



GIFFT



Sustainable Glass Industry

Alternative Gas Production and Their Integration into Glass Industry

July 2024

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Table 1: Document information

Document Information	
Project name:	Sustainable Glass Industry with Fuel-Flexible Technology
Project acronym	GIFFT
Project number:	101122257
Start date:	01/10/2023
Duration:	48 Months
Work package number	WP2
Task number	T2.3
Deliverable number	D2.2
Lead beneficiary	LEI
Due date of deliverable	Month 10

Table 2: Dissemination level of this report

Dissemination level of this report	
PU	Public



Table 3: List of Abbreviations

Abbreviation	Definition
AVG	Average electricity and natural gas price scenario
BFB	Bubbling fluidised bed
BtX	Biomass-to-X
CAPEX	Capital expenditures
CCUS	Carbon capture, utilization, and storage
CFB	Circulating fluidised bed
CHP	Combined heat and power
C _x H _y	Hydrocarbons
DD	Downdraft-gasifier
DFB	Dual fluidised bed
DME	Dimethyl ether
EF	Entrained flow
ER	equivalence ratio
FF	Further fuels
FT	Fisher-Tropsch syncrude
GEC	Green (free) electricity case
GDP	Gross domestic product
LHV	Lower heating value
LPG	Liquid petroleum gas



MAX	High electricity and natural gas price scenario
MIN	Low electricity and natural gas price scenario
OPEX	Operational expenditures
RDF	Refuse derived fuel
TRL	Technology readiness levels
MeOH	Methanol
OPEX	Operational expenditures
PAEF	Plasma assisted entrained flow
SCR	Selective catalytic NOx reduction
SMR	Steam methane reforming
SNCR	Selective non-catalytic NOx reduction
SNG	Synthetic natural gas
SLS	Soda lime silica
UD	Updraft gasifier



ACKNOWLEDGMENT & DISCLAIMER

This project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101122257.

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EXECUTIVE SUMMARY

Deliverable D2.2 is a review report that offers insights into the potential integration of various gasification systems for targeted applications within the GIFFT project. The study reviews existing advanced substitute gas production processes that could be integrated into the glass industry. It emphasizes the advantages of advanced entrained flow gasification over other existing substitute gas production processes in the glass industry. The D2.2 result introduces an overview of the glass industry, detailing primary glass products, melting processes, and the GIFFT partners representing these sectors. The paper examines current energy sources and explores alternative fuel options, discussing and comparing their characteristics. The most promising alternative fuel, synthetic gas, has been identified for implementation in the GIFFT project. Furthermore, the paper debates the advantages of different production technologies, presenting and comparing their characteristics and parameters, and costs.



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1 Glass industry

Glass is a quickly cooled, solid, inorganic amorphous material that can occur naturally or artificially. Nowadays, glass is created by heating inorganic substances widely found in nature in specific proportions to the melting point before cooling to the solid form. The composition is tailored to meet the desired of the application, from food containers to precision optics. Glass types are grouped by composition and properties into the broad categories of soda lime silica (SLS) glass, lead crystal and crystal glass, borosilicate glass and special glass.

The global distribution of glass production shows that 61% comprises glass container and flat glass production, due to its highly favourable properties: recyclability, excellent transparency, chemical inertness, and surface smoothness. Most importantly, it is relatively low-cost to produce. The rest consists of specialized glass such as stained glass and tinted glass, intaglio or etched glass, others (33%) and fibreglass (6%) [1]. The European Union is the world's largest producer of glass containers, producing 22 million tons per year (2006). In terms of production, glass containers take the first place among all glass products and account for about 56% [2] of the total production. Glass production is an energy-intensive process due to the high melting temperatures (above 1000 °C) achieved by mainly burning fossil fuels in a continuous production process. The European glass industry is estimated to consume 344 PJ of total final energy (2007), of which 83% is primary fuel – fossil gas and liquid fuel, and the remaining 17% is electricity [3]. The EU needs to improve its technological development and productivity further to compete in the global market.

This section will observe prominent examples of the glass industry, such as GIFFT project participants and suitable target groups.

1.1 Container glass (JSC Panevezio Stiklas)

The Lithuanian company "Panevezio Stiklas" has produced glass products since 1961. The factory started its activity with sheet glass for the construction industry. Over time, the production volume expanded, and the range of manufactured products grew. Workshops for producing glass blocks, mosaic tiles, and glass fibre (non-woven reinforcement) appeared. After the economy transitioned to free market conditions, "Panevezio Stiklas" focused its production capacity on producing standard and specialised glass containers. In 2017, "Panevezio Stiklas" invested in a new glass melting furnace, which increased production capabilities. Currently, the melting furnace produces 140 tons of glass production per day. The company participates in the circular economy and delivers products from used glass collected by residents.

Glass containers are made from SLS glass in gas or liquid fuel furnaces by automated individual section machines and are divided into five stages:

1. Production of a piece of molten glass (gob) of suitable mass and temperature;
2. Forming the primary form in the first template (blank mould) with compressed air or a metal plunger;
3. Transportation of the primary form to the production of the final form;
4. Finishing the mould by blowing compressed air into the final mould;
5. Transportation of manufactured products to the final process (post-forming process)

The melted glass moves from the end-fire regenerative or cross-fire furnace through a forehearth to reach a gathering bowl (spout) at the end. From the base of the gathering bowl, one to four parallel glass streams are created through appropriately sized openings. These glass streams, regulated by a mechanical plunger system, are then cut into precise lengths by a shear mechanism to form basic, sausage-shaped glass masses known as "gobs". The system responsible for creating these gobs is called the "feeder mechanism". Gobs are simultaneously cut from the parallel glass streams and shaped in parallel moulds on the forming machine.



Table 1.1 gives typical characteristics of glass containers.

Table 1.1 Typical composition of container glass

Component	Mass fraction, %
Silicon dioxide (SiO ₂)	71 – 73
Sodium oxide (Na ₂ O)	12 – 14
Calcium oxide (CaO)	9 – 12
Magnesium oxide (MgO)	0.2 – 3.5
Aluminium oxide (Al ₂ O ₃)	1 – 3
Potassium oxide (K ₂ O)	0.3 – 1.5
Sulphur trioxide (SO ₃)	0.05 – 0.3
Colour modifiers, etc.	Traces

From the feeder mechanism, the gobs are directed by a system of chutes into the blank moulds on the forming machine where the forming process occurs. The forming process occurs in two stages, as illustrated in Fig 1.1. The initial shaping of the blank is achieved either by pressing with a plunger or by blowing with compressed air, depending on the type of container. These processes are called “press and blow” and “blow and blow”, respectively. Press and blow forming are well-suited for producing jars and are commonly used to craft lightweight bottles. Blow and blow forming, conversely, are more versatile and the preferred method for creating standard-weight bottles and more intricate shapes. The final moulding operation always involves blowing to achieve the desired hollow shape.

Cooled-down and solidified containers move on a continuous conveyor for subsequent production stages. High volumes of compressed air are used for heat extraction from the surface and the moulds. The rapid cooling of the outer surface of the containers induces high differential stresses in the glass, leading to increased fragility. Cooling under controlled conditions (annealing) to prevent the development of additional stresses is done in lehr. Lehrs are typically heated by gas or electricity, and once they reach the operating temperature, the incoming containers contribute the majority of the heating energy.

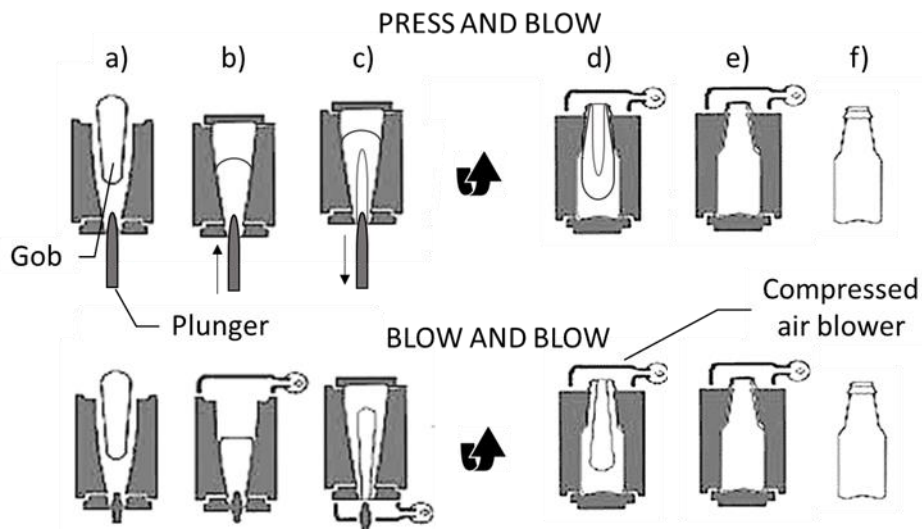


Fig. 1.1 "Press and blow" and "blow and blow" glass containers forming processes

Surface coatings can be applied immediately after forming to enhance product performance. The glass containers still over 500 °C can be hot-end coated with SnO₂ or cold-end coated with polymers after annealing. Typically, a combination of hot-end and cold-end treatments is employed, with coatings applied to the outside surface of the containers. Hot surface coatings, usually tin oxide or titanium oxide, are applied immediately after leaving the forming machine. Combined with subsequent lubricating cold surface coatings, this prevents glass surface damage during handling. The metal oxide coating is a substrate to retain lubricating organic molecules, ensuring scratch resistance with food-safe lubricants. Hot-end treatment also enhances mechanical resistance.

After manufacturing, glass containers may undergo a secondary process to add decoration and identify characteristics before being sent to customers. This can involve pressure-sensitive or heat-shrink labels or heat-applied ceramic decoration.

1.2 Special glass: flat glass (SCHOTT)

Schott Glass Company was founded in 1884 in Jena, Germany, by Otto Schott, Ernst Abbe, and Carl Zeiss. Originally named Glastechnisches Laboratorium Schott & Genossen, the company aimed to advance glass science and technology. Now, the company's headquarters is in Mainz; Schott's is a known special glass manufacturer, mainly for medical applications, home appliances, as well as automotive applications, aerospace, and optics. The Schott company is committed to corporate social responsibility, sustainability, and supporting community initiatives and educational programs. Schott company made an ambitious commitment to become a carbon-neutral manufacturer by 2030. This goal of the company will be achieved through the implementation of four areas of activity:

1. Technology change
2. Improvement of energy efficiency
3. Consumption of green electricity
4. Compensation for remaining emissions

From 2018 to 2020, Schott Glass Company took significant strides towards its sustainability goals by introducing green electricity to all production sites all over the world. This strategic move significantly reduced the company's CO₂ footprint by over 60% [4], underscoring Schott's commitment to environmental stewardship. Further



reduction will be done by technological change, e.g. drastic increase in electric boosting, electric heating by plasma or microwave, or the use of green hydrogen or renewable bio-fuels.

One of Schott's special glass products is flat glass made by float glass production or made by rolling processes. Schott develops and supplies special glass e.g. to home appliance and commercial refrigeration customers. Flat glass products are named according to their shape. All flat glasses manufactured in a flat form are described as flat glass, irrespective of the production method. Flat glass can be produced by float or rolled glass methods.

A typical composition for borosilicate glass flat glass is provided in Table 1.2 [5], one of glass ceramic is provided in Table 1.3 [6].

Table 1.2 Typical composition of borosilicate floated flat glass (DURAN)

Component	Mass percentage
Silicon dioxide (SiO ₂)	81.0
Sodium oxide (Na ₂ O)	3.2
Boron Oxide	13.0
Aluminium oxide (Al ₂ O ₃)	2.0
Potassium oxide (K ₂ O)	0.8
Colour modifiers, etc.	Traces

Table 1.3 Typical composition of glass ceramic rolled flat glass (Narumi)

Component	Mass percentage
Silicon dioxide (SiO ₂)	65.0
Sodium oxide (Na ₂ O)	1.0
Lithium oxide (Li ₂ O)	4.0
Magnesium oxide (MgO)	1.0
Aluminium oxide (Al ₂ O ₃)	22.5
Potassium oxide (K ₂ O)	1.0
Phosphorous oxide (P ₂ O ₅)	1.0
Titanium oxide (TiO ₂)	2.0
Zirconium oxide (ZrO ₂)	2.5
Colour modifiers, etc.	Traces



The float glass production method is based on molten glass pouring onto a bath, i.e., a float tank of molten tin, forming a ribbon where the upper and lower surfaces become parallel due to the influence of gravity and surface tension. The float tank, supported by a steel framework and lined with refractory blocks containing molten tin, is approximately 55 to 60 meters long, 4 to 10 meters wide, and divided into 15 to 20 bays. The tank maintains an airtight environment, with a slightly reducing atmosphere achieved by injecting a mixture of nitrogen and hydrogen. This atmosphere is crucial to prevent oxidation of the tin surface, preserving the critical contact surface between the glass and the tin.

The most typical and extensively used melting technique for the flat glass is predominantly manufactured using cross-fired regenerative furnaces. Schott's furnaces are cross-fired use airfuel-firing or oxyfuel-firing for higher energy efficiency and to reach the higher temperatures which are needed to melt the special glass. Molten glass travels from the furnace through a refractory-lined canal, which is heated to maintain the correct glass temperature. The glass is poured onto the tin bath at the canal's end through a unique refractory lip, known as "the spout", ensuring proper glass spreading. The glass flow is controlled by an adjustable suspended refractory shutter in the canal, referred to as the front "tweel". Upon initial contact with the tin, the metal's temperature is around 1000 °C, cooling to approximately 600 °C at the bath's exit. As the glass traverses the bath's surface, it attains a uniform thickness and adopts the nearly perfect flatness of the molten tin.

Fig 1.2. provides a schematic representation of the float glass process.

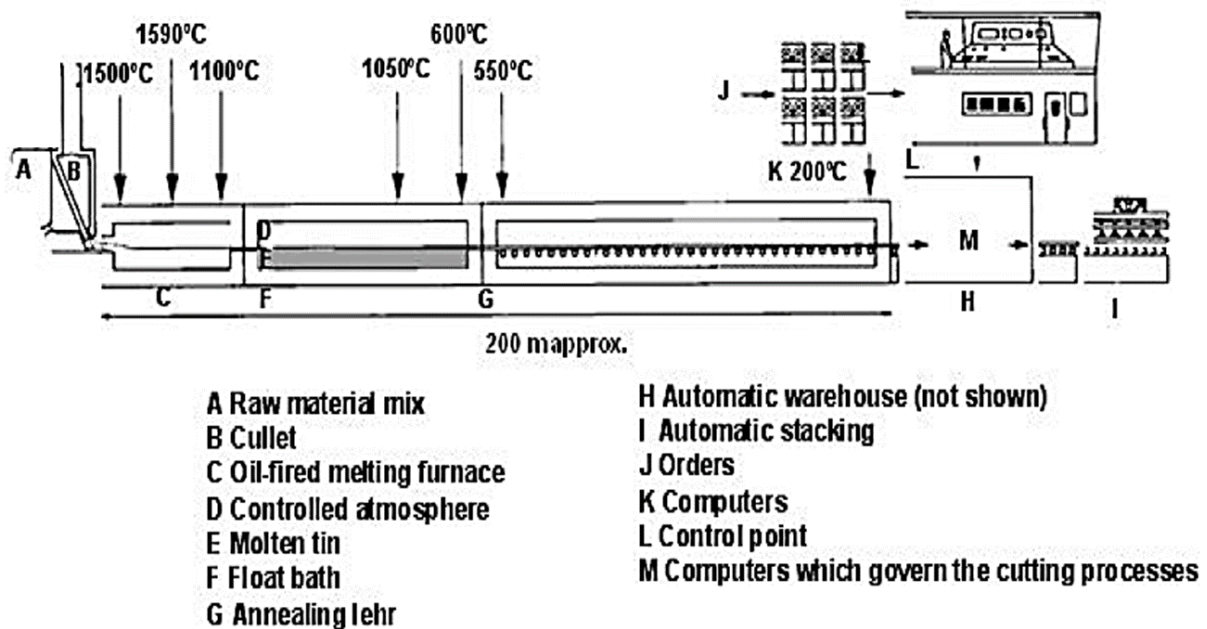


Fig. 1.2 The typical float glass processes [7]

Numerous pairs of water-cooled top rollers operate within the float tank and are adjustable in direction, height, penetration, and angle. These rollers engage the glass sheet's edges using cog wheels, drawing it in length and width. The glass thickness, typically ranging from 1.5 to 19 mm, is governed by the rate of glass flow and the rotation speeds of the rollers. Graphite barriers can be introduced to produce thicker glasses, especially on the tin surface, where the glass achieves its maximum natural thickness.

