermal Gasification

In an allothermal gasifier, heat is supplied to the gasification chamber from an external heat source, typically through the use of a separate burner or a combustion chamber (**Figure 13**). This external heat source can be a variety of fuels, such as natural gas, oil or even the syngas produced by the gasifier itself in some cases. The heat generated in the external combustion chamber is transferred to the gasification chamber, where it initiates and sustains the gasification reactions.

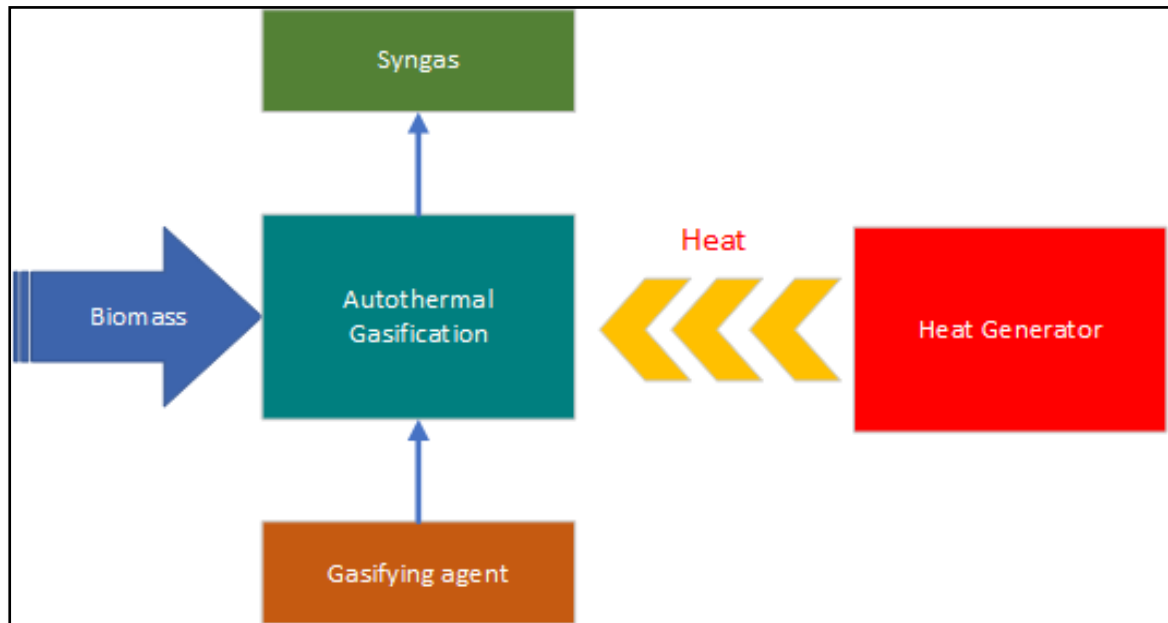


Figure 13: Allothermal gasification flow diagram (adapted from [46])

2.2.2 Steam gasification

The utilization of steam as a gasifying agent for the thermochemical conversion of biomass leads to a product gas that is enriched with hydrogen and is significant for the production of hydrogen from waste. Steam leads to increased hydrogen yields due to the additional hydrogen that is produced from the decomposition of H_2O . In addition, compared with partial oxidation using air, the product gas has a higher heating value because dilution with nitrogen is avoided [47]. In the absence of oxygen, conventional steam gasification is an endothermic process, which means that additional heat source from an exothermic reaction is required to drive the reaction system [34]. Based on this, steam gasification of biomass falls under the category of allothermal gasification since the generation of heat for the production of steam needs to be supplied from a combustion chamber or a heat exchanger in order to supply the necessary thermal energy for the endothermic reactions to occur. Different kinds of gasifiers such as dual fluidized bed gasifiers and circulating fluidized bed gasifiers are capable of transferring heat from exothermic processes to an endothermic gasification process. These gasifiers will be covered in the next segment.

2.2.3 Types of gasification reactors

Biomass gasification is an extensively studied process, with a relatively high technological development [48]. Hence, there are a large array of reactor configurations, some of these technologies are as follows [31]:

- Entrained flow gasifier
- Fixed bed
 - Updraft
 - Downdraft
- Fluidized bed
- Rotary kiln reactor
- Plasma reactor

Not all gasification processes are however suitable for waste-to-hydrogen applications and certain sources place special emphasis on certain types of gasifiers which are more suitable for WtH gasification. In this section we will take a look at the design and performance characteristics of these gasifiers.

2.2.3.1 Entrained Flow Gasifier

Entrained flow gasifiers (**Figure 14**) are normally utilized for large-scale gasification of coal, biomass, and refinery residues [49]. These gasifiers involve utilizing liquid fuel, fine particles of solid fuels or slurry of solid and liquid fuels which are first distributed uniformly at the gasifier top space and then gasified with oxygen as gasification agent [50]. The utilization of biomass can prove to be challenging for these gasifiers and need to be highly pulverized [49]. Gasification temperatures occur between 1000 and 1500 °C which assist in cracking tar down to light hydrocarbons and a production of clean producer gas [49] [50]; operation can be at atmospheric pressure or pressurized [50]. Residence time of gas is very short, usually a few seconds.

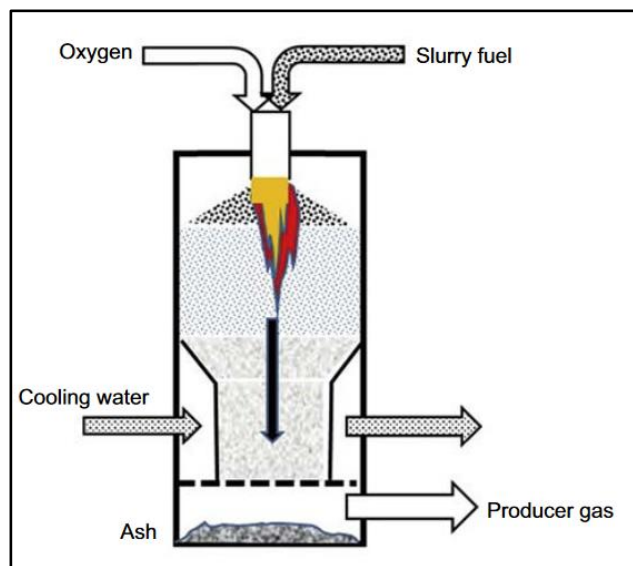


Figure 14: Sketch of an entrained-flow gasifier [50]

There are two variations of entrained flow gasifiers, top entrained flow gasifiers are vertically aligned cylindrical shaped vessels [49]. Finely refined fuel particles and gasifying media come in the form of a jet from the top end of a reactor (see?). An inverted burner results in their combustion followed by gasification. Product gas is taken out from the side of the lower section, whereas slag is deposited at the bottom of the reactor [49]. Another variation is the side-fed gasifier where the pulverized fuel and gasifying agent are fed through nozzles present in the lower part of the reactor [49]. Other important issues that process designs need to deal with are slagging, fouling, and corrosion. These issues arise out of the inorganic species present in the biomass and are, therefore, dependent to a large part on the biomass composition [49]. Due to the pre-treatment requirement for the fuels (liquid, fine particles or slurry slate), the application of the entrained flow gasifiers is limited to large-scale plants [50].

2.2.3.2 Fixed bed reactor

Fixed bed gasifiers involve gasification above a stationary grate which is a meshed barrier that admits air. They can be further divided into downdraft and updraft gasifiers depending on the flows of the gasification agent and the producer gas (i.e., syngas) [50].

2.2.3.2.1 Downdraft fixed bed reactor

Figure 15 shows a downdraft gasifier. The gasification agent (air or O₂) is fed into the middle of the bed (combustion zone) above the stationary grate and the producers gas flows out from the gasifier beneath the stationary grate. In this type of gasifier, the fed solid fuel moves downwards together with the gases through a drying zone, a pyrolysis zone, an oxidation (combustion) zone and a reduction zone [50].

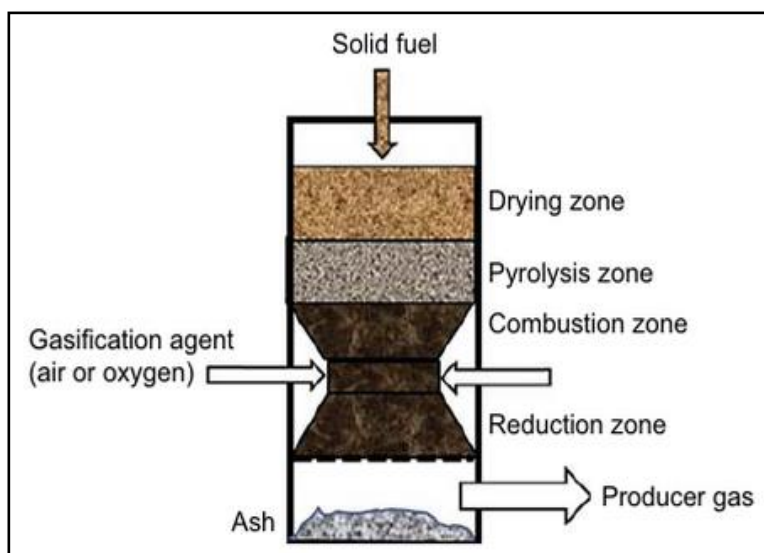


Figure 15: Downdraft gasifier (Source: [50])

In the drying zone, moisture is vaporized, drying the solid fuel. As the dry solid fuel moves downward, it is further heated, leading to its decomposition into char and gases through pyrolysis. Continuing its descent, a gasification agent is introduced, causing partial combustion of the char and some combustible gases. This process generates the necessary heat to maintain the target gasification temperature. Finally, the gases and char move into the reduction zone, where gasification reactions take place and producer gas is formed.

The temperature varies across different zones. In the drying zone, it typically remains at 200 °C or lower before the solid fuel begins to degrade. In the pyrolysis zone, temperatures can reach 500-600 °C, depending on the equivalence ratio (ER), which is the ratio of oxygen provided to the stoichiometric requirement. The oxidation zone experiences the highest temperatures, up to 1500 °C, where tars and other heavy hydrocarbons are thermally cracked into lighter hydrocarbon gases. Below the oxidation zone, the remaining char, ash, producer gas, and water vapor move into the reduction zone. Here, the water vapor can react with char (steam gasification reaction), CO (water-gas shift reaction), and CH₄ (steam-methane reforming reaction) to produce the desired hydrogen. Due to the significant variation in temperature profiles within the gasifier, it is typically used for small to medium-scale applications (100 kWth to 5 MWth).

2.2.3.2.2 Updraft fixed-bed gasifier

Updraft fixed-bed gasifiers are similar to downdraft fixed-bed gasifiers instead the gasification agent (air or O₂) is introduced from the bottom of the gasifier, and the producer flows out of the gasifier from the upper part of the gasifier as shown in Figure 16. The gasification process in the updraft fixed-bed gasifier also has four zones, namely, the drying zone, the pyrolysis zone, the oxidation zone and the reduction zone is above it. At the top layer of the gasifier, the solid fuel is dried by the pyrolysis gases and upwards-moving gases from the lower reduction zone and the oxidation zone. At the same time, char from the pyrolysis zone moves downward to the reduction zone and the oxidation zone in which gasification reactions occur [50]. There is also a significant variation in the temperature profile within the updraft gasifier, making it suitable for small to medium-scale applications (1-10 MWth).

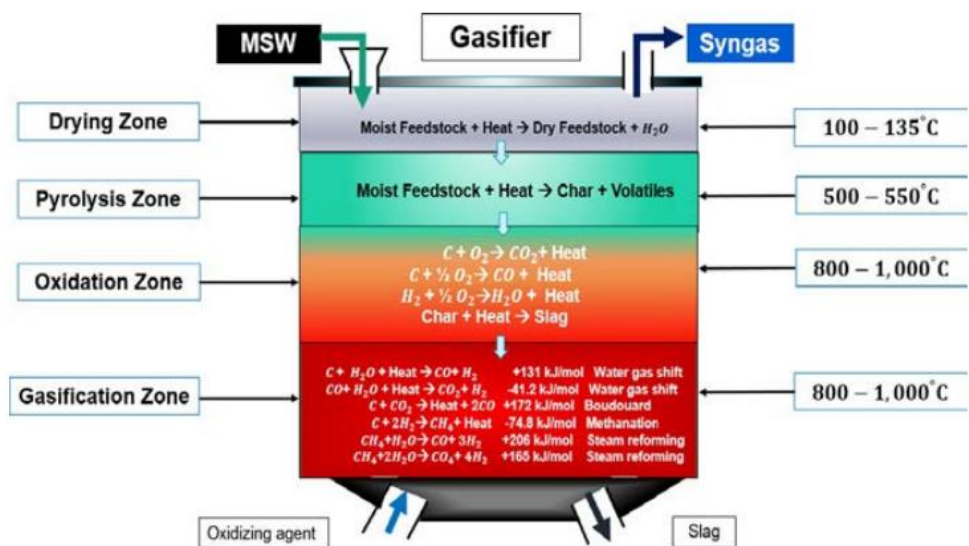


Figure 16: Updraft Gasifier (Source: [51])

Table 6 lists the advantages and disadvantages of downdraft and updraft gasifiers.

