GASIFICATION

Diversification of biomass processing and waste utilisation

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EBA
European Biogas
Association

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About EBA

Founded in 2009, the association is committed to the expansion of sustainable biogases production and their use across the continent. EBA counts on a well-established network of over 300 national associations and other organisations covering the whole biogas and biomethane value chain throughout Europe and further afield.

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Executive summary

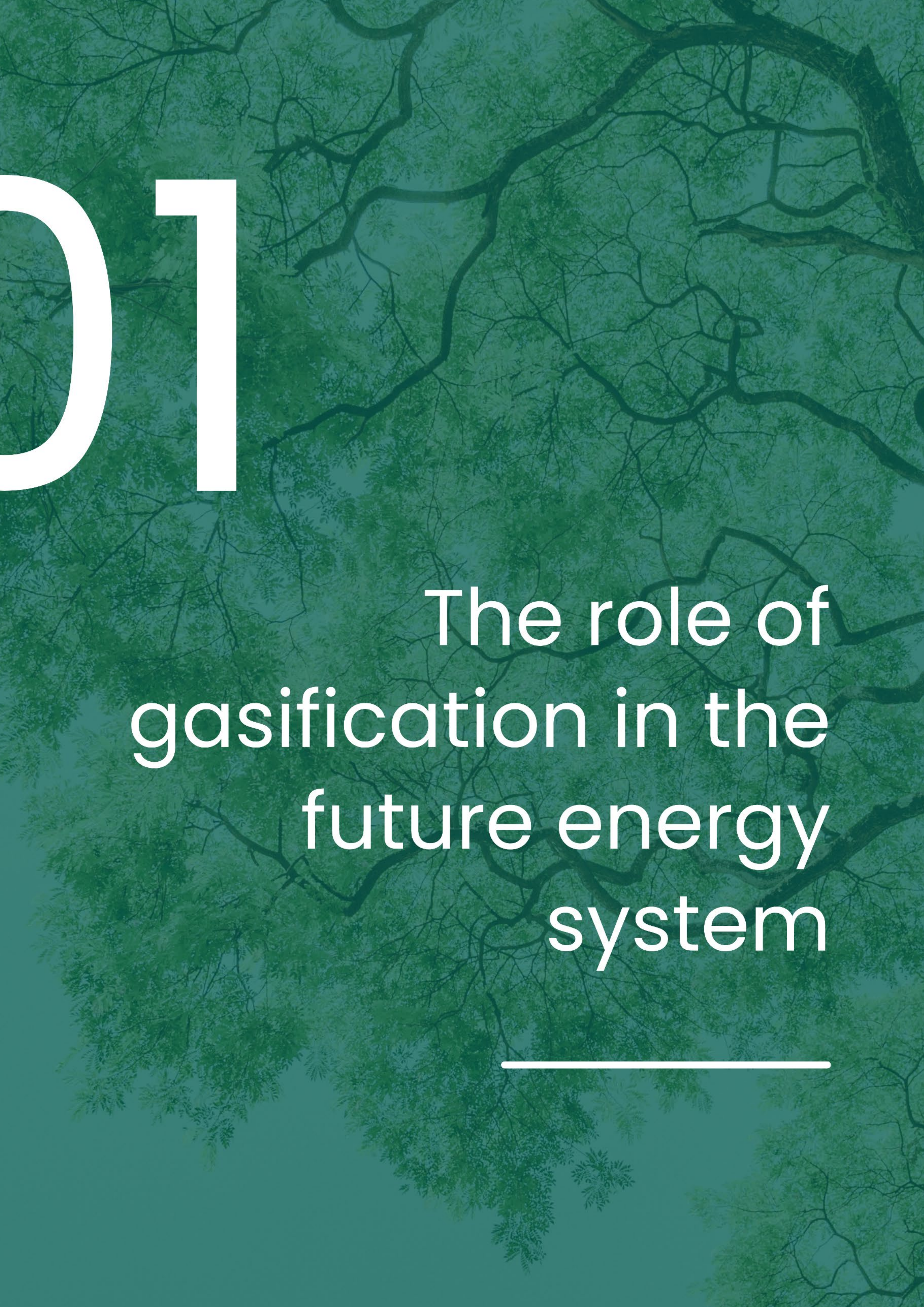
The global energy landscape is undergoing a transformative shift, as nations strive to reduce their reliance on fossil fuels and mitigate the impacts of climate change. The European Union's commitment to achieving net-zero emissions by 2050 has spurred interest in renewable gases as part of its broader strategy for decarbonising the energy sector. Among the various renewable energy technologies, gasification has emerged as a promising solution, offering a versatile approach to converting organic materials into clean energy.

The European Biogas Association (EBA) has drafted a paper exploring the state of play of biomass and waste gasification in Europe. Chapter 1 includes a discussion about the role of gasification in the future energy system, with an emphasis on relevant policies driving its deployment. Chapter 2 covers an introduction of key technological aspects of this field, such as feedstock pretreatment, gasification operational parameters and state-of-the-art technologies. Chapter 3 summarises the upgrading pathways to convert syngas resulting from gasification into various end products, as well as the discussion of the valorisation of biochar, a gasification by product. Furthermore, European operational and planned gasification installations have been mapped and main trends analysed in Chapter 4. Chapter 5 addresses market and economic considerations affecting the gasification sector with an emphasis on techno-economic aspects.

Policies promoting renewable energy sources, financial incentives for biomass projects and regulatory frameworks aimed at reducing greenhouse gas emissions are vital for fostering investment in the gasification technology. As technology advances and market conditions evolve, biomass and waste gasification could play an integral role in transitioning towards sustainable energy solutions, while mitigating the environmental impacts associated with fossil fuel consumption.

List of acronyms

AD	Anaerobic Digestion
CHP	Combined Heat and Power
CLG	Chemical Looping Gasification
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CAPEX	Capital Expenditure
CMC	Component Material Category
CRCF	Carbon Removals and Carbon Farming
CAGR	Compound Annual Growth Rate
DME	Dimethyl Ether
DPBP	Discounted Payback Period
ETS	Emission Trading System
ER	Equivalent Ratio
FiTs	Feed-in Tariffs
FT fuels	Fischer-Tropsch fuels
FPR	Fertilising Products Regulation
GC	Gas Chromatography
GHGs	Greenhouse Gases
HTC	Hydrothermal Carbonisation
HRSG	Heat Recovery Steam Generator
HHV	Higher Heating Value
IRR	Internal Rate of Return
IGCC	Integrated Biomass Gasification Combined Cycle
LHV	Lower Heating Value
LCOE	Levelized Cost of Electricity
MSW	Municipal Solid Waste
MAG	Microwave-Assisted Gasification
NPV	Net Present Value
NOx	Nitrous Oxides
OPEX	Operational Expenditure
OCC	Overnight Construction Cost
PFC	Product Function Category
PAH	Polycyclic Aromatic Hydrocarbons
R&D	Research and Development
RCF	Recycled Carbon Fuels
SAF	Sustainable Aviation Fuel
SNG	Synthetic Natural Gas
SRF	Solid Recovered Fuels
SCW	Supercritical Water
SWG	Supercritical Water Gasification
SDG	Sustainable Development Goals
SPB	Simple Payback Period
SB	Steam-Biomass ratio
SDA	Semi-Dry Absorption
SCR	Selective Catalytic Reduction
SCNR	Selective Non-Catalytic Reduction
TRL	Technological Readiness Level
VOCs	Volatile Organic Compounds
Wt	Weight



01

The role of gasification in the future energy system

The global energy landscape is undergoing a transformative shift, as nations strive to reduce their reliance on fossil fuels and mitigate the impacts of climate change. Among the various renewable energy technologies, thermal gasification has emerged as a promising solution, offering a versatile approach to converting organic materials into clean energy. This paper aims to explore the state-of-the-art technologies in biomass and waste gasification, relevant policies driving its deployment, and to provide an inventory of gasification plants across Europe.

Gasification is a thermochemical process that converts organic materials — such as agricultural residues, forestry by-products, wood waste and organic fraction of municipal solid waste or solid recovered fuels (SRF) — into syngas (a mixture of hydrogen, carbon monoxide and other hydrocarbons). This process not only produces energy, but also enables the recycling of waste materials, thereby contributing to a circular economy, as presented in the EBA report (Gasification: A Sustainable Technology for Circular Economies). The syngas generated can be utilised in various applications, such as electricity and heat generation through combined heat and power (CHP) systems, production of renewable natural gas (RNG) or recycled carbon fuels (RCF), and as a feedstock for synthetic fuels and chemicals. The ability to convert diverse feedstocks into valuable energy products positions gasification as an essential player in achieving net-zero emissions targets.

In the current energy landscape, the urgency to address climate change and reduce greenhouse gas emissions has led to a growing interest in renewable energy technologies. Gasification stands out as a flexible solution capable of addressing multiple challenges simultaneously. Market research agencies report that the global biomass gasification market size is expected to reach €204.03 billion by 2032,[1] at a Compound Annual Growth Rate (CAGR) of 7.6% during the 2023-2032 forecast period. This technology is poised for significant growth and adoption across various sectors. However, further reductions in capital and operational costs are essential to the commercial success of this technology.

The significance of thermal gasification extends beyond traditional energy generation. As countries commit to ambitious climate goals, there is an increasing focus on innovative pathways that go beyond cogeneration. For instance, upgrading syngas to methane through methanation processes presents an attractive option for integrating gasification into existing natural gas infrastructure. This not only enhances energy security, but also provides a means to store renewable energy in the form of methane, which can be used during periods of high demand or low feedstock availability. Advances in gasification technology are paving the way for integrated solutions that enhance efficiency and reduce environmental impacts. Moreover, the integration of advanced gas cleaning technologies ensures that the syngas produced meets stringent quality standards for downstream applications. Continuous efforts in research focused on improving efficiency, scalability and environmental performance is required in the future. These developments are critical for facilitating the transition from conventional energy systems to more sustainable alternatives. These innovations not only increase the viability of biomass and waste as an energy source, but also enable its integration into existing energy infrastructure.

Several limitations constrain gasification widespread adoption in the energy future. A primary concern is biomass availability, which is inherently limited by land use competition, sustainable harvesting practices and seasonal variations in feedstock supply. According to Guidehouse modelling in the "Biogases towards 2040 and beyond" report, the potential for thermal gasification is estimated at 37 bcm in 2040, of which 33 bcm relates to the EU27. This number can be

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[1] Converted from $216.87 billion

achieved through the utilisation of all appropriate feedstocks and unlocking additional potential from novel feedstocks such as crops grown on marginal or contaminated land, seaweed and digestate as well as landfill gas. Furthermore, the heterogeneous nature of biomass feedstocks and their geographical dispersion pose challenges for consistent supply chains and standardised gasification processes. The technological readiness and uptake of thermal gasification systems also present significant hurdles. While small-scale gasification units have achieved commercial status, large-scale biomass gasification remains at the demonstration stage. Additionally, the high capital costs associated with gasification plants and the need for sophisticated gas cleaning systems hinder widespread commercialisation.

Supportive policies and market dynamics are crucial to fully realising the potential of thermal gasification in the renewable energy transition. The European Union's commitment to achieving net-zero emissions by 2050 has spurred interest in renewable gases as part of its broader strategy for decarbonising the energy sector. Policies promoting renewable energy sources, financial incentives for biomass projects and regulatory frameworks aimed at reducing greenhouse gas emissions are vital for fostering investment in this technology. As public awareness grows regarding the benefits of gasification—such as its ability to generate clean energy while managing waste—there is an opportunity for increased political support. This backing will be essential in overcoming barriers to implementation and ensuring that gasification technologies can scale effectively.

Policy context:

Sustainability of Syngas from Forest Biomass Gasification

Syngas from biomass gasification is considered by EU legislation as a gaseous biomass fuel, a renewable energy carrier, provided it complies with the sustainability criteria of the Renewable Energy Directive. Indeed, to count towards EU renewables targets or to be eligible for state aid, renewable energy sourced from biomass needs to fulfil sustainability criteria. In the case of a gasification plant employing woody biomass, the sourcing of feedstock must comply with the sustainability requirement of Article 29 of the Renewable Energy Directive 2018/2001 (RED III). The recast of Directive 2018/2001 added new criteria for forest biomass based on a risk-based approach. This requires operators to demonstrate that the country of origin is party to the Paris Agreement and has laws in place that: a) avoid the risk of unsustainable harvesting and; b) account for emissions from forest harvesting. If such evidence cannot be provided, operators need to demonstrate sustainability compliance at biomass sourcing area level.

As mentioned, to minimise the risk of using forest biomass that is not compliant with sustainable harvesting criteria, economic operators should carry out a risk-based assessment, building on existing sustainable forest management legislation, including monitoring and enforcement systems, in force in the country of origin of the forest biomass. To that end, the harvested forest biomass should be subject to national and sub-national laws and regulations that meet the harvesting criteria laid down in point (a) of Article 29(6) of Directive (EU) 2018/2001. Economic operators should also assess whether there are monitoring and enforcement systems, and whether there is no evidence of a significant lack of enforcement of the relevant national or sub-national laws. To that end, economic operators should use legal assessments and reports prepared by the European Commission, international or national governmental organisations, including information provided by non-governmental and scientific forest expert organisations. The risk-based assessment should also take account of any relevant ongoing infringement procedures launched by the Commission, which are reflected in the Commission's publicly available infringements database, and consider any relevant infringement rulings of the Court of Justice of the European Union as evidence of a lack of enforcement.

Where there is no evidence of compliance at national level with one or more of the harvesting criteria laid down in point (a) of Article 29(6) of Directive (EU) 2018/2001, forest biomass should be considered high-risk. In such cases, economic operators should provide more detailed evidence that the harvesting criteria set out in point (b) of Article 29(6) of Directive (EU) 2018/2001 are complied with, through management systems at sourcing area level. In that respect, it is necessary to establish in more detail the evidence of sustainability, which should be provided by economic operators through management systems at forest sourcing area level, when compared to that required under the national and sub-national compliance assessment. This will ensure that the harvesting criteria are effectively met, in particular the criteria on forest regeneration, conservation of protected areas, minimisation of harvesting impacts on soil quality and biodiversity, and on the maintenance or improvement of the forest's long-term production capacity.