The float glass manufacturing process is precise, highly efficient and continuous. Exiting the float bath, the glass ribbon is swiftly removed by lift-out rollers and passes through a lehr for annealing. At the lehr's beginning, SO₂ is sprayed on both sides of the ribbon to provide a surface treatment protecting the glass against roller contact. The lehr, divided into sections with heating and indirect or direct cooling by forced and natural convection, gradually cools the glass from 600 to 60 °C, reducing residual stresses from the forming process to an acceptable



level. This efficient process, from pouring onto the float bath to the cutting line, spans a continuous up to 200 meter ribbon of glass. A travelling cutter online cuts the cooled glass ribbon at the end of the production process. Online coatings, such as low-emissivity glazing, can be applied to enhance product performance.

Rolling glass manufacturing is another way of making a flat glass product. This process forms a ribbon with a carefully controlled thickness and surface pattern (see Fig 1.3).

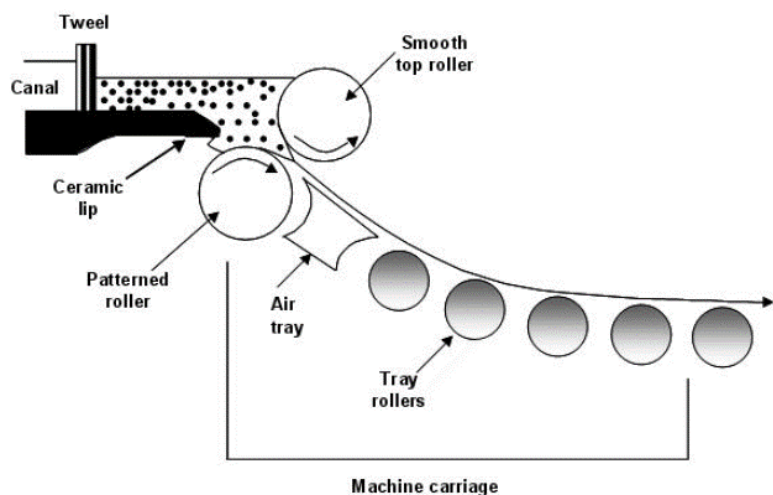


Fig. 1.3 The rolled glass process [7]

Roller glass is manufactured through an ongoing double-roll procedure. Molten glass, reaching temperatures of approximately 1000 °C, is compressed between water-cooled steel rollers. This process usually creates a less smooth and uniform surface than float glass. It is typically also a continuous processing, but also batch process is possible where smaller sheets are produced.

1.3 Glass melting furnaces

Glass melting furnaces are categorised into regenerative and recuperative furnaces, designed to recover and reuse heat during glass production. The term "regenerative" refers to a heat-recovery system used in glass making. Regenerative glass furnaces are divided into End-fire regenerative and Cross-fire regenerative furnaces. Glass container plants typically employ either end-fired or cross-fired regenerative furnaces. In contrast, all float glass furnaces adhere to a cross-fired regenerative design.

A regenerative furnace has two regenerator chambers. In regenerative furnaces, the heat in the waste gases is used to preheat air before combustion. It is achieved by passing the waste gases through a chamber containing refractory material that absorbs heat, i.e. checker bricks. While one chamber is heated by waste gas from combustion (flue gas), the other preheats incoming combustion air. Typical air preheat temperatures (depending on the number of ports) generally range to 1400 °C. These elevated temperatures contribute to exceptionally high thermal efficiencies in the glass manufacturing process - the regenerative furnace fires on only one of two sets of burners simultaneously. After a predetermined period, usually 20 minutes, the firing cycle of the furnace is reversed, and the combustion air is passed through the chamber previously heated by the waste gases.

Most of the glass production is done in a cross-fired regenerative furnace due to the high production capacity, which can vary from 20 to 1000 tons per day [7]. In the cross-fired regenerative furnace, a design that optimizes space, combustion ports and burners are strategically positioned along the sides of the furnace. The regenerator chambers are located on either side and connected to the furnace via the port necks (Fig 1.4).



The flame, a key element in the combustion process, passes above the molten material and directly into the opposite ports. The number of ports used, which can be as many as eight, is determined by the size and capacity of the furnace and its specific design. The regenerator chambers are divided for each burner port in some larger furnaces. This design effectively utilises a multitude of burners and is particularly suitable for larger installations, as it facilitates the differentiation of the temperature along the furnace length necessary to stimulate the required convection currents in the glass melt.

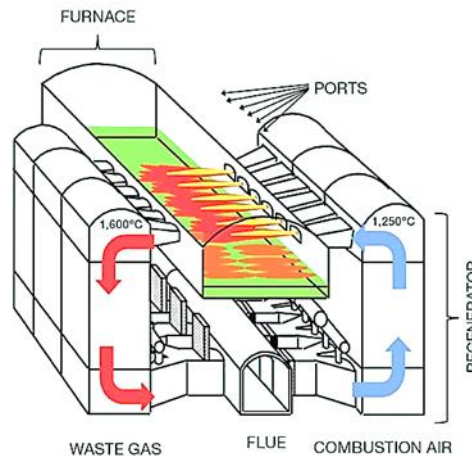


Fig. 1.4 Schematic diagram of a cross-fired regenerative glass furnace [8]

An end-fired regenerative furnace works the same operation principles by recovering the waste energy. However, it distinguishes itself by placing two regenerative chambers at a single end of the furnace, each equipped with a solitary port (Fig 1.5). The flame follows a U-shaped path, returning to the adjacent regenerator chamber through the second port. While this arrangement promotes a more cost-effective regenerator system than the cross-fired design, it has a trade-off of reduced flexibility in adjusting the furnace temperature profile. Consequently, this design is less favoured for larger furnaces.

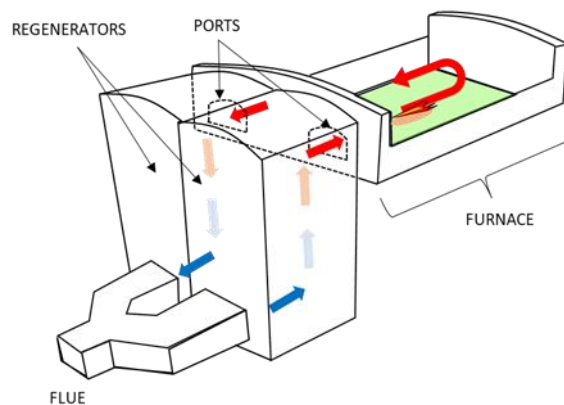


Fig. 1.5 Schematic diagram of an end-fired regenerative glass furnace

Overall, end-fired furnaces demonstrate higher energy efficiency than cross-fired furnaces, primarily due to two factors. First, the lower number of burner ports minimizes energy loss through these openings, which can be significant. Second, the extended residence time of combustion gases in the end-fired furnace allows the flames more time to radiate energy to both the batch blanket and the glass melt.



Recuperative furnaces represent another widely used heat recovery system, particularly in small to medium-capacity installations. Although higher capacity furnaces (> 400 tonnes per day) are not uncommon. In this setup, cold incoming air is indirectly preheated by the continuous flow of waste gas passing through a metal or ceramic heat exchanger. For metallic recuperators, air preheat temperatures are typically limited to around 800 °C, resulting in lower recovered heat than regenerative furnaces. The diminished direct energy efficiency can be compensated by additional heat recovery systems on waste gases, serving purposes such as preheating raw materials or steam production.

Capacity limitation can be partially mitigated by incorporating electric boosting. While earlier unit melters or direct-fired furnaces may not have featured initial recuperators, the current practice exclusively associates the term “unit melter” with the conventional recuperative furnace. Burners are positioned along each side of the furnace, creating convective flow patterns that strategically direct hot combustion gases above the relatively cold batch blanket. This optimization enhances heat transfer to both the batch and the glass melt before the gases exit the combustion chamber through the exhaust port.

2 Fuel sources

Glass manufacturing is an energy-intensive process, where up to 75% of energy is used for raw material melting. Glass production typically utilises various energy sources for different processes. The glass industry needs energy diversification. It uses primary and secondary energy sources, which rely on the consumption of traditional fossil fuels. The choice of energy source depends on factors such as the type of glass produced, furnace design, environmental regulations, and the cost and availability of energy resources in a specific region. This section will compare conventional (fossil) and possible (alternative) fuels.

2.1 Fossil fuels

Fossil fuels are the main source of primary energy, meeting 79% of humanity's energy needs. There are generally four types of fossil fuels produced from raw materials, which are naturally occurring but require a range of processing (refining) methods to become fuels that can be used. They are typically used for transportation, industry, residential, commercial and other sectors:

1. Natural Gas is the most commonly used fuel. It covers approximately 62% of the total energy demand in the glass industry [9]. Natural gas is often considered a cost-effective fuel (depending on the region and economic situation). Natural gas is a hydrocarbon gas primarily composed of methane, with smaller amounts of other hydrocarbons, such as ethane, propane, and butane. It may also contain traces of non-hydrocarbon gases like carbon dioxide, nitrogen, and helium. Because of its composition, natural gas is considered a cleaner-burning fossil fuel often used in regenerative and recuperative furnaces. Its versatility and wide availability make it suitable for various industrial processes beyond glass production, such as power generation and heating.
2. Fuel Oil is an energy source whose use depends on factors such as furnace design, energy efficiency goals, and economic considerations. Its composition differs from natural and liquid petroleum gas, with a higher carbon content, sulphur, and other compounds. Because of this, the combustion of liquid fuels can result in a higher quantity of pollutants such as sulfur dioxide and particulate matter. As environmental regulations become more stringent, glass manufacturers may implement measures to control emissions or explore cleaner fuel alternatives.
3. Coal is a historic energy source for glass furnaces, used as the primary energy source till the 17th century. Rapid deforestation and wood biomass depletion have fostered the use of this alternative. It had a practical advantage against previously used wood biomass due to its preferable characteristics, i.e., stable composition, heating value and humidity, which eventually led to much greater production. However, at present, it is a least desirable fuel, and its consumption has, over time, decreased due to several environmental and economic factors. Coal is the fuel that emits the most carbon dioxide per



energy unit. In addition, coal tends to have higher NO_x, SO₂, and particulate matter emissions compared with liquid or gaseous fossil fuels, the levels of which depend on the coal type and combustion technology.

4. Liquefied petroleum gas (LPG) is artificially produced as a byproduct of the oil extraction and refining process. It is a versatile and convenient fuel that consists mainly of propane and butane. It is stored and transported in a liquid state but is vaporized before being used in combustion processes. In the glass industry, LPG may be employed as a fuel in furnaces, particularly in smaller-scale operations or where natural gas is not readily available for geographical or economic reasons. LPG's high energy content, ease of handling, and relatively clean combustion make it a useful alternative to natural gas in some circumstances.

The extensive use of these fuels led to rapid growth in industry, improved living standards and population growth. The technological and sociological changes made possible by the use of fossil fuels have significantly improved the quality and duration of life for many, but it is now recognised that their continued use has negative consequences for the planet. The prospects for fossil fuels depend on many technological, economic and social factors. Their impact must be assessed complexly and changes over time, but the overall trend is clear. Factors influencing the outlook for fossil fuels are highlighted below.

Fossil fuels have long been pivotal to the development and economies of civilizations. The Romans were the first in the Western world to use coal in the first century AD in Britain, but wider consumption in Europe did not come until the Industrial Revolution (18th century). The concentration of available fossil fuel deposits in certain regions leads to political unrest and acts as a political tool. Since World War II, there have been at least several global oil crises with varying global economic effects. One of the most prominent is the oil crisis of 1973, which affected the global economy. It is estimated that at that moment, due to the sudden shortage of this fossil fuel, Europe's gross domestic product (GDP) shrank by 2.5% (US – 4.7%, Japan - 7%). Price fluctuations and the general trend indicate that this fuel type can be seen as a temporary energy source (see Fig 2.1). Over the past 50 years, the average price of oil, adjusted for inflation, has increased 1.8 times. Based on the historical prices of crude accumulated so far, there is no reason to believe that the cost of fossil fuels will have a downward trend in the future. According to the fundamental laws of market supply and demand, if the known resources of this fossil fuel continue to deplete and the demand remains high because of the lack of the will to switch to alternative energy sources, its price will inevitably increase.

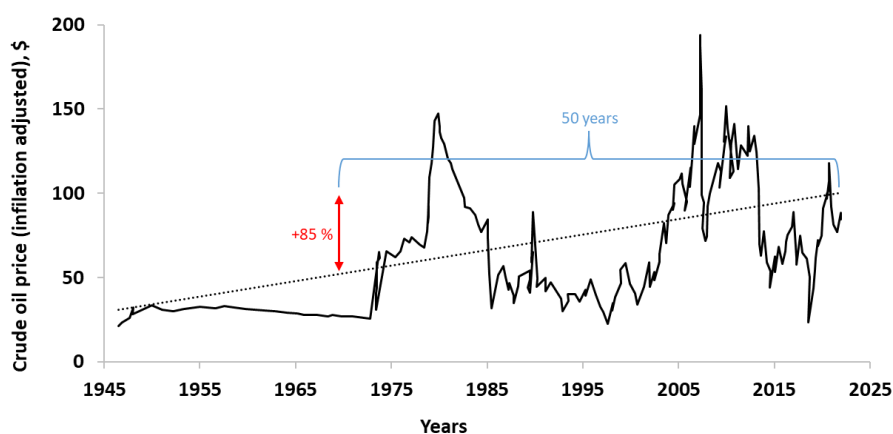


Fig. 2.1 Historical prices of crude oil [10]

However, these price dynamics are not unique to oil; they represent broader trends affecting all types of fossil fuels. An increase in oil prices in a free market economy often leads to concurrent rises in natural gas and coal costs, as these commodities are interlinked through production, consumption, and energy market mechanisms. To demonstrate it, Ahmed et al. [11] calculated real oil price as a ratio of nominal oil price to the US producer



price index of all commodities. Fig. 2.2 illustrates the price trends of various fossil fuels over the past three decades, highlighting the pervasive nature of price volatility across these energy sources. This correlation underscores the interconnectedness of fossil fuel markets and the susceptibility of all fossil fuels to similar economic and geopolitical factors.

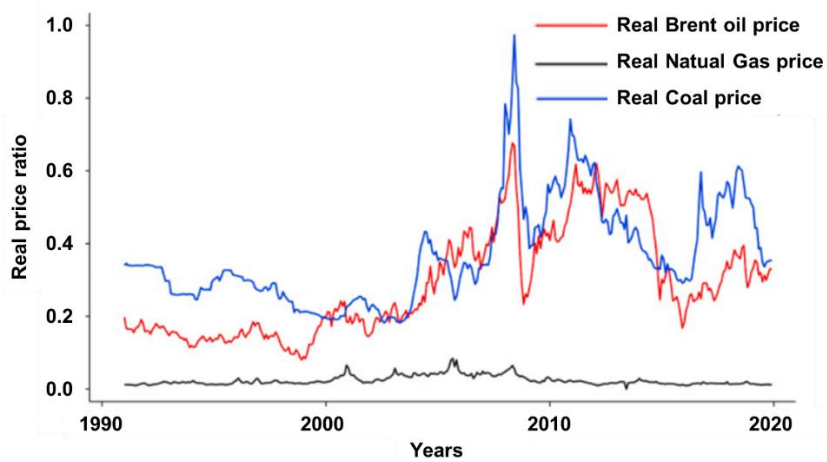


Fig. 2.2 The trend of real brent oil price, real coal price, and real natural gas price [11]

In addition to the negative economic aspects, the use of fossil fuels is accompanied by a carbon footprint. Burning fossil fuels that contain carbon produces carbon dioxide (CO₂), which depends on the amount of carbon in the fuel. It is estimated that for the same amount of energy, wood emits about six times less CO₂ than natural gas, eight times less than oil, and even ten times less than coal [12].