Table 6: Advantages and disadvantages of downdraft and updraft gasifiers

Reactor Type	Advantage	Disadvantage
Downdraft gasifier	<ul style="list-style-type: none"> Tars are cracked down in the oxidation zone hence the syngas has lower tar content compared to other gasifiers [50]. 	<ul style="list-style-type: none"> The syngas can be easily contaminated by ash and other fine particles. Separation devices such as a two-stage cyclone is needed to clean the syngas [50]. Relatively high syngas temperatures which results in lower gasification efficiency [50].
Updraft gasifiers	<ul style="list-style-type: none"> Simple in structure and operation [50]. The syngas has low temperature hence the gasifiers have high gasification efficiency [50]. Can handle solid fuel with a relatively high moisture content of up to 50% [50]. 	<ul style="list-style-type: none"> High tar content in the syngas [50]. Significant variations in the temperature profile of the gasifiers [50]

2.2.3.3 Fluidized-bed gasifier

The distinguishing feature of a fluidized bed gasifier is the use of a bed of inert material (typically sand or small ceramic beads) that is 'fluidized' by an upward flow of gas. Due to their flexibility and robustness, fluidized beds are more suitable for small applications and for treating gross and heterogeneous feedstock [52] [53].

2.2.3.3.1 Bubbling fluidized-bed gasifier

Figure 17 shows a schematic diagram of a bubbling fluidized bed reactor. A bubbling fluidized bed reactor is made of a bed of inert granular material (sand) held in a condition of fluidization where the gasification agent is fueled bottom-up from the bed through a distribution grid, with a velocity between 1 and 3 m/s. In these conditions, the bed of inert solid behaves like a liquid, and is continuously stirred by the presence of gas bubbles whose mobility ensures uniform conditions both of exchange of matter and heat between the solid and gas [31]. The solids begin to bubble at what is known as the 'minimum fluidization velocity' however in practical applications the operating gas velocity is higher than the minimum but lower than the 'terminate velocity' where the solid material is carried out of the gasifier [50]. This is an important factor that distinguishes between a bubbling fluidized-bed gasifier and a circulating fluidized-bed gasifier which will be discussed in the next section.

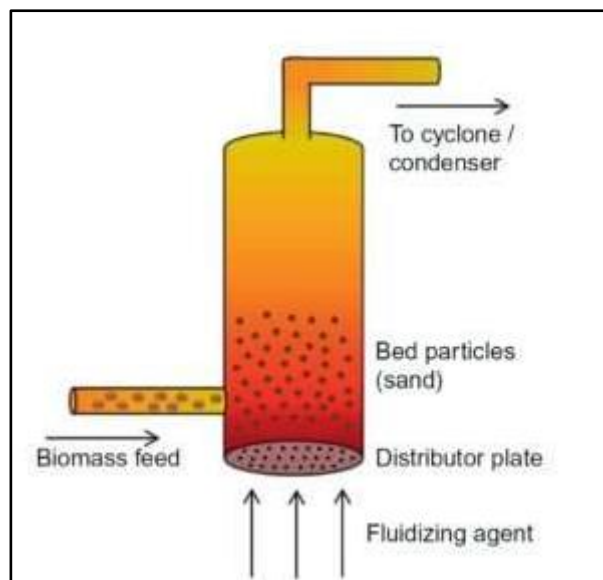


Figure 17: Simple diagram of a fluidized bed reactor [54]

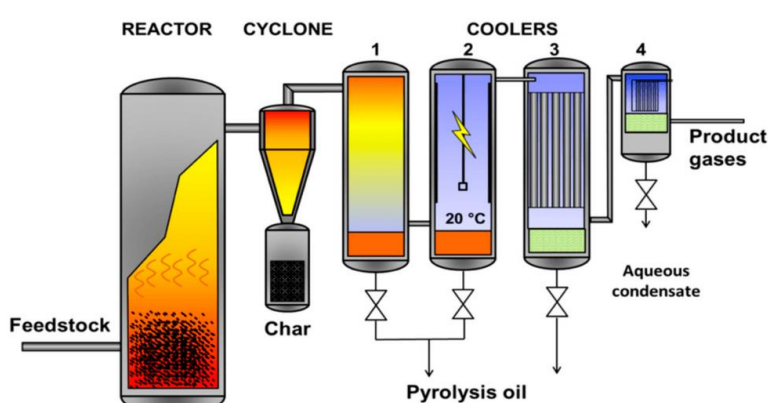


Figure 18: Fluidized bed reactor in a complete gasification process [54]

Once the feedstock enters the gasification chamber, it is rapidly heated by the bed material and pyrolyzed. Generating char, tars, complex hydrocarbon compounds and non-condensable

gases as the initial products. This process is followed by the gasification reactions in the upper layers of the bed [50]. The reactions may also occur in the freeboard space above the bed is that space is high enough [55].

Figure 18 provides an image of the fluidized bed reactor in a complete syngas treatment and cleanup process. Various sources mention that the fluidized bed is the most promising technology in biomass gasification as much as for tar conversion: it has high mixing capabilities, with a high mass and heat transfer rate, which secures constant temperatures all over the gasifier, and moreover catalysts can be used as part of the gasifier bed, affecting tar reforming [56] [57]. Fluidized bed reactors are suitable for biomass steam gasification processes because high H_2 productions (6.6 – 9.4 wt%), gas yields (around 1-1.9 Nm^3/kg biomass), low tar (0.6 - 38 g/Nm^3) are obtained⁸ (see sources [47] [58] [59] [60] [61]).

2.2.3.3.2 Circulating fluidized-bed gasifier

In a circulating fluidized-bed gasifier (**Figure 19**) the gas velocity is higher than the terminate velocity hence bubbling particles cover the full space of the reactor and are carried out of the gasifier from the top [50]. The bubbling particles are separated from the syngas by directing them to a cyclone, where the solid particles are flushed from the bottom and the syngas is expelled from the top. The flushed particles are re-introduced into the gasifier chamber while the syngas is sent for further cleaning and cooling (similar to **Figure 18**)

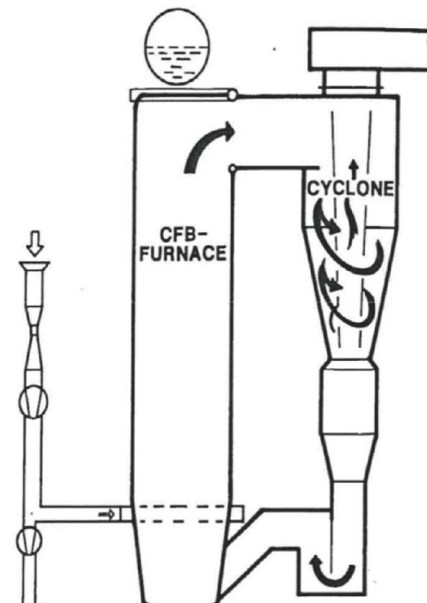


Figure 19: Circulating fluidized-bed gasifier
(Source: [135])

⁸ The values here are based on the gasification of almond shells, miscanthus and pinewood chips. Refer to the references for more information on the ranges acquired.

Table 7 provides the advantages and disadvantages of fluidized bed reactors.

Table 7: Advantages and disadvantages of fluidized bed reactors [31] [62] [63] [64] [65]

Reactor type	Advantage	Disadvantage
Bubbling fluidized bed	<ul style="list-style-type: none"> • High mixing and gas-solid contact • High carbon conversion • High thermal loads • Good temperature control (temperature distribution along the reactor) • Can handle material with different characteristics • Good flexibility both of load and process • Suitable for highly reactive fuels such as biomass and municipal waste pre-treated • Low level of tar in the syngas • Ease of start-up, shutdown and control • No moving parts • Good ability to scale-up 	<ul style="list-style-type: none"> • Loss of carbon in the ashes • Dragging of dust and ashes • Pre-treatment needed with heterogeneous materials • Need to have a relatively low process temperature to avoid phenomena of de fluidization of the bed (temperature lower than the softening point of the solid residues) • Restrictions on the size • High investment costs and maintenance costs • Possibility of casting the ashes
Circulating fluidized bed	<ul style="list-style-type: none"> • Lower tar production • Flexible load • Reduced residence times • Good ability to scale-up 	<ul style="list-style-type: none"> • Requires the reduction of size and preparation supply (the solid material must be finely pulverized, with dimensions lower than 100 mm) • Restricted solid-gas contact • Need for special materials • Technology complex and difficult to control • Security issues • High start-up and investment costs

2.2.3.4 Rotary Kiln Reactor

A rotary kiln reactor is a cylindrical, rotating furnace that is useful for a variety of processes such as calcination, pyrolysis, sintering and others. It consists of a long, inclined, rotating tube with internal lining made of refractory material. The material to be processed is fed into the upper end of the cylinder, and as it moves through due to the rotation of the kiln, the new solid surfaces are subjected to various temperature zones and reactions. At the outlet of the kiln, two product streams exist: syngas which is further processed and cleaned and biochar (**Figure 20**, **Figure 21**).

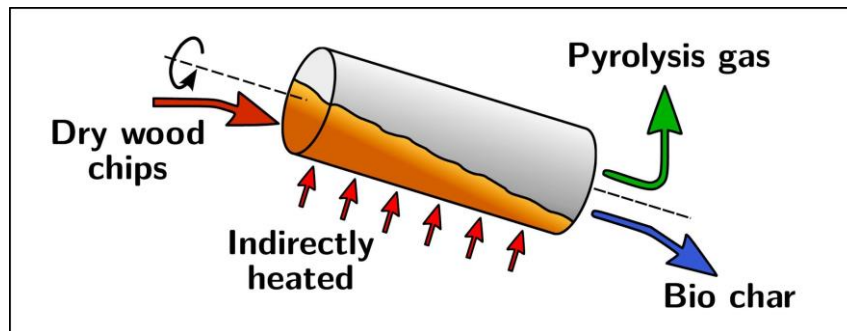


Figure 20: Simplified inputs and outputs of a rotary kiln reactor [66]

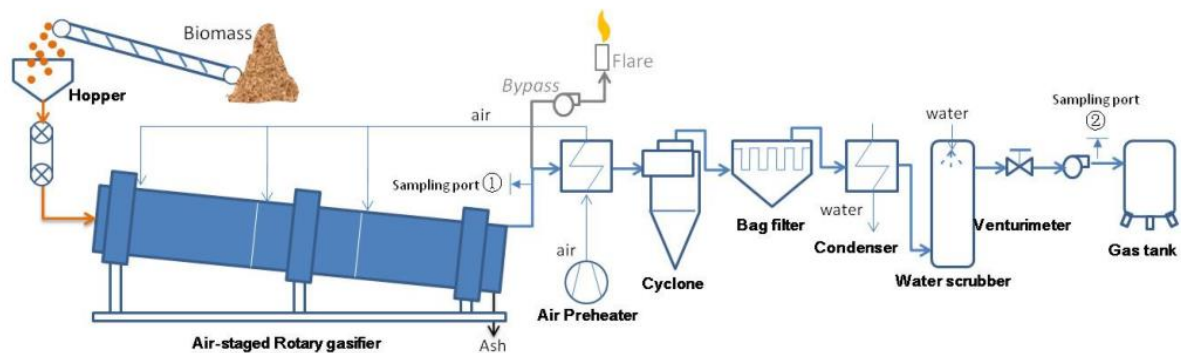


Figure 21: Rotary kiln incorporated within a full gasification system [67]

The conditions for the exchange of matter and heat between the solid and the gas are not very effective and the residence time is higher than those with other gasification technologies [31]. One way to improve the solid-gas contact is the installation of barriers inside the drum which increases the handling of the solid material and improve contact with the gaseous stream [31]. Advantages and disadvantages of rotary kiln reactors are listed in **Table 8**.