Policy context:

Sustainability of Syngas from Forest Biomass Gasification

To ensure that biogenic emissions and removals associated with forest biomass harvesting are correctly accounted for, the forest biomass must meet LULUCF criteria at national level (maintenance of sinks). In particular, the country or regional economic integration organisation from which the biomass is sourced should be a party to the Paris Agreement. In addition, the relevant country or regional economic integration organisation should have submitted a National Determined Contribution (NDC) in the context of the Paris Agreement, covering emissions and removals from land use, agriculture and forestry, which ensures that changes in carbon stock associated with biomass harvest are accounted towards the country or regional economic integration organisation's commitment to reducing or limiting greenhouse gas emissions, as specified in the NDC. Alternatively, it should have national or sub-national legislation, applicable to the area of harvest, to conserve and enhance carbon stocks and sinks. In addition, evidence should be provided that the reported LULUCF-sector emissions do not exceed removals and that forest carbon sinks are maintained or strengthened over a relevant reference period. Where compliance with the LULUCF criteria laid down in Article 29(7) of Directive (EU) 2018/2001 cannot be demonstrated, it is necessary that economic operators provide additional evidence of the existence of management systems at sourcing area level, in order to ensure that both forest carbon stock and sink levels are maintained or strengthened in the long term. Such systems should at least include information from forward-looking planning and periodic monitoring of the development of the forest carbon stocks and sinks at forest sourcing area level.

Finally, the latest review of the sustainability criteria for forest biomass has been extended, with more detail on what is regarded as sustainable harvesting, such as no conversion of forest land into plantations, minimising large clear cuts, no use of roots or stumps and no degradation of primary or old growth forest.

Furthermore, Member States may not grant direct financial support for the use of saw logs, veneer logs, industrial-grade roundwood, stumps or roots for energy.

Finally, the GHG emissions savings thresholds indicated in Article 29 must be respected and vary depending on the plant's final output (heat, power or transport fuel), size and entry into operation. See Annex II for conditions on using biomass fuel in transport, electricity, heating and cooling production.

To mitigate the retroactive effect of the new GHG emissions requirements[2], the Renewable Energy Directive as of 2023 includes a grandfathering clause stipulating that RED II criteria may still apply if certain conditions were in place before RED III came into force (Article 29 (15)). The conditions are that RED II has been transposed and that the Member State has put in place a long-term state aid scheme compliant with the Climate, Energy and Environmental Aid Guidelines (CEEAG, see Question 3 of Chapter 8). If these conditions are met, the grandfathering clause can apply:

- If the installation became or will become operational between 1 January 2021 and 31 December 2025, it shall apply at least 70% greenhouse gas emission savings.
- If the installation will become operational from 1 January 2026, it shall apply at least 80% greenhouse gas emission savings.

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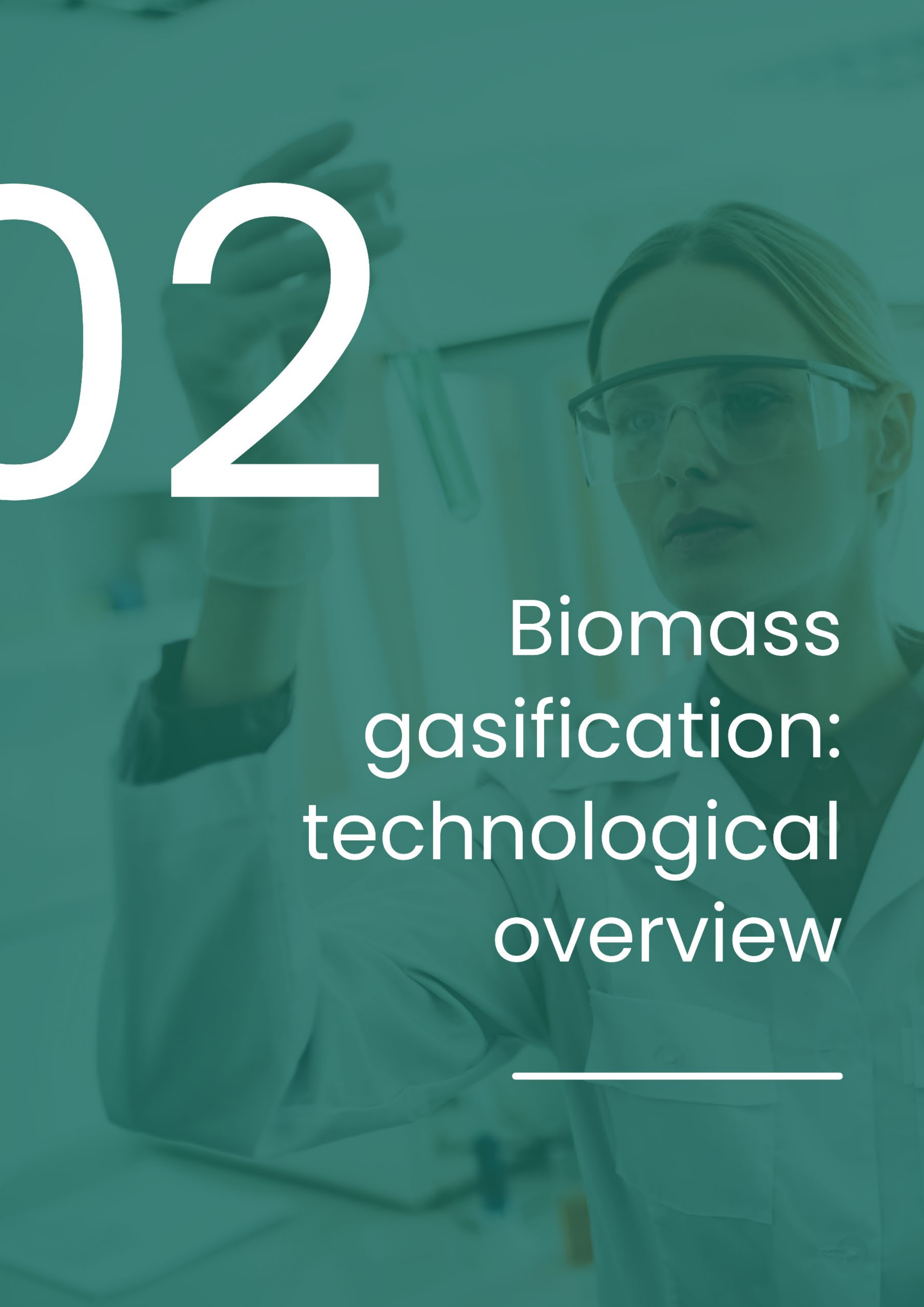
[2] Sustainability requirements were strengthened during the revision of the Renewable Energy Directive in 2023. The measures must be transposed.

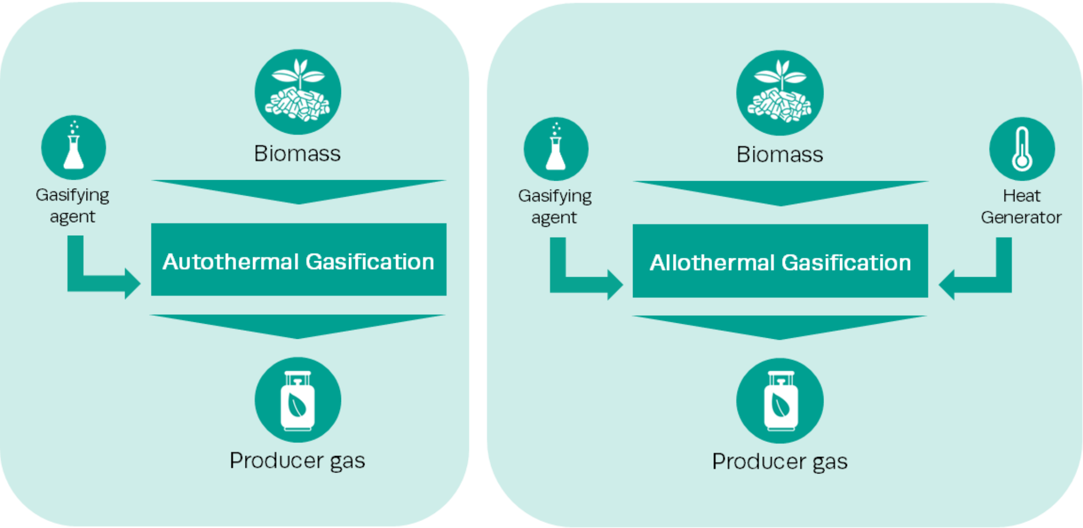


02

Biomass gasification: technological overview

Thermal gasification usually refers to the thermochemical process which converts organic material into a gas mixture and a solid by-product fraction. This is achieved by reacting the material at high temperatures (above 700 °C), without combustion, with a controlled amount of oxidising agent (see Annex I). If heat is required to support the process, it is considered endothermic. Depending on how the heat is supplied, it can also be categorised as autothermal (uses heat form the process itself) and allothermal (uses external heat). Figure 1 shows both a schematic of the gasification process in general as well as the difference in applied heat.

Figure 1. Schematic representation of autothermal and allothermal gasification



Technical characteristics of the gasification process

When evaluating thermal gasification systems, a comprehensive understanding of operational parameters is crucial for assessing their efficiency, performance and environmental impact. Each parameter provides valuable insights into the gasification process and its ability to convert biomass and waste into renewable energy effectively. For instance, metrics such as rated electrical power, gas production and lower heating value (LHV) are fundamental indicators of a system's energy output and overall viability. Additionally, parameters like biomass consumption and producer gas yield are essential for evaluating the sustainability and economic feasibility of biomass utilisation.

Moreover, the integration of these parameters allows for a holistic assessment of gasification technologies. Factors such as the equivalent ratio or steam-to-biomass ratio, cold gas efficiency and gasifier type influence operational efficiency and fuel flexibility. Operating conditions—including temperature and pressure—play a significant role in determining the quality of the producer gas generated. Furthermore, considerations related to emission control, gas cleanup efficiency and tar removal methods are critical for ensuring compliance with environmental regulations and optimising the quality of the syngas produced. By examining these operational parameters collectively, we can better understand the capabilities and limitations of different gasification systems, paving the way for informed decision-making in the deployment of renewable energy technologies. The principal parameters discussed in the context of gasification are summarised in Table 1, with a detailed discussion in Annex I.

Table 1. Technical operational parameters considered in the thermal gasification process

Parameter	Units	Comment
Rated electrical power	kW_e	Max. amount of electrical power generated under normal operating conditions (for CHP)
Gas production	Nm^3/h	Flow of volumetric product output
LHV	kJ/Nm^3	Energy content of the gas
Biomass consumption	Kg/h	Plant processing capacity
Equivalent ration (ER) **Or** **Steam-to-biomass ratio (SB)**	ratio	Ratio of gasifier agent supplied to stoichiometric gasifier agent for combustion or amount of steam to biomass fed in the gasifier
Producer gas yield	Nm^3/kg	Amount of producer gas generated per unit of feedstock
Cold gas Efficiency (η_{cg})	%	LHV cold gas to LHV feedstock (efficiency of gasification at low temperatures)
Gasifier	Type of reactor	Affects efficiency, gas composition, tar content etc.
Integration with CHP	Yes/no	Combined with CHP to optimise plant operation
Operating conditions (T, P)	C, bar	Reaction conditions
Emission control	Semi-dry absorption scrubbers (SDA), baghouses, selective catalytic reduction (SCR), selective non-catalytic reduction (SNCR)	Measures to control emissions of pollutants (NOx, SO_2, VOCs) (in case of reactor implying atmospheric emissions)
Gas clean-up efficiency	% or type of technology	Removing impurities (particles) to meet standards for future utilisation
Gas composition	Proportion or % (molar) of H_2, CO_2, CO CH_4 etc	Gases in the mix
Tar removal type	Primary/Secondary	During or post gasification step
Gasifier agent	O_2/Air/CO_2/Steam/SCW/mix	Oxidising agent used in reactor
Biomass type/substrate	Main concerns: moisture content and particle size	Determines cellulose to lignin ratio
Ash/biochar production	Wt % or kg/h	By-product production
Producer gas output T	˚C	Impacts the final gas composition
Catalyst	Mineral/alkali/transition metal	Affects process efficiency

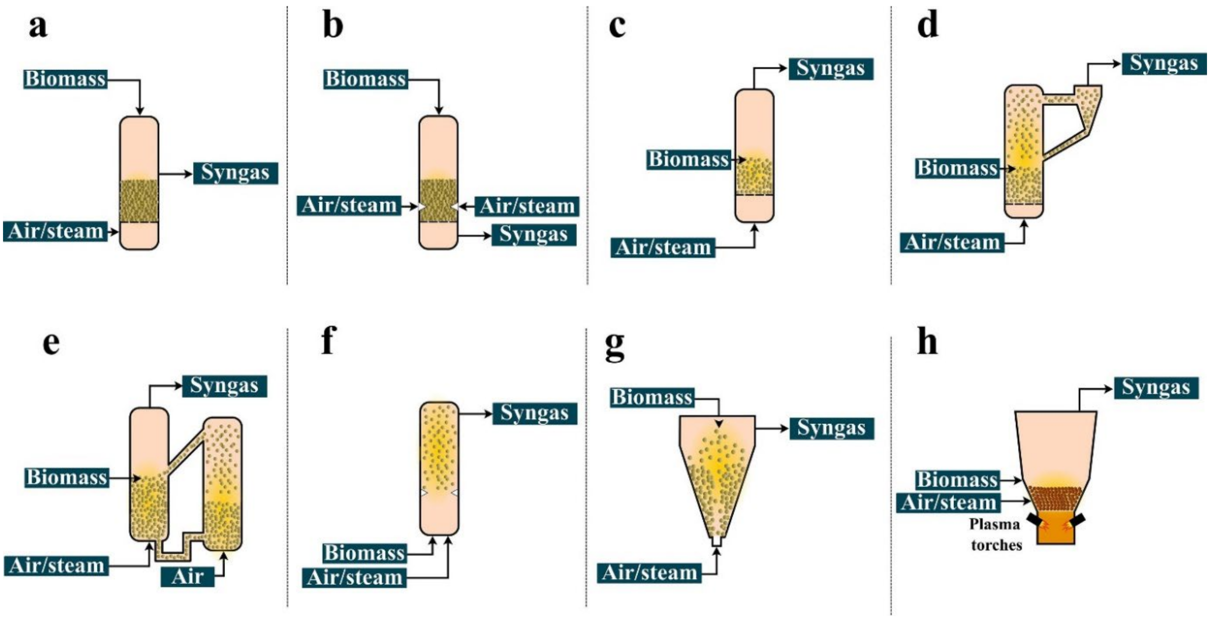
The process of gasification happens in the reactor, known as a gasifier. There are five principal types of gasification reactors commonly used in today's market: fixed bed, fluidised bed, dual fluidised bed, entrained flow and plasma reactors. They offer a flexible range of capacity from kW to GW and can integrate various types of feedstocks.

Fixed bed gasifiers are the simplest gasification technology. These types of reactors are relatively easy to design and operate, but they have limited capacity. Therefore, they are typically used in small – to medium – scale operations. Fixed bed reactors are mainly subdivided based on the input of oxidising agent flow into updraft, downdraft and cross-draft.

Compared to fixed bed gasifiers, fluidised bed reactors have faster gasification rates and higher gas production rates. Fluidised bed gasifiers offer uniform heat and mass distribution, which reduces the risk of fuel stack agglomeration. They have the advantage of feedstock flexibility and high efficiency. Fluidised bed reactors are usually divided into bubbling, dual and circulating. A more innovative technology is dual fluidised gasifiers, which can overcome the drawbacks of fluidised bed reactors. Dual fluidised bed offers the possibility to produce nitrogen free syngas without the need of an air separation unit (ASU) and a high carbon conversion efficiency (since the char is combusted).