It is generally accepted that fossil fuel consumption is directly linked to increased CO₂ concentrations, global warming and climate change. The global energy consumption, atmospheric CO₂ concentration and global average temperatures show the same exponential trendlines since the beginning of the “Age of Oil” (Fig 2.3).

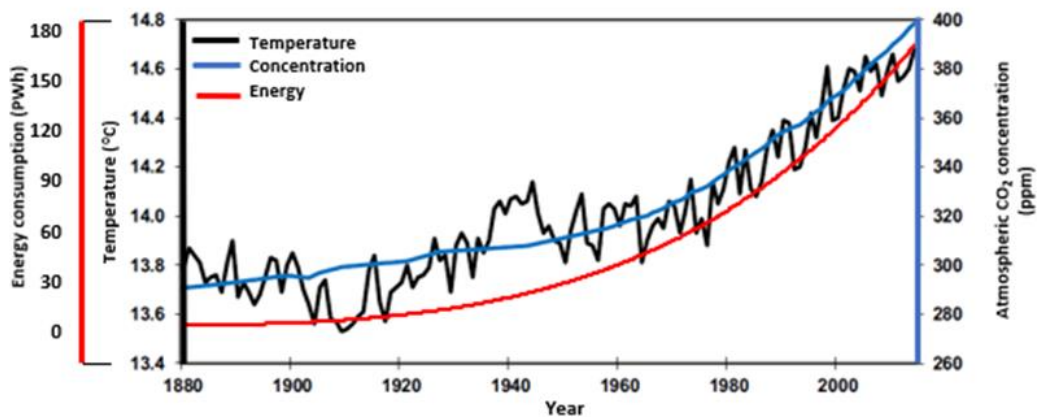


Fig. 2.3 Historical records of global primary energy consumption, atmosphere CO₂ concentrations and global temperature [13]

The environmental impact of burning fossil fuels, including air pollution and contribution to climate change, has prompted increased efforts to limit their use. Fossil fuel consumer behaviour, corporate practices, and government policies are influenced by growing public awareness of environmental issues and activism around climate change. There is increasing pressure on businesses and governments to adopt sustainable practices and reduce dependence on fossil fuels. Government policies and international agreements play a crucial role in shaping the future of fossil fuels. Many countries have committed to reducing carbon emissions and increasing



the share of renewable energy in their energy mix. Efforts to mitigate these emissions include developing and implementing cleaner technologies, such as advanced combustion processes, using cleaner fuels, and adopting renewable energy sources. Regulatory measures and international agreements aim to reduce emissions and address the environmental and health impacts of burning fossil fuels.

Another essential factor is limited fossil fuel reserves. According to the latest estimates, considering the world's energy demand and known fossil fuel resources, it has been reported that these reserves are rapidly depleting and will be exhausted entirely by the end of this century (Fig. 2.4).

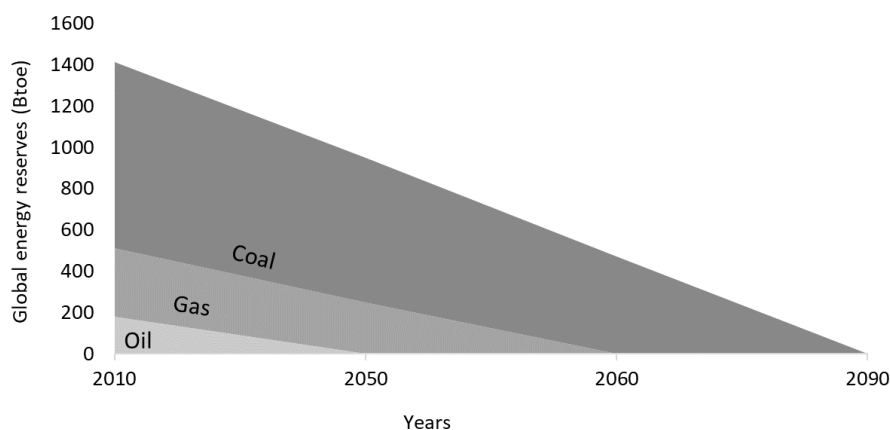


Fig. 2.4 Energy reserves in billions of tons of oil equivalent [14]

However, as technology advances and oil prices rise, previously considered economically unfeasible reserves can be brought into operation, and new ones are discovered. Because of these reasons, the fossil fuel depletion date is not entirely certain, risking the continued use of this resource and a slower transition.

The transition to renewable energy sources is seen as a crucial step in reducing the carbon emissions footprint of energy production. The transition from fossil fuel involves significant economic challenges and opportunities. While industries heavily reliant on fossil fuel may face economic restructuring, those investing in renewable energy stand to gain, potentially leading to growth and job creation.

2.2 Alternative fuels

Glass manufacturers must comply with environmental regulations governing emissions from combustion processes. The glass industry is continually engaged in research and development to identify alternative fuels and enhance energy efficiency. Alternative fuels are energy sources derived from materials other than fossil fuels. These fuels are generally more environmentally friendly compared to conventional fossil fuels due to their renewable nature, low to zero carbon emissions, or ability to be used for renewable energy storage. This section will examine the major types of alternative fuels, exploring their production processes, environmental benefits, and potential applications.

Biomass is an alternative fuel generally accepted as a renewable energy source that could mitigate environmental impact. Unlike fossil fuels, using biomass for combustion contributes to the CO₂ cycle, i.e., carbon dioxide released when fuel is burned and absorbed during photosynthesis, making it a carbon-neutral or low-carbon option. This contrasts with finite conventional fuels like coal, oil, and natural gas. Biomass can include organic materials like wood, agricultural residues, or other plant-based fuels. Some estimations show that biomass could meet up to 20% of the glass industry's total energy needs [9]. However, biomass generally has a lower energy density than fossil fuels, meaning that larger volumes are required to produce the same energy. This can have a negative effect on storage, transportation, and combustion processes, creating significant logistics, technology, and infrastructure investments.



Biogas, unlike biomass, is a gaseous fuel produced by naturally occurring anaerobic activity, i.e., organic waste anaerobic digestion. Biogas mainly consists of CH_4 (50-75%), CO_2 (25-50%), N_2 (2-8%) and traces of other compounds. Biogas is produced in a controlled environment, and collection contributes to the mitigation of GHG for two reasons. First, using these renewable energy sources, an equivalent amount of energy in oil-equivalent resources is preserved, saving corresponding CO_2 emissions. Secondly, anaerobic digestion also occurs in nature, where methane enters the environment uncontrolled, e.g., from wetlands, termites, etc. Primary sources of biogas are:

1. Agriculture (cattle and poultry manure);
2. Municipal waste (wastewater treatment, landfills);
3. Industrial and commercial wastes.

Wasted methane is estimated to have 28 times higher global warming potential in 100 years and 82 times higher in 20 years. A methane collection reduces GHG escape and recovers wasted energy potential. Recent studies show what recovered biogas can be injected into an existing gas network infrastructure [15]. However, the anaerobic digestion process is sensitive to a various of inhibitory substances. The unexpected appearance of feedstock contamination with heavy metals, ammonia, and sulfides can affect the anaerobic digestion process and even stop it. It could take two or more months to restart biogas production.

Syngas or synthetic gas is a combustible gas typically containing CO (30-60%), H_2 (25-30%), and CH_4 (0-5%), together with a small amount of CO_2 , H_2S , H_2O , etc. Synthetic gas is produced by the more rapid thermochemical process, compared with anaerobic processes requiring a long feedstock retention time. Depending on the gasification technique, produced gas can be generated instantly in entrained flow gasification. However, syngas has a lower LHV compared with biogas. Depending on feedstock and gasification conditions, syngas LHV can be approximately 7.5 MJ/Nm^3 , while biogas is typically higher at 21.5 MJ/Nm^3 .

Syngas production is feedstock flexible. It is possible to produce syngas from degradable and non-degradable organic and synthetic materials, i.e., agricultural (straws, oat husks, sunflower hulls, olive pits, etc.), industrial (wood processing and demolition wastes, paper industry, etc.), and municipal solid wastes (paper, plastics, textile, etc.). Thermochemical conversion is conducted under controlled conditions and is insensitive to feedstock type and its contamination compared with anaerobic digestion.

Hydrogen has gained attention due to its potential to be used as a clean and sustainable energy source. H_2 combustion produces water vapour as the primary byproduct, making it a clean fuel in terms of carbon emissions. However, this fuel is not commonly used in glass-melting furnaces and is still in the industrial development stage. A pioneering initiative has been undertaken to launch a pilot project to transition from natural gas to hydrogen in the glass industry. One of the solutions is to use a thermochemical conversion, i.e., gasification, to convert biomass into H_2 . Research [16] concluded that hydrogen production through gasification offers the best hydrogen yield. Currently, the outcomes are limited to laboratory-scale experiments, and it will take some time before reaching industrial-scale implementations.

Ammonia is one of the new frontier among alternative fuels. It is also considered a zero-carbon-containing fuel with several advantages compared to hydrogen. Ammonia is considered as a hydrogen carrier, which is much more energy-dense (15.6 MJ/l) compared to liquid H_2 (9.1 MJ/l). That means it has a reasonable advantage during marine and land transportation. NH_3 also has higher storage efficiency and a more extended storage period because of a higher boiling point ($-33 \text{ }^\circ\text{C}$) compared with hydrogen's cryogenic temperature ($-253 \text{ }^\circ\text{C}$). Such temperature differences make ammonia easier to liquefy in terms of energy and do not necessarily require evaporators to combust. However, NH_3 also has a disadvantage related to high concentrations of fuel NO_x during combustion, which must be treated accordingly by implementing selective catalytic or non-catalytic reduction (SCR / SNCR) systems. In addition, it is worth noting that ammonia is a toxic and corrosive substance, which poses significant challenges in its handling. Proper storage and transportation of this fuel are crucial to ensure safety and efficiency. This necessitates the use of specialized equipment, such as corrosion-resistant containers and advanced ventilation systems, to mitigate the risks. Furthermore, personnel involved in the handling of ammonia must undergo rigorous training to manage potential hazards effectively.



Electricity stands out as one of the major alternative energy options for various energy sectors transitioning from the consumption of fossil fuels. It is the same energy source used in all glass melting furnaces as a driving force for auxiliary and other equipment. It supports various stages of the glass production process, i.e., melting, heating and annealing, finishing and handling. It can also be used as an exclusive energy source or combined with fossil fuels for furnace heating. On an industrial scale, electricity is used for resistive heating, passing a current through molten glass. Electric furnaces are employed in specific specialised applications, such as producing high-quality glass for electronics or laboratory equipment. They have several advantages, but relatively high energy costs limit their wide application.

2.3 Fuel properties comparison

Observed fuels have highlights and drawbacks in certain technological and environmental aspects. On the one hand, fossil fuels are already standard because of their reliability, competitive cost and easy access. Fossil fuels generally have a high calorific value, fixed composition, and other preferable parameters (low concentrations of impurities, water vapour, hydrogen sulphide, ammonia, etc.). Because of these reasons, all related infrastructure, i.e., gas network, auxiliary equipment and combustion technology, are developed according to the properties of fossil fuels. On the other hand, its further use raises environmental, security, and social concerns, named in section 2.1. Europe's target is to reach a net-zero carbon emission by 2050, meaning further consumption of fossil fuel must be phased out.

Here is why alternative low or zero-carbon fuels play a crucial role. During combustion, CO₂ emissions come from carbon-containing fuels, i.e., C_xH_y compounds. Its carbon footprint depends on carbon content and heating value (Fig. 2.5). In some cases, fuels with higher carbon content by weight (%) and calorific value, e.g., fuel oil, can emit less CO₂ emissions (270 kg CO₂-eq/MWh) compared with lower carbon content and lower calorific value fuel like coal (355 kg CO₂-eq/MWh) [12]. Meanwhile, LPG emits approximately 254 kg of CO₂ per MWh [17]. Biomass-based alternative fuels are considered low or net-zero CO₂ emitters because of their relatively fast regeneration and carbon neutrality. Depending on the biomass type, its mass can double in hours (algae) to several years (fast-growing woody biomass species). During woody biomass photosynthesis, atmospheric CO₂ is converted to glucose to build the primary structural material in cell walls and ensure raw material growth. Later, this material can be used for energy production following CO₂ release. Once emitted, it will be absorbed by growing biomass, thus initiating a cycle where CO₂ is continually recycled, ensuring renewability.

Fig. 2.5 demonstrate how much CO₂ can be saved during combustion of various fuel sources to produce one tone of glass mass. Estimated hydrogen and ammonia CO₂ emissions savings do not include the calculation of embedded CO₂ released during the production and transportation of these alternative fuels. It is assumed that all H₂ and NH₃ are produced using renewable energy sources, making them green hydrogen and green ammonia.

For the calculations, it is presumed that producing one ton of glass requires 7.8 GJ of energy [3]. Coal serves as the benchmark for CO₂ emissions, releasing the highest amount (769 kg) of CO₂ per tonne of glass. Meanwhile, fuel oil emits 585 kg/t_{glass}, and gaseous fossil fuels such as LPG and natural gas emit 550 and 444 kg/t_{glass}, respectively. Wood biomass combustion stands out for its significantly (up to 90%) reduced CO₂ emissions compared to fossil fuels. It is estimated that the converting from coal to biomass for heat production would save up to 693 kg of CO₂ emissions per ton of glass.

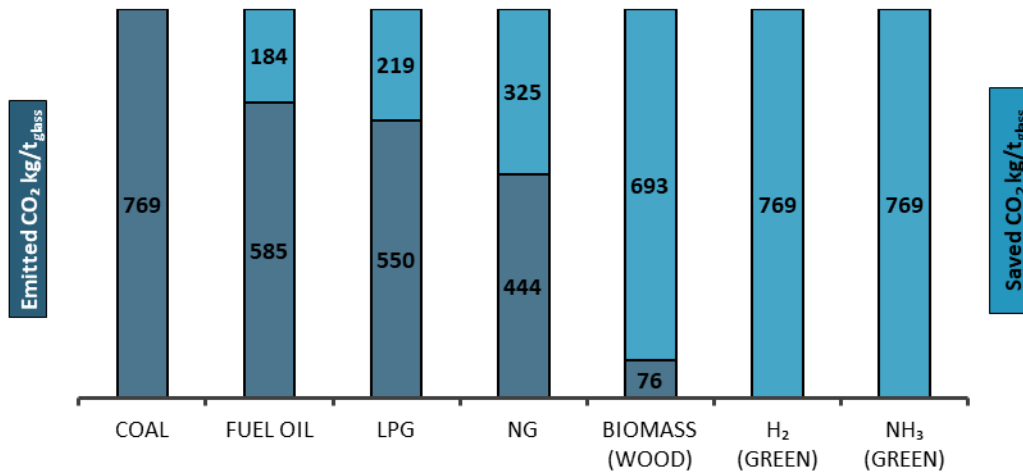


Fig. 2.5 Comparison of CO₂ emissions from different fuel sources for production of 1 ton of glass

Unfortunately, the current green hydrogen and ammonia production capacity is insufficient to meet industrial energy needs. Moreover, alternative hydrogen production methods, such as grey, black, and brown, rely on fossil fuels like natural gas or coal for processes like steam methane reforming (SMR) and gasification. These methods produce substantial CO₂ emissions as a by-product and worsen global warming due to additional energy-intensive conversion steps. On the other hand, blue hydrogen production, which incorporates carbon capture, utilization, and storage (CCUS) technologies, also involves an energy-intensive process and contributes to a carbon footprint. Transitioning to hydrogen and ammonia also necessitates significant infrastructure changes linked to CO₂ emissions.