Table 8: Advantages and disadvantages of rotary kiln reactors [31] [68] [69]

Reactor type	Advantage	Disadvantage
Rotary Kiln	<ul style="list-style-type: none"> • Low sensitivity to changes in composition, humidity and size of the feed • Maximum loading flexibility • Suitable for waste that can melt • Simplicity of construction and high reliability of operation • Reduced investment costs 	<ul style="list-style-type: none"> • Significant difficulty in starting and temperature controlling • Presence of moving parts and their problems with leakage and wear • Low capacity of heat exchange • High content of dust and tar • High maintenance costs

2.2.3.5 Plasma Reactor

The plasma reactor (**Figure 22**) is from the group of allothermal gasifiers which is normally used in combination with other reactors [70]. Plasma technology involves the creation of a sustained electrical arc by the passage of electric current through a gas in a process referred to as electrical breakdown. Because of the electrical resistivity across the system, significant heat is generated, which strips away electrons from the gas molecules resulting in an ionized gas stream, or plasma [71]. At 2000 °C gas molecules dissociate into the atomic state and when the temperature is raised to 3000 °C, gas molecules lose electrons and become ionized. In this state, gas has a liquid-like viscosity at atmospheric pressure and the free electric charges confer relatively high electrical conductivities that can approach those of metals [72]. Electrically generated thermal plasmas can reach temperatures up to 20,000 °C or more [71]. The attainment of such high temperatures allows for implementing thermal plasma treatment technologies for a variety of applications, one being the destruction and treatment of hazardous waste materials [71]. This has led to increasing usage of plasma reactors for waste treatment applications due to its ability to completely decompose the input material into a tar-free synthetic gas and an inert, environmentally stable, vitreous material known as slag [73]. The principal advantages that plasma offers to thermal conversion processes, besides the already mentioned tar/ash related issues absence, are a smaller installation size for a given waste throughput, and the use of electricity as energy source, characteristics which permit the technology to treat a wide range of heterogenous and low calorific value materials [73].

Stand alone or two stage plasma processes are particularly suitable for processing waste feedstock due to the high quantity of ash, organic and inorganic contaminants, and typical

fluctuating quality of the feedstock, notwithstanding that the presence of an air separation unit and plasma electrode make the process particularly energy intensive [73]. However, a complete comparative cost evaluation often demonstrates the economic viability of plasma-based technologies [71]. **Table 9** provides the advantages and disadvantages of plasma reactors.

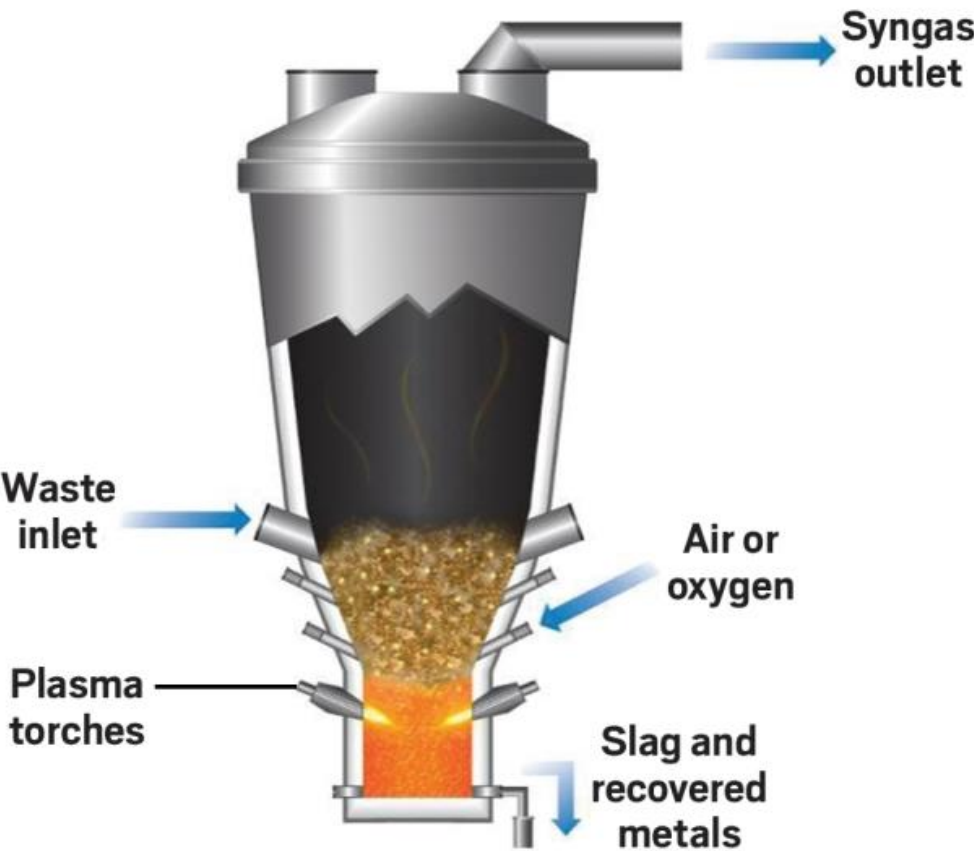


Figure 22: Plasma gasifier [74]

Table 9: Advantages and disadvantages of plasma reactors [31] [75] [76]

Reactor type	Advantage	Disadvantage
Plasma reactor	<ul style="list-style-type: none"> • Production of vitrified, completely inert and non-leaching slag, which includes heavy metals • Vitrified ash products show excellent mechanical and anti- 	<ul style="list-style-type: none"> • Presence of nanoparticles in syngas • High plant, operational and exercise costs • Solidification of molten material in the ducts

	leaching properties, and are suitable as construction materials [76] <ul style="list-style-type: none"> • Contains extremely limited polluting compounds in syngas • Extremely short reaction times • No problems of scale-up 	<ul style="list-style-type: none"> • Frequent changing of the electrodes • Necessity of auxiliary fuel for obtaining homogenous temperatures inside the reactor
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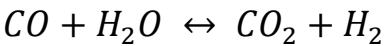
2.2.4 Syngas cleanup

A vital step after the gasification process are the steps undertaken in order to treat the syngas through a gas cleaning system. **Figure 7** depicted a diagram where several stages of the production of hydrogen from biomass through the gasification process was displayed. The fuel gas exits the gasification stage at temperatures usually higher than 800 °C and comprises mostly H₂, CO, H₂O and CO₂ and a number of minor contaminants. After heat recovery, the syngas has to go through a gas cleaning system to remove tars, particulates, vapor phase metals, acid gases (mostly Cl- and S- based), and a myriad of trace species released from RDF which could hinder the effective syngas utilization downstream [73]. Catalytic conversion units are necessary in order to treat the intermediate products. The syngas that leaves the gasification reactor requires several complex and costly purification steps in order to meet specifications for the downstream catalytic conversion processes, which are designed for removing the particulate matter (micron size char and ash), the N, S and Cl containing gaseous compounds (such as NH₃, HCN, H₂S and HCl) and specially the tar components in the gas [14] [77] [78] [79]. Various strategies exist in order to obtain a tar free (or low tar content) syngas, and they can be classified into primary processes, which hinder tar formation in the gasifier, or secondary processes, which imply a cleaning of the produced syngas [14].

The cleaning from these problematic species down to values that are acceptable for different downstream catalysts are of crucial importance for successful implementation of waste gasification technology, and in particular bioH₂ applications [73]. These systems are asked to deal with a much wider and heterogenous range of contaminants compared to other biomass applications, and at the same time respond to more stringent specifications dictated by catalysts for bioH₂ production. The success of new gasification technologies for the treatment of waste feedstocks in the future will be assessed on this basis [73].

2.2.5 Syngas upgrading

Water gas shift reactors (WGS) are an important component in the production of hydrogen and purification of syngas. The WGS reaction involves the conversion of carbon monoxide and water vapor into carbon dioxide and hydrogen gas in the presence of a catalyst. The reaction is as follows:



Equation 3: Water-gas shift reaction

The aim of the reaction is to reduce the concentration of carbon monoxide which is generally considered as an undesirable impurity. Also, the reaction is essential in adjusting the ratio of hydrogen and carbon monoxide in syngas to meet the requirements of downstream processes. WGS reactors are a key component in the overall process of producing hydrogen from natural gas through steam ethane reforming (SMR). In the SMR process, methane reacts with steam to produce syngas, and the WGS reactor is used to adjust the CO to H2 ratio before the hydrogen is separated and purified. The same WGS approach for SMR is also implemented in the WtH process since hydrogen production from waste gasification is insufficient to sustain a WtH plant. The produced hydrogen is obtained in a two-stage process with two sequential reactors. Hydrogen production is favored by low temperature, often obtained with two sequential reactors with intercooling stage [73]. Both HTS and LTS catalysts are sensitive to sulphur content, with the latter starting to deactivate at concentrations as low as 1 ppm. Cobalt/Molybdenum-based shift catalysts are instead widely used for syngas streams that contain very high levels of sulphur [73]. Ultimately the aim in bioH2 production is to push the WGS reaction to a practical limit, while providing a clean and good quality syngas to ensure high catalyst longevity [73].

Table 10 provides some of the main specifications of HTS and LTS reactors.

Table 10: Specifications of High-Temperature Shift Reactors and Low-Temperature Shift Reactors

	High-Temperature Shift Reactor	Low-Temperature Shift Reactor
Purpose	Maximize the conversion of CO and water vapor to hydrogen and carbon dioxide at elevated temperatures.	The LTS reactor follows the HTS reactor and serves to further shift the equilibrium of the WGS reaction by removing any remaining CO to increase hydrogen production.
Temperature Range	320 °C – 450 °C [80]	190 °C – 220 °C [81]

Catalyst	Ferrochrome (Fe-Cr) oxide-based formulations [80]	Copper/zinc oxides supported on alumina substrates (Cu/ZnO/Al ₂ O ₃) [81]
Equilibrium Shifting	At high temperatures, the HTS reactor helps shift the chemical equilibrium of the WGS reaction towards the desired production of hydrogen	The LTS reactor helps to drive the WGS reaction to completion by favoring the production of hydrogen and carbon dioxide at lower temperatures

2.2.6 CO₂ removal and upgrading

The output product from the water-gas shift process is a mixture of H₂ and CO₂ with some other minor components such as nitrogen, methane and carbon-monoxide [73]. The degree to which how much CO₂ is separated from the stream is highly dependent on the required specifications of the hydrogen but also affected by the temperature and pressure conditions of the inlet and outlet streams [73]. Hydrogen produced from a WtH2 plant could have applications in fuel cells which require a 99.95%⁹ with additional restrictions on certain contaminants [82]. Other applications are use in the gas network, in industry, or blended into the natural gas network.

Techniques such as Pressure swing adsorption (PSA) is commonly used to achieve purity levels of >99.5% for hydrogen. PSA is a gas separation technology used to separate specific gases from a mixture of gases. The key principle behind PSA is the selective adsorption of gases onto a solid adsorbent material at different pressure levels. Some literature has mentioned that PSA techniques to lead to significant “slippage” of hydrogen [83]. Slippage refers to the phenomenon where a certain amount of the target gas does not get fully captured by the adsorbent material during the adsorption phase. Instead, it “slips” through the adsorption bed and is not efficiently separated from the non-target gases. Some sources [73] mention that PSA techniques might be inappropriate for small scale WtH plants and other technologies could be considered such as membrane separation, physical solvents and amine systems [84] [85] [86] [87]. Utilizing Benfield-type potassium carbonate systems has also been recommended [73] since it covers high CO₂ recovery, high CO₂ selectivity and good heat integration with low electrical loads and pressure drop for product streams [88]. Hence, slippage of hydrogen into the CO₂ stream is very low, giving good H₂ yields and a captured CO₂ stream at a purity

⁹ For mobility applications 99.97 % purity hydrogen is needed. If WtH is at all used for mobility purposes then additional purification requirements need to be met but meeting those requirements could be costly.

suitable for sequestration [73]. The residual CO in the stream can be sent to a CO polishing methanation stage, with a high-nickel catalyst, where residual CO is converted to methane [89]. This methane could have use cases.

2.3 Pyrolytic routes of hydrogen production

The previous section focused on biomass conversion processes utilizing the full temperature ranges of steam gasification for hydrogen production. Another approach involves solely implementing pyrolysis stage temperatures as a conversion process. Hydrogen can be derived from the pyrolysis stage: this involves the conversion of carbonaceous materials into value-added products such as bio-oil, bio-char, and product gas at temperatures of 350 – 550 °C, and pressures of 0.1 – 0.5 MPa in the absence of oxygen [90] (see **Figure 23**).

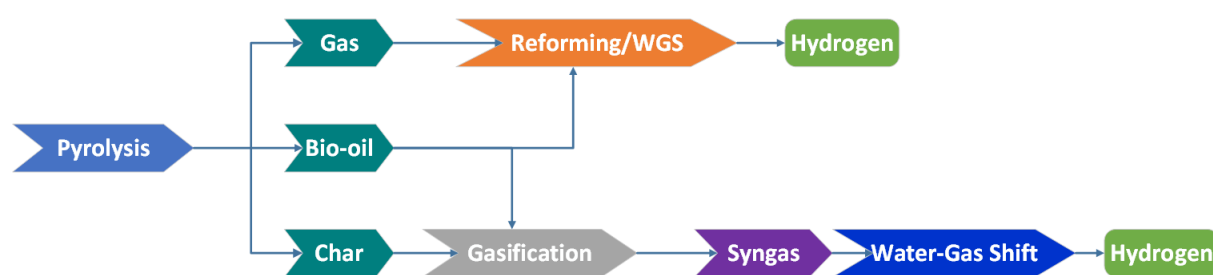


Figure 23: Schematic representation of the main processes involved in the pyrolytic routes for hydrogen production (adapted and edited from [14])

Many pyrolysis systems are small scale modular plants with feedstock throughput capacities ranging from 7,000 – 10,000 tons per annum. These systems are suited to the conversion of niche waste streams, or the production of niche fuels, rather than large scale production [1]. Several pyrolysis systems are in commercial application, but these are small modular plants which do not have the capacity for large scale production [1]. As was described in section 2.2, the pyrolysis reaction is a step that occurs within the gasification process of biomass and involves the generation of gases (e.g., CO, H₂, CO₂, CH₄, H₂O), liquids (tar) and solids (char). Essentially, both gasification and pyrolytic methods could lead to the production of hydrogen (recall **Figure 3**) but the pyrolysis process allows for the generation of other intermediate products such as bio-oil and char which could further be used for the production of hydrogen (**Figure 23**) or other final products such as light olefins, benzene-toluene-xylene (BTX), gasoline and diesel. Through a steam reforming process occurring between 600 – 800 °C hydrogen can be produced from both the gas and the bio-oil.