Entrained flow gasification is a mature technology that has been adapted from coal gasification. The reactors are operated at a high T (1200–1600 °C) and high pressure (20–80 bar), with oxygen as the gasifying agent. The process happens above the melting point of ash and produces little tar content.

Figure 2. Reactor configurations for thermal gasification: (a) updraft fixed bed; (b) downdraft fixed bed; (c) bubbling fluidised bed; (d) circulating fluidised bed; (e) dual fluidised bed; (f) entrained flow; (g) spouted bed and (h) plasma reactors. (source: doi.10.1016/j.enconman.2022.116496)



Pretreatment of feedstocks

Feedstock pre-treatment is a crucial topic in the current renewable energy landscape due to its potential to enhance the efficiency and sustainability of waste-to-energy conversion processes. Effective pre-treatment can expand the range of viable feedstocks, including challenging materials like municipal solid waste, agricultural residues and forestry residue, thus addressing waste management issues while simultaneously producing renewable energy.

The objective of this step is to homogenise the feedstock and remove moisture content to below 35 wt% (with an ideal range of 10-15%), which would improve product quality, conversion efficiency and energy density. The main methods of pretreatment are *mechanical* (e.g. grinding, pelletization), *biological* (e.g. AD, enzymatic hydrolysis), *chemical* (e.g. water or/and acid leaching) and *thermal* (e.g. torrefaction and hydrothermal carbonisation (HTC)). Mechanical pretreatment is always a necessary step, since the raw feedstock has poor bulk density, an irregular shape and high water content, making it difficult to transport and store. However, excessive mechanical processing requires high energy consumption and should be carefully evaluated to achieve optimal techno-economical balance. Below are two examples of state-of-the-art pretreatment technologies in the gasification field currently transitioning to commercial maturity.

Torrefaction is a pretreatment process in thermal gasification that enhances the efficiency and effectiveness of converting biomass into syngas. Typical operational conditions include temperatures between 200 °C and 300 °C and an inert or low-oxygen environment, which leads to the partial pyrolysis of the feedstock. This thermal treatment induces several physical and chemical changes in the biomass. Hemicellulose, the most thermally labile component of feedstock, undergoes significant decomposition, releasing water, carbon dioxide and a range of volatiles. Cellulose and lignin, although more resistant to thermal decomposition, also undergo partial degradation. The result is a solid, brittle and hydrophobic material, with reduced moisture content and increased energy density compared to the raw biomass. The torrefied biomass becomes brittle and can be easily ground into a fine powder, facilitating efficient feeding and mixing in gasification systems, as well as more cost-effective storage and transportation. This uniformity leads to a more predictable and stable gasification performance. Thermal pretreatment during torrefaction helps in breaking down complex organic molecules, which subsequently reduces the formation of tar in the gasifier. Torrefaction leads to the partial removal of oxygenated compounds, resulting in syngas with a higher concentration of combustible gases like carbon monoxide, hydrogen and methane. This improves the overall calorific value of the produced syngas. Additionally, emissions of pollutants such as particulates, nitrogen oxides and sulphur compounds can be minimised. Over the last decade, torrefaction has rapidly developed from pure R&D to the stage of market introduction and commercial operation.

Hydrothermal carbonisation (HTC) is a process that converts wet feedstocks into a high-carbon solid at temperatures between 180-250 °C and pressures of 2-4 MPa. The main product – hydrochar – resembles lignite or brown coal. HTC can use feedstocks with high moisture content like food waste, sewage sludge and aquatic biomass. This pretreatment influences the product gas, resulting in higher CO concentration and lower CO_2 concentration. Regarding syngas yield and syngas calorific value, HTC has demonstrated to be more efficient than torrefaction. While torrefaction removes moisture and volatile components, HTC additionally densifies biomass. Hydrothermal carbonisation can be considered an emerging technology that is advancing towards maturity but still requires further development and research.

Advancements in gasification technologies

The field of thermal gasification has seen significant advancements in recent years, driven by the growing demand for renewable energy solutions and the need to address climate change. Current state-of-the-art technologies in gasification are characterised by their improved efficiency, versatility and environmental performance. The following technologies have been the focus of academic and industrial research over the past five years.

Co-gasification is a process that integrates structurally different feedstocks for better application of resources, waste utilisation, pollution reduction and carbon recycling. Plastic and biomass, for example, are co-gasified together, which improves process performance through a synergistic effect. This is attributed to various physio-chemical properties of organic waste, as well as the catalytic effect of mineral matter in one of the components. The main advantage comes from its ability to achieve the desired gas composition by altering the feedstock and mixing ratio (see Annex I for blending ratio).

Hydrothermal gasification is a generally used term for supercritical water gasification (SWG). The process occurs in the presence of supercritical water at high temperatures and pressures (>374 °C, >22 MPa). Under these conditions, water acts as both the reaction medium and a reactant, enabling complete biomass conversion into syngas. The process avoids the step of biomass drying, hence making it suitable for high-moisture feedstocks. Additionally, pressurisation of gases is inherent in the process, eliminating the need for additional energy-consuming steps like pressurising gases for storage and transport, unlike in the thermal gasification method. While SWG technology employs steam as a gasification agent, it is a distinctly different process from steam gasification. This technology is considered the most promising for biomass and waste gasification, as it both offers significant improvements in process output and higher technological readiness than other emerging technologies.

Plasma gasification refers to a technology where plasma torch is used in the fuel injection zone. The temperature produced is so high (up to 4,500 °C) that complex hydrocarbons completely decompose into simple gases and inorganic vitrified slag (consisting of melted glass, silicones and heavy metals). The resulting clean gas mixture is high in H_2 and CO, and has a low CO_2 concentration. An additional advantage is that this process can utilise wet feedstocks such as sewage sludge and is not affected by particle size. Plasma gasification is becoming more popular in the area of hazardous waste utilisation, plastic and rubber treatment. Unlike typical incineration, the process reliably destroys highly toxic furans, dioxins and benzopyrene, making it an environmentally-friendly waste removal method. There are several varieties of plasma gasification, including microwave plasma, ionic plasma and entrained flow plasma. Nevertheless, the high energy consumption and high capital costs are significant downsides of this technology.

Microwave-assisted gasification (MAG) helps to overcome an inherent problem in biomass heating, i.e. poor heat distribution. Microwave absorbers, such as activated carbon and metal oxides, improve biomass heating and the conversion efficiency of biofuels, leading to selective, fast and energy-efficient process.

Inclined rotary kiln reactors have drifted from cement manufacturing to waste disposal and are now emerging as a promising technology in the thermal gasification sector. This process allows for a good mixing of solids, while uniformity of temperature prevents slagging and clinkering. Indirect slow pyrolysis rotary kilns are an energy-efficient and economical technology to produce biochar, biofuel and producer gas from waste wood chips, agricultural residue and municipal waste.

Chemical looping gasification (CLG) technology is based on a dual-reactor system (fuel reactor and air reactor), which are interconnected through metal oxide media that carry oxygen. Both the oxygen and heat produced in the exothermic regeneration are transported between the reactors, constantly reigniting the new cycle of gasification. Unlike traditional gasification, there is no need for an air separation unit, as CO_2 is separated intrinsically. This process is gaining increasing attention in the gasification sector due to its significant benefits, such as high concentration of H_2 and low tar content in product gas, nitrogen-free syngas (with control of NO_x emissions), and its cost-effective separation of CO_2 (CCS). CLG for combined hydrogen production and carbon capture represents a significant pathway for clean fuels.

Integrated Gasification Combined Cycle (IGCC) merges gasification with a combined cycle power system to improve the efficiency of electricity generation. The cleaned syngas is used as fuel in a gas turbine to generate electricity. The hot exhaust gases from the gas turbine are then used to produce steam in a heat recovery steam generator (HRSG). Among the benefits of IGCC are its higher efficiency compared to direct biomass combustion, lower emissions (particularly of SO_2 and NO_x) and potential for carbon capture (as CO_2 can be more easily separated from the syngas before combustion).

Multi-step gasification is a process that involves multiple stages to optimise the conversion of biomass into syngas. This can include separate stages for pyrolysis, gasification and gas cleaning, allowing for better control over reaction conditions for each step, thereby maximising efficiency and minimising by-product formation, and often called pyro-gasification. By separating the gasification and cleaning processes, the overall system can achieve a higher quality of syngas with reduced tar content. Multi-step systems also can accommodate various feedstocks, including those with higher moisture content or contaminants. An example of this type of technology is two-stage gasification with integrated catalytic hot gas cleaning.

03

Beyond syngas: upgrading and by-product utilisation

Syngas, the primary product of gasification, serves as a versatile platform for the synthesis of various high-value chemicals and fuels. Understanding upgrading options is crucial for optimising gasification systems and tailoring them to specific end-use applications, thereby maximising the value extracted from feedstocks. Additionally, the valorisation of biomass gasification byproducts presents a multifaceted opportunity to enhance process efficiency and economic viability. To access the full spectrum of value streams from biomass and waste gasification, both syngas upgrading and biochar utilisation need to be assessed. This integrated approach is essential for developing economically viable and environmentally sustainable gasification systems, which align with circular economy principles and contribute to the broader goals of renewable energy deployment and carbon management.

Pathways of syngas upgrading

Syngas energy density can be up to 30% lower than that of natural gas and cannot be injected as such in the natural gas grid. This leads to the integration of gasification with second-stage processing. Product gas can be upgraded for various end-use applications, each with its own advantages and challenges. Gasification is usually combined with second-stage processing for the following end-uses:

- cogeneration into power and heat;
- water-gas shift into hydrogen;
- CH_4 generation via methanation;
- Fischer-Tropsch (FT) into transportation fuels (e.g. diesel);
- high temperature industrial processes;
- chemical synthesis into balk chemicals (e.g. DME, ethanol, methanol).

Table 2 summarises the evaluation of these pathways according to energy efficiency, technological readiness and thermodynamic losses.

Table 2. Comparison of syngas upgrading pathways

Syngas upgrading			
	Energy efficiency	Technological readiness	Thermodynamic losses
Direct CHP	high	mature	low
Methanation	moderate	mature	moderate
Hydrogen upgrading	moderate	low	moderate
FT fuels	low	mature	high
Chemicals synthesis	low	moderate	high
High T industrial process	low	mature	moderate

Energy Efficiency:

- Highest Efficiency: Direct CHP (80-90% overall efficiency with heat recovery)
- Moderate Efficiency: Methanation (60-70% and up to 85% with heat recovery) and hydrogen upgrading (60-70%)
- Lower Efficiency: Fischer-Tropsch fuels (45-55%), high T industrial processes (40-65%) and chemical synthesis (40-60%)

Technological Readiness:

- Most Mature: CHP, high T industrial processes, Fischer-Tropsch fuels and methanation (commercially available and widely implemented)
- Moderately Mature: Chemical synthesis (variable readiness depending on the target chemical)
- Emerging but Mature: Hydrogen upgrading (commercially available with ongoing research and improvements)

Thermodynamic Losses:

- Lowest Losses: Direct CHP (efficient heat recovery)
- Moderate Losses: Methanation, high T industrial processes (depends on specific process) and WGS hydrogen upgrading (manageable heat management)
- Higher Losses: Fischer-Tropsch fuels (synthesis inefficiencies and gas conditioning) and chemical synthesis (variable depending on the process)

Direct CHP systems offer the highest overall efficiency and technological maturity, making them a reliable option for immediate implementation. Methanation (especially with heat recovery) and hydrogen upgrading also offer high energy efficiency and mature technologies, with significant potential for future growth. The market potential and application of different end-products of gasification are discussed in more detail in the report "Gasification – A Sustainable Technology for Circular Economies", released by EBA in 2021.

Biochar

The valorisation of gasification byproducts makes the process more economically viable and environmentally sustainable, while also opening up new avenues for technological innovation and resource utilisation. Even if most of the gasification applications help maximise syngas production, some gasifiers may also produce a small amount of biochar/char, the quality of which depends directly on the pollutant component of the gasified feedstock. Biochar is one such byproduct that could be further used for energy generation or considered as a commodity material. Biochar is a solid material similar to coal, is based on biomass and can be considered as a carbon sink. It is estimated that around 2.0-2.6 tonnes of CO_2 are trapped per tonne of biochar. As long as it is not used thermally, carbon is preserved for hundreds of years. Additionally, it is a valuable bioproduct whose application offers significant benefits beyond soil amendment (Table 3). Some biochar valorisations could thus directly contribute to Sustainable Development Goals (SDG)[3] in clean water and sanitation, affordable and clean energy, responsible consumption and production, and climate change, to name a few.

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[3] The 2030 Agenda for Sustainable Development, adopted by all United Nations (UN) Member States in 2015, lays out a collective roadmap for peace and prosperity for both people and the planet, now and into the future. Central to this agenda are the 17 Sustainable Development Goals (SDGs), which represent an urgent call to action for every nation, whether developed or developing, to engage in a global partnership.

Table 3. Overview of biochar applications potential

Application		Benefits
Environment		
Carbon sequestration	Long-term storage of carbon in stable form (CCS)	Reduces atmospheric CO_2
GHG emission reduction	Alters soil microbial processes to the pathway with less gas emissions; reduces emissions from compost	Reduces NO_x and CH_4 emissions
Water filtration	Porous structure absorbs contaminants	Improves water quality
Agriculture and farming		
Soil fertility	Improves nutrient retention; fosters microbial communities	Improves crop yield, reduces chemical fertiliser use
Nutrient management	Reduces nutrient leaching; slows fertiliser release	Improves nutrient efficiency
Pest control	Alter soil conditions to reduce pest population	Reduces pesticide use
Soil remediation	Adsorbs heavy metals and organic pollutants	Improves soil quality; prevents ground water contamination
Animal feed additive	Improves digestion	Reduces methane emissions from manure; improves animal health
Industrial		
Material enhancement	Additive in plastics, concrete and other materials; catalyst support with high surface area	Improves material properties; supports sustainable processes
Bioenergy	Improves efficiency of AD when used as an additive	Increases system stability; adsorbs impurities; improves CH_4 yield

Policy context:

Biochar Regulatory Framework

In recent years, biochar has been progressively regulated by EU policies. Its first mention as a possible carbon removal methodology was included in the 2018 impact assessment of the European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. [4]

Within this context, it was for the first time considered as one of the possible carbon removal options, but its possible impact was not further assessed. Currently, biochar is being regulated as soil amendment under the EU fertiliser product regulation, offering the possibility to commercialise compliant biochar within the EU internal market, and in the context of EU carbon removal and carbon farming certification regulation, where the European Commission and a group of sector experts are currently working on operational criteria.