No fuel source can be unequivocally evaluated. Because of this reason a comparison table of various parameters provided to define what alternative fuel could be most promising for the glass industry (Table 2.1). It should be noted that electricity and coal are not included. Electricity is considered a secondary energy source, meaning that all comparable parameters are related to a primary source. As long as a primary source is uncertain, all related parameters and emissions are unknown and cannot be compared. Coal is considered as an outdated source of fuel. Also, neither of these fuels has the same gaseous state as alternative fuels.

When comparing only gas fuel, fossil fuel stands out with a high calorific value of 25-45 MJ/m³. Such a high calorific value also leads to a high energy density, which gives fossil fuels a more significant advantage over alternatives due to conventional marine and land transportation and storage. Also, all the currently used supply accounting and burning infrastructure has already been adapted to the use of this fuel. Despite these advantages, further use of this fuel is no longer possible for the reasons mentioned above.



Table 2.1 Fuels parameters comparison

Parameters	Fossil fuels				Alternative fuels				
	Natural Gas (NG)	Liquid Petroleum Gas (LPG)	Fuel Oil	Syngas (coal, air-blown)	Biogas	Syngas (biomass, plasma assis., air-blown)	Hydrogen	Ammonia	
Molar fraction	H ₂	0%	0-1%	0%	9.8%[18]	0-2%[19]	22.7%[20]	90-100%	0-5%
	CO	0-1%	0-1%	0%	6.7%[18]	0-1%[19]	36.4%[20]	0-1%	0-1%
	CO ₂	0-5%	0-1%	0%	16.2%[18]	30-50%[19]	0.7%[20]	0-1%	0-1%
	CH ₄	80-95%	0-2%	0%	2.8%[18]	50-80%[19]	0%[20]	0-1%	0-1%
	C _x H _y	Varies	95-100%	95-100%	1%[18]	-	-	Varies	Varies
	NH ₃	0-1%	0-1%	0%	-	Traces[19]	-	0-1%	95-100%
	H ₂ O	Varies	0-10%	0.1-2%	-	Saturation[19]	5.3%[20]	0-1%	Varies
	N ₂	Varies	Varies	Varies	63.2%[18]	0-1%[19]	34.9%[20]	Varies	Varies
Wobbe in.	48-53 MJ/m ³	70-87 MJ/m ³	-	12-15 MJ/m ³	25-30 MJ/m ³	10-18 MJ/m ³	45-56 MJ/m ³	18-21 MJ/m ³	
LHV	35-45 MJ/Nm ³	94-116 MJ/Nm ³	35-40 MJ/kg	2.9 MJ/m ³ *	15-25 MJ/m ³	7.1 MJ/m ³ *	10-11 MJ/m ³	10-12 MJ/m ³	
Advantages	Developed production, distribution and	Developed production, distribution and	Developed production, distribution and	Developed production, distribution and	Reduction of fossil fuel consumption. CH ₄ recovery and GHG pollution prevention	Reduction of fossil fuel consumption. Reduction of biomass waste	Reduction of fossil fuel consumption. Net-zero CO ₂ emitter	Reduction of fossil fuel consumption	



	combustion technologies	combustion technologies.	combustion technologies	combustion technologies	Reduction of local bio-waste.		Net-zero CO ₂ emitter.	
Disadvantages	Fossil CO ₂ emitter. Major CH ₄ methane emitter (system leaks)	Fossil CO ₂ emitter	Fossil CO ₂ emitter	Highest (NO _x , SO _x , CO ₂ , PM) emission factors. Fossil fuel CO ₂ emitter	Slow and feedstock-sensitive process. Slow adaptivity to energy demand. Need desulfurization	Has lower LHV compared with biogas. Distribution and combustion need further investigation	Higher transportation and storage expenses are due to low energy density. Distribution and combustion need further investigation	Equipment must be chemically compatible because of high corrosivity and toxicity of NH ₃ .
Challenges	Not viable fuel in the long term. Sensitive to geopolitical factors and market price fluctuations	Not viable fuel in the long term. Sensitive for geopolitical factors and market price fluctuations	Not viable fuel in the long term. Sensitive for geopolitical factors and market price fluctuations	Not viable fuel in the long term. Sensitive for geopolitical factors and market price fluctuations	It is challenging to ensure a high production capability	Lower energy density compared with NG can be insufficient for existing plants. Management of toxic CO	Lower energy density compared with NG can be insufficient for existing plants	Management of toxic NH ₃
Risks	Supply disorder is caused by natural or geopolitical factors	Supply disorder is caused by natural or political factors	Soil-groundwater contamination. Supply disorder is caused by natural or political factors	Risk of supply disorder caused by natural or political factors	Production downtime due to feedstock contamination or failed parameters	Risk of personnel exposure to toxic CO	Higher explosion risk: wide LEL and UEL limits, low ignition energy, and high volatility	Risk of personnel exposure to toxic NH ₃

*Estimated

Biogas has similar properties to natural gas due to its close (up to 80%) methane content. This concentration can be increased to 99% by applying enrichment technologies (upgrading/purification) such as membrane filters. However, this technology has significant drawbacks. First, its production process is sensitive to environmental factors (temperature changes, pH, raw material contamination). These changes can eliminate the entire culture and take at least several months to recover. It may take more time to meet market demand. Hydrogen and ammonia are receiving much research attention because they are considered carbon-neutral fuels. Depending on the production process and fuel source, they can still impact the climate differently depending on production source. Around 75-80% of global hydrogen produced is grey, made from fossil fuel - natural gas. The lowest carbon intensity alternative fuels can be achieved by producing these fuels from renewable energy sources using sustainable, i.e., green methods. Carbon-neutral fuels also face transportation and storage challenges. The energy equivalent of liquefied hydrogen occupies 2.7 times and ammonia 1.8 times the volume of methane. This increases transportation and storage costs. In addition, the storage period of hydrogen at cryogenic temperature (-253 °C) reaches seven days due to boiling and small molecular size. Moreover, carbon-neutral products exhibit up to 34% higher average investment costs compared to carbon-based counterparts and are still not economically viable [16].

Syngas made from biomass shows great potential as fuel for glass industry applications. This type of fuel combines all the best characteristic features. Synthetic fuel produced from renewable raw materials makes it a sustainable energy source. The syngas production process can reduce plant-based biomass wastes, such as lignin, straw, sunflower husks, etc. At the same time, this allows the use of local energy sources, creates a workplace and increases independence from imported fossil fuels. Syngas contains exclusively hydrogen and carbon monoxide. Depending on the chosen gasification agent, e.g. air, oxygen, steam or its combination, syngas can also include a significant amount of nitrogen. Nitrogen reduces the volume fraction of combustible compounds and the total calorific value. For example, a syngas produced by a plasma-assisted air-blown gasifier with 7.1 MJ/m³ LHV is shown. This value can be increased by removing the nitrogen and using pure oxygen as an oxidizer. Studies of biomass gasification [21] have demonstrated that oxygen improved the overall composition of syngas and increased the calorific value because it promotes the release of heat in the combustion stage and reactions of the gasification. Therefore, the LHV of the produced gas is increased.

Syngas production is a fast and high thermochemical conversion of all organic material into gaseous combustible products and char. The Gasification process can take as few seconds under entrained flow gasifying conditions, which means that syngas production can react to rapid energy demand changes instantly and is flexible for high energy demand changes. Moreover, combustible gases can be produced from both degradable and non-degradable biomass. On the contrary, anaerobic digestion is a relatively slow process which can use exceptionally fast degradability biomass. Slow degradability biomass e.g., wood, straws, etc. is challenging to decompose because anaerobic bacteria aggravated break down into complex compounds. The remaining solid byproduct of biomass thermochemical conversion - char can be used as a fuel or for agricultural purposes to increase soil fertility and crop productivity. Its porous and low-density properties based on nanotechnology studies has led to increased studies for water purification processes [22].

When evaluating gases for industrial applications, it is essential to consider their availability and compatibility with existing distribution and combustion equipment. The Wobbe index, a key metric for assessing the interchangeability of fuel gases, plays a crucial role in this evaluation. A closer alignment of the Wobbe index with the gases currently used in the glass industry indicates a higher level of compatibility, which is a significant factor to consider when adopting new energy sources.

In order to determine the perspective of using renewable fuel for energy production, a comparison was made with conventional fuel types. Figure 2.6 shows indicative prices for various types of energy per 1 MWh calculated for the 2023-2024 period [23]–[30].

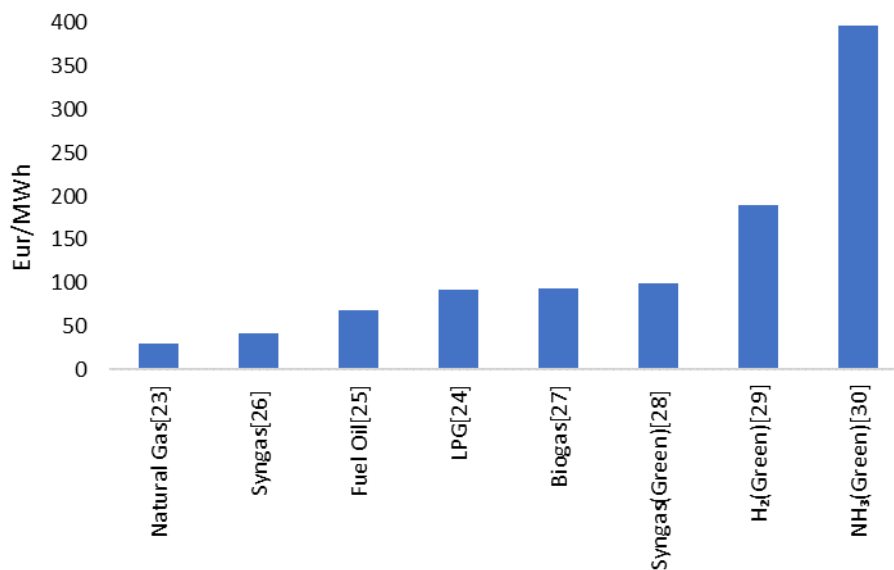


Fig. 2.6 Comparison of energy prices of different types of fuel

The presented graph demonstrates high price differences ranging from 30 Eur (Natural Gas) to 397 Eur (Green Ammonia). Primary fuel prices are the most economically favourable compared to alternative fuels; however, their perspectives are finite. In addition, grey or hybrid energy sources produced from fossil fuels are susceptible to market fluctuations, primarily due to natural gas quotations [30], [31]. Predicting its future price range is challenging, primarily due to geopolitical reasons. On the other hand, alternative fuels also associated with secondary energy products involve additional conversion processes, materials, and energy sources, inevitably leading to higher final fuel prices. Studies also show that the price of biomass-feedstock matter affects the biomethane production price.

In summary, the outlook for the future use of fossil fuels appears unfavourable due to adverse economic feasibility and limited resources. Alternative fuels exhibit varying advantages and disadvantages across different aspects. However, biomass-derived syngas is emerging as the most promising renewable energy source. This is attributed to its comparable heating value and increased compatibility with existing distribution networks and infrastructure, such as pipelines and valve materials. When comparing the prices of sustainable energy sources, it's evident that syngas and biogas are similarly priced and are approximately two times cheaper than green hydrogen and even four times cheaper than green ammonia. Produced syngas are more versatile, faster, and cleaner than biogas, making them a significantly superior fuel option.

3 Assessment of potential of gasification technologies

3.1 Advantage of plasma assisted entrained flow gasification

Gasification is a thermochemical process that converts biogenic residues and wastes into useful gaseous and solid products in an oxygen-deficient environment. Gasification represents a more promising and efficient thermochemical conversion than traditional incineration for extracting energy and reducing emissions. The gas produced in this process is called synthesis gas (syngas), mainly containing components such as H₂, CO, CO₂, etc. Syngas produced in gasification can potentially deliver valuable products, such as Waste-to-Value and Waste-to-Chemicals solutions, and be used in internal combustion engines, gas turbines, fuel cells, liquid fuel production, chemical synthesis or can be converted into heating oil, and electricity generation [18], [32].



Syngas is a viable alternative to fossil fuels, requiring minimal furnace modifications due to its comparable characteristics. It is produced through a thermochemical process that converts solid fuels into synthesis gas in a high-temperature, oxygen-starved environment created within a specific type of gasifier. Over time, various gasification technologies have been developed and optimised to improve efficiency, reduce emissions, and lower costs. Now, gasifiers are categorised into different types, which depend on application, feedstock, and requirements for syngas quality. In this study, we will distinguish these main gasifiers:

1. Entrained Flow;
2. Plasma-Assisted Entrained Flow;
3. Bubbling Fluidised Bed;
4. Circulating Fluidised Bed;
5. Dual-Fluidised Bed;
6. Updraft;
7. Downdraft.

Gasifiers classified based on fluid dynamics (updraft, downdraft), modes of heat transfer to the gasification process (autothermal, gasifiers/directly heated gasifiers or allothermal, gasifiers/indirectly heated gasifiers), gasification agents (air, oxygen or steam blown), and pressure (atmospheric or pressurised) [33]. The choice of gasifier type depends on the feedstock, product quality requirements, economic conditions, and other specific requirements. A review and comparison of gasifying technologies is presented, equipping the audience with a thorough understanding of the field.

3.1.1 Entrained flow (EF) gasifier

Entrained flow gasifiers are among the most researched and developed types in coal conversion to combustible gas in industrial-scale applications. It is estimated that approximately 94% of all registered gasification projects worldwide that are in operation or the planning stage are based on entrained flow gasification [34]. This type of reactor is known to operate under challenging conditions with the ability to achieve better cold gas efficiency and a near 100% carbon conversion rate [35]. EF reactors are versatile and can be used for a wide range of solid feedstock, e.g., petroleum coke, refinery residues, other solid, high carbon-containing materials, and even liquid fuels. Lignite and biomass can also be used as feedstock after preparation.

Entrained flow gasification is fed with finely ground feedstock and oxidant (Fig 3.1). The feedstock is pulverized to a size of 0.1 - 1 mm to ensure airborne ability and mass transfer. The oxidant, chosen from air, oxygen, and steam or water mixtures, plays a crucial role in the process. The high temperature of the gasification process evaporates water rapidly, which later is consumed during char and steam-methane reforming and water-gas shift reaction to produce valuable H₂ and CO gases [36]. However, improving the efficiency of the process requires additional energy and equipment.