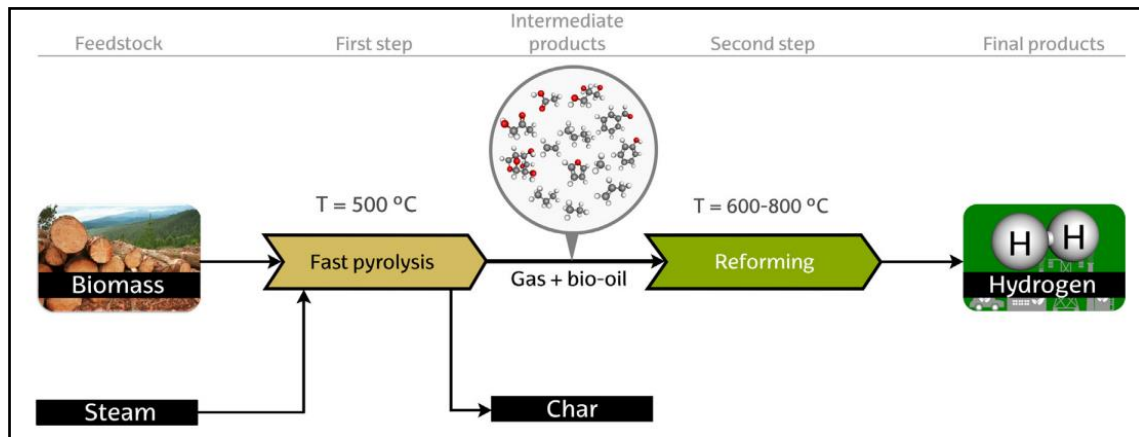


Figure 24: Schematic representation of the pyrolysis reforming of biomass [14]

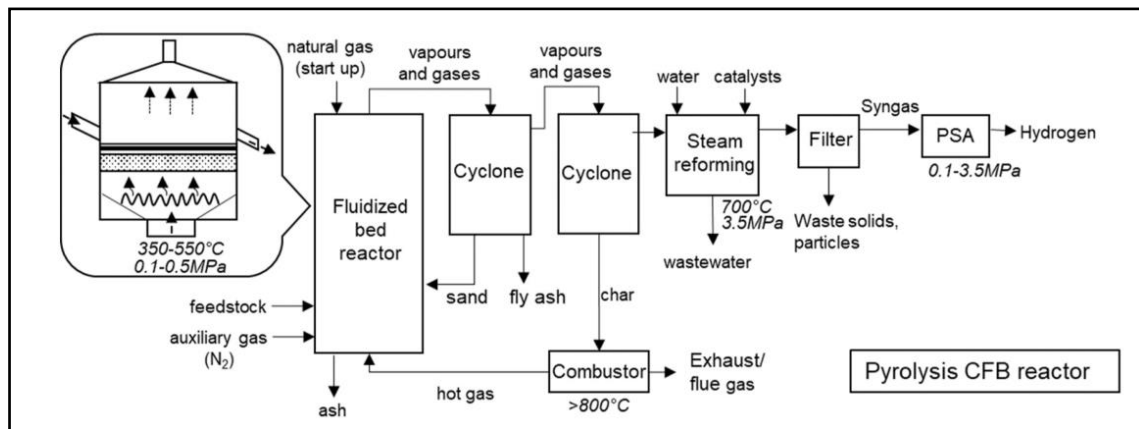


Figure 25: Flow diagram of the pyrolysis process using circulating fluidized bed reactors [17]

Figure 25 provides a flow diagram of how the gases from the pyrolysis of waste could be utilized to produce hydrogen in a process similar to the gasification approach. For more information on the pyrolysis reforming of biomass for the purpose of producing hydrogen see [14].

3. Overview of Waste Volumes

Topics covered in this chapter:

- Types of waste sources considered
- Biowaste supply in the Netherlands per province
- Equivalent hydrogen volumes based on biowaste supplies
- Types of sectors that could be served

Chapter 2 (Section 2.1) involved a brief description about the general composition of waste derived fuel and the separation and conversion of municipal waste to RDF/SRF for gasification. An important condition of operation for a waste-to-hydrogen plant or generally any waste-to-energy plant is the allocation of a reliable supply of suitable waste streams. Having a significant understanding of the expected volumes of municipal waste generation is essential for conducting any feasibility study of hydrogen production via waste, hence this chapter will focus on the generation volumes of biodegradable municipal waste in the Netherlands for hydrogen production.

3.1 Description of the source data

The historical/expected volumes of biowaste generation explored in this study are inspired from a waste supply database from the S2Biom project, however independent calculations based on new data have been conducted in order to compare results. S2Biom was an EU-funded project that focused on the whole biomass delivery chain – from primary biomass to end-use of non-food products, and from logistics and pre-treatment to conversion technologies [91]. One aspect of the project had to do with the creation of a database on the sustainable supply and cost of roadside collection of solid lignocellulosic biomass from forestry, dedicated energy cropping, agricultural residues, and secondary residues from wood and food industry as well as from *household waste* [92]. This data was provided for 2012, and projected for 2020 and 2030. The various lignocellulosic biomass that was assessed by S2Biom includes biomass originating from the following sources [92]:

- Primary residues from agriculture
- Dedicated cropping of lignocellulosic biomass on agricultural area
- Wood production and primary residues from forests
- Other land use
- Secondary residues from wood industry
- Secondary residues of industry utilizing agricultural products
- **Waste collection/tertiary residues¹⁰**

¹⁰ In the S2Biom database, the aforementioned categories of waste are provided for several supply 'potentials' including a 'technical potential' and a 'base potential' considering currently applied sustainability practices. The 'technical potential' represented the amount of biomass assuming only technical constraints and a minimum of constraints by competing uses. 'Base potential' showed the sustainable technical potential, considering agreed sustainability standards. In the case of biowaste - which is the category that is of interest to us - the base potential equals the technical potential hence these two values are the same.

The S2Biom study defines biowaste based on the EU Waste Framework Directive (2008/98/EC): **“biodegradable garden and park waste, food and kitchen waste from households, restaurants, catering and retail premises and comparable waste from food processing plants.”** [93]. Biowaste is part of biodegradable municipal waste, defined in the EU Landfill Directive (1999/31/EC) as any “waste that is capable of undergoing anaerobic or aerobic decomposition, such as food and garden waste and paper and paperboard” [94].

Within the S2biom study a further distinction has been made between the “separately collected biowaste” and “biowaste as part of mixed waste”. The former refers to biodegradable waste of separately collected municipal waste (excluding textile and paper) and the latter refers to biodegradable waste of not separately collected municipal waste (excluding textile and paper) [92]. Seeing how the results related to the availability of biowaste for the S2Biom study were released in 2015, the 2012 values were calculated based on actual data while the values for 2020 and 2030 were projections.

The methodology in order to determine the availability of biowaste in the S2biom database was determined as [92]:

$$MSW \text{ generated per capita } \left(\frac{kg}{capita} \right) \times biowaste \text{ fraction } (\%) \\ \times population \text{ of the NUTS area (persons)}$$

Equation 4: Calculating the availability of biowaste

“*MSW generated per capita*” indicates the amount of waste that is generated per capita. In the S2Biom calculations, these were derived from “municipal waste generation and treatment databases” on Eurostat which is the statistical office of the European Union. This data is available on a per country basis (NUTS 1¹¹), but also on provincial (NUTS 2) and smaller regions often corresponding to administrative districts or counties (NUTS 3).

‘*Biowaste fraction*’ denotes the share of biodegradable waste in municipal waste. The S2Biom calculations based this percentage on a study by Arcadis and Eunomia [95]. Different biowaste fractions were considered for EU-27 countries however seeing how data from the Netherlands is the focus of our study its unclear exactly what percentage was considered for the Netherlands but data from the ‘afvalmonitor’ indicates that for 2020, 34% of household residual waste were composed of organic waste and organic residues [96]. **Figure 26** provides this share for a variety of years. Overall, it seems that since 2014 there has been a downward trend in the fraction of biowaste except in 2020 where it increased to 34%, this potentially could’ve been caused by the COVID-19 pandemic. There is no data beyond 2020 at the moment of writing.

In the S2Biom study ‘*population*’ data was taken from Eurostat up to the NUTS3 level.

Equation 4 will also be used to calculate available waste based on the independent calculations that we will be conducting as well.

¹¹ In the European Union, NUTS stands for “Nomenclature of Territorial Units for Statistics.” It’s a hierarchical classification system used to divide the territory of EU member states and other European countries for statistical purposes.

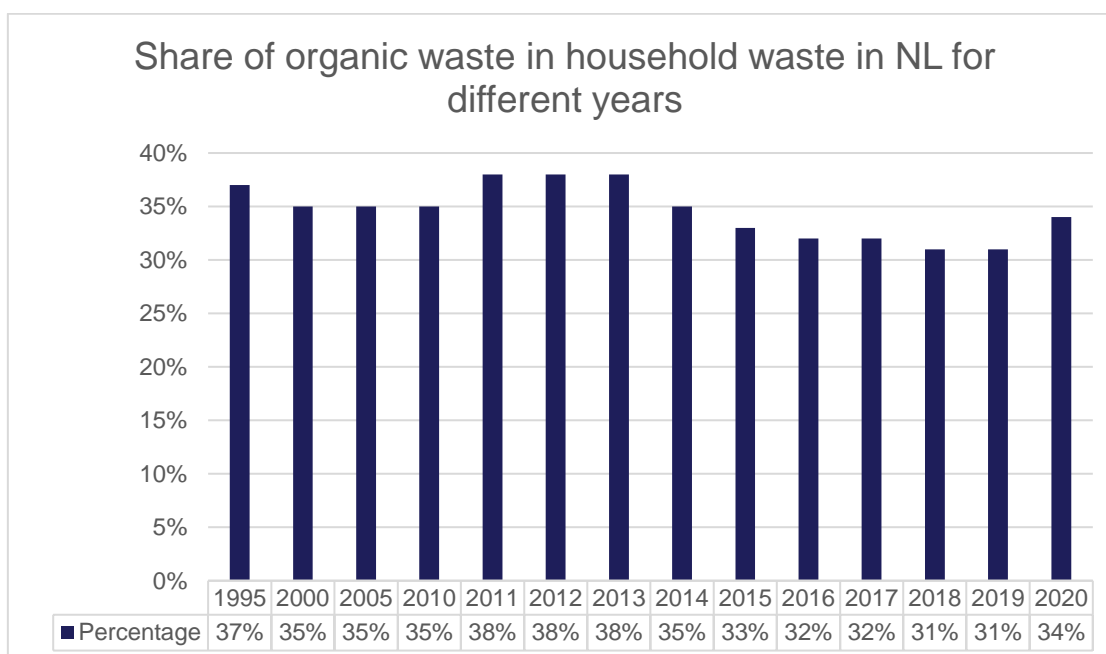


Figure 26: Trends regarding the share of organic waste in household waste in the Netherlands [96]

3.2 Volumes of biodegradable waste

Volumes of biowaste are presented in this section. **One important factor to be aware of is that the S2Biom study was conducted in 2015. Hence, calculations for the supplies of waste for 2012 was based on actual statistical data while projections were made for 2020 and 2030.** At the time of writing (2024), new calculations regarding waste supply can be made for 2020 in order to potentially see how the S2Biom projections regarding waste supply compare against actual historical data; this will be presented as well in order to see how the projections compare. We will also provide a new projection for 2030 and compare it to the projections from the S2Biom study for 2030.

3.2.1 Volumes of biodegradable waste based on S2Biom calculations

Table 11 lists the expected/actual supply of 'separated' and 'unseparated' biodegradable waste in kton for 2030, 2020 and 2012 for the 12 provinces of the Netherlands based on data from the S2Biom study. Separated waste refers to waste that is already separated at the point of collection i.e. containers that are only meant for disposing biodegradable waste.