EU Fertilising Products Regulation

If manufacturers wish to market biochar as a CE-marked fertilising product, which can be commercialised across EU Member States, they will have to demonstrate compliance with Fertilising Products Regulation (EU) 2019/1009 (FPR)[5].

FPR requirements include the following (Article 4):
Biochar meets the requirements for the relevant component material category (CMC) or categories set out in Annex II.

- It meets the requirements for the relevant product function category (PFC) set out in Annex I.
- It is labelled in accordance with the labelling requirements set out in Annex III.
- It has successfully passed the relevant conformity assessment procedure set out in Annex IV.

Under the FPR, one component material category is specifically made for biochar – "CMC 14 Pyrolysis and gasification materials" and the product function category that is likely to be used is "PFC 3(A) Organic Soil Improver" (see Annex II, Table A1 and Table A2 for requirements to be fulfilled according to CMC and PFC).

EU Carbon Removals and Carbon Farming (CRCF) Certification Regulation

On 30 November 2022, the European Commission proposed a Union Certification Framework for Carbon Removals to boost carbon removals and support EU climate neutrality by 2050. Following the EU legislative process, the European Parliament adopted the final text on 10 April 2024, renaming it the "EU Carbon Removals and Carbon Farming (CRCF) Certification Regulation". Formally approved by the new Parliament on 21 October 2024, the text now awaits Council approval before being published in the Official Journal and entering into force.

The objective of the CRCF is to boost the development of carbon removals across the EU and to fight greenwashing by setting an EU-wide voluntary framework for carbon removal.

In the CRFC, carbon removals are divided in three broad categories of activities or projects, with each type of activity generating certified units.

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[4] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0773

[5] Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003

Table 4. Carbon removal activities and certification units

Type of activity	Description	Certified unit
Permanent carbon removal	Includes a range of industrial technologies designed to capture carbon from the atmosphere and store it for several centuries, preventing its release back into the air. Storage occurs in geological formations, reactive minerals or through permanently chemically-bound carbon in products. Examples: direct air CCS and biomass with CCS.	Permanent carbon removal unit
Carbon farming	Involves practices and processes applied to agricultural lands, wetlands, forests and coastal environments to store/sequester carbon from the atmosphere through biological means or to reduce GHG emissions from soils. Examples: reduced tillage, the introduction of legume or rotation crops, improved forest management, reforestation and agroforestry. Carbon farming activities can reduce emissions of NOx associated with the excessive use of fertilisers. Some carbon farming activities, such as peatland rewetting, can both reduce soil carbon emissions and increase biogenic carbon removals.	Carbon farming sequestration unit or Soil emission reduction unit
Carbon storage in products	Atmospheric or biogenic carbon is captured and stored in long-lasting products (wood-based construction elements of buildings or bio-based insulation materials). Excludes short-lived products like paper or furniture.	Carbon storage in product unit

Policy context:

Biochar Regulatory Framework

To be certified, eligible activities need to meet the four criteria (so-called "QU.A.L.ITY" criteria):

- **Quantification** (article 4): certified activities need to deliver a measurable net benefit for the climate. Therefore, carbon removals or soil emission reductions generated by activities over their entire duration (called 'activity period') must go beyond a baseline and outweigh any direct or indirect greenhouse gas (GHG) emissions associated with the implementation of the activity.
- **Additionality** (article 5): certified activities must be additional, i.e. they need to go beyond standard practice. In other words, operators must carry out activities that are not already imposed upon them by applicable law.
- **Long-term storage** (article 6): to ensure that carbon is stored permanently or over the long term, operators must monitor and guarantee the storage of carbon over a given period (so-called "monitoring period") – and are liable for any carbon reversal occurring during the monitoring period. For instance, permanent carbon removals need to be stored for several centuries (i.e. at least 200 years), carbon storage in long-lasting products for at least 35 years and carbon farming for at least five years.
- **Sustainability** (article 7): to contribute to wider sustainability objectives, activities must meet minimum sustainability requirements, which will build as appropriate on the "Do No Significant Harm" Screening Criteria set out under the Taxonomy Regulation.

To operationalise the quality criteria, the Commission is developing EU certification methodologies for a wide range of carbon removal and carbon farming activities, by means of delegated acts (Article 8). Under the Regulation (article 9), the European Commission will recognise (public or private) certification schemes that will be responsible for implementing the certification framework on the ground. The recognition will be granted for five years and based on a thorough assessment of the scheme's governance, rules and procedures.

This first legislative step paves the way for developing an EU methodology to certify biochar as a permanent carbon removal activity.

More information on existing carbon certification standards for biochar is available in the IBI Manual for Biochar Carbon Removal.

04

Gasification plants in Europe

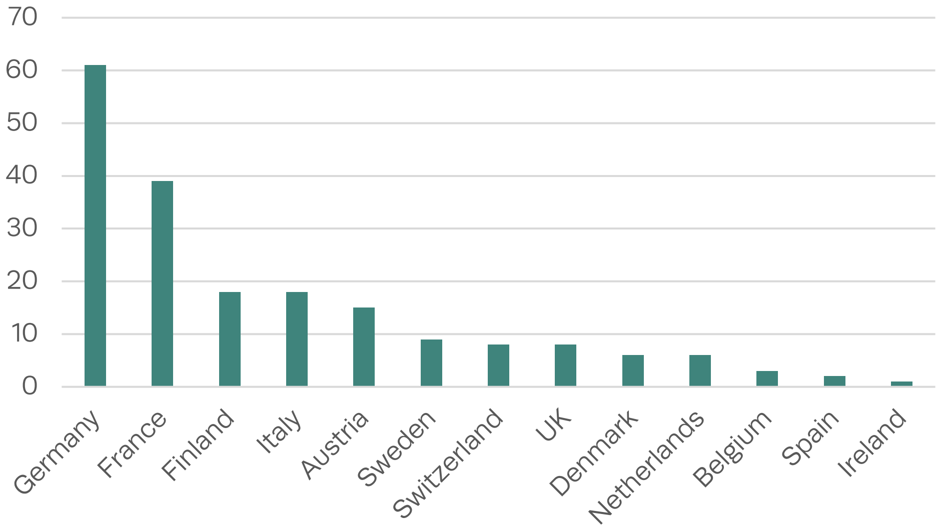
To provide a comprehensive understanding of the current landscape of thermal gasification in Europe, this paper includes a mapping analysis of existing gasification plants across Europe. Data for EBA Gasification Map was sourced from peer-reviewed research publications, contributions from EBA members and the IEA Task 33 database. By examining their operational parameters and geographical distribution, we can identify trends and opportunities for future development. Understanding these dynamics is essential for stakeholders seeking to navigate the complexities of deploying renewable energy technologies effectively. This is an ongoing activity, with more information on gasification facility locations to come, as well as more details to be added on each plant.

Statistics

Number of plants

As of 2023, in Europe there were approximately 141 existing biomass and waste gasification installations and 54 installations at different stages of development or with an unknown construction date. Germany is the leading country regarding the number of installations, with 61. The majority of the plants are in the pilot or demo stage. Several plants are located in research centres and universities, as they are built around innovative technologies. The country with the second largest number of projects is France. In France, five plants are in operation, while 34 plants are under development. Finland and Italy share third place in the number of installations (18 each), as well as the fact that over 80% of their installations are TRL ≥ 8. Figure 3 shows plant distribution across European countries.

Figure 3. Distribution of gasification plants in Europe (existing plants and plants under development)



Start of operation and TRL

There was significant plant building activity in the late 2000s and early 2010s (see Figure 4). This was most likely a response to various legislation adopted in 2008-2009. The Renewable Energy Directive (RED), adopted in 2009, set binding targets for the share of renewable energy sources for Member States. Many European countries introduced feed-in tariffs (FiTs) and other financial incentives for renewable energy production after RED implementation, making investments in biomass gasification technology more attractive. The introduction of carbon pricing mechanisms, such as the EU Emission Trading

System (ETS), created financial incentives for reducing greenhouse gas emissions. The EU Waste Framework Directive was adopted in 2008 and emphasised waste management practices, including energy recovery from waste. Biomass gasification was promoted as a cleaner alternative to fossil fuels, thus benefiting from these regulatory frameworks.

A series of crises in the early 2020s put a constraint on building new projects, but there are signs of revitalisation of the sector. It remains to be seen, however, if these emerging installations can progress to operating on an industrial scale. The majority (61%) of existing gasification plant are reported to be at a TRL of 9. Nevertheless, there are a number of projects that have not achieved a high technological readiness level over the years (24% of plants built before 2018 are not yet at full maturity, with a TRL ≤7). Figure 5 shows the distribution of technological maturity across all installations and projects.

Figure 4. Distribution of plant start of operation date

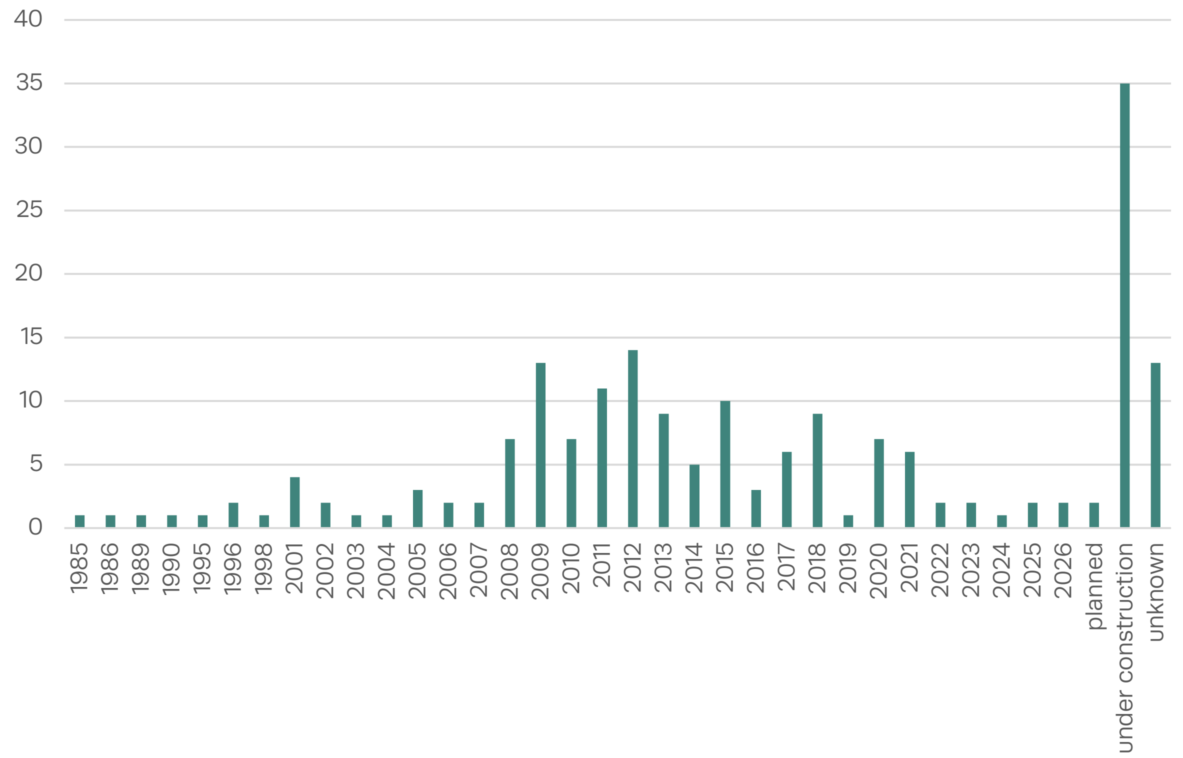
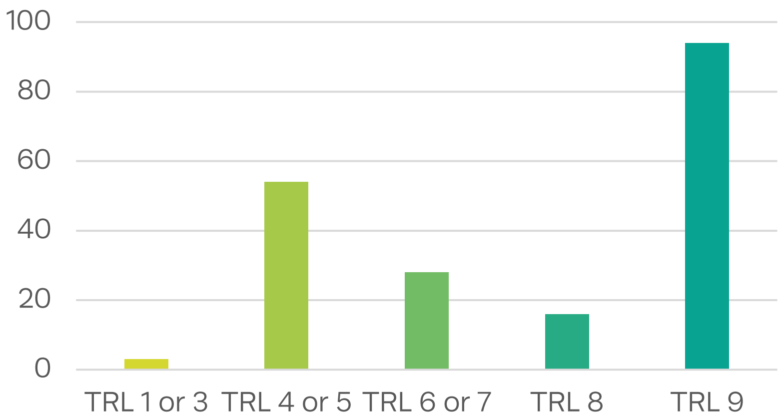


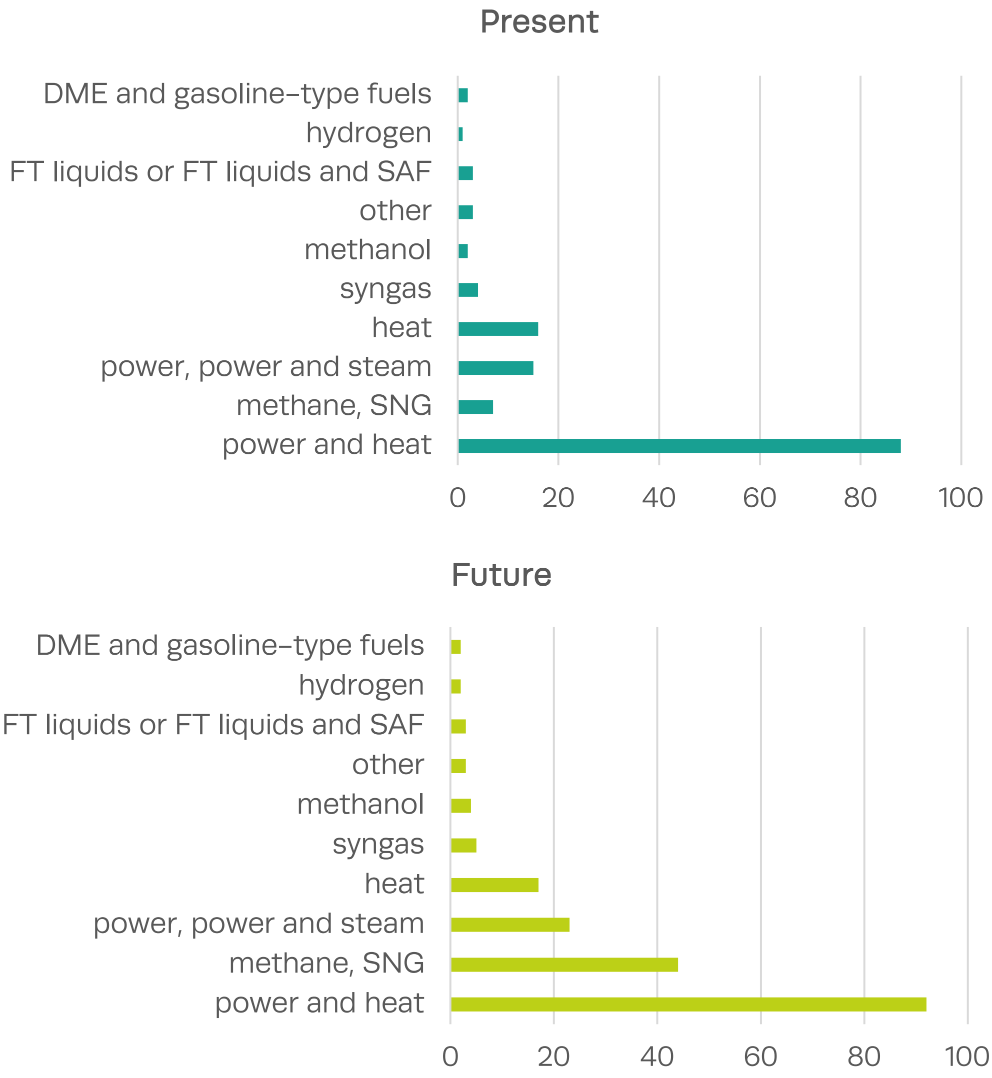
Figure 5. TRL prevalence among European gasification installations



Gasification products

The plant output at the moment is primarily CHP (84% of all installations), whether utilising both power and heat or just one of the components. The minority of plants upgrade syngas to further products, with a couple of installations each for hydrogen, methanol, SAF and other products (Figure 6, top). Methanation from H_2 to CH_4 is a field that is currently receiving a lot of scientific and industrial attention, as besides renewable energy, it provides a way to utilise biogenic CO_2. The topic of e-methane is covered in the report "Mapping e-methane plants and technologies" produced by EBA in September 2024. At the time of publication, there were seven known operational plants upgrading from gasification product gas to methane. Worthy of note, according to the French grid operators database ODRE, France declares having 40 existing installations based on pyrogasification technology, all of which can upgrade to SNG and will be connected to the gas grid. Five of them are at the demo stage and 35 are in various stages of preliminary development. Many of these projects are seeking financial support to start fully operating. Additionally, there are several projects in Europe in the construction stage that are planning on utilising CO_2 separated from the product gas mixture for e-methane synthesis.