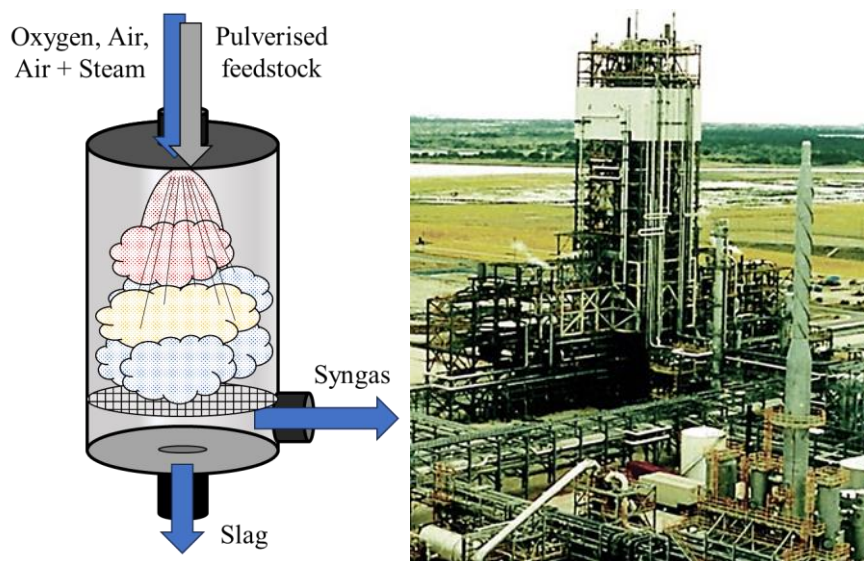


Fig. 3.1 Left - Basic principle of entrained flow gasifier process, Right - Tampa coal IGCC 260 MW gasification plant (TRL 10), Polk County, Florida (The U.S. Department of Energy and Tampa Electric Company, 2000)

When using a solid feedstock, the feedstock dust is pneumatically fed with a pressurized oxidizer to the top of the shaft-type reactor and dispersed. The entrained flow gasification process occurs at high temperatures (1300 - 1700 °C) and high pressures (25 - 45 bar). The temperature of the raw gases that are produced is above 1000 °C. Under these conditions, regular feedstock particle residence time takes up to a few seconds [37]. In these extreme conditions involving high operating temperatures and pressures, entrained-flow gasifiers mandate intricate reactor designs and the utilisation of sophisticated construction materials. Because of high reaction temperature and oxygen-to-fuel ratio, produced syngas consist mainly of H₂, CO, and CO₂ and a negligible amount of methane and other gases [38]. High temperature also causes the ash to melt, forming a slag that is removed from the gasifier's bottom. The slagging range limits the selection of suitable feedstock due to different ash melting points.

Moreover, the aggressive nature of molten ash poses a significant challenge, leading to a considerable reduction in the lifespan of the gasifier's refractory lining and the requirement for higher-quality gasifier materials [37]. Despite this drawback, due to their high reaction temperature, these reactors offer a distinct advantage in efficiently eliminating tar.

3.1.2 Plasma-assisted entrained flow (PAEF) gasifier

The operation of plasma-assisted entrained flow gasifiers is based on the gasification of raw materials and the treatment of gaseous products with a plasma-generated high-energy electric arc. PAEF is advantageous over other gasification technologies due to its ability to process challenging and contaminated feedstocks, such as municipal solid waste, automotive residues, and waste from electrical and electronic equipment [39]. Feedstock is processed by high-temperature, i.e., up to 5000 °C [20] plasma torch in the absence of free oxygen (Fig 3.2). During this interaction, organic components are converted to low molecular hydrocarbons (syngas), while inorganic components transform into vitreous slag. With the help of thermal energy, large molecules are cracked down into smaller species, promoting the decomposition reactions of organic compounds and ensuring the absence of tars and furans, resulting in gas with lower trace contaminants than other gasifier types. High-temperatures tar cracking leads to higher calorific value and cleaner content syngas suitable for internal combustion engines and solid oxide fuel cells without a tar removal process [40].

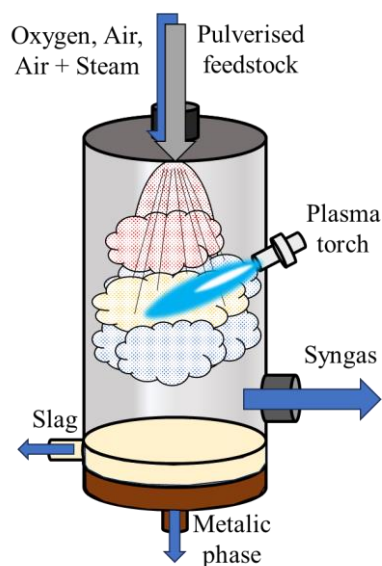


Fig. 3.2 Left - Basic principle of Plasma-Assisted Entrained-Flow gasifier process, Right - Swindon waste and biomass residues 20 MW gasification plant (TRL 10), Swindon, United Kingdom [41]

Plasma-assisted entrained flow gasifiers exhibit better flexibility than EF gasifiers in feedstock composition and size, making them suitable for various materials. This adaptability is especially beneficial for waste materials, given their heterogeneous composition, batch variations, and challenging utilisation in other processes. Plasma-assisted gasifiers have high efficiency for biomass gasification and energy recovery. High reactor temperatures result in better biomass degradation into smaller biochar particles, decreasing biochar yield overall [22]. Moreover, the tar cracking reaction is intensified, breaking down tars under high-temperature plasma. This leads to a low concentration of tars, particularly heavy components, in the product gas [20].

It's crucial to acknowledge that many gasifier designs encounter significant challenges at the commercial scale. However, despite relatively high capital and energy costs, small-scale gasifiers are often recommended for hydrogen or electricity production from biomass. The electricity demand can be substantial, representing around 15–50% of the gross plant output. These challenges, however, have not deterred the application of plasma gasification to various waste streams, including biomedical waste. It has shown promise in both on-site and off-site processing of medical wastes, primarily due to its ability to handle microbes, viruses, and hazardous components.

In conclusion, plasma gasification is a relatively new and advantageous technology, offering potential benefits over conventional thermal gasification methods. Its ability to operate at extremely high temperatures, produce clean syngas, and handle diverse waste materials makes plasma gasifiers a promising solution for waste-to-energy applications.

3.1.3 Bubbling fluidised bed (BFB) gasification

The Bubbling Fluidized Bed is a straightforward fluidized bed reactor developed for power generation. Unlike conventional boilers, the combustion process occurs in a bed at the chamber's bottom, and heat-capture water tubes are often placed within the BFB for efficient energy capture. The reaction time is longer due to the lower temperature than in a pulverized coal furnace.

The BFB gasifier involves a vessel with a grid at the bottom for uniformly distributing the gasifying agent (see Fig 3.3). A moving bed of fine-grained material is located above the grid, into which prepared biomass feed is introduced. The gasifying agent is supplied in two zones: the first within the fluidized bed to maintain the required temperature and the second above the bed to convert entrained unconverted volatiles and char



particles into fuel gas. To increase BFB versatility, an additional pulverized coal burner might be used above the fluidized bed combustion chamber to enhance efficiency when burning waste or biomass.

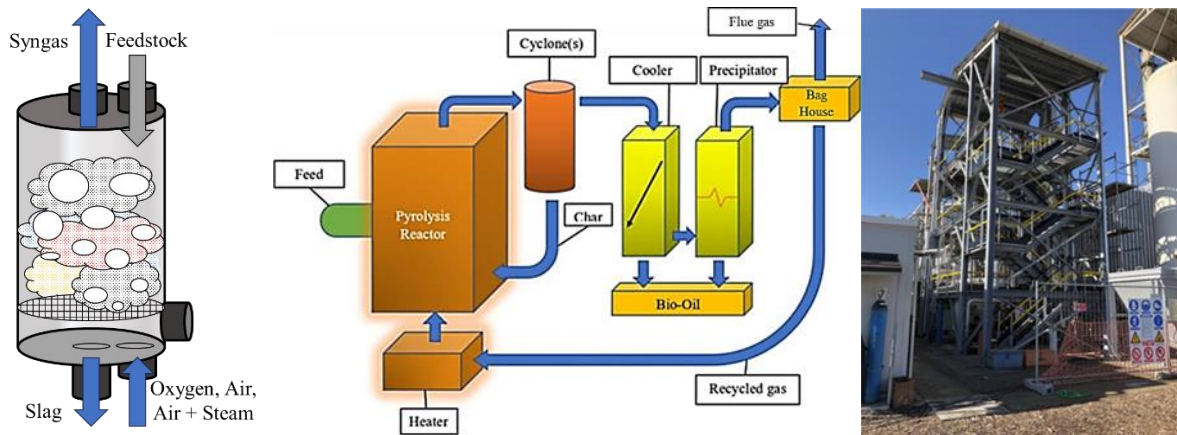


Fig. 3.3 Left to Middle - Basic principle of bubbling fluidized bed gasifier process, [42], Right - Società Tecnologie Avanzate Low Carbon SpA biomass 500 kWth gasification plant (TRL 7-8), [43]

The reactor is water-wall cooled, featuring refractory lining in the lower portion for erosion/wear protection. The reactor temperature is regulated between 700 - 900 °C by adjusting air distribution in the furnace, and heat is removed by water walls and the convection pass, resulting in relatively low tar conversion rates. The lower combustion temperature compared to pulverized coal combustion reduces nitrogen oxide formation, potentially eliminating the need for additional nitrogen oxide removal (SCR / SNCR) systems, depending on environmental restrictions.

Bubbling Fluidized Bed gasifiers leverage a bed material fluidized by the gasification agent or the product gas. BFB reactors feature moderate fluidization velocities, with gas bubbles dominating the fluid mechanic behaviour. In fluidized bed gasifiers, biomass is kept fluidized by an upward-flowing gasifying agent with a velocity of 1.2 m/s. The fluidised flow effectively controls the residence rate of solids and volatiles. The lower velocity minimizes material elutriation from the reactor, and there is no recycling of collected solids back to the lower bed, as in the Circulating Fluidized Bed reactor (see Section 3.1.4). Biomass is mixed with inert or catalytic bed material to enhance heat transfer, and various processes like drying, devolatilization, oxidation, and gasification co-occur in the conversion zone. The fluidized bed consists of particles with diameters between 0.5 and 1 mm, exhibiting clear boundaries to the freeboard, the space above the fluidized bed. The feedstock size also influences the reactor's heating rate and char residence time.

While the BFB gasifier has unique advantages, including the absence of a recycling system, simplifying design and lowering capital and operating costs for units below ~100 MW, challenges such as low temperature in the top section causing high tar concentrations in the syngas need attention. Also, challenges such as bed agglomeration and deposits on heat transfer tubes may arise, especially with certain biomasses containing elements like potassium and chlorine. Nevertheless, the BFB reactor offers the potential for integrating multiple functionalities through bed materials and the freeboard region, contributing to process intensification.

3.1.4 Circulating fluidized bed (CFB) gasification

Circulating fluidized beds (CFB) reactors, well known for conducting moderate to fast heterogeneous catalytic and combustion reactions, offer distinct advantages. These include large solids circulation rates for high heat transfer, continuous catalyst regeneration in catalytic reactions, and achieving smaller reactor sizes due to high solids fluxes and gas rates. The inorganic heat carrier exhibits catalytic properties, causing char adhesion to the catalyst surface. The circulating design allows for continuous abrasion of sorbent particles, facilitating the



exposure of fresh reactive surface areas. CFB reactors have advantages in gas-solid contact efficiency and less axial dispersion than conventional fluidized beds. CFB reactors share similarities with Bubbling Fluidized Bed Reactors, differing primarily in the residence time of gases and volatiles. A distinctive feature of these reactors is the utilisation of recirculating heated sand from a secondary char combustor to supply heat and fluidizing velocity in the lower bed region for CFB gasification units, typically 3.3 m/s.

CFB reactors encompass both dry and semi-dry systems. The widely applied dry CFB system effectively removes Hg, HF, HCL, SO₂, and SO₃ from a flue gas stream. It utilises hydrated lime Ca(OH)₂ injected directly into a CFB reactor and water, operating close to adiabatic saturation temperature. A fluidized bed reactor uses a tall vessel (Pyrolysis Reactor) where gas–solids interactions occur throughout the entire reactor height, devoid of a distinct interface between the bed and freeboard. The structure of a CFB reactor is depicted in Fig. 3.4.

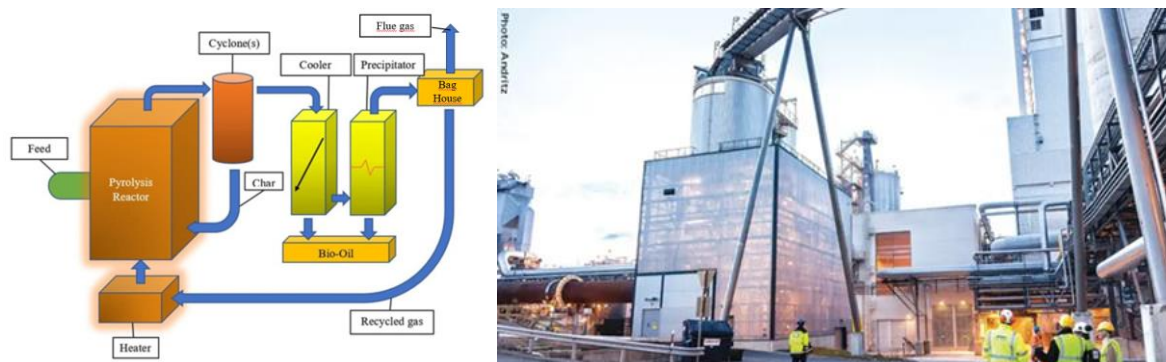


Fig. 3.4 Left - Basic principle of circulating fluidized bed gasifier process [42], Right - Metsä Fibre Joutseno biomass 48 MW gasification plant (TRL 10), Lappeenranta, Finland [44]

Differentiating CFBs from fluidized bed reactors, the former involves a first fluidized bed unit for the pyrolysis reaction. The temperature inside the reactor is considered much lower compared with conventional boilers and typically deviates within the 850 - 950 °C range [45] under higher than atmospheric pressure (up to 10 bar) [46]. Low temperatures are maintained to avoid ash melting and agglomeration. After pyrolysis, a processed feedstock with the inorganic heat carrier laden with produced char is fed into a second fluidized bed unit - the combustor. Before entering the combustor, a high-temperature cyclone separator is used for gas cleaning. After cyclone processing, gaseous products are drafted to the cooler, where volatile matter cools down to the condensation point and is separated from the flue gas stream. Later, gas is additionally filtered with bag filters before being partially recycled and emitted into the atmosphere. Before repeatedly entering the pyrolysis reactor, recycled flue gas is reheated. The second unit combusts the char within the inorganic heat carrier, generating heat for the first pyrolysis unit.

Notable features include mild steel construction, no moving parts, and the ability to handle only dry solids. Despite these benefits, challenges arise, such as the need for significant heights to ensure satisfactory gas residence times and the potential for higher gas velocities causing tube erosion and solids attrition. Also, the higher particulate matter concentration downstream may necessitate improvements to the particulate removal device.

3.1.5 Dual-fluidised bed (DFB) gasifier

One of the latest developments in the middle of the 20th century was the dual-fluidized bed (DFB) gasifier, initially dedicated to coal gasification and then converted to biomass conversion. DFB is considered a more advanced gasification system because of higher heat transfer efficiency and syngas quality. The gasification process in any gasifier is highly endothermic and energy-consuming. For this reason, a key concept is integrating energy production with syngas production processes. DFB comprises two interconnected reactors: a bubbling



fluidized bed gasifier, which converts biomass into raw syngas or producer gas, and a circulating fluidized bed combustor, which oxidizes the residual char and generates heat for the gasification process (Fig. 3.5).