Table 11: Known and projected supply of separated biodegradable waste in kton for 2030/2020/2012 for provinces of the Netherlands based on S2biom data [92].

Province	Year					
	2030 – supply (kton)		2020 – supply (kton)		2012 – supply (kton)	
	Separated	Unseparated	Separated	Unseparated	Separated	Unseparated
Groningen	54	44	53	43	46	48
Fryslân	60	49	59	48	51	53
Drenthe	46	37	45	37	39	41
Overijssel	106	87	103	85	90	94
Flevoland	37	30	36	29	31	33
Gelderland	187	153	183	150	160	166
Utrecht	115	94	112	92	98	102
Noord-Holland	253	207	246	202	215	224
Zuid-Holland	331	271	323	264	282	293
Zeeland	36	29	35	28	30	29
Noord-Brabant	230	188	224	183	195	203
Limburg	105	86	102	84	89	93
Total (kton)	1560	1275	1521	1245	1326	1379

Table 12 provides the national total of biowaste ‘unseparately’ and ‘separately’ collected for the various years from the S2Biom study.

Table 12: Total sum of biodegradable waste ‘separately’ and ‘unseparately’ collected based on S2Biom data.

	2030	2020	2012
Biowaste unseparately collected (kton)	1275	1245	1379
Biowaste separately collected (kton)	1560	1521	1326
Total (kton)	2835	2766	2705

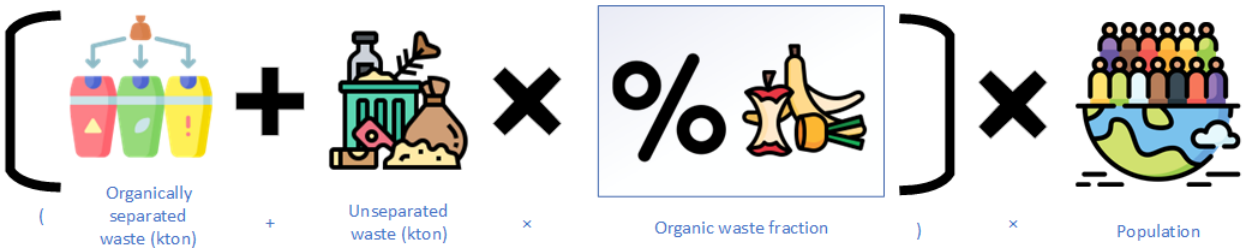
3.2.2 Volumes of biodegradable waste based on own calculations

The calculations for this section are focused on own calculations regarding biodegradable waste volumes. The intention is to compare and see if there are significant differences between the projections that had been made for 2020/2030 based on the S2Biom study and calculations based on actual statistical data from 2020 and a new projection for 2030 based on updated statistical information.

Table 13 provides the data considered and the resulting volumes of waste based on statistical data from 2020. Data regarding the kg per capita of mixed household waste per province was sourced from the ‘Central Bureau voor de Statistiek’ (CBS) themes on municipal waste [97]. In order to derive the share of organic waste from this per capita value, the fraction of organic waste has to be derived. On a national level this lies at 34%¹², by multiplying the per capita mixed household waste by this value the share of biodegradable waste in mixed waste can be derived, this results in unseparated organic waste. Data on separated biodegradable waste availability was also derived from the municipal waste database from CBS from the category of ‘organic, kitchen and garden waste’ in kg per capita [97]. Population values were derived from the CBS as well. In order to utilize this information in a manner similar to the calculations shown in the last column shows the theoretical hourly production WtH plant capacity per province based on 8000 operational hours in a year.

The calculations are based on **Equation 5** which is similar to **Equation 4** but with an addition of separated waste:

(Organically separated waste (kton) + Unseparated waste (kton) × Organic waste fraction (%)) × Population



Equation 5: Total availability of waste based on separated and unseparated waste

¹² No information could be found on a provincial level but it's expected that the fluctuations are minimal and thus negligible.

Table 13: Supply of separated and 'unseparated' biodegradable waste based on own calculations for 2020

Province	Mixed household waste (kg per capita) – Unseparated Organic Waste	Organic waste fraction	Organic, kitchen and garden waste (kg per capita) – Separated Organic Waste	Population	Mixed Organic Waste Availability (kton) (Unseparated)	Separated Waste Availability (kton)	Total availability (kton)
Groningen	173	34%	107	586,937	34.52	62.80	97.33
Fryslân	196	34%	142	651,435	43.41	92.50	135.92
Drenthe	153	34%	164	494,771	25.74	81.14	106.88
Overijssel	107	34%	134	1,166,533	42.44	156.32	198.75
Flevoland	183	34%	72	428,226	26.64	30.83	57.48
Gelderland	106	34%	138	2,096,603	75.56	289.33	364.89
Utrecht	173	34%	88	1,361,153	80.06	119.78	199.84
Noord-Holland	211	34%	65	2,888,486	207.22	187.75	394.97
Zuid-Holland	234	34%	58	3,726,050	296.44	216.11	512.56
Zeeland	208	34%	130	385,400	27.26	50.10	77.36
Noord-Brabant	130	34%	109	2,573,949	113.77	280.56	394.33
Limburg	130	34%	103	1,115,872	49.32	114.93	164.26

Figure 27 compares biodegradable waste per province based on both the projection from the S2Biom study and the calculations from this study. While there are some differences among certain provinces, it can be seen that the trends are very similar. **Figure 28** provides the same information but for the year of 2030 and compares it to the 2030 projections from the S2Biom study. For the own calculation, 2030 projections for the population were taken from [98] while the per capita contribution to separated organic waste and unseparated organic waste was based on 2022 data from [97]. For the biowaste fraction a constant value of 34% was used.

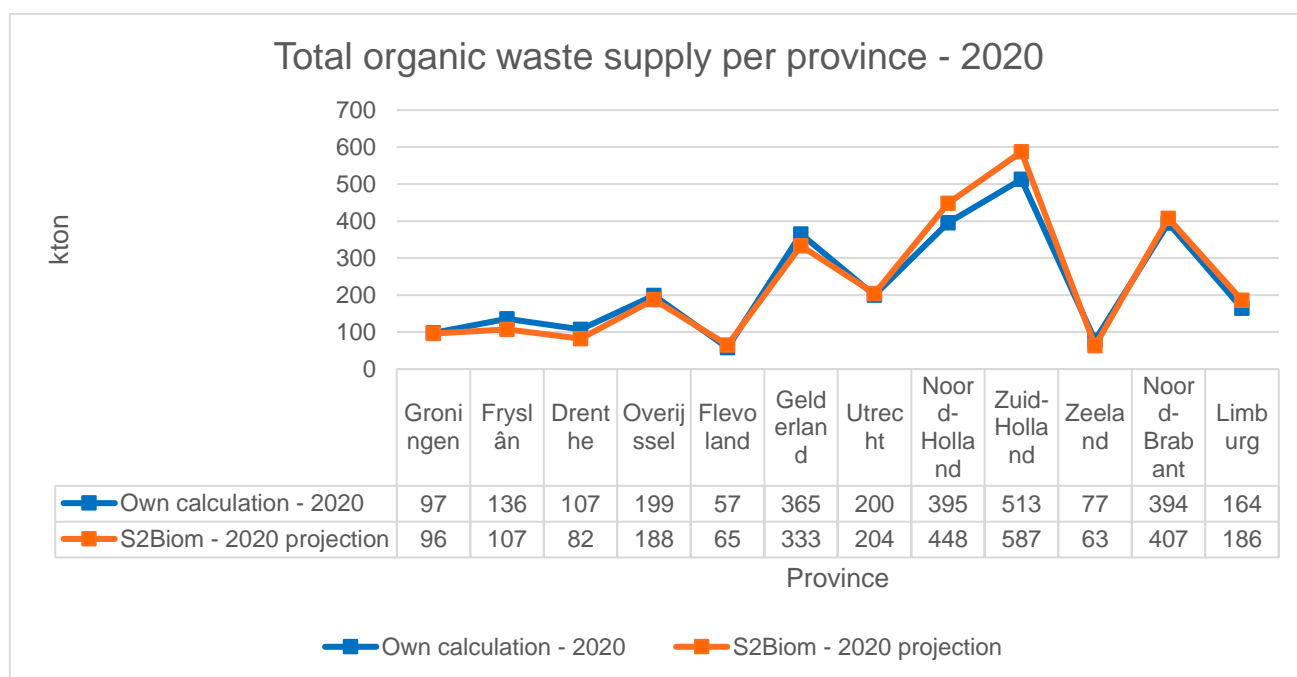


Figure 27: Own calculation for total supply of biodegradable waste in blue versus projections from the S2Biom study for 2020

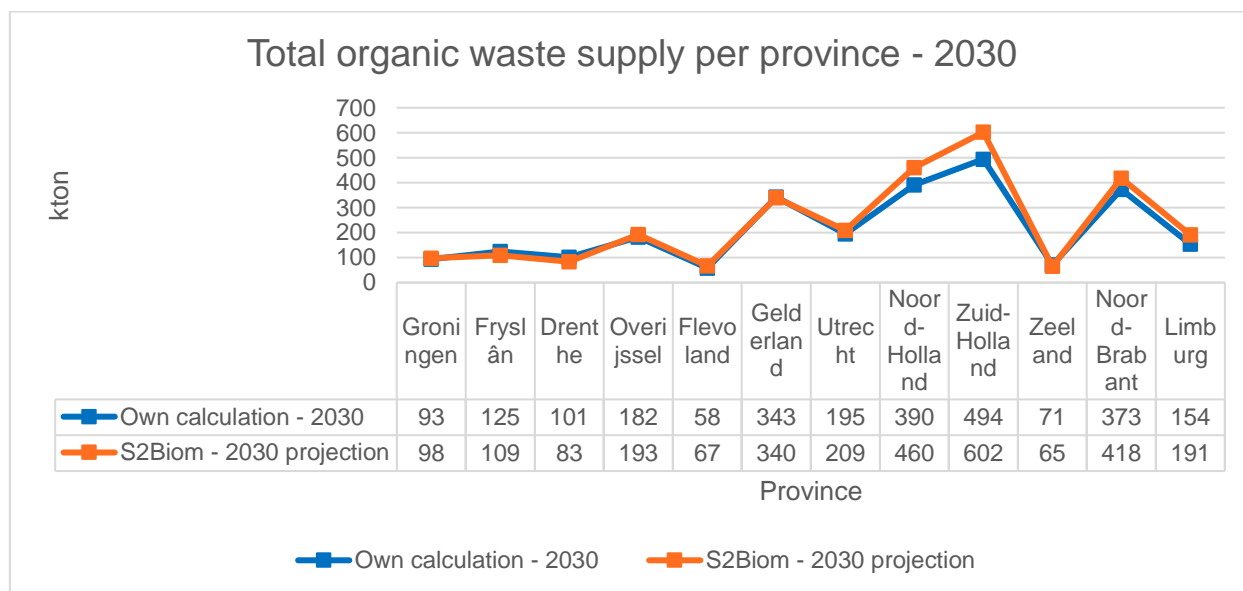


Figure 28: Own calculation for total supply of biodegradable waste in blue versus projections from the S2Biom study for 2030

Table 14 provides the total sum of biowaste unseparately and separately collected based on own calculations. In comparison to **Table 12** total values for 2020 are about the same (2766kton from the S2biom study versus 2704.56kton from own calculations) while for 2030 the total waste is less (2835kton from the S2biom study versus 2579.32kton).

Table 14: Total sum of biodegradable waste ‘separately’ and ‘unseparately’ collected based on own calculations.

	2030	2020
Biowaste unseparately collected (kton)	956.74	1022.39
Biowaste separately collected (kton)	1622.58	1682.17
Total (kton)	2579.32	2704.56

3.3 Expected volumes of hydrogen production

In order to be able to calculate the expected volumes of hydrogen production based on waste supplies, it's imperative to figure out how much MSW/RDF feedstock is needed to produce a certain energy amount of hydrogen (e.g., in MJ).

Data from a study by Materazzi et. al [22] looking into the carbon intensity of various methods of hydrogen production provides information on how much feedstock is required to produce a certain amount of transport grade hydrogen. **Table 15** provides the relevant information. The functional unit considered in the study is 1 MWHHV which is the power generation capacity of hydrogen based on the higher heating value (HHV); the HHV of hydrogen is approximately 142 MJ/kg and the lower heating value (LHV) is 120 MJ/kg [99]; the value can be used to calculate the amount of hydrogen that could be derived from waste; 1MWh is equivalent to 3600 MJ.