Figure 6. Gasification products dynamic: only currently operating facilities (top) vs current and planned projects realised (bottom)



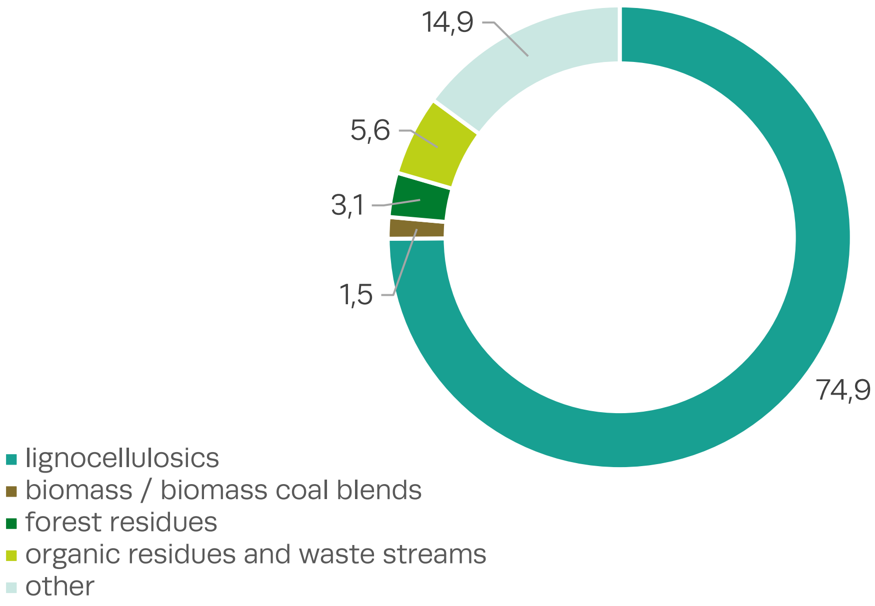
Feedstock

The feedstocks used in thermal gasification play a crucial role in determining the process efficiency and the quality of the produced syngas. A wide variety of biomass resources can be utilised, including agricultural residues (corn stover, rice husks and wheat straw), forestry wastes (sawdust, bark and logging residues), energy crops (switchgrass, miscanthus and short-rotation woody crops like willow and poplar) and municipal solid waste (MSW).

Agricultural residues are typically characterised by high cellulose and hemicellulose content, which can be effectively converted into syngas. Forestry wastes represent a significant source of biomass for gasification in regions with substantial forestry industries. MSW as a feedstock for gasification offers the dual benefits of waste management and energy recovery. The heterogeneous nature of MSW presents challenges in terms of feedstock preparation and process control, but advancements in sorting and pre-treatment technologies have improved its viability.

The majority of gasification plants (75%) are reported to use lignocellulosic materials, such as forestry and agricultural residues. Waste streams contribute around 5%. The remaining plants use mixed feedstock sources (Figure 7).

Figure 7. Proportions of feedstocks (%) for biomass and waste gasification



Case studies

Case 1. Industrial-scale ultra-pure syngas (CORTUS, Sweden)

The CORTUS plant, located in Höganäs (Sweden), represents a significant step in industrial-scale biomass gasification, demonstrating the feasibility of producing high-quality syngas from biomass for industrial applications. The plant uses CORTUS's proprietary WoodRoll® process for gasification. This is a several-step technology, using an entrained flow gasification reactor, operating at 1050 °C and at atmospheric pressure. This gasification plant has a nominal syngas output of 6 MW. It processes about 1900 kg/h of dry biomass, which currently consists mainly of wood chips with 40% moisture content. It is also capable of using woody waste products like logging residues or municipal yard trimmings.

This installation can handle feedstock with up to 45% moisture without pre-drying. The produced syngas is used as a green energy input for steel powder manufacturing by an adjacent industry (Höganäs AB). The CORTUS gasification plant is the first of its kind to produce ultra-pure nitrogen free syngas on an industrial scale from woody biomass. It aims to replace fossil gas in Höganäs AB's manufacturing process, contributing to decarbonisation efforts.

Case 2. Austria's Largest Wood Gasification Plant (Fürstenfeld, Austria)

The wood gasification plant in Fürstenfeld, Austria has been developed by Burkhardt GmbH. This facility is designed to enhance energy independence and sustainability in the region. It aligns with Austria's broader goals for sustainability and renewable energy production. The groundbreaking ceremony for the plant took place on 20 June 2023, and the plant was completed in record time.

The plant has an impressive output of 2,000 kW for electricity and 3,000 kW for heat. It is expected to produce approximately 16,000 MWh of electricity annually, which covers about 75% of Fürstenfeld's annual electricity consumption. The facility will also generate about 20,000 MWh of heat, fulfilling nearly all the energy requirements of the local district heating network.

The plant operates using wood gas produced from wood pellets, which powers 12 MAN engines across 12 lines. It employs a two-stage gasification process that efficiently converts biomass into usable energy while minimising emissions. Equipped with state-of-the-art filters and catalysts, the plant is designed to be virtually emission-free.

Case 3. Benchmark in biomass CHP (Güssing, Austria)

The Güssing Biomass Gasification Plant represents a successful implementation of innovative technology for renewable energy production. Its advanced dual fluidised bed steam gasification process not only provides electricity and heat, but also supports local sustainability efforts by utilising biomass resources efficiently. The Güssing plant was one of the first successful demonstrations of steam biomass gasification for CHP production on a commercial scale.
The plant has been in operation since 2002, accumulating over 100,000 operating hours, proving the technology's reliability and durability. The success of the 8 MW Güssing plant has led to the development of larger-scale projects based on the same technology.

The plant has an output of 2,000 kW of electricity and 4,500 kW of heat. Biomass chips are transported from a daily hopper to a metering bin and fed into the fluidised bed reactor via a rotary valve system and a screw feeder. The fluidised bed gasifier consists of two zones, a gasification zone and a combustion zone. The gasification zone is fluidised with steam, which is generated by waste heat from the process to produce a nitrogen-free producer gas. The combustion zone is fluidised with air and delivers the heat for the gasification process via the circulating bed material. Wood chips are used and delivered by local wood farmers, who have established a regional wood farmers' association to guarantee the continuous supply of the plant in Güssing as well as the supply of other biomass installations in Burgenland. To saving on transport costs, the material is obtained within a radius of about 25 kilometres.

The gasification plant in Güssing has got an overall efficiency of about 85%. The electrical efficiency is about 28%. It is worth noting that, in comparison to conventional bio-energy plants, for example steam turbines, efficiency is much higher in this new biomass conversion technology. The plant has contributed significantly to Güssing's transition to a 100% renewable energy supply, transforming the local economy. The technology demonstrated at Güssing has proven suitable for various applications beyond CHP, including hydrogen production and synthesis gas generation. In addition to providing power and heat for the municipality, the plant has served as a platform for numerous research projects.

Case 4. Biomethane production via pyrogasification (GAYA, France)

Led by ENGIE, the GAYA project brought together 11 excellent partners with complementary know-how to demonstrate the technical, environmental and economic feasibility of producing biomethane by gasification from dry biomass. Inaugurated in October 2017, ENGIE's experimental platform, located in Saint-Fons (Auvergne-Rhône-Alpes), implements an innovative chain of biomethane production processes on a semi-industrial scale, with the aim of reducing production costs and validating technical and environmental performance.

Today, around 22 engineers and technicians, combining the fields of R&D and operations, work on the site. At the end of 2020, the first cubic metres of synthetic methane were produced from SRF (Solid Recovered Fuels), demonstrating the robustness and flexibility of the technology chain developed. The tests also validated the functionality of the innovative methanation reactor designed by the ENGIE Lab CRIGEN, ENGIE's Corporate Research Centre, which operates and converts both syngas (from gasification) and a mixture of CO_2 and H_2 (typical of a power-to-gas process) to produce biomethane.

Today, the platform is used more than ever to support the sector's industrialisation, in particular by removing the various risks and allowing the development of the first commercial project based on GAYA technology: the Salamander project, which will be located in the port area of Le Havre, and which will produce 170GWh/year of bioSNG, fed with wood waste and SRF. The platform also continues to diversify the inputs that can be recovered by GAYA – by collaborating with waste producers.

05

Economic aspects of biomass and waste gasification

The biomass and waste gasification market presents significant opportunities for growth and investment, driven by the need for sustainable energy solutions and effective waste management. While the market faces challenges such as high capital costs, technological risks and regulatory uncertainty, the potential economic benefits and positive environmental impact make gasification an attractive investment area. The continued development and adoption of gasification technologies, supported by favourable policies and public-private partnerships, are essential for realising the full potential of this market. As the global push towards renewable energy and sustainability intensifies, biomass and waste gasification will play a crucial role in the transition to a cleaner and more resilient energy future.

Key Market Drivers

Environmental Regulations: worldwide implementation of stringent regulations to reduce greenhouse gas emissions and promote renewable energy encourage the adoption of gasification technologies to convert waste and biomass into clean energy.

Energy Security: countries are increasingly looking to diversify their energy mix to include renewable sources. Gasification offers a reliable and sustainable energy source, reducing dependence on fossil fuels and enhancing energy security.

Waste Management: effective waste management is a significant challenge for urban areas. Gasification provides a solution by converting municipal solid waste (MSW) into valuable energy, reducing landfill use and mitigating environmental pollution.

Technological Advancements: innovations in gasification technologies are improving efficiency, reducing costs and expanding the range of feedstocks that can be processed.

Supply and Demand: the availability and cost of feedstocks, such as agricultural residues, municipal waste and forestry by-products, influence the economic viability of gasification projects.

Key Challenges and Risks

High Capital Costs: initial investment for setting up gasification plants is high, which can be a barrier to entry for many investors.

Technological Risks: as gasification technologies are complex and require advanced engineering and operational expertise, the risk of technological failures and operational issues can deter investment.

Regulatory Uncertainty: changes in government policies and regulations can impact the gasification market, hence investors need to navigate regulatory risks and ensure compliance with evolving environmental standards.

Market Competition: the renewable energy sector is highly competitive in relation to market share. Gasification technologies must compete with solar, wind and other renewable energy sources for investment and adoption.

Techno-economic evaluation

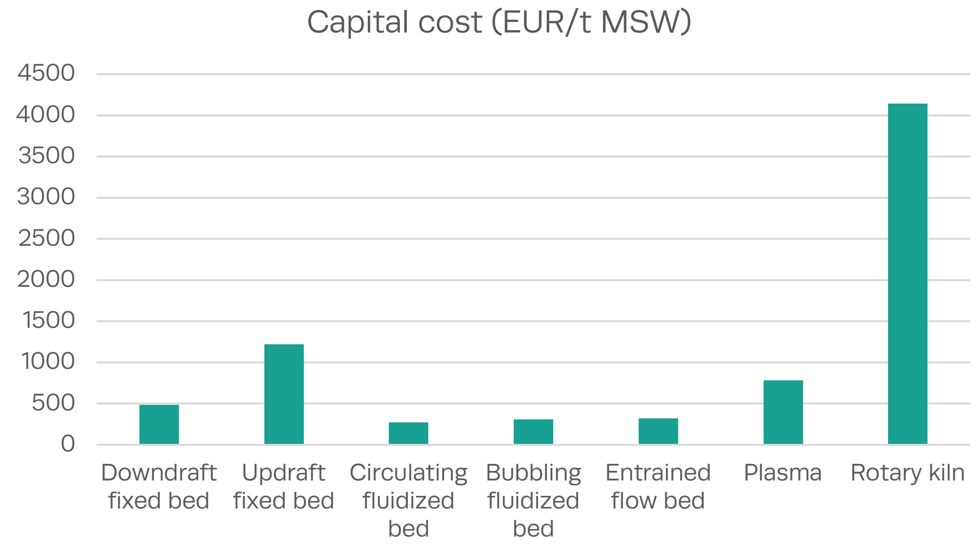
Gasification is already a mature technology in some parts of the world (China, India, USA), while penetration in the European market is still ongoing. Successful implementation hinges on careful consideration of the techno-economical parameters discussed below.

The standard methods of financial appraisal usually include the net present value (NPV), internal rate of return (IRR), simple and discounted payback period (SPB and DPBP respectively) and levelized cost of electricity (LCOE). Studies have shown that larger-scale plants tend to exhibit more favourable economic indicators due to economies of scale. For instance, NPV increases with plant size, reflecting higher profitability potential, ranging from approximately €122,000 for smaller systems to over €4 million for larger installations. DPP typically decreases with increased capacity; smaller plants may experience payback periods exceeding five years, while larger systems could achieve payback within six months to two years. The typical payback for bioenergy projects is 5-10 years, and it is typically assumed that the payback period for thermal gasification installations is around 8 years. The lifespan of the plant is usually assumed to be 15-30 years, with 20 years being used as a standard estimate.