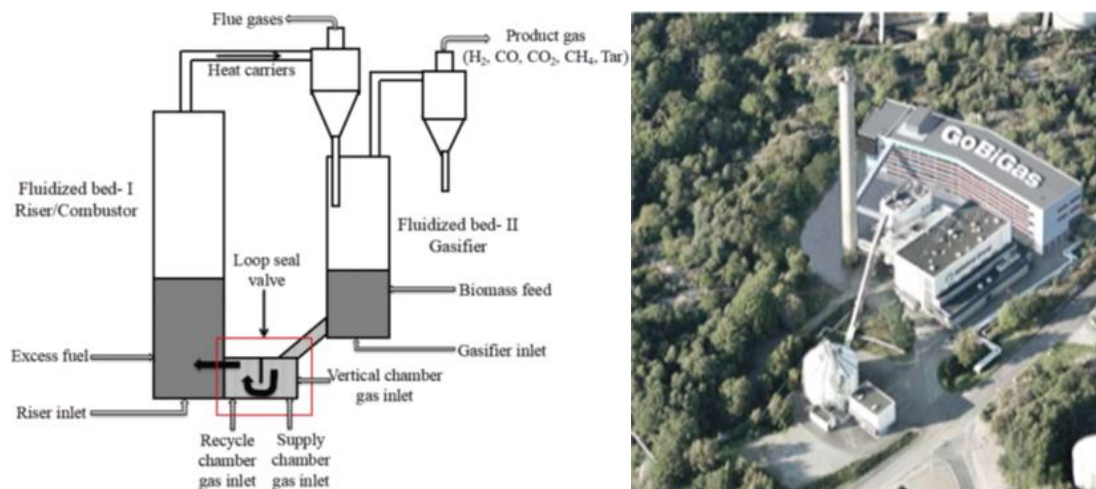


Fig. 3.5 Left - Schematic of dual-fluidised bed reactor scheme [33], Right - GoBiGas biomass 20 MW gasification plant (TRL 8), Gothenburg, Sweden [47]

These reactors are controlled separately and split by a soft loop valve to maintain the distinction between the processes, prevent combustion air from entering the gasifier, and ensure nitrogen-free products. The energy produced from exothermic reactions is used to carry out endothermic gasification reactions. That is why DFB is referred to as an allothermal gasification system. An additional or excess fuel inlet is provided to the riser to maintain the reactor's temperature and ensure optimal gasification process operation. The biomass feed is supplied to the gasifier using a screw conveyor.

Additionally, a cyclone separator separates the heat-carrying materials and the flue gases in the riser section. The heat-carrying material, consisting of bed particles and char, is returned to the gasifier to provide heat for the gasification reactions. At the same time, the flue gases are directed to the heat recovery system for further utilisation.

3.1.6 Updraft (UD) gasifier

Updraft (UD) gasifiers are a prevalent and straightforward type of gasifier for solid fuels. Generally, fixed-bed gasifiers in updraft configuration rely on gravity feed for fuel and extracting coarse ash at the bottom. The biomass undergoes continuous decomposition, moving downward through zones of drying, degasification, oxidation, and reduction in the reactor. Distinct zones are established for each gasification step, and partial combustion of the feedstock supplies the necessary heat to sustain the process.

In UD gasifiers, the feedstock is introduced from the top, and preheated air is supplied from the bottom through a grate (Fig. 3.6). The gasification temperature is controlled by regulating the feedstock fed ratio or air, oxygen and steam ratio in the gasification medium. Feedstock and oxidising agents currently move counter-downwards in the gasifier, with the combustion zone at the lower portion, where char and volatiles are formed. During partial combustion, the temperature rises to approximately 730 °C. This temperature exceeds the ignition temperature of carbon, and a highly exothermic combustion reaction takes place, warming up the upward-moving gas and reducing the zone above the combustion area.

Further up, the hot gases pyrolyze and dry the incoming fuel, cooling the gases to about 200 - 300 °C. Pyrolysis releases volatiles and forms a certain amount of tar, some of which may leave with the outgoing gases. The overall process efficiency is relatively high due to the low exit gas temperatures, and filtration through the packed bed helps lower the particulate content of the outgoing gas. Using a cyclone for particulate matter capture may



not be feasible, and the gas, already at a lower temperature, can be wet scrubbed and dried before being sent to the engine.

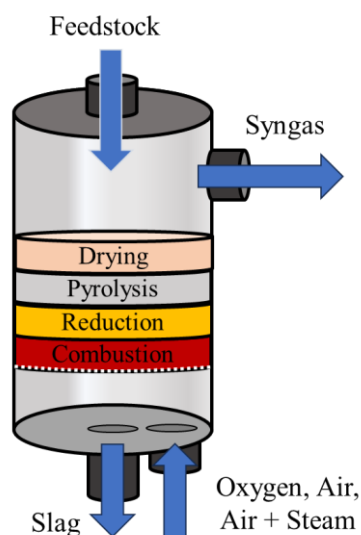


Fig. 3.6 Left - Basic principle of updraft fix-bed gasifier process, Right - Società Tecnologie Avanzate Low Carbon SpA 5 MW biomass gasification (TRL 7-8) [43]

The devolatilization process produces volatiles and char, with volatiles exiting with outgoing gas, while char undergoes combustion. Produced syngas usually has a higher tar concentration than downdraft gasifiers (see section 3.1.7). About three-quarters of the biomass energy content typically appears in the syngas, accounting for radiation heat losses. The remaining one-quarter of the energy is used to heat up the char content. This char can be gasified further to enhance gas yield. The typical char yield varies from 20% to 40% by dry biomass weight, and reactivity varies based on char composition, primarily carbon and nitrogen content.

One limitation of updraft gasifiers is the restricted feed particle size. The height-to-diameter ratio of the moving bed is typically greater than 3:1, with a recommended diameter limit to avoid material flow problems. Fine feed particles may be entrained and left undecomposed, leading to size range or minimum feed size specifications.

3.1.7 Downdraft (DD) gasifier

Downdraft (DD) fixed-bed gasifiers, also known as co-current gasifiers, are the most common gasifiers. The term “downdraft” is used because air moves in the same direction as the biomass feedstock. This design yields a clean mixture of combustible gases in the exit stream, and its main advantage is producing syngas with low tar content, making it suitable for gas engines. The reaction regions are different compared with updraft gasifiers. The oxidation (combustion) zone is below the pyrolysis zone, and the reduction zone is below the oxidation zone. In downdraft gasifiers, biomass feedstock is supplied from the top, gasification agent (air or O_2) flows downward, and syngas exits from the bottom. The gasification agent is introduced into the middle of the bed (combustion zone) above the stationary grate.

The position of the oxidation zone is a critical parameter in downdraft gasifier design. The basic principle of a downdraft gasifier is presented in Fig. 3.7.

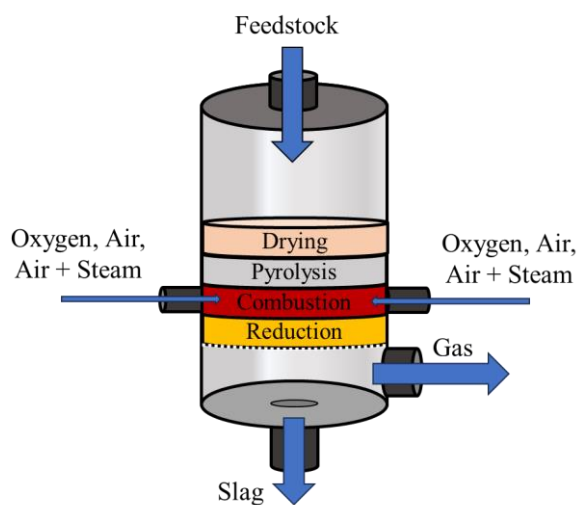


Fig. 3.7 Left - Basic principle of downdraft fix-bed gasifier process. Right - WALTER mobile 100 kW gasifier Volter (TRL 10), Emå Dairy in Hultsfred, Sweden [48]

The syngas flows out from the bottom of the gasifier beneath the stationary grate. The solid fuel moves downward through various zones, including a drying zone, a pyrolysis zone, an oxidation (combustion) zone, and a reduction zone. The drying zone, maintaining a temperature typically at 200 °C or lower, vaporizes moisture from the solid fuel. In the pyrolysis zone, temperatures reach 500 - 600 °C, depending on the equivalence ratio. The equivalence ratio (ER) is the actual fuel/air ratio to the stoichiometric fuel/air. The oxidation zone experiences the highest temperature, up to 1500 °C, where tars and heavy hydrocarbons are thermally cracked into lighter hydrocarbon gas species. Below the oxidation zone, the remaining char, ash, syngas, and water vapour flow through the reduction zone. In this zone, steam gasification, water-gas shift, and SMR reactions occur, producing hydrogen.

One of the significant advantages of downdraft fixed-bed gasifiers is the cracking down of tars in the oxidation zone, resulting in lower tar content in the syngas compared to other gasifier types. However, ash and other fine particles can contaminate the syngas, necessitating a separation device (e.g., two-stage cyclone and ceramic filter) to clean the gas. A cyclone captures large particulate matter; the gas can either be wet, scrubbed, or cooled and passed through a sand or cloth filter. In addition, a drawback of this gasifier type is the relatively high temperature of the exit syngas, leading to lower gasification efficiency.

3.2 Comparison of gasification technologies

Various gasification technologies are employed to transform organic materials into diverse products. Depending on the desired products, these methodologies encompass a spectrum of processes designed to convert carbonaceous substrates, such as coal, biomass, or waste, into synthesis gas or, in other words, biomass-to-x (BtX) products. Based on the previously performed characteristics comparison of the alternative fuels, it is decided to compare gasification technologies only in producing synthetic gas, which could be a feasible alternative in exchange for fossil fuels in the glass industry. As an alternative to syngas direct combustion, these compounds can also be used for ammonia, hydrogen (including carbon capture) or synthetic fuels - BtX production. Lepage et al. [49] investigated gasification processes for optimal hydrogen yield, and Swanson et al. [50] analysed the production of FT-Fuels from biomass via EF and fluidised bed gasification. Studies have found that EF-based technology requires additional process steps, leading to higher investment costs and, therefore, higher absolute uncertainty in the calculated fixed capital investment [16]. However, higher carbon conversion offset these, resulting in lower production costs.



Synthetic gas quality and yield depend on feedstock composition, gasification conditions and gasifier type. The latter must be chosen in advance to get the best syngas composition suitable for the glass industry. Each technology exhibits distinct characteristics tailored to specific applications, requiring individual scrutiny to ascertain suitability. Table 3.1 observes and evaluates the parameters of the EF, PAEF, BFB, CFB, DFB, UD, and DD gasifiers. The table includes the most relevant cases of biomass gasification technologies based on physical and chemical parameters. All examples of gasification technologies utilize woody biomass as a feedstock, except for entrained flow gasification. For this specific case, publicly available commercial data provided by an industrial manufacturer was chosen. The gasifier with the most suitable parameters for the glass industry will be highlighted. The table compares the prevalent and promising gasification technologies' key parameters, products, advantages, and drawbacks. This comparative table exclusively focuses on biomass applications utilising various technologies. This decision is rooted in recognising biomass as a fuel source characterised by negligible carbon dioxide emissions, thus playing a crucial role in mitigating environmental impact.

Biomass physical parameters are essential to gasification process efficiency, syngas and char composition. A low moisture, low ash content with high calorific value feedstock is preferable. However, in nature, biomass has a wide range of compositions, which depend on the location of the origin, the soil composition, the type of plant itself, and even the harvesting season. Ensuring a proper composition will be a challenge that needs to be dealt with. Biomass feedstock parameters are critical for efficient, reliable and long-term gasifier operation.

One of the most significant differences is observed in the required feedstock size. The dimensions and configuration of the fuel particles play a crucial role in dictating both the challenges associated with the fuel's transportation and delivery and the fuel's subsequent performance within the gasifier. Entrained flow and plasma-assisted entrained flow gasifiers require a small fraction of feedstock, which can be pulverised co-currently with a compressed oxidiser. An acceptable fraction size (0.01-1 mm), high pressure and temperature and sufficient equivalence ratio in EF reactors lead to enhanced degradation of carbon, tar, oil, phenols, and other liquid by-products into hydrogen, carbon monoxide, and light hydrocarbons. Increasing carbon conversion rates reduces residual carbon, the main ash quality parameter, which is a crucial factor in reusing this waste as a raw material for glass production.

In contrast, bubbling, circulating, and dual fluidised bed gasifier reactors use a more significant fraction size (< 6 mm) of feedstock, which may not have the necessary fluid-like behaviour, leading to uneven gasification and decreased gasifier performance. These larger particles might also lack the necessary surface area for efficient gasification reactions. Updraft and downdraft gasifiers also have specific feedstock fraction requirements, with a fraction that is too small, causing resistance through the layer and potential clogging.

Table 3.1 Parameters comparison of solid fuel gasification technologies

Parameters	Entrained flow	Plasma-assisted Entrained Flow	Bubbling Fluidized Bed	Circulating Fluidized Bed	Dual-Fluidised Bed	Updraft	Downdraft	
Biomass Feedstock	Required feedstock size, mm	0.01 -1 (Dust)	0.01 -1 (Dust)	<6[51]	<6[51]	<40[52]	30[53]	30[53]
	HHV, MJ/kg	15.3-22.0[53]	15.3-22.0[53]	15.3-22.0[53]	15.3-22.0[53]	15.3-22.0[53]	15.3-22.0[53]	15.3-22.0[53]
	Required moisture, %	<12[54]	<12	<20	<20	<40[52]	<20[55]	<20[55]
	Ash content, %	6-35[54]	6-35	<20	<20	40[52]-50[56]	1-5[53]	1-5[53]
Temperature, °C	1300-1700 [54]	>2000	800-1100[51]	800-1100[51]	650–870[52]	600-800	800-1000	
Pressure, bar	25-45[54]	1-30	1-2	1-2	1-10	<30[51]	<30[51]	
Parameters	Typical syngas composition, %							
	H₂	12.0-18.0[57]	22.7[20]	5.0-16.3[55]	15.0-22.0[55]	34.1-37.2[52]	10.0-14.0[55]	15.0-21.0[55]
	CO	21.0-31.0[57]	36.4[20]	9.9-22.4[55]	13.0-15.0[55]	16.8-24.4[52]	15.0-20.0[55]	10.0-22.0[55]
	CO₂	7.0-16.0[57]	0.65[20]	9.0-19.4[55]	13.0-15.0[55]	21.7-28.1[52]	8.0-10.0[55]	11.0-13.0[55]
	CH₄	0.0-4.0[57]	0[20]	2.2-6.2[55]	2.0-4.0[55]	10.6-11.6[52]	2.0-3.0[55]	1.0-5.0[55]
	C_xH_y	n.d.[57]	n.d.	0.2-3.3[55]	0.1-1.2[55]	Not defined[52]	Not defined[55]	0.5-2.0[55]
	N₂	n.d.[57]	34.9[20]	41.6-61.6[55]	Remaining[55]	Not defined[52]	Remaining[55]	Remaining[55]
X products*	MeOH, H ₂ , NH ₃ , FT, FF, DME, SNG/NH ₄ [16], biochar	MeOH, H ₂ , NH ₃ , FT, FF, DME, SNG/NH ₄ , CH ₄ , FF, biochar	MeOH, H ₂ , FT, FF[16], biochar	MeOH, H ₂ , NH ₃ , FT, FF[16], biochar	MeOH, H ₂ , NH ₃ , FT, FF[16]	H ₂ , CH ₄ [32], FF, biochar	H ₂ , CH ₄ , biochar	



LHV (MJ/m³)	6.6-10.5[58]	8.1-11.7[20]	3.7-8.4[55]	3.6-5.9[55]	9.6-11.3**	3.7-5.1[55]	4.0-5.6[55]
Tar, g/Nm³	Negligible	Negligible	<1-3[55]	2-30[55]	0.1-18[52]	10-150[55]	0.01-6[55]
η (cold gas), %	65-80	<90[16],[59]	60-80	70-85	75[56]-80	60-70	60-80[53]
Wastes	Vitreous slag, “Black water” when using coal ¹ ,	Vitreous slag	Char-ash, Fly ash, Tars, Silica Sand	Char-ash, Fly ash, Tars	Ash, Fly ash, Tars	Char-ash, Fly ash, Tars	Char-ash, Fly ash, Tars
Residual carbon, %	12-15	<15	1-5	1-5	<1	5-15	10-20