From the table, it can be seen that 442.2 kg of MSW or 283.6kg of RDF can produce hydrogen at a capacity of 1MWh/3600MJ. This is equivalent to $\approx 25\text{kg}$ of hydrogen if HHV is used and 30kg if LHV is used. Both values are used to calculate the amount of hydrogen produced but LHV is used in most practical applications, such as home heating or industrial application, since the water vapor remains in its gaseous form as it is released into the atmosphere without condensing back to liquid.

$$3600 \text{ MJ of H}_2 \times 1\text{kg}/142\text{MJ} = 25.352\text{kg} \approx 25\text{kg H}_2$$

$$3600 \text{ MJ of H}_2 \times 1\text{kg}/120\text{MJ} = 30\text{kg H}_2$$

Table 15: Data determining the required feedstock in order to produce 1MWh (or 3600 MJ) of biohydrogen (Adapted from Source: [22])

Key flows	Units	Biohydrogen (MSW)
Input		
Feedstock type		MSW/RDF
Feedstock	kg	442.2/283.6
Oxygen	kg	89.4
Electricity	MJ	514
Thermal Energy	MJ	1550
Output		
Hydrogen [MJ]	MJ	3600
Materials recovered [kg]	kg	17.1
CO2 released [kg]	kg	46.5
Sequestered CO2 [kg]	kg	414.4

Hence, by considering that about 442.2kg of MSW can produce 25kg of H₂ we can derive the maximum theoretical production of hydrogen based on a total MSW generation potential (e.g., any value in **Table 12**). The calculation is as follows:

$$1245\text{kton MSW} \times 1,000,000\text{kg}/1\text{kt} \times 25\text{kg H}_2/442\text{kg MSW} = 70,418,552.04 \text{ kg H}_2 \text{ or } \approx 70 \text{ kton H}_2$$

The energy equivalent can be calculated as follows:

$$1245\text{kton MSW} \times 1,000,000\text{kg}/1\text{kt} \times 442.2\text{kg}/3600\text{MJ} = 10,135,685,210 \text{ MJ} = 10.13 \text{ PJ}$$

Table 16 and **Table 17** provide this calculation for ‘unseparated’ and separated biodegradable waste respectively. Once again, it’s important to emphasize that this calculation shows the maximum theoretical production of hydrogen that could be achieved. From a practical point of view, it’s impossible to collect all of this waste and convert it to hydrogen.

Table 16: Maximum theoretical potential of hydrogen production based on the national total of ‘unseparately’ collected biowaste from S2Biom study.

Year	Biowaste unseparately collected (kton)	kton H ₂ based on HHV	kton H ₂ based on LHV	Energy equivalent (PJ)
2030	1275	73.10	86.50	10.37
2020	1245	71.30	84.50	10.13
2012	1379	79.06	93.55	11.22

Table 17: Maximum theoretical potential of hydrogen production based on the national total of separately collected biowaste from S2Biom study.

Year	Biowaste separately collected	kton H ₂ based on HHV	kton H ₂ based on LHV	Energy equivalent (PJ)
2030	1560	89.4	105.83	12.7
2020	1521	87.2	103.18	12.38
2012	1326	76.02	89.96	10.79

The total values are provided below in **Table 18**.

Table 18: Maximum theoretical potential of hydrogen production based on the sum of both separate and unseparated biowaste from S2Biom study.

Year	Total biowaste (kton)	kton H ₂ based on HHV	kton H ₂ based on LHV	Energy equivalent (PJ)
2030	2835	162.53	192.33	23.08
2020	2766	158.57	187.65	22.51
2012	2705	155.08	183.51	22.02

Table 19 provides the theoretical potentials based on own calculations which in terms of energy equivalents is quite the same for 2020 and 2030 in comparison to the S2Biom results.

Table 19: Maximum theoretical potential of hydrogen production based on the sum of both separate and unseparated biowaste from own calculations.

Year	Total biowaste (kton)	kton H ₂ based on HHV	kton H ₂ based on LHV	Energy equivalent (PJ)
2030 - unseparated	956.74	54.85	64.1	7.79
2030 - separated	1622.58	93.02	110.01	13.21
2030 - total	2579.32	147.87	174.9	21
2020 - unseparated	1022.39	58.61	69.36	8.32
2020 - separated	1682.17	96.44	114.12	13.7
2020 - total	2704.56	155.05	183.48	22.02

3.3.1 Sectors that could be served based on the calculated energy potentials

Total biowaste supply for the years of 2012, 2020 and 2030 ([Table 18](#) and [Table 19](#)) averaged around 2700 kton which is equivalent to ≈ 155 kton of hydrogen (based on HHV) and an energy potential of ≈ 22 PJ. It's worth determining to what extent these values could cover the energy requirements of various energy consumption sectors such as industry, mobility, etc. [Table 20](#) provides an overview of the temperature ranges for a variety of industrial processes and what this could mean in terms of utilizing hydrogen for a specific process. Indirect applications refer to processes where there is no contact between the gas flame and the product, an example of an indirect heating process is utilizing hydrogen boilers for steam or hot water production which can be utilized in a variety of industries such as the food industry, paper and textiles. Other examples include drying which could have applications in the ceramic, food, paper, textile and wood industries [100]. Most indirect processes require a lower utilization of high temperatures [100]. Direct applications refer to processes where the gas flame is in direct contact with the product and directly affects the product quality. This is, for example, typically the case in the ceramic industry where certain products (e.g., roof tiles) are affected by the composition of the gas flame [100]. Other examples include the glass industry where melting and glowing are primary processes. For direct processes temperature ranges are high.

Table 20: Temperature ranges for a variety of processes in the industrial sector and the expected type of hydrogen application (direct/indirect) and the expected required quality of the hydrogen gas stream [101].

Industrial Sector	Type of H2 demand (Direct/indirect)	Required Quality of H2 gas stream
Food & beverages	Hot water/steam generation: indirect (0-100°C), Drying: indirect (100-200°C), Chemical conversions: indirect/direct (100-600°C), Distillation: indirect (100-600°C).	The quality will depend on the type of application. For indirect applications lower quality is sufficient but for direct applications (e.g., roasting coffee) specific purity demands may be needed.
Textile & clothing	Hot water/steam generation: indirect (0-100°C), Drying: indirect (100-200°C).	Only indirect heating so quality is of lower importance.
Paper and carton	Hot water/steam generation: indirect (0-100°C), Drying: indirect (100-200°C).	Only indirect heating so quality is of lower importance.
Chemicals	Feedstock: direct (variable temperatures), Drying: indirect (100-600°C), Chemical conversions: indirect (100-600°C),	For indirect heating quality is of lower importance. As feedstock of very high quality is desired (>99.9%) to prevent undesired side reactions.

	Distillation: indirect (100-600°C).	
Glass	Melting: direct (1200-1650°C), Annealing: direct (200-900°C)	Flue gas composition is important for product quality and heat transfer. Thus, low variation in H2 stream composition and knowledge of impurities is important.
Ceramics	Baking: direct (1000-1200°C), Drying: indirect (<100°C)	Hydrogen quality will have a direct influence on product properties such as color and hardness. Hence, it's vital that there are little variations in quality.
Other (e.g. cement)	Heating (Cement): direct and indirect (1800 - 2200°C). Heating (Asphalt): indirect (hot mix asphalt 120 – 190°C) (warm mix asphalt 100 – 150 °C) (half-warm asphalt 70-100 °C)	For clinker production hydrogen could have an impact on cement quality. Addition of hydrogen can improve the combustion characteristics.
Basic metals	Melting: direct (up to 2000°C), Annealing: direct (200-900°C)	For steel hardening, the interaction between the product and the flue gas affects its properties. Thus, purity of the gas stream is very important.
Metal products and machine industry	Annealing: direct (200-900°C), Heating: direct/indirect (1800 - 2200°C for ferrous metals), Heating: direct (500 - 1500°C for non-ferrous) e.g., copper, aluminium, tin, zinc, etc. in smelting furnaces with flue gases	Temperature, radiation and flue gas composition are important for product quality and heat transfer.
Other manufacturing	Indirect: gas-fired oven for drying powder coating on furniture manufacturers	Highly dependent on use case
Construction	Direct: hydrogen fuel cells for construction vehicles or hydrogen generators for construction sites	Assumed >99.97% H2 purity required since fuel cells are utilized

Table 21 provides the total natural gas demand of the aforementioned sectors in PJ/y for 2023 based on information from the Central Bureau of Statistics of the Netherlands [101]. The volumetric energy equivalent for both natural gas and hydrogen has been provided in Mm³/yr and a mass equivalent has been provided as well in kton/yr.

Table 21: Energy requirements of various sectors within industries and their hydrogen equivalent both in PJ and kton [101].

Industries	Total energy demand (PJ/yr)	Total NG demand (Mm ³ /yr)	Total H2 demand (Mm ³ /yr)	Total H2 demand (kT/yr)
Food & beverages	60.7	1918.12	5631	471.86
Textile & clothing	2.3	72.68	213	17.88

Paper and carton	15.8	499.28	1466	122.82
Chemicals	172.4	5447.84	15993	1340.18
Glass	6.6	208.56	612	51.31
Ceramics	7.3	230.68	677	56.75
Other (e.g. cement)	4.7	148.52	436	36.54
Basic metals production	11	347.6	1020	85.51
Metal products and machine industry	8	252.8	742	62.19
Other manufacturing	0.9	28.44	83	7.00
Construction	2.6	82.16	241	20.21

Seeing how we derived a theoretical maximum of ≈ 22 PJ from all the separated and unseparated biodegradable waste, the annual energy needs of industries such as textile & clothing, paper and carton, building material categories, basic metals and other groups could be theoretically fulfilled; these groups have been highlighted in green in **Table 21**.

Details regarding the conversions in **Table 21** is as follows:

1PJ is equivalent to 31,600,000 normal cubic meters (Nm^3) of natural gas [102]. We can convert this energy content to its hydrogen fuel equivalent by using the LHV¹³ of hydrogen:

$$1PJ \times \frac{1\text{Nm}^3\text{H}_2}{10.78\text{MJ}} \times \frac{10^9\text{MJ}}{1PJ} \approx 92,764,378\text{Nm}^3\text{H}_2$$

Hence 31,600,000 Nm^3 of natural gas is equal to 92,764,378 Nm^3 of hydrogen. Essentially, for the same amount of energy (here, 1PJ) hydrogen occupies ≈ 3 times more volume compared to natural gas which underlines the higher compression energy requirements for storing hydrogen.

The mass equivalent can be found by using the density of hydrogen at NTP¹⁴ conditions which is 0.0838 kg/m^3 :

$$92,764,378\text{Nm}^3\text{H}_2 \times \frac{0.0838\text{kg H}_2}{1\text{Nm}^3\text{H}_2} \approx 7,773,655\text{kg H}_2 \approx 7.7\text{kton H}_2$$

¹³ It was decided to use the LHV of hydrogen since in most practical applications, such as home heating or industrial processes, the water vapor remains in its gaseous form as it is released into the atmosphere without condensing back into liquid

¹⁴ NTP, or normal temperature and pressure is defined as a temperature of 20 °C (293.15 K) and a pressure of 1atm (101.325 kPa)

4. Opportunities and Challenges of Waste-to-Hydrogen

4.1 SWOT analysis of WtH

A successful implementation of Waste-to-Hydrogen (WtH) facilities requires understanding where the risks and opportunities lie. For this purpose, a SWOT analysis has been conducted ([Figure 29](#)) where various Strengths, Weaknesses, Opportunities and Threats have been outlined.

Strengths and Weaknesses

The main strengths of WtH lie in the substantial decarbonization capacity and that the levelized cost of hydrogen (LCOH) produced through this method is closer in competitiveness to SMR and certainly most cost effective in comparison to other renewable forms of hydrogen production (i.e., electrolysis) [11]. Additionally, the already existing infrastructure for waste collection and management can play an important role in a more responsive implementation of WtH.

Some of the weaknesses of WtH lie in the high capital costs required to construct and operate the plant and the relatively costly operations for the collection, storage and processing of waste. The additional steps required to rid the hydrogen of contamination from waste is another limiting factor, certain bottlenecks such as the accumulation of tars and char through the purification process need to be reliably overcome. Certain promising types of catalysts such as nickel-based Al_2O_3 and CeO_2 have proven increase hydrogen yields [103] [104].

Opportunities and Threats

Opportunities for WtH are the ability to deploy at smaller scales which can allow for more decentralized distribution of the technology in proper coordination with the sufficient waste streams required to economically and efficiently to run a plant. While the technology of producing hydrogen from syngas already has a TRL of 9 (e.g., in SMR applications), waste gasifiers for the purpose of producing hydrogen have TRL's around 6 – 8 [105]. There is no extant and diversified technology base at TRL 9 that could support the immediate and widespread implementation of thermochemical hydrogen facilities at this time [22]. Hence the

development of suitable gasification technologies solely for producing hydrogen from waste is vital. This is also fundamental for the upscaling and commercial deployment; without a demonstration of the technical feasibility of the process at larger scales and commercial scales, deployment will not happen [73]. Another issue relates to the potential scarcity of municipal solid waste (MSW), which could impact the operational costs of waste-to-hydrogen in several ways. If a significant portion of MSW is diverted to gasification facilities, there could be a reduced supply of waste available for waste-to-hydrogen plants. This scarcity may drive up competition for the remaining waste, potentially increasing gate fees for waste-to-hydrogen plants in order to cover operation costs. The plus side is that a scarcity of MSW may incentivize investment in research and development to improve the efficiency of waste-to-hydrogen technologies or to explore new feedstock sources. This could lead to innovations that help waste-to-hydrogen plants adapt to changing waste supply dynamics.