The initial or capital expenditure (CAPEX) required for a gasification plant varies significantly based on the scale and technology employed. The breakdown of CAPEX typically includes costs associated with equipment procurement, installation, engineering and project management. It can also include grid connections, roads and any improvements to existing infrastructure. For instance, small-scale gasification systems (approximately 50 kW) have reported CAPEX ranging from €1.2 million to €1.5 million, while larger systems (up to 200 kW) require much higher investments. The estimated numbers for gasification are €3-10 million for every MW of installed capacity. Waste recycling gasification plants may entail somewhat higher investments. Reactor type has one of the most significant effects on the cost. For example, fluidised bed technology has the lowest capital cost, while rotary kiln reactors have the highest (Figure 8). Previous estimates were calculated for projects with direct CHP. Plants that do further upgrading from syngas into different end products, like hydrogen and methanol, require CAPEX of approximately €10-20 million per MW.

Operational expenditure (OPEX) encompasses the ongoing costs associated with running a gasification plant, including maintenance, labour, utilities and feedstock procurement. The OPEX of each technology also varies, with plasma gasification being one of the most expensive. Estimates suggest that OPEX can range from €50 to €250 per MWh of energy produced. The same considerations apply as with CAPEX; gasification costs less than waste and CHP operation costs less than upgrading to other end-products. Gasification technologies have to be operated in a different way than other renewable energy sources, as they require higher maintenance and the correct approach. Most small-scale plants need to be "tailored" around specific applications, which add to the cost.

Figure 8. Comparison of the capital costs of different gasification technologies (adapted from doi.10.3390/waste1010011)



The feedstock costs and cost of electricity generated from thermal gasification are crucial factors in assessing the economic viability of these plants. Feedstock is a critical input for gasification plants and can significantly impact overall economic feasibility, as its price can contribute up to 50% of the total cost of electricity produced. The cost of feedstock varies widely based on type and availability. For example, the forest residue price depends primarily on the cost of collection and transportation, and for this feedstock it is desirable to have the shortest transportation distance possible (local). The lowest priced feedstock in the agricultural residues category is usually straw and bagasse. Note that the utilization of waste can incur the lowest expenses, as often the feedstock itself is free and the cost incurred comes purely from transportation. The choice of feedstock affects not only operational efficiency, but also the environmental footprint of the gasification process.

The LCOE for thermal gasification typically ranges from €0.06 to €0.29 per kWh, depending on capital and feedstock costs. For instance, smaller-scale plants may have a higher LCOE due to lower economies of scale but can still be competitive with conventional energy sources when low-cost feedstocks are utilised effectively. Operational and maintenance costs can make a significant contribution to LCOE, accounting for 9% to 20% of the total.

Another parameter discussed in the context of gasification plant economy is overnight construction cost (OCC). OCC refers to the total cost required to construct a facility without accounting for financing or interest during construction. For thermal gasification plants, the OCC typically reflects the direct costs of materials and labour involved in building the plant infrastructure. Reports indicate that the OCC can be approximately 70–80% of total CAPEX for gasification projects, depending on location and specific project requirements. It is estimated that an overnight cost for a gasification plant can be in the €1,320–€4,000 per kWe range. Many models assume an estimate of around €2,500–€3,000 per kWe for an average installation.

Overview of Key Cost-Benefit Considerations

Capital and Operational Costs: the capital costs for gasification plants are substantial and need to be meticulously planned.

Revenue Generation: gasification plants generate revenue through the sale of syngas, electricity and by-products such as biochar and ash. The economic viability of gasification projects depends on market prices for these products and the ability to secure long-term contracts.

Economic Impact: gasification provides several economic benefits, including job creation (especially locally), reduced waste disposal costs and decreased reliance on fossil fuels (increasing energy independence, security and resilience). Cleaner air, reduced landfill use and sustainable energy production improve public health and quality of life.

Subsidies and Incentives: government subsidies and incentives play a crucial role in the economic feasibility of gasification projects. These can include tax credits, grants, feed-in tariffs and renewable energy certificates.

In summary, biomass and waste gasification presents a promising avenue for renewable energy production, with substantial economic potential. However, there is an urgent necessity for policies and financial incentives for biomass gasification projects. According to estimate provided in the European Commission's report "Development of outlook for the necessary means to build industrial capacity for drop-in advanced biofuels", under current market conditions, the energy contribution of gasification technologies can reach 0.62 bcm by 2030 and 9.9 bcm by 2050. However, according to Guidehouse modelling in the "Biogases towards 2040 and beyond" report, the potential for biomethane production from thermal gasification can reach 37 bcm. Accelerated growth is expected after 2030 when all currently developing technologies will enter the technologically mature stage, the production chain will be fully optimised and all appropriate feedstocks (including novel feedstocks) will be utilised accordingly. A lot of regulatory work is still needed to extract the full potential from this technology. Future research should focus on optimising operational efficiencies and reducing costs to enhance the competitiveness of biomass gasification in the renewable energy sector. One of the solutions is in the power generation plants using locally-sourced by-products, which can be an active part of smart-grid systems, coexisting with local communities that are adequately trained about the opportunities and limitations of gasification technologies. As technology advances and market conditions evolve, biomass and waste gasification could play an integral role in transitioning towards sustainable energy solutions, while mitigating the environmental impacts associated with fossil fuel consumption.

Bibliography

Chapter 1

S. Heyne, T. Liliedahl, M.Marklund, *Biomass Gasification – a Synthesis of Technical Barriers and Current Research Issues for Deployment at Large Scale*, The Swedish Knowledge Centre for Transport Fuels, Report from an f3 project, **2013**

Guidehouse, *Biogases towards 2040 and beyond*, European Biogas Association, Brussels, Belgium, **2024**

N. Nesterenko, I. C. Medeiros-Costa, E. B. Clatworthy, H. Cruchade, S. V. Konnov, J.-P. Dath, J.-P. Gilson, and S. Mintova, *Methane-to-chemicals: a pathway to decarbonization*, National Science Review **2023**, 10, 116

Spherical Insights.com / Global Biomass Gasification Market Size, Share, Analysis - 2030.

GlobeNewswire.com / Biomass Gasification Industry Forecast to Cross $143

Marketsandmarkets.com / Biomass Gasification Market Growth Drivers & Opportunities | MarketsandMarkets

Chapter 2

M. Mukamwi, T. Somorin, R. Soloha, E. Dace, *Databases for biomass and waste biorefinery – a mini-review and SWOT analysis*, Bioengineered **2023**, 14:1, 2286722

M. Worley, J. Yale, *Biomass Gasification Technology Assessment: Consolidated Report*, National Renewable Energy Laboratory, Golden, **2012**

National Renewable Energy Laboratory, *Process Design and Economics for Conversion of Lignocellulosic Biomass to Ethanol - Thermochemical Pathway by Indirect Gasification and Mixed Alcohol Synthesis,* NREL, **2011**

Z. Wu, Z. Zhang, G. Xu, S. Ge, X. Xue, H. Chen, *Thermodynamic and economic analysis of a new methanol synthesis system coupled with a biomass integrated gasification combined cycle,* Energy **2024**, 300, 131647

T. J. Schildhauer and S. M. A. Biollaz, Eds., *Synthetic Natural Gas from Coal, Dry Biomass, and Power-to-Gas Applications*. Hoboken, NJ: John Wiley & Sons, **2016**

IEA Bioenergy Task 33, *Emerging Gasification Technologies for Waste & Biomass*, International Energy Agency Bioenergy, **2020**

J. Schröder, E. Remmele, and K. Thuneke, *Monitoring renewable energies in transport*, DBFZ Report No. 44, Deutsches Biomasseforschungszentrum gemeinnützige GmbH, Leipzig, Germany, **2023**

Q. He, X. Zhao, J. Rao, X. Huang, P. Sun, C. Lian, *The role of various biomass feedstocks in the design and optimization of an integrated gasification combined cycle*, Fuel **2022**, 327, 125182

P. Ghodke, A. Sharma, A. Jayaseelan, K. Gopinath, *Hydrogen-rich syngas production from the lignocellulosic biomass by catalytic gasification: A state of art review on advance technologies, economic challenges, and future prospectus*, Fuel **2023**, 342, 127800

J. Makwana, A. Dhass, P. Ramana, D. Sapariya, D. Patel, *An analysis of waste/biomass gasification producing hydrogen-rich syngas: A review*, International Journal of Thermofluids **2023**, 20, 100492

I. Siddique, A. Salema, *Production of syngas from oil palm shell biomass using microwave gasification*, Energy **2024**, 306, 132468

C. Freda, E. Catizzone, A. Villone, G. Cornacchia, *Biomass gasification in rotary kiln integrated with a producer gas thermal cleaning unit: An experimental investigation*, Results in Engineering **2024**, 21, 101763

O. Condori, A. Abad, F. García-Labiano, L. de Diego, M. Izquierdo, J. Ad´anez, *Parametric evaluation of clean syngas production from pine forest residue by chemical looping gasification at the 20 kW_{th} scale*, Journal of Cleaner Production **2024**, 436, 140434

Y. Niu, Z. Chi, M. Li, *Advancements in biomass gasification research utilizing iron-based oxygen carriers in chemical looping: A review*, Materials Reports: Energy **2024**, 4, 100282

Y. Pang, X. Zhu, N. Li, Z. Wang, *Experimental study on co-gasification of cellulose and high-density polyethylene with* CO_2, Journal of the Energy Institute **2024**, 117, 101839

V. Nagar, R. Kaushal*, A review of recent advancement in plasma gasification: A promising solution for waste management and energy production*, International Journal of Hydrogen Energy **2024**, 77, 405

Y. Shen, *Biomass pretreatment for steam gasification toward* H_2*-rich syngas production – An overview*, International Journal of Hydrogen Energy **2024**, 66, 90

D. Cvetinovic, A. Eri, M. Mladenovic, J. Buha-Markovic, Bojan Jankovic, *Thermal plasma gasification of sewage sludge: Optimisation of operating parameters and economic evaluation*, Energy Conversion and Management **2024**, 313, 118639

M. Yan, N. Afxentiou, P. Fokaides, *The State of the Art Overview of the Biomass Gasification Technology*, Current Sustainable/Renewable Energy Reports **2021**, DOI:10.1007/s40518-021-00196-2

A. Bukar, M. Oumarou, B. Tela, A. Eljummah, *Assessment of Biomass Gasification: A Review of Basic Design Consideration*s, American Journal of Energy Research **2019**, 7, 1-14

A. Ramos, E. Monteiro, A. Rouboa, *Biomass pre-treatment techniques for the production of biofuels using thermal conversion methods – A review*, Energy Conversion and Management **2022**, 270, 116271

R. Aguado, A. Baccioli, A. Liponi, D. Vera, *Continuous decentralized hydrogen production through alkaline water electrolysis powered by an oxygen-enriched air integrated biomass gasification combined cycle*, Energy Conversion and Management **2023**, 289, 117149

A. Goel, E. Moghaddam, W. Liu, C. He, J. Konttinen, *Biomass chemical looping gasification for high-quality syngas: A critical review and technological outlooks*, Energy Conversion and Management **2022**, 268, 116020

L. Nunes, *Biomass gasification as an industrial process with effective proof-of-concept: A comprehensive review on technologies, processes and future developments*, Results in Engineering **2022**, 14, 100408

Y. Gao, M. Wang, A. Raheem, F. Wang, J. Wei, D. Xu, X. Song, W. Bao, A. Huang, S. Zhang, H. Zhang, *Syngas Production from Biomass Gasification: Influences of Feedstock Properties, Reactor Type, and Reaction Parameters*, ACS Omega **2023**, 8, 31620

Chapter 3

E. Meers, G. Velthof, E. Michels, and R. Rietra, Eds., *Biorefinery of Inorganics: Recovering Mineral Nutrients from Biomass and Organic Waste*. Hoboken, NJ: John Wiley & Sons, **2020**

O. Soka, O. Oyekola, *A feasibility assessment of the production of char using the slow pyrolysis process,* Heliyon **2020**, 6, e04346

USDA, *Technical Evaluation Report -Biochar*, Compiled by Savan Group for the USDA National Organic Program, **2021**

M. García-Prats, E. Olivera-Begué, D.González, A. Sánchez, *Biochar: An emerging material for the improvement of biological treatment of organic waste,* Waste Management Bulletin **2024**, 2, 120

International Renewable Energy Agency (IRENA), *Biomass for Power Generation*, IRENA Working Paper, vol. 1, no. 1/5, **2012**

B. Garcia, O. Alves, B. Rijo, G. Lourinho, C. Nobre, *Biochar: Production, Applications, and Market Prospects in Portugal*, Environments **2022**, 9, 95

M. Afshar, S. Mofatteh, *Biochar for a sustainable future: Environmentally friendly production and diverse applications*, Results in Engineering **2024**, 23, 102433

J. Schroeder, H.W.J.P. Neomagus, J.R. Bunt, R.C. Everson, R.C. Uwaoma, *Steam gasification kinetics of biochar at elevated pressures,* Heliyon **2024**, 10, e31172

European Biogas Association, *Gasification: A Sustainable Technology for Circular Economies*, EBA, Brussels, Belgium, **2021** / www.europeanbiogas.eu/gasification-a-sustainable-technology-for-circular-economies

European Commission , *EU Carbon Removals and Carbon Farming (CRCF) Certification Regulation* | Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL establishing a Union certification framework for carbon removals, COM/2022/672 final

European Commission, *Union certification framework for carbon removals* / https://www.europarl.europa.eu/doceo/document/TA-9-2024-0195_EN.html

European Commission, *Manual for biochar carbon removal* / https://biochar-international.org/manual-for-biochar-carbon-removal/

13. A. Poluzzi, G.Guandalini,M. C. Romano, *Flexible methanol and hydrogen production from biomass gasification with negative emissions*, Sustainable Energy Fuels **2022**, 6, 3830

Y. Pleshivtseva, M. Derevyanov, A. Pimenov, A. Rapoport, *Comprehensive review of low carbon hydrogen projects towards the decarbonization pathway*, International Journal of Hydrogen Energy **2023**, 48, 3703

A. Mertins, M. Heiker, S. Rosenberger, T. Wawer, *Competition in the conversion of the gas grid: Is the future of biogas biomethane or hydrogen?*, International Journal of Hydrogen Energy **2023**, 48, 32469

Chapter 4

G. Allesina, S. Pedrazzi, *Barriers to Success: A Technical Review on the Limits and Possible Future Roles of Small Scale Gasifiers*, Energies **2021**, 14, 6711

E. Monteiro, A. Ramos, A. Rouboa, *Fundamental designs of gasification plants for combined heat and power,* Renewable and Sustainable Energy Reviews **2024**, 196, 114305

G. Lourinho, O. Alves, B. Garcia, B. Rijo, P. Brito, C. Nobre, *Costs of Gasification Technologies for Energy and Fuel Production: Overview, Analysis, and Numerical Estimation*, Recycling **2023**, 8, 49