Gasification

CAPEX	Small range of licensing	High capital cost; Licensing, permits, and approvals acquired.	Licensing, permits, and approvals acquired.	Licensing, permits, and approvals acquired.	Licensing, permits, and approvals acquired.	Licensing, permits, and approvals acquired.	Licensing, permits, and approvals acquired.
OPEX	Insurance and Administrative, Environmental Compliance and Waste, Consumables (feedstock, electricity, oxygen, etc.), Competent labour, Maintenance, Energy and Feedstock expenditures	Insurance and Administrative, Environmental Compliance and Waste, Consumables (feedstock, electricity, oxygen, etc.), Competent labour, Higher expenditures for equipment maintenance	Insurance and Administrative, Environmental Compliance and Waste, Consumables (feedstock, Sand, Catalysts, Ca(OH) ₂ , etc.), Competent labour, Maintenance, Energy and Feedstock expenditures	Insurance and Administrative, Environmental Compliance and Waste, Consumables (feedstock, Sand, Catalysts, Ca(OH) ₂ , etc.), Competent labour, Maintenance, Energy and Feedstock expenditures	Insurance and Administrative, Environmental Compliance and Waste, Consumables (feedstock, Sand, Catalysts, Ca(OH) ₂ , etc.), Competent labour, Maintenance, Energy and Feedstock expenditures	Insurance and Administrative, Environmental Compliance and Waste, Consumables (feedstock, Sand, Catalysts, Ca(OH) ₂ , etc.), Competent labour, Maintenance, Energy and Feedstock expenditures	Insurance and Administrative, Environmental Compliance and Waste, Consumables (feedstock, Sand, Catalysts, Ca(OH) ₂ , etc.), Competent labour, Maintenance, Energy and Feedstock expenditures
Advantages	High feedstock variability; high flexibility due to fast start-up procedure. Fewer auxiliary equipment, compact layout; fewer wearing	High temperatures and efficiency; wide range of feedstock compatibility (suitable for wet and low calorific value feedstock; High-quality syngas (low tar content)	High conversion rate with low tar content compared with UDG and DDG; uniform heat transfer between material; wide range of fuel fraction; vigorous	High conversion rate with low tar content compared with UDG and DDG; uniform heat transfer between material; wide range of fuel fraction ⁴ ; vigorous	High conversion rate with low tar content compared with UDG and DDG; uniform heat transfer between material; wide range of fuel fraction;	Proven technology, Low-cost process, fuel flexible (tolerant), proven technology	Proven technology, Lower tar content compared with UDG. Cyclone not essential ⁴



	parts and less maintenance costs, longer operation period		mixing and long particle residence times suitable for lower quality fuels. Low-temperature fluid bed prevention from ash melting	mixing and long particle residence times suitable for lower quality fuels. Low-temperature fluid bed prevention from ash melting	suitable for lower quality fuels. Low-temperature fluid bed prevention from ash melting		
Disadvantages	Sensitive for feedstock (type, moisture, ash content and brittleness), Higher fuel preparation costs, e.g. drying, crushing and milling, Wet waste	High capital and operational cost Plasma Torch Wear and Tear. Lack of operating commercial examples (low level of TRL)	Large bubble size may result in gas bypass through the bed ⁴	Heat transfer less efficient than bubbling fluidized bed; Erosion of the equipment due to the abrasiveness of the bed material	Heat transfer less efficient than bubbling fluidized bed; Erosion of the equipment due to the abrasiveness of the bed material	Requires intensive cleanup from tars ⁴	Low carbon conversion ratio; more fuel sensitive; higher slagging; lower heating value compared with UDG
Developed TRL	3-4	3-4	6-7	6-7	8	7-8	10
Challenges	Getting the right hydrogen/CO ratio, Raw-gas cooling	Monitoring Polychlorinated dibenzodioxins emissions; Ensuring high electrical energy supply	Challenging start-up and shutdown procedures; Pressure fluctuations	Size of fuel particles determine minimum transport velocity	Size of fuel particles determine minimum transport velocity	Reduction of tar and fine particles, Finance unfeasibility of feedstock supply and power sales contract is not long-term secured	Finance unfeasibility of feedstock supply and power sales contract is not long-term secured
Risks	Inhomogeneous Feedstock	Hazardous environment in case of malfunction. Risk of unexpected technological challenges due to the lack of examples of long-term performance	Agglomeration; High velocities of bed material may result in equipment erosion	Agglomeration; High velocities of bed material may result in equipment erosion	Agglomeration; High velocities of bed material may result in equipment erosion	Environmental pollution and work hazardous in case of malfunction	Environmental pollution and work hazardous in case of malfunction

*- MeOH (Methanol), FT (Fisher-Tropsch syncrude), FF (Further fuels), DME (Dimethyl ether), SNG (Synthetic natural gas)

**-Estimated

The potential of gasification processes and waste upcycling for sustainable energy production is immense. High ash content tolerance enhances the flexibility to utilise a wide range of biomass and its waste, opening up avenues for higher potential exploitation. However, it's important to note that BFB, CFB, DFB, UD, and DD gasifiers face challenges under high temperatures. At BFB, CFB, and DFB temperatures higher than 600 – 1100 °C (depending on feedstock ash melting point), feedstock particles start agglomerating, disrupting the fluidisation process and reducing reactor efficiency. Similarly, agglomerates can clog the gas flow passage in fixed-bed UD and DD reactors. Entrained and plasma-assisted entrained flow gasifiers are designed to operate at much higher temperatures (~1500 °C), slagging and drawing the slag toward the bottom of the gasifier for discharge. The use of plasma to produce syngas has increasingly been applied with pure waste treatment for its ability to almost entirely decompose the input material into tar-free syngas and an inert, environmentally stable product. Tars are still considered the major obstacle in applying biomass and waste gasification, especially for fixed and fluidised beds in operating temperatures below 900 °C [39].

Generally, entrained flow gasifiers usually have higher H₂, CO, C_xH_y, overall LHV and cold gas efficiency. A competitor for entrained flow gasifiers could be Dual-Fluidised Bed reactors, which also have great efficiency due to high carbon conversion ratio. This is achieved by combining a circulating fluidised bed (CFB) combustor and a bubbling fluidised bed BFB gasifier, making the system autothermal (heat is generated directly by the partial oxidation inside the gasifier). These systems improve the carbon conversion efficiency compared with the single fluid bed design [52].

Entrained flow gasification slag contains the coarse slag discharged from the bottom of the gasifier and the fine slag (fly ash) carried by the gas flow. During thermochemical conversion, a certain amount of fuel is not entirely gasified, and the gasification slag contains some residual carbon. Experimental measurements shows that entrained flow gasifiers slag contains from 11.64 to 15.13% [60]. Dual-fluidised bed gasifiers exhibit shallow carbon content in ash due to a more thorough combustion process and typically contain no more than 1% carbon content. Conversely, due to the low reaction rate, temperature and poor oxygen access, the most significant carbon content (up to 20%) is determined exclusively in updraft and downdraft fixed-bed reactors. As low as possible, slag's residual carbon content is preferred for several reasons. First, lower residual carbon content means a higher carbon conversion ratio, higher yield of produced syngas, improved conversion efficiency and enhanced energy recovery. Higher reaction temperatures can increase the biomass feedstock degradation rate and reduce carbon content [22]. Second, the low carbon content slag can serve as a raw material in the glass industry, offering the prospect of replacing raw feedstock like high-value soda ash, limestone, and dolomite.

However, the carbon content of this waste is critical as it influences the quality of the glass product, including its transparency, and has the potential to form metallic inclusions which can damage refractories and cause manufacturing defects. Carbon is detrimental to glass production primarily because it affects the clarity and colour of the glass and can form metallic inclusions in the melt which sink to the bottom of the tank due to higher density, and then drill into the oxide refractories, causing damage. When the glass melt contains carbon, carbon and / or metallic inclusions can form [61], which appear as dark spots or streaks in the glass. These inclusions reduce the transparency and quality of the glass, making it less suitable for applications where transparency and aesthetics are essential, such as in windows, bottles, or optical lenses [62]. It can cause defects in the final glass product, such as bubbles or blisters, compromising its mechanical strength and overall quality. Transparency requirements are less strict for beverage and pharmaceutical containers made of amber glass. Carbon can also affect the melting behaviour of the glass batch, leading to excessive energy consumption and production costs. This interference with the melting process often requires higher temperatures and longer processing times to obtain a homogeneous melt. Therefore, to ensure the production of high-quality, multi-purpose transparent glass, reducing the amount of carbon in the raw materials used for glass production is economically crucial. In plasma gasification, residual carbon can be retained as process soot. It can be significantly lower than that produced in conventional pyrolytic processes due to H₂ and steam inhibiting residual carbon formation [39].

Syngas also contains some tar, which can contribute to the glass batch's carbon fouling. Hence, a lower concentration is desirable, while high tar concentrations can clog and foul downstream equipment's gas lines, valves, sensors, and even the engine's combustion chambers [56], [59]. This risk arises when the tar's relatively high (~350 °C) condensation temperature is reached. In the Dual-fluidising bed, recirculating fly ash in the presence of alkali salts can control tar species [56]. However, fluidised bed gasifiers generally tend to produce gaseous products contaminated with higher levels of fly ash, resulting from the loss of bed material, mainly silica sand. Research [20] shows that tar-derived pyrolysis oil can be used as an ethanol additive to improve the performance of an internal combustion engine. In addition, other authors have investigated the fact that



pyrolysis oil blends with diesel and biodiesel can emit significantly less NO_x and CO compared to a blend without pyrolysis oil [63].

4 Techno-economic assessment

The capital investment for each technology varies considerably and is influenced by numerous factors, notably feedstock composition. Consequently, prudent evaluation mandates a comprehensive consideration of the resultant products and the associated capital and operational expenses. Entrained flow gasifiers are more expensive than bubbling fluidised bed units on a dry tons basis but more economical on a heat output basis. This section will identify major cost investment and operational cost drivers and highlight options for cost reductions.

The operating costs of gasification technology, which include everyday expenses like wages and real estate rent, are typical across all gasifiers, but differences exist. For instance, the electricity consumption of a plasma assisted entrained flow gasifier is about 30-50% higher than the amount of electricity used during the plasma discharge compared with a regular gasifier. Scaling up plasma-assisted gasification may increase plasma torch efficiency and reduce electricity consumption. However, this can only be presumed at this moment, and further investigation is needed. This high electricity consumption in PAEF gasifiers leads to its more intense thermal processes, resulting in better gasification efficiency and higher-quality syngas production. The use of plasma also allows for the treatment of a broader range of feedstocks, including hazardous or difficult-to-process materials, further enhancing the versatility and effectiveness of the gasification process. It also positively affects the quality and quantity of the produced gas and the recyclable waste. This plasma-assisted gasification versatility for feedstock has a noteworthy advantage compared with other technologies. Also, a good advantage is a quick reaction to load changes, which is difficult, especially in fixed-bed reactors.

When assessing the cost-effectiveness of alternative fuels, it is imperative to consider the capital expenditure (CAPEX) associated with the technology being adopted. This financial aspect is often overlooked but can significantly impact the overall cost-effectiveness of a project. A comprehensive analysis of the implementation of different gasification technologies has been conducted. Investigated that finding analogous facilities for comparison regarding size, feedstock utilised, and final product is challenging. Moreover, projects that provide publicly available descriptions are usually very general because the information is considered confidential business data, and specific process details are unknown. Nevertheless, pilot and industrial cases within the observed conditions are accepted for the indicative price. Those cases differ significantly in technical characteristics due to the more complex production technology and specialized equipment, e.g. production of higher (more advanced) value-added products like methanol, Fisher-Tropsch syncrude, dimethyl ether and further fuels (see Table 3.1). For instance, a 35 MWth capacity GoBiGas biomass Dual-Fluidised bed gasification plant project investment amounted to 230 million US\$ in 2014. However, this first-of-its-kind plant has an additional methanation complex to purify syngas to a biomethane level suitable for the national natural grid of Sweden (Fig. 4.1).

GoBiGas [64] project aimed to demonstrate that this technology can convert biomass into grid-quality biomethane with up to 65-70% conversion efficiency. However, the current status of this project is non-operational [65]. During this project, several key lessons were learned: managing gas quality and tar levels in the gasifier-produced gas; controlling flue gas emissions effectively; addressing challenges with product gas cooling and gasifier start-up; managing operational challenges associated with fuel feed; and evaluating and optimizing activated carbon adsorption beds [47]. There were also several other close attempts to develop waste plasma-assisted gasification plants with bubbling fluidised bed reactors and separate plasma processing devices: in 2014, a 20 MWth refuse derived fuel (RDF) gasification in Birmingham, United Kingdom and a 100 MWth RDF gasification demonstration plant in Ontario, Canada, and but both these projects surrendered and no longer active. However, in 2022, a new similar design plant to demonstrate waste using plasma gasification to produce bio-methane was successfully launched in Swindon, United Kingdom. It became the first facility in the world to convert municipal waste into grid-quality biomethane. However, the total investment cost of this project is estimated at 34 million Eur (Adjusted Price) [66]. Such innovative projects' investment cost is many times higher



compared to all other gasification technologies because of the early stage of development. They are typically designed to address emerging issues and necessitate structural reorganisation, resulting in significantly higher installation time and costs than established commercial gasification plants.

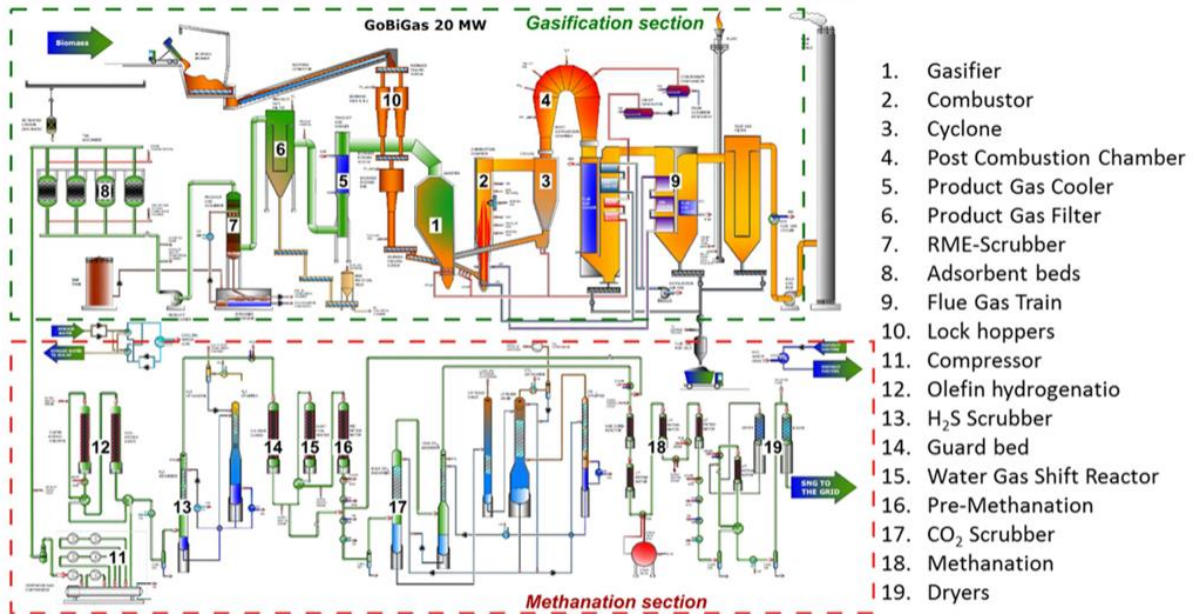


Fig. 4.1 A Schematic overview of the GoBiGas-plant including a list of the major process steps [56]

Fig 4.2 presents the approximate installation price for industrially and commercially developed gasifier types, found in publicly available data sources [48], [67]–[70]. For comparison reasons, their installation prices are expressed in the same relative unit, i.e., million euros per one thermal megawatt.