The next sections will look into certain challenges and considerations in relation to waste collection distances, plant capacities, gate fees, environmental performance, legal barriers and some technological limitations.

4.2 Waste collection routing and population densities

Integrating renewable hydrogen production plants into societal livelihoods would involve considering numerous factors to determine the feasibility of establishing WtH conversion facilities in specific municipalities and communities [106]. The optimal routing and timely collection and handing of MSW is integral to the operation of a WtH facility. The collection and transportation process alone, for instance, accounts for approximately 60% - 80% of total cost for solid waste management [107]. Normally this task is handled by municipalities or third-parties that are involved in the collection of waste. Seeing how production of hydrogen from waste features a low or negative carbon footprint, planning the routes and collection process in order to reduce environmental impacts and costs is important. To minimize the travel times and distances, collection routes should be optimized based on the characteristics of the community [108]. Considering the relationship between the population density of communities and environmental impacts is also an important factor. For example, lower population densities could lead to an increase in waste collection distances in order to maintain the necessary waste inflow towards WtH facilities [106]. This could lead to higher environmental impacts and waste collection costs. Generated waste within an area is also influenced by the type of community. For example, using waste biomass could be more suitable in rural areas where agricultural or forestry activities are prevalent. MSW can be more appropriate in urban areas where biomass waste from agriculture or forestry is scarce [106].

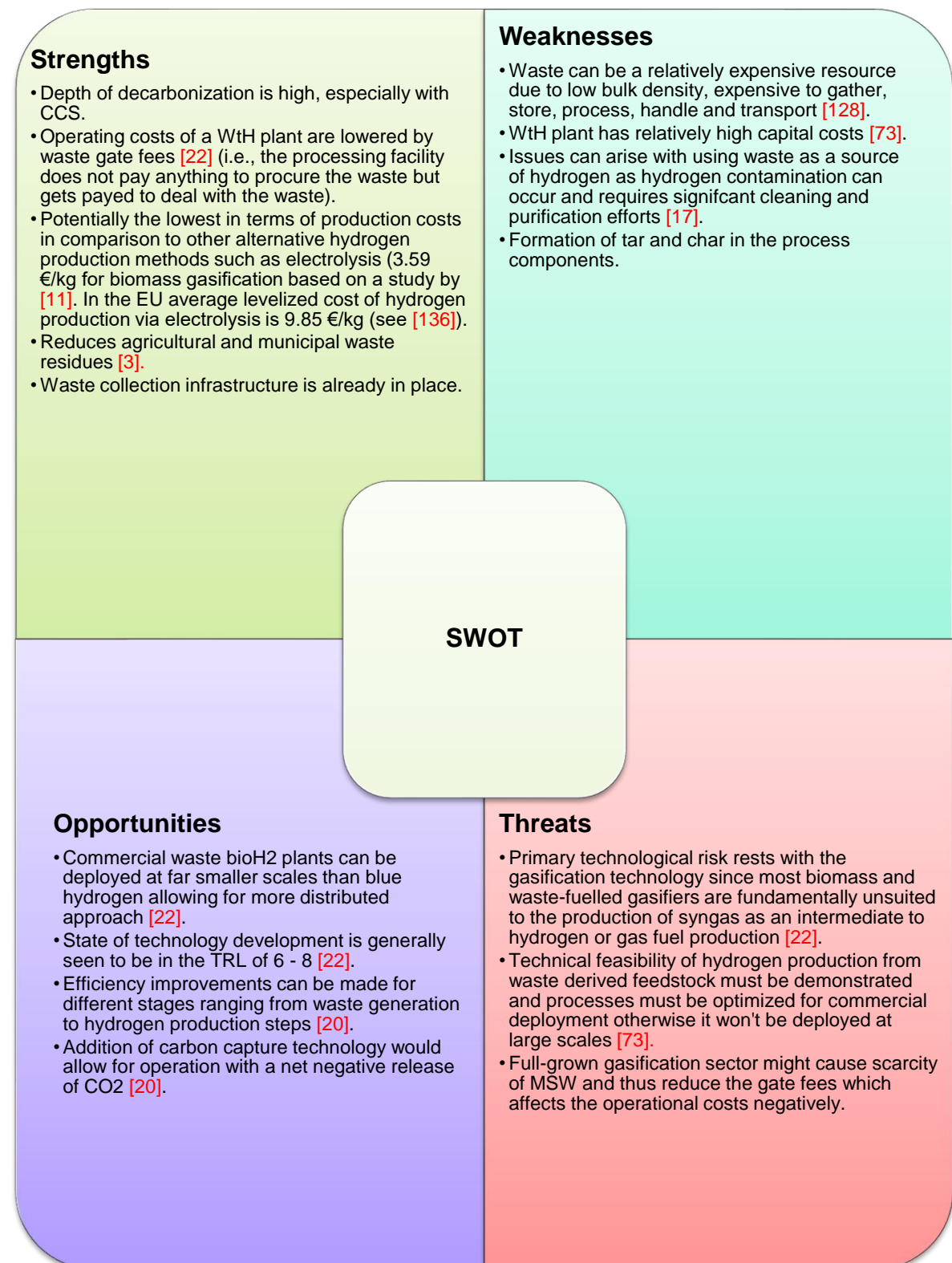


Figure 29: SWOT analysis of WtH

4.3 Plant capacities and economies of scale

Selecting plant capacity is a fundamental aspect governing land requirements, financial needs and procurement of other raw materials during the establishment and commissioning of any processing plant [94]. Capacity is especially critical for plants converting waste into high-value products since waste supply highly depends on location [109]. These constraints need to be considered in order to account for proper plant capacities. The amount of waste that a plant processes should be harmonious with the handling capacity of the plant.

Economies of scale refers to the reduction of production costs of a product due to increased production capacity. Seeing how WtH is still a niche form of energy recovery, there are no specific indications on suitable plant capacities and the unit cost of production. However, a study by the Department for Business, Energy & Industrial Strategy of the UK in regard to Advanced Gasification Technologies [110] [1] provides indications with regard to plant performance (**Table 22**) and the levelized cost of hydrogen.

Two types of WtH plants were defined based on the waste handling capacities of 100,000 tons per annum (tpa) and 550,000 tpa. Based on the information, a 36 MW_{th} WtH plant which has a waste handling capacity of 100,000 tpa has a hydrogen production of 3900 tpa. A 199 MW_{th} plant which has a waste handling capacity of 500,000 tpa has a hydrogen production of 22,000 tpa.

Table 22: Operational characteristics of a 36 MW_{th} and 199 MW_{th} WtH plant (Source: [110])

Model Parameter	Units	Model Outputs	
		100,000 tpa	550,000 tpa
Process Streams	--	1	2
Feedstock throughput	t/h	13	74
Thermal input rate	MW _{th}	36	199
	MW _{th} /year	268,100	1,481,800
Syngas output from gasifier	t/h	121,000	665,900
Syngas output from reformer	t/h	75,000	413,700
Hydrogen yield	kg/odt	67	69
Hydrogen production	tpa	3,900	22,000
Electricity production	MWe	5	29
	MWh/year	37,800	208,100
Plant availability	%	85	85
Energy efficiency	%	38	39
Main consumables	tpa natural gas	235	1,295
	tpa oxygen	29,100	160,000
	tpa steam	70,500	387,700
	tpa water	75,700	416,100
	tpa chemicals	5,300	32,000
Key material output streams	tpa CO ₂	76,900	432,000
	tpa flue gas	152,500	850,700
	tpa flue gas CO ₂	17,000	87,000

	tpa bottom ash and char	10,700	58,900
	tpa effluent	81,500	448,100

Table 23: WtH Levelized cost of Hydrogen with and without CCS (Source: [1])

	100,000 tpa	500,000 tpa
LCOH without CCS	£7.53 ≈ €8.79	£3.52 ≈ €4.10
LCOH with CCS	£7.79 ≈ €9.10	£3.81 ≈ €4.48

Table 23 provides the LCOH for the 36 MWth and 199 MWth plants in pounds with its euro equivalent based on the results from the study done by the BEIS [105] [1]. With an increase in plant capacity the levelized costs decrease by about half, here the economies of scale are prevalent. The LCOH via utilization of CCS is also included, the addition of carbon capture obviously increases LCOH.

4.4 Effect of Gate fees and biochar production in reducing LCOH

An important element within the realm of waste management are gate fees. Any facility that handles and manages waste such as landfills or energy-from-waste facilities will charge a fee from a municipal government for collecting the waste. A WtH facility using MSW as its feedstock can generate revenue by charging an acceptance fee from MSW generators [106]. This fee ultimately drives down the levelized cost of hydrogen (LCOH) via this additional revenue inflow [106]. WtH production facilities can strategically incentivize on this via accepting lower acceptance fees compared to the other forms of handling waste while maintaining the profitability of their activities.

Figure 30 provides information on average waste disposal costs for a handful of European countries. The dark blue bar represents the typical gate fees while the light blue bar shows the landfill tax. Compared to the other countries, the Netherlands has significantly lower waste gate fees (€33/ton) and landfill tax (€13/ton). The low prices for landfilling are because only 2-3% of the total waste generation of some 60 million tons per year in the Netherlands is landfilled and a large majority of waste is either incinerated or recycled. Added to that is that landfills have reduced throughout the years (from 80 to 22) due to the implementation of landfill bans since 1995 [111].

The production of biochar from the WtH process can also generate revenues for a WtH plant and can reduce the cost per kilogram of hydrogen. Price of biochar within Europe is between €300 to €2000 per ton, depending on its quality, in European Markets [112].

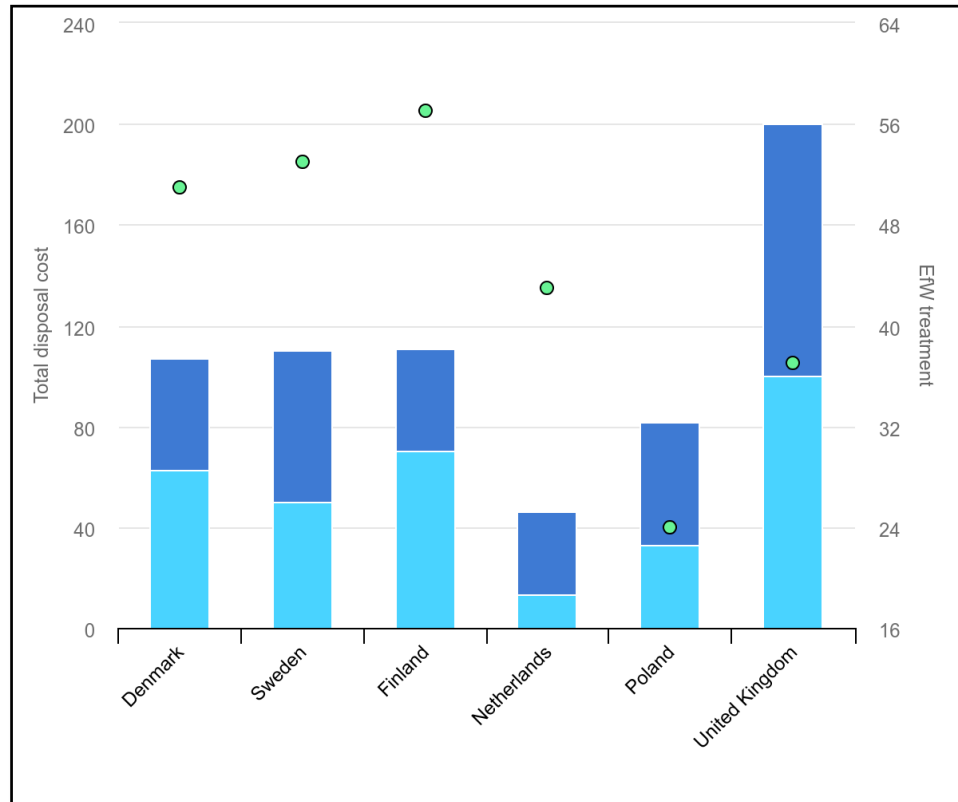


Figure 30: Waste disposal costs and share of EfW in selected countries [113].

4.5 Environmental aspects

One of the significant and attractive aspects of hydrogen production from municipal waste is the limited carbon intensity involved in the process; negative carbon emissions can also be achieved if the separated CO₂ is sequestered. Implementing WtH production plants must maximize profitability while maintaining the environmental footprint as low as possible [106]. Conducting a detailed analysis of the carbon impact of WtH is a significant endeavor and beyond the scope of this study, however there have been various scientific papers and articles that have provide detailed analysis. In this section we will take a brief look at the results of some of these studies and understand how the carbon intensity of the WtH ranks to other methods of hydrogen production.