European Biogas Association, *Mapping e-methane plants and technologies*, EBA, Brussels, Belgium, **2024** / https://www.europeanbiogas.eu/mapping-e-methane-plants-and-technologies-2/

ODRE database / Projets de production de gaz renouvelable et bas carbone par pyrogazeification pour injection dans les réseaux gaziers — Open Data Réseaux Énergies (ODRÉ)

Chapter 5

G. Allesina, S. Pedrazzi, *Barriers to Success: A Technical Review on the Limits and Possible Future Roles of Small Scale Gasifiers*, Energies **2021**, 14, 6711

M.A. Nemitallah, A.A. Alnazha, U. Ahmed, M. El-Adawy, M.A. Habib, *Review on techno-economics of hydrogen production using current and emerging processes: Status and perspectives*, Results in Engineering **2024**, 101890

R. Aguado, D. Vera, D. López-García, J. Torreglosa, F. Jurado, *Techno-Economic Assessment of a Gasification Plant for Distributed Cogeneration in the Agrifood Sector,* Appl. Sci. ***2021**, 11, 660*

D. Sánchez-Lozano, A. Escámez, R. Aguado, S. Oulbi, R. Hadria, D. Vera, *Techno-Economic Assessment of an Off Grid Biomass Gasification CHP Plant for an Olive Oil Mill in the Region of Marrakech-Safi, Morocco*, Appl. Sci. **2023**, 13, 5965

R. Rauch, Y. Kiros, K. Engvall, E. Kantarelis, P. Brito, C. Nobre, S. Santos, P. Graefe, *Hydrogen from Waste Gasification*, Hydrogen **2024**, 5, 70

S. Santos, A. Assis, L. Gomes, C. Nobre, P. Brito, *Waste Gasification Technologies: A Brief Overview*, Waste **2023**, 1, 140

N. Rubinsin, N. Karim, S. Timmiati, K. Long Lim, W. Isahak, M. Pudukudy, *An overview of the enhanced biomass gasification for hydrogen production*, International journal of hydrogen energy **2024**, 49, 1139

G. Lourinho, O. Alves, B. Garcia, B. Rijo, P. Brito, C. Nobre, *Costs of Gasification Technologies for Energy and Fuel Production: Overview, Analysis, and Numerical Estimation*, Recycling **2023**, 8, 49

European Commission, *Development of outlook for the necessary means to build industrial capacity for drop-in advanced biofuels*, Publications Office of the European Union, Luxembourg, **2024** / https://op.europa.eu/en/publication-detail/-/publication/b1c97235-c4c3-11ee-95d9-01aa75ed71a1

C.Cormos, M.Dragan, L. Petrescu, A. Cormos, S.Dragan, A. Bathori, S. Galusnyak, *Synthetic natural gas (SNG) production by biomass gasification with CO_2 capture: Techno-economic and life cycle analysis (LCA)*, Energy **2024**, 312, 133507

Annex

R.W.R. Zwart, *Gas cleaning downstream biomass gasification - Status Report 2009*, Energy Research Centre of the Netherlands (ECN), Petten, The Netherlands, Rep. ECN-E-08-078, **2009**

T. J. Schildhauer and S. M. A. Biollaz, Eds., *Synthetic Natural Gas from Coal, Dry Biomass, and Power-to-Gas Applications*. Hoboken, NJ: John Wiley & Sons, **2016**

N. Rubinsin, N. Karim, S. Timmiati, K. Long Lim, W. Isahak, M. Pudukudy, *An overview of the enhanced biomass gasification for hydrogen production*, International Journal of Hydrogen Energy **2024**, 49, 1139

M. Cortazar, L. Santamaria, G. Lopez, J. Alvarez, L. Zhang, R. Wang, X. Bi, M. Olazar, *A comprehensive review of primary strategies for tar removal in biomass gasification*, Energy Conversion and Management **2023**, 276, 116496

V. Marcantonio, L. Zotto, J. Ouweltjes, E. Bocci, *Main issues of the impact of tar, H_2S, HCl and alkali metal from biomass-gasification derived syngas on the SOFC anode and the related gas cleaning technologies for feeding a SOFC system: A review*, International Journal of Hydrogen Energy **2022**, 47, 517

A. Kushwah, T.R. Reina, M. Short, *Modelling approaches for biomass gasifiers: A comprehensive overview*, Science of the Total Environment **2022**, 834, 155243

M. Szul, K. Głód, T. Iluk, *Influence of pressure and CO_2 in fluidized bed gasification of waste biomasses*, Biomass Conversion and Biorefinery **2021**, 11, 69

N. Coutoa, A. Rouboa, V. Silvaa, E. Monteiro, K. Bouziane, *Influence of the biomass gasification processes on the final composition of syngas*, Energy Procedia **2013**, 36, 596

S. Mishra, R. Upadhyay, *Review on biomass gasification: Gasifiers, gasifying mediums, and operational parameters*, Materials Science for Energy Technologies **2021**, 4, 329

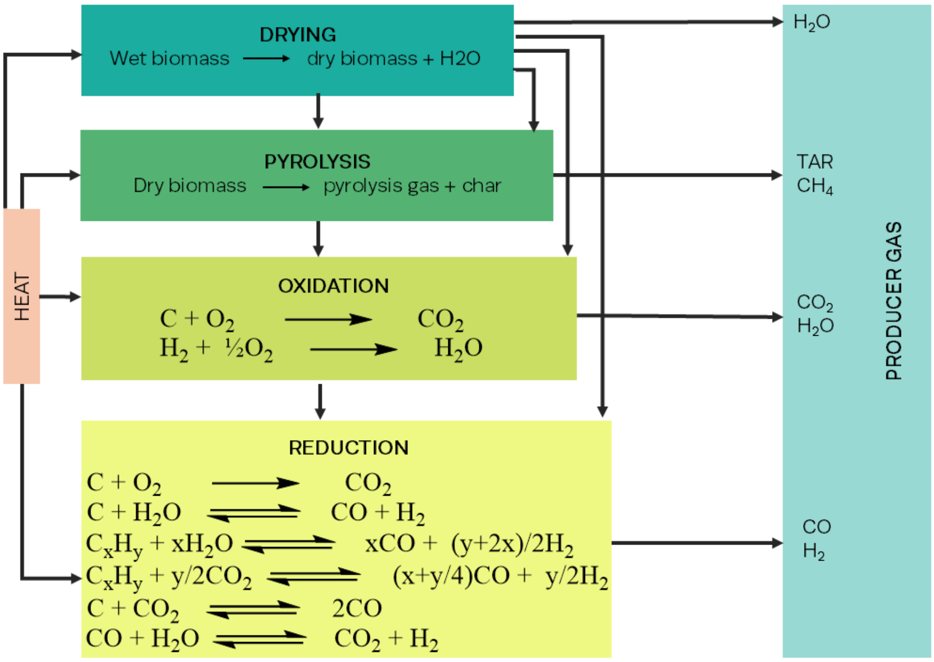
A. Larssona, M. Kuba, T. Vilches, M. Seemann, H. Hofbauer, H. Thunman, *Steam gasification of biomass – Typical gas quality and operational strategies derived from industrial-scale plants*, Fuel Processing Technology **2021**, 212, 106609

Annex

Operational parameters of a thermal gasification installation

The process usually consists of four stages with different operating conditions: pretreatment/drying, pyrolysis, oxidation/combustion and reduction. The major reactions occurring during the gasification process that are commonly considered relevant are shown in Figure A1.

Figure A1. Primary reactions and stages of the gasification process



Pyrolysis stage

During this step, feedstock is thermally decomposed (150–500 ˚C) in an oxygen-free environment into solid charcoal, liquid wood tar and pyroligneous liquor, and combustible gases. Product selectivity depends on temperature, gasifier type and biomass composition. The main components of feedstock decompose at different temperature ranges: a) hemicellulose (150–350 ˚C), b) cellulose (275–350 ˚C) and c) lignin (250–500 ˚C). A higher T yields more gases and liquids and less charcoal. Hemicellulose and lignin produce more char than cellulose. If making char is an objective, then 300 ˚C is a sufficient temperature.

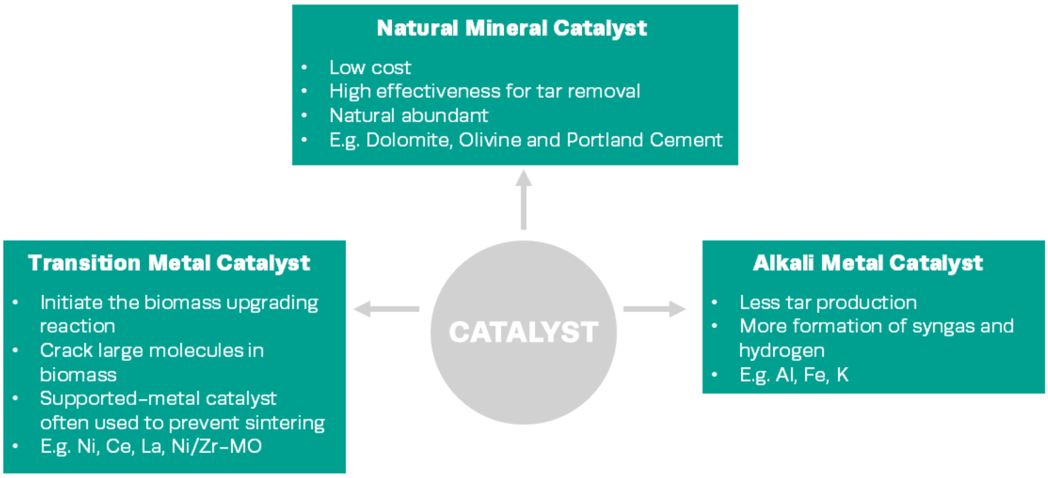
Oxidation and reduction stages: Influence of gasification parameters

Effect of operation conditions (T, P). Operating conditions differ according to objectives and the material used. Operating gasifying T affect the composition and quantity of product gas, and tar formation, as it affects chemical reactions associated with the process. A higher T (above 800 ˚C) accelerates the production of H_2 and CO and reduces CO_2 and CH_4, and also promotes tar reforming and cracking reactions. However, excessively high temperatures (over 1,000 ˚C) lead to catalyst deactivation and reduction of H_2 concentration in the product gas. Conversely, a reduction of ash agglomeration requires a lower T, which in practice may limit gasification to temperatures only up to 750 ˚C. The gasification performance and product gas quality are also influenced by the gasification pressure and particle pressure of gasifying agents. Gasification at elevated pressures provides higher reaction efficiencies and kinetics, leading to improved overall process efficiency and gasification performance. However, the tar yields tend to increase with rising pressure levels, which can be attributed to change in the pathways of secondary pyrolysis reactions.

Effect of gasifying agent. The main agents used for oxidation reactions in gasification process are oxygen, carbon dioxide, air and steam. There are different gasification reactions with different reaction rates resulting from those agents, which influence the composition of gaseous stream, the heating value of the produced gas and tar content. The choice is determined by the balance between the required syngas quality and the process cost. The most common gasification agent due to its low cost is air. However, the process has a lower syngas yield and the produced gas has low calorific value due to the high nitrogen content in the air. Oxygen gasification involves some additional cost for a gasifying agent, but the produced gas has the lowest tar content and medium energy content. Steam is widely used as a gasifying agent, since the chemical equilibrium is shifted to promote hydrogen generation. The resulting gas has high energy content, although higher tar concentration is also produced. Alas, excessive steam could decrease temperature. Adding to the fact that the process is highly endothermic, the steam gasification requires an external energy supply. In view of these facts, air/steam gasification seem to be garnering more attention, as it is promising both from the chemical and economical points of view.

Catalyst influence. Bed material plays a prominent role in the choice of gasifier, since it can be inert or catalytic. The presence of a catalyst could lead to a higher yield and lower tar content, as it enhances cracking and reforming reactions, resulting in cleaner gas with higher calorific value. The use of these catalysts can be divided into primary (directly in the reactor) or secondary (in the downstream processes). Figure A2 shows three main types of catalysts used in gasification: alkali metal, transitional metal and natural mineral. Overall, alkali metal catalysts are very effective at reducing tar formation and increasing syngas yield. The most common are mineral oxides and Ca or Mg carbonates. Transition metal catalysts provide stability, a large surface area and potential for metal-support interaction. Ni supported on a variety of materials (Al_2O_3, ZrO_2, TiO_2, CeO_2, MgO) is used the most in research and industrial settings. However, the drawbacks of nickel, namely toxicity and rapid deactivation caused by carbon deposits, have recently shifted attention onto Fe as a more appealing option. Natural mineral catalysts, such as dolomite, olivine and limestone, are the least expensive option in the group. Although the tar content in the product gas does not meet requirements for downstream application, the mineral catalyst can act as a guard catalyst to avoid rapid deactivation of an expensive secondary catalyst.

Figure A2. Types of catalysts in gasification (adapted from doi.10.1016/j.ijhydene.2023.09.043)



Natural Mineral Catalyst
- Low cost
- High effectiveness for tar removal
- Natural abundant
- E.g. Dolomite, Olivine and Portland Cement

Transition Metal Catalyst
- Initiate the biomass upgrading reaction
- Crack large molecules in biomass
- Supported-metal catalyst often used to prevent sintering
- E.g. Ni, Ce, La, Ni/Zr-MO

Alkali Metal Catalyst
- Less tar production
- More formation of syngas and hydrogen
- E.g. Al, Fe, K

Equivalent ratio (ER) and steam-biomass ratio (SB). ER is a ratio of actual air-to-biomass relative to fuel stoichiometrically required for total biomass conversion (X). A higher ER means more air in the gasifier and an increase in CO_2 formation due to oxidation reactions and a decrease in hydrogen production. An ER near 1 approaches full oxidation conditions, while a value close to 0 shifts the process towards pyrolysis. For atmospheric pressure gasification, the optimum ER was found to be in the range of 0.19–0.43, with values around 0.32 considered ideal for maximising syngas quality. The optimal ER depends on factors like gasifier type, feedstock, and the gasifying agent used. There is a strong correlation between ER and gasification T.

$$ER = \frac{Oxygen\ mass\ (air)[kg]/Dry\ basis\ biomass\ [kg]}{Oxygen\ stoichiometry\ (air)[kg]/Biomass\ ratio\ [kg]}$$

SB is evaluated when the oxidising agent is not air but steam (X). It is defined as the mass flow rate of the steam fed into the reactor relative to the biomass flow rate. The observed range of SB in gasification is 0.3 to 1.5, with the optimal range considered to be between 0.6 and 0.85. A higher SB means displacement of the WGS reaction equilibrium and higher gas yields. However, excess steam could lead to enhanced tar formation.

$$SB = \frac{Steam\ flow\ [\frac{kg}{h}]}{Biomass\ flow\ [\frac{kg}{h}]}$$

Biomass blending ratio. Blending different types of biomass feedstocks or combining biomass with other materials such as coal or plastic waste can significantly influence the gasification performance. The ratio of these blends affects key process parameters including syngas composition, heating value, gas yield and carbon conversion efficiency. The blending ratio also impacts the physical and chemical properties of the feedstock, such as moisture content, volatile matter, fixed carbon and ash composition, which in turn affect the gasification reactions and overall process stability. Benefits of blending include: a) utilisation of a wider range of feedstocks, including those that may be challenging to gasify individually; b) mitigation of operational issues such as agglomeration or slagging, which may occur with certain biomass types; c) tailoring the ratio enables fine-tuning of the syngas composition to meet specific end-use requirements; d) reducing the need for downstream gas cleaning or conditioning.