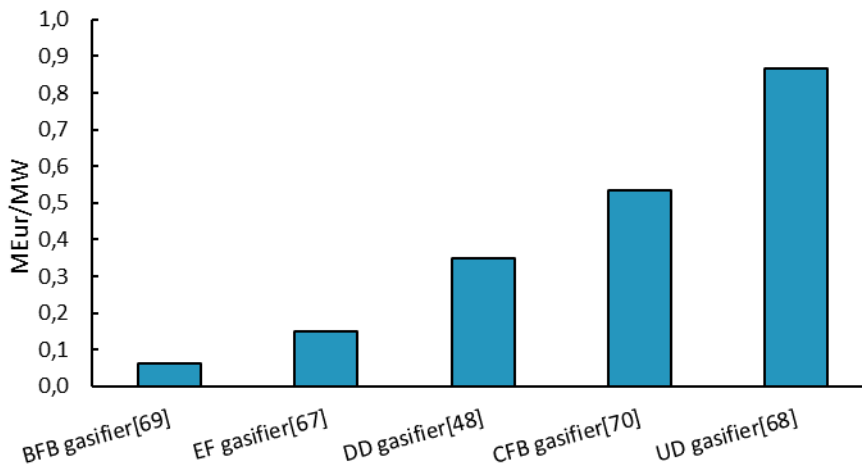


Fig. 4.2 Estimated gasifier installation cost by type (Adjusted Price)

Cost data collected from literature and correlations show significant variability for the same power capacity, with installations in the examples ranging from 2005 to 2018. For this reason, prices have been recalculated, taking into account inflation. Based on a review of installed units, Entrained flow and Bubbling fluidised bed gasifiers were found to have a minimal relative installation cost per megawatt because of the simplicity of the gasification process and the reduced need for auxiliary equipment. Their installation cost is between 0.06 and 0.15 million



EUR per 1 MW of installed thermal power. However, it is elusive to find a suitable commercial example of the plasma-assisted entrained flow gasifier for synthesis gas production that could be used to evaluate the installation and operating costs. Considering the installed production capacities, the necessary investments for technological devices, their start-up, and factory construction must be assessed comprehensively. Investment costs are highly dependent on the installation power of the equipment. When calculating the relative costs of capacity or production, they are generally lower for larger plants. It was decided to calculate a medium-sized, i.e. 1 MW syngas combustion technology encompassing plasma-assisted entrained flow gasification installation, operating costs, and cash flow.

The techno-economic feasibility study of EF, PAEF, BFB, CFB, DFB, UD, and DD gasifiers syngas production costs are estimated using various technical and economic parameters, such as product yields, capital, and raw material prices. According to the HORIZON-RIA GIFFT proposal No. 101122257, assumed that torrefied wood is used as energy raw material, which has a lower calorific value - 20.1 MJ/kg [71]. The price of torrefied wood was accepted to be in free different cases: min. price – 107.83 Eur/t, avg. – 171.53 Eur/t, max. – 235.23 Eur/t (Adjusted Price) [72]. The entrained flow gasifier is expected to work with 70% efficiency, assuming that remaining energy withdraws with char and is emitted as heat losses. Other OPEX members - electricity and gas prices and employee salaries –are based on the economic factors of Lithuania, whose GDP per capita is close (89 %) to the EU average [73]. Expenses are strongly influenced by economic assumptions that are not known with absolute precision, leading to uncertainty in the model's output (i.e., production costs). While acquiring more data can reduce this uncertainty, complete certainty in the model's estimates is unachievable, particularly for new plant projects and Plasma-assisted entrained flow gasification technologies, which lack real-life operational experience. Given that the EU and the world are moving towards sustainable energy, it is accepted that investments in gasification and oxygenation facilities will naturally become cheaper due to increased market demand and supply considering market demand and competition.

Capital Expenditure (CAPEX) refers to the fund's most significant expense on equipment and installation. CAPEX includes the installation price of the entrained flow gasifier and gasification assistance - Plasmatron. It is assumed that the relative installation cost of entrained flow gasifier is 200 000 (Eur/MW_{output}), and assisted plasmatron 35 941 for 1 MW of total gasifier energy output power. More detailed investment and operating costs of the Plasmatron are presented by Bromberg et al. [74]. Investments are evaluated according to the scenario, where there will only be investments in main technological equipment and their start-up, considering that technological equipment will be implemented in already existing plant projects with relevant buildings and necessary infrastructure.

Operational expenditures (OPEX) costs of one production unit include costs for energy, biomass (feedstock), maintenance, materials used, and personnel for operating the gasification and combustion process (Table 4.1). It is assumed that the variable operating costs associated with plasmatron variable OPEX will be equated to 0.002 Eur. Four scenarios were adopted to evaluate the calculations: low electricity and natural gas price (MIN), average price (AVG), high price (MAX), and green electricity case (GEC).

Table 4.1 Summarised production operating costs of plasma-assisted entrained flow gasifier

OPEX	Units	MIN	AVG	MAX	GEC
Electricity Power price	€/kWh	0.10	0.25	0.50	0.01
Feedstock price	€/t	107.83	171.53	235.23	235.23
Gasifier OPEX	€/kWh	0.015	0.015	0.015	0.015
Natural gas	€/kWh	0.015	0.035	0.08	0.08

The gasifier is assumed to operate throughout non-stop the year (8 760 hours per year). Such a regime is adopted on the basis that the glass-melting furnace must work without stopping until the next capital equipment maintenance. Interest is calculated with a 5% investment discount rate. The project's cash flow analysis was



evaluated for a 25-year operating period compared with the import of natural gas on the Lithuanian border without taxes. Since the price of this fuel is very volatile and difficult to predict, four different scenarios, i.e., MIN, AVG, MAX, and GEC scenarios, were taken into account for profitability and depicted in Fig. 4.3.

For comparison reasons plasma-assisted entrained flow gasifier installation cash flow compared with other (EF, BFB, CFB, DFB, UD, DD) gasification technologies.

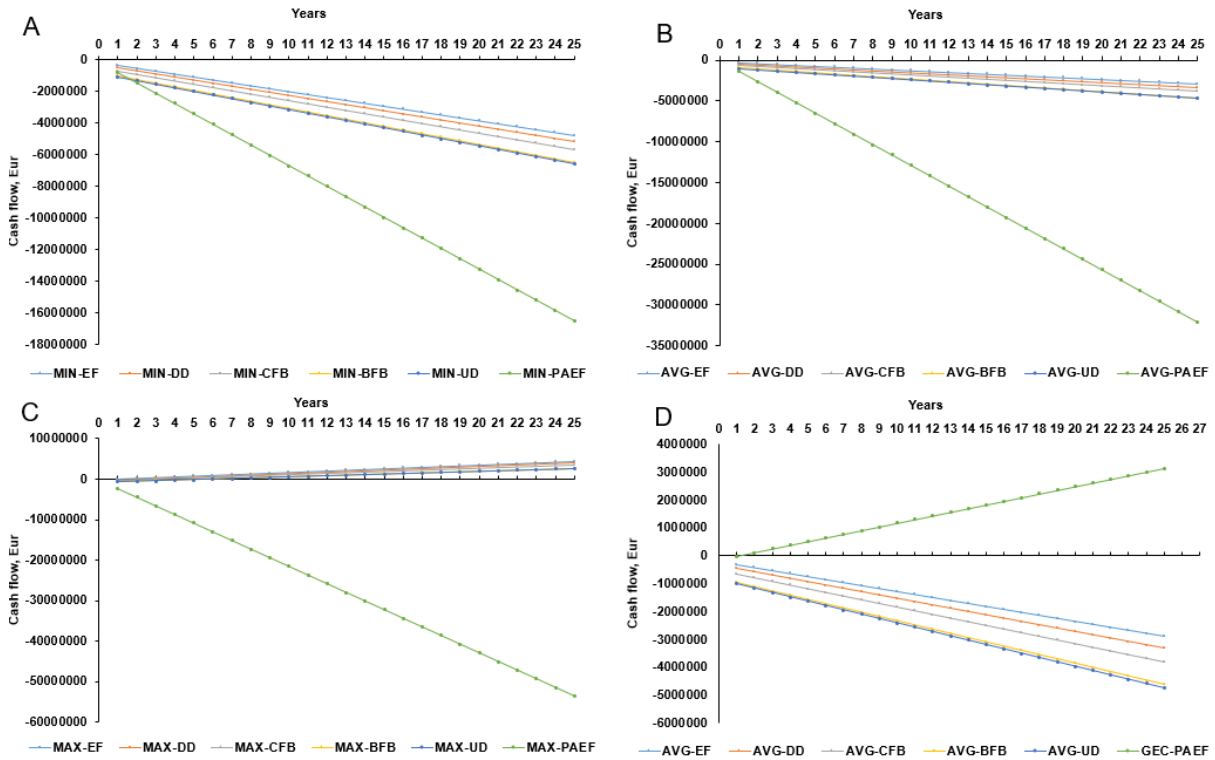


Fig. 4.3 Cashflow scenarios of plasma assisted entrained flow gasification compared with natural gas. Scenario MIN (A), AVG (B), MAX (C), and GEC (D)

The techno-economic calculation results show that investments and operational costs of each gasification technology reach the break-even point at the first few operating years only with the highest energy (electricity and natural gas) prices, i.e., case MAX, except plasma-assisted entrained flow gasification. PAEF gasification is profitable if this project is implemented with green power generation plants, assuming all electricity will be free. If fossil fuel and electricity prices represent average or low-price case scenarios, all observed gasification solutions for transitioning from fossil fuels will become unfeasible. However, the financial profitability of the project could be improved with state subsidies that promote the installation of renewable energy sources.

A comprehensive review of potential alternative syngas production processes and their integration into the glass industry identifying alternative fuels with renewable biomass origins that possess properties similar to those of natural gas, specifically in terms of providing sufficient heat and maintaining high purity levels during combustion. The promising solution involves the use of synthesis gas (syngas) produced with a plasma-assisted entrained flow gasifier. This advanced gasification technology leverages plasma to enhance the production of syngas, significantly increasing its calorific value while simultaneously reducing tar content. The elevated calorific value ensures that the syngas can effectively replace natural gas, providing the necessary thermal energy for glass production processes. Furthermore, the operation of entrained flow gasifiers generates ash, commonly referred to as vitrified slag. This byproduct can be utilised in glass production, thereby contributing to a circular economy and minimizing the carbon footprint of the glass manufacturing process. The integration of vitrified slag not only reduces CO₂ emissions but also addresses the disposal challenges associated with conventional ash waste. Despite these advancements, it is important to note that biomass plasma-assisted entrained flow



gasification need further research and development in the following GIFFT project stages to overcome existing technological barriers, e.g., residual carbon in ash. It needs to be minimised to improve carbon conversion efficiency and energy recovery and preserve the transparency and quality of the produced glass.

Plasma-assisted gasification with inclusive flow is a promising approach with both environmental and economic benefits. However, the adoption of this process requires supportive policies and subsidies, changing the tax environment for fuels, especially fossil fuels. In conclusion, the adoption of plasma-assisted entrained flow gasification presents a viable pathway, offering both environmental and economic benefits. However, achieving widespread implementation requires supportive policies and subsidies in case of competitive prices of fossil fuels.

5 Conclusions and recommendations

A comprehensive examination of the glass industry's production processes and fuel utilisation underscores its heavy reliance on fossil fuels, particularly natural gas. This dependence is evident in manufacturing flat glass for construction and glass containers for food and beverage applications. Given its substantial energy requirements, up to 85% of which are met by fossil fuels, the glass industry emerges as a pivotal sector ripe for transition towards sustainable energy sources. This imperative is driven by mounting concerns over climate change, societal welfare, and global initiatives to foster sustainable production practices. The transition requires the adoption of alternative fuels derived from renewable biomass sources. Such fuels must represent similar properties of natural gas, notably their calorific value and purity, to ensure minimal impact on glass melting furnace modification and operation. A review of alternative gas reveals a promising substitute gas that meets these stringent criteria.

It is estimated that transitioning from natural gas to wood biomass could yield a remarkable reduction of up to 90% in CO₂ emissions, translating to potential savings of 693 kg of CO₂ emissions per ton of glass produced. Solid biomass must convert into a gaseous form known as syngas to provide a suitable form of fuel for a glass-melting furnace. While hydrogen and ammonia are regarded as carbon-neutral alternatives, their adoption is hindered by transportation, storage, and cost challenges, as well as the lack of capacity for producing (especially green H₂ or NH₃) for new energy markets and the slow pace at which such capacity can be built. Their prices range from 8.3 to 17.3 times higher, respectively, compared to syngas. Various gasifiers, such as entrained flow, fluidized, and draft gasifiers, facilitate this thermochemical conversion, yielding distinct gaseous and solid byproducts.

Plasma-assisted entrained flow reactors are distinguished by their ability to operate under challenging conditions, achieving superior cold gas efficiency and carbon conversion rates. These gasifiers are capable to adapt to energy demand fluctuations rapidly and are highly flexible in accommodating high energy demands and different fuel types. PAEF syngas composition features high H₂ and CO concentrations with negligible tar concentrations. Moreover, the vitrified ash slag produced by the plasma-assisted entrained flow gasification process could substitute conventional raw materials in the glass industry, potentially displacing valuable raw materials such as soda ash, limestone and dolomite. However, a lower amount of residual carbon in the ash content is preferred. Otherwise, it can compromise the quality and mechanical integrity of the final glass product.

A thorough techno-economic assessment of plasma-assisted entrained flow gasification necessitates an evaluation of both capital and operational expenditures. The scarcity of pilot and industrial-scale implementations under comparable conditions poses challenges for precise cost estimations. Initial projections indicate the profitability of plasma-assisted entrained flow gasification when integrated with green power generation plants, assuming zero electricity costs. In scenarios where fossil fuel and electricity prices remain competitively lower, sustained financial viability may necessitate state subsidies to incentivise the adoption of renewable energy sources. Notably, economic projections are subject to inherent uncertainties, underscoring the need for a more detailed analysis encompassing factors such as production costs and lifecycle assessments.

Further insights into the techno-economic and environmental assessment of plasma-assisted entrained flow gasification will be presented in the forthcoming stages of the GIFFT project, particularly within Work Package



7. This package will comprehensively examine process feasibility, efficiency, production costs, and environmental impact, thereby enriching understanding of the technology's viability and potential contribution to sustainable industrial practices.

Recommendations:

- Syngas typically exhibits a lower LHV in comparison to the conventional fuel used in the glass industry, namely natural gas. To mitigate this, enhancing the calorific value becomes imperative, achieved by substituting the oxidizing agent with oxygen. This substitution prevents dilution with nitrogen and concurrently reduces NO_x emissions.

- The Wobbe Index, an indicator of the interchangeability of fuel gases such as natural gas, is an important factor to consider. In order to aligning the syngas Wobbe number with that of natural gas necessitates ensuring a syngas mixture characterized by a higher heating value and diminished specific gravity gas content. This entails maximizing the presence of hydrogen (H₂) and methane (CH₄) within the syngas composition.

- Stringent control over residual carbon ash content, which has a crucial influence on glass transparency and quality, is mandated to realize the objective of substituting conventional raw materials such as soda ash, limestone, and dolomite. Maintaining optimal gasification conditions, encompassing requisite temperature, pressure, and equivalence ratio, is pivotal to achieving the highest carbon conversion ratio. Supplementary methodologies, including feedstock pretreatment and catalytic gasification, could be applied if possible.

- In scenarios where plasma-assisted entrained flow gasification lacks access to free renewable energy sources and electricity costs remains moderate (low to average), proactive financial intervention, such as state subsidies, is advisable. Such support mechanisms can facilitate the installation of renewable energy infrastructure or alleviate production costs, thereby strengthening the economic viability.



6 Literature

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HISTORY OF CHANGES		
VERSION	PUBLICATION DATE	CHANGE
1.0	10.05.2024	Initial version
1.1	31.05.2024	Revised version
1.2	11.06.2024	The first version was sent to all partners
1.3	21.06.2024	Final day for partners comments
1.4	27.06.2024	Comments from partners have been taken into account
1.5	01.07.2024	The final version was sent to all partners for second revision
1.6	04.07.2024	Final day for partner comments
1.7	05.07.2024	Revised and approved version by all partners