4.5.1 CO₂ capture in the WtH process

Capturing CO₂ streams within WtH processes will depend significantly on the actual equipment configurations and design parameters considered for syngas generation, hydrogen generation and the separation of hydrogen. Hence, each specific configuration could have its own CO₂ mass flow rates and compositions but two CO₂ process streams can be generally identified [105]:

- CO₂ removed from the syngas prior to the upgrading process
- Flue gas from the gasifier

4.5.2 CO₂ removal in the syngas upgrading phase

CO₂ has the potential to be sequestered from the post-syngas generation phase and typically occurs at the post water-gas shift (WGS) stage in a gasification or pyrolysis plant [22] (**Figure 31**).

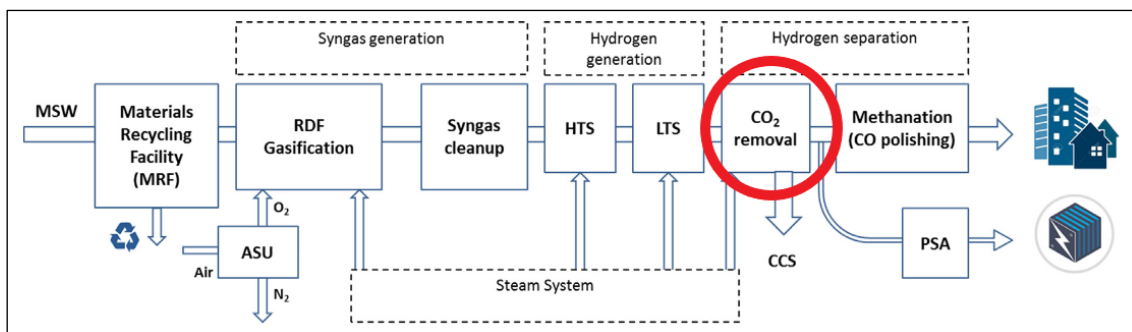


Figure 31: Post-combustion CO₂ removal typically occurs after the water-gas shift stage [73].

The gas stream from the WGS stage is replete with high pressure CO₂ which makes it ideal for capturing. Today's commercially available pre-combustion carbon capture technologies generally use physical or chemical adsorption processes, and will cost around 60\$/tonne to capture CO₂ generated by an integrated gasification combined cycle power plant [114]. The goal of research efforts within bio-hydrogen research efforts is to reduce the cost to \$30/ton of CO₂ [22].

4.5.3 CO₂ removal from the flue gas of the gasifier

Depending on whether a gasifier is used in which some portion of the flue gas is vented (this could be for e.g., temperature control, gas composition adjustment, safety considerations such as preventing pressure build-up, and process optimization), dilute CO₂ can be removed from the flue gas. The concentration of CO₂ for these gas streams is ~5-15% [22]. It is comparatively more expensive to capture CO₂ from smaller and more dilute process streams [1] this is mostly due to the lower concentration of CO₂ which requires extensive separation processes which can be energy-intensive and costly.

4.5.4 Carbon reduction potentials

The carbon reduction potential of utilizing CCS in the WtH process is significant and can lead to negative carbon emissions which is a typical feature of BECCS (Bio-energy carbon capture and storage) processes. **Figure 32** displays the contributions per hydrogen production technology

and only takes into account the environmental burdens allocated solely to the production of hydrogen¹⁵ [22]. Bio-H₂ production in combination with CCS shows the lowest contribution to climate change equating to -293 kgCO₂ for waste wood and -118 kgCO₂ eq/FU¹⁶ for MSW [22]. Blue hydrogen produced via steam methane reforming process (SMR) with CCS process (carbon capture rate of 90%, with MDEA CO₂ adsorption) produces 143 kg CO₂ eq. per MWHHV H₂ as modelled by [115]. With 96 kgCO₂ eq. per MWHHV, ATR combined with CCS has less of an impact due to a higher composition of CO₂ in the syngas mix, hence allowing for more effective carbon capture. The electricity demand of the electrolyzer and hydrogen compression unit met by electricity produced from 100% solar and 100% offshore wind contribute 99kg CO₂ eq. per MWHHV H₂, and 23kg CO₂ eq. per MWHHV H₂, respectively¹⁷ [22]. While not shown the climate change impact of Bio-H₂ production without CCS has been reported at 46 kgCO₂eq/MWh¹⁸ [73]. Succinctly put, from a global-warming reduction standpoint, bio-H₂ production via waste/waste-wood outperforms other competitive low-carbon forms of hydrogen production.

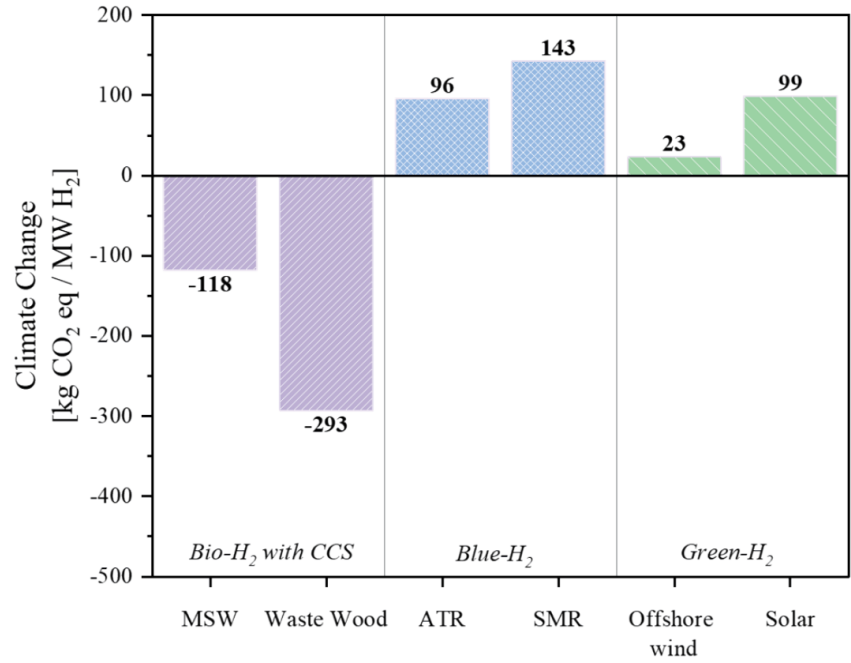


Figure 32: Climate Change contribution comparison of Bio-H₂, Blue-H₂ and Green-H₂ production technologies [22].

¹⁵ i.e., excluding system expansion methodology. Also, CO₂ transportation and storage have not been included across technologies for consistency.

¹⁶ FU: functional unit. The function unit here is 'MWHHV of Hydrogen' i.e., CO₂ released for the production of 1 MW of hydrogen based on high heating value.

¹⁷ It's important to emphasize that no CO₂ is released for the production of green hydrogen and that the greater climate impact from solar compared to offshore wind is attributed to the manufacturing of silicon cells.

¹⁸ Here the system boundaries include emissions associated with production and transport of material inputs and product use (see [73]).

4.6 Legal barriers

Currently there are no legal frameworks for hydrogen produced from biomass in the Netherlands and is not supported by Dutch subsidy schemes. Targets that have been set under REDIII for industry and transport focus on hydrogen from renewable fuels of non-biological origin (RFNBO) actively discriminating against biohydrogen. The directive does not feature to date an inclusive definition of renewable hydrogen covering all possible production pathways, such as raw biogas and biomethane steam reforming [116]. It's hoped that new classifications lead to an inclusion of WtH under new subsidy schemes.

4.7 Technological bottlenecks of gasification

Thermochemical processes are typically hampered by the production of unwanted compounds such as tars in the gasification process which has far-reaching effects on downstream applications and operations [117]. Tar condenses at temperatures between 200 – 600 °C, within this range damage to equipment and operation issues can occur including gas passage clogging, deactivation of sulfur removal systems, and damage to gas engines [77]. Formation of tar also leads to the deactivation of catalysts which can lead to a reduction in the efficiency of the gasifier. It is vital that problematic species are cleaned down to values that are acceptable for different downstream catalysts and are of crucial importance for the successful implementation of waste gasification technology [73]. The success of new gasification technologies for the treatment of waste feedstocks in the future will be assessed on this basis [73]. For the gasification of MSW content of tar should be no more than 1 mg/m³ in the product gas or syngas [77]. Contaminants such as sulfur are widespread in waste derived syngas and higher molecular weight compounds are stubborn, normally requiring plasma reforming or high temperature hydrotreatment for removal [73]. Metal hydrides and (arsine/phosphine) and acid gas components (HF/HCl) are other contaminants that require treating [73].

Another bottleneck of gasification has to do with its low energy conversion efficiency: due to its endothermic nature, it requires a great deal of energy [117]. Catalyst utilization in the biomass gasification process can improve the gasification rates, reduce tar formation, enhance hydrogen production, increase the calorific value of the outlet gas, and suppress a certain amount of components in the gaseous product [118]. Catalysts that are commonly used in the gasification process include alkaline earth metals such as Al, Fe, K, and other metal-based catalysts such as Ni, Ce, and La, and mineral or natural catalysts such as cement and olivine [119]. Alkaline earth metal catalysts show effective catalytic activity in gasification with less tar production and more formation of syngas and hydrogen [120]. Examples include MgCO₃ (Magnesium Carbonate) and alkaline earth metals doped with CeO₂ (Cerium Oxide) such as Ni/CeO₂. The fly

ash produced during the syngas formation process can contain alkali, alkaline earth, and heavy metals which can poison and deactivate catalysts, developing catalysts that are resistant to these types of metals are important [121] [122].

5. Conclusions

The technology for converting waste to hydrogen is a promising and rapidly advancing field, demonstrating significant potential for addressing both waste management and renewable energy needs. Current methods, including thermochemical processes (such as gasification and pyrolysis) have shown varying degrees of efficiency and scalability. The primary advantages of waste-to-hydrogen technology lie in its dual capability to reduce the environmental impact of waste disposal and produce a clean, sustainable energy source. Despite the potential, the technology faces challenges related to economic viability, feedstock variability, and process optimization.

To enhance process efficiency and economics in the waste-to-hydrogen sector, it is essential to invest in research and development aimed at optimizing catalysts. By creating more efficient and durable catalysts, operational costs can be reduced, and hydrogen yield can be increased. Additionally, a focus on scaling up pilot projects to commercial-scale operations is crucial for demonstrating the economic viability and reliability of these technologies. Developing integrated systems that combine waste processing with hydrogen production will further maximize resource utilization and minimize costs, contributing to overall efficiency.

Expanding feedstock flexibility is another key area of focus. Research into the effective processing of various types of waste, including municipal solid waste, agricultural residues, and industrial by-products, will enhance the versatility and applicability of the technology. Furthermore, it is important to develop standardized methods for pre-treating and processing different types of waste. This standardization will ensure consistent quality and performance in hydrogen production, regardless of the feedstock used.

Strengthening policy and market support is also vital for the growth of the waste-to-hydrogen sector. Encouraging governmental policies that provide subsidies, tax incentives, and grants for waste-to-hydrogen projects will help lower initial investment barriers and stimulate market growth. Additionally, establishing clear regulatory frameworks will support the development and integration of waste-to-hydrogen technologies within existing waste management and energy systems, ensuring they can thrive in a supportive regulatory environment.

Advancing research and development remains critical to the sector's evolution. Investing in cutting-edge research to explore novel technologies and approaches, such as bio-electrochemical systems and advanced plasma gasification, could further improve efficiency and reduce costs. Conducting comprehensive life cycle assessments will also help evaluate the environmental impact of waste-to-hydrogen processes and identify areas for improvement, ensuring that the technology is both sustainable and effective.

Promoting public and private partnerships will drive innovation and resource sharing. Fostering collaborations between research institutions, industry players, and government agencies will pool resources and share knowledge, accelerating progress in the sector. At the same time, increasing public awareness and acceptance of waste-to-hydrogen technology through educational campaigns and transparent communication about its environmental and economic benefits will help build broader support and drive demand. An example of such collaboration in the Netherlands is the FUREC project where RWE is set to construct a waste pre-treatment plant in Zevenellen, Limburg, to convert non-recyclable municipal solid waste into solid recovered fuel pellets and another plant in the Chemelot industrial park in Limburg to convert

the pellets to hydrogen. This project, funded by the EU Innovation Fund, is fully financed through the EU Emissions Trading System (ETS). The Fund aims to provide approximately €38 billion in support for the commercial demonstration of innovative low-carbon technologies from 2020 to 2030, with the goal of bringing industrial solutions to market that will help decarbonize Europe and support its transition to climate neutrality.

By addressing these key areas, the waste-to-hydrogen sector can overcome current challenges and play a crucial role in the global transition to sustainable energy and effective waste management.

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