Gasifiers. The process of gasification happens in the reactor, known as a gasifier. These are some of the process requirements based on which the gasifier is chosen: a) biomass or waste type and moisture content; b) gasification agent; c) operating T; d) heat transfer mode and e) pressure. The gasification approach can be classified into two categories, based on the density factor: 1) *dense phase reactors*, where input materials have maximum space occupation (fixed bed gasifiers); 2) *lean phase reactors,* with a spacious reaction chamber for better reaction flow (fluidised bed gasifiers and entrained flow gasifiers).

Fixed bed gasifiers are the simplest gasification technology. They have built-in grates to maintain a stationary reaction bed and to support feedstock. These types of reactors are relatively easy to design and operate, but they have limited capacity. Therefore, they are typically used in small- to medium-scale operations. Fixed bed reactors are mainly subdivided based on the input of oxidising agent flow into updraft, downdraft and cross-draft.

Compared to fixed bed gasifiers, fluidised bed reactors have faster gasification rates and higher gas production rates. Fluidised bed gasifiers offer uniform heat and mass distribution, which reduces the risk of fuel stack agglomeration. They have the advantage of feedstock flexibility and high efficiency. The commonly used bed materials are silica, sand, dolomite and glass beads. The operating temperature is largely dependent on the melting T of bed material and ash, and usually falls within the temperature range of 650–950 ˚C and pressure range of 0–70 bar. Fluidised bed reactors are usually divided into bubbling, dual and circulating. A more innovative technology is dual fluidised gasifiers, which can overcome the drawbacks of fluidised bed reactors. This system either connects circulating or bubbling reactors or operates as a single unit and consists typically of endothermic gasification and exothermic combustion units. Dual fluidised bed offers the possibility to produce nitrogen free syngas without the need of an air separation unit (ASU) and a high carbon conversion efficiency (since the char is combusted). The resulting gas has higher CH_4 and H_2 concentrations.

Entrained flow gasification is a mature technology that has been adapted from coal gasification. The reactors are operated at a high T (1200–1600 ˚C) and high pressure (20–80 bar), with oxygen as the gasifying agent. The process happens above the melting point of ash and produces little tar content. There are two types of entrained flow gasifiers: slagging (liquid ash leaves the reactor as a liquid slag) and non-slagging (slag free walls).

Table A1. Dense phase gasification reactors

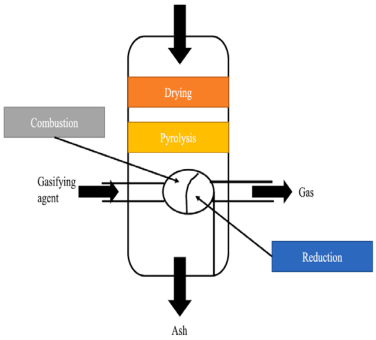
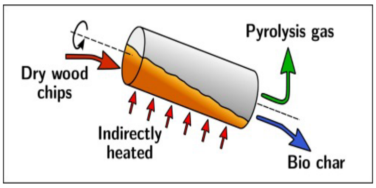
Gasifier	Advantages	Disadvantages
Updraft fixed bed (counter-current/downstream) *See figure 2 a*	• Can handle biomass with high moisture content • Overall good thermal efficiency • Utilises heat of combustion effectively • Less pressure drop • Slight tendency to form slag	• Ideal only for small-scale uses • Highest tar yield (30-150 g/N.m3) • Not suitable for high volatility fuels • Takes a long time to start the engine • Low production of syngas • Low reaction capability
Downdraft fixed bed (co-current/upstream) *See figure 2 b*	• Lower tar production rate (0.015-3 g/N.m3) • Takes less time to ignite	• Induces low thermal efficiency • High particulate content
Cross-draft fixed bed  	• Lowest tar production (0.01-0.1 g/M.m3) • Good permeability of bed • Start time of engine is relatively low • Can handle high moisture biomass only if top part of gasifier remains open • Quick load response	• Only suitable for small-scale units • Not suitable for high ash and tar content • Lower total energy efficiency

Table A2. Lean phase gasification reactors

Gasifier	Advantages	Disadvantages
Bubbling fluidised bed *See figure 2 c*	• High carbon conversion rate • Good mixing leads to uniform distribution of mass and T • Fuel flexibility • Easy T control • Easy construction and operation	• Significantly influenced by operating conditions • Not as efficient as carbon conversion • Increase in fly ash and char particles in gas product • More CO2/CH4
Circulating fluidised bed *See figure 2 d*	• Higher carbon conversion efficiency • Good residence time • High gas yield • God for large scale • Low tar production • Beds have improved combustion efficiency and low NOx emissions	• Severe back mixing can occur • High cost • Bed agglomeration can cause defluidisation
Dual fluidised bed (twin-bed fluidised bed) *See figure 2 e*	• Fuel flexibility • High carbon conversion • Potential for CO2 capture • Efficient heat transfer	• High capital and operating cost • Difficult scale-up • Lower heating value due to gas mixing
Entrained flow *See figure 2 f*	• Mature technology • High fuel conversion • Compact design • Low tar content • Suitable for large scale	• Challenging gasifier material selection • Ash melting • Short residence times • Energy-intensive • Not suitable for waste gasification
Spouted bed *See figure 2 g*	• Allows handling of larger particles • High heat and mass transfer rates • Simple design • Lower sand/biomass ratio required	• Short gas residence time • Lower tar conversion and lower process efficiency
Plasma reactor *See figure 2 h*	• Controlled syngas composition • Reduced tar	• High capital investment and operational costs
Rotary kiln 	• Efficient mixing • Can handle challenging waste materials • High carbon conversion • Low tar	• Low thermal efficiency • Scale-up challenge • Additional pollution control required

Biomass conversion efficiency. The efficiency of gasification is a critical parameter in evaluating the performance and viability of gasification systems. Gasification efficiency, often expressed as cold gas efficiency (CGE), represents the ratio of the chemical energy content of the produced syngas to the energy content of the input biomass. It can be calculated using the following equation:

$$CGE = \frac{V(gas) * HHV(gas)}{M(biomass) * HHV(biomass)}$$

Where V(gas) is the volumetric flow rate of the produced gas (Nm^3/h), HHV(gas) is the higher heating value of the gas (MJ/Nm^3), M(biomass) is the mass flow rate of the biomass feedstock (kg/h), and HHV(biomass) is the higher heating value of the biomass (MJ/kg). Note that the CGE value can be calculated using either the Higher Heating Value (HHV) or Lower Heating Value (LHV), depending on the specific context and convention used in analysis. The efficiency is influenced by various factors, including gasification temperature, pressure, equivalence ratio, steam-to-biomass ratio and biomass properties such as moisture content and particle size.

Gas cleaning and conditioning

The thermochemical conversion of biomass mainly results in gases (H_2, H_2O, CO, CO_2 and C_xH_y) but also in carbon-rich particulate matter and impurities (tars, sulphur compounds, alkali, halide, nitrogenous compounds and trace elements). Their presence and amount depend on the feedstock gasifier technology and operating conditions. Since these impurities reduce the performance of downstream equipment, efficient gas cleaning is required.

Table A3. Impurities in producer gas

Contaminant	Common compounds	Associated problems	Cleaning method
Particulates	Ash, char, fluidised bed material	Erosion	Barrier filtration, wet scrubbing, electrostatic precipitation
Alkali metals	Sodium (Na), potassium (K) compounds	Hot corrosion	Cooling, adsorption, condensation, filtration
Fuel-bound nitrogen	NH_3, HCN, C_2H_5N	NO_x formation	Wet scrubbing, SCR, SNCR
Tars	Refractive aromatics	Clogs filters; Difficult to burn; Deposit internally; Inhibits catalysts	Catalytic and non-catalytic tar removal; physical removal
Sulphur, chlorine	H_2S, carbonyl sulphide, mercaptans, HCl	Corrosion; Emission	Lime or dolomite, wet scrubbing, absorption
Heavy metals	Traces of Hg, Cd	Emissions, ash disposal costs increase	Sorption, membrane filtration

Ash removal. Ash is an inorganic residual biproduct of gasification, which is left after volatile components of biomass are removed. It mainly consists of K_2O, SiO_2, Cl and P_2O_5 salts. In general, forestry biomass has less ash content than agricultural biomass. A high ash content can lead to slagging or catalyst sintering, which reduces syngas production. Ash from thermal gasification can be utilised as a catalyst to improve gasification performance.

Tar removal. Tar is a broad term for condensable hydrocarbons, found in producer gas. The agreed definition is that only components of higher molecular weight than benzene (C_6H_6) are counted towards tar composition. Widely-used classification recognises five classes of tar components based on their molecular weight, solubility and condensability: Class I – GC undetectable (very heavy, with more than eight aromatic rings); Class II – heterocyclic, highly soluble single ring aromatics with heteroatoms (pyridine, phenol, quinoline etc.); Class III – light aromatic, single ring aromatics with solubility problem (toluene, styrene, ethylbenzene etc.); Class IV – light PAHs (naphthalene, anthracene, biphenyl etc.); Class V – heavy PAHs (pyrene, fluoranthene etc.).

Tar removal is one of the primary concerns in producer gas cleaning, as it can damage the equipment due to condensation and corrosion, inhibition of catalytic centres or sorption materials, and soot deposition. In addition, the formation of tar also represents an energy loss, which reduces the efficiency of the gasification process. There are broadly two types of methods used to reduce tar – primary (in the gasifier) and secondary (after the gas exits the gasifier). Primary methods usually focus on the optimisation of gasification parameters, such as reactor design, operation conditions, catalyst, equivalence ratio (ER) and residence time. Secondary methods focus on treating resulting hot gases, including physical removal (wet scrubbers, cyclones, barrier filters etc.), thermal cracking and catalytic cracking (mineral and synthetic catalysts).

Additional policy context

If the gaseous biomass fuel is to be used in the transport sector (Article 29(10) (a), (b), (c)):

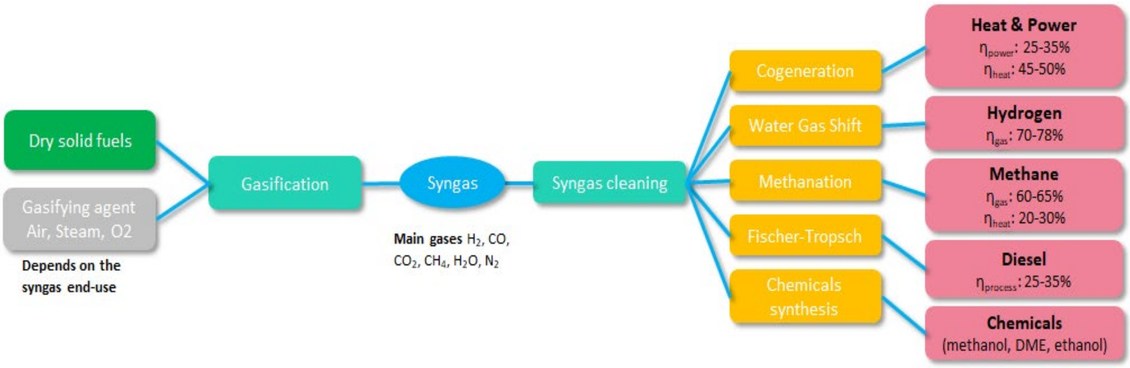
- If the installation became operational on or before 5 October 2015, it shall apply at least 50% greenhouse gas emission savings.
- If the installation became operational between 6 October 2015 and 31 December 2020, it shall apply at least 60% greenhouse gas emission savings.
- If the installation started operating from 1 January 2021, it shall apply at least 65% greenhouse gas emission savings.

When the gaseous biomass fuel is to be used for electricity, heating and cooling production (Article 29(10) subparagraph (d), (e), (f), (g), (h)):

- If the installation started operating after 20 November 2023, it shall apply at least 80% greenhouse gas emission savings.
- If the installation started operating between 1 January 2021 and 20 November 2023, it must apply the following criteria in order for its biogas or biomethane to be considered as sustainable:
  - ➢ If the installation has a total rated thermal input equal to or exceeding 10 MW, it shall apply at least 70% greenhouse gas emission savings. After 31 December 2029, an 80% criterion will have to be applied.
  - ➢ If the installation has a total rated thermal input equal to or lower than 10 MW, it shall apply at least 70% greenhouse gas emission savings. After the plant has been in operation for 15 years, an 80% criteria will have to be applied.
- If the installation started operating before 1 January 2021 and has been operating for 15 years, it shall apply the following criteria:
  - ➢ If the installation has a total rated thermal input equal to or exceeding 10 MW, it shall apply at least 80% greenhouse gas emission savings after it has been operating for 15 years, at the earliest from 1 January 2026 and at the latest from 31 December 2029.
  - ➢ If the installation has a total rated thermal input equal to or lower than 10 MW, it shall apply at least 80% greenhouse gas emission savings after it has been operating for 15 years, at the earliest from 1 January 2026.

Upgrading pathways

Figure A3. Technological pathway to produce energy and chemicals products from solid fuels



Biochar: additional considerations

Technological pathways for biochar production from biomass feedstocks

Biochar production involves several industrial processes, each designed to optimise the conversion of biomass into a carbon-rich, stable product suitable for various applications. Here are the main industrial processes that lead to biochar production:

1. **Slow Pyrolysis:** involves heating biomass in the absence of oxygen at moderate temperatures (typically between 300 °C and 700 °C) for extended periods (hours). This process produces high yields of biochar with high carbon content and stability, suitable for soil amendment and carbon sequestration.
2. **Fast Pyrolysis:** involves rapidly heating biomass to high temperatures (400 °C to 600 °C) in the absence of oxygen, with very short residence times (seconds to minutes). This produces bio-oil that can be used as a renewable fuel or chemical feedstock. It generates biochar as a by-product, albeit in lower quantities compared to slow pyrolysis.
3. **Gasification:** involves converting biomass into syngas (a mixture of carbon monoxide, hydrogen and other gases) at high temperatures (800 °C to 1,200 °C), in the presence of a controlled amount of oxygen or steam. This produces syngas that can be used for power generation, chemical synthesis or as a fuel. It generates biochar that can be utilised for soil amendment (under specific conditions) or carbon sequestration.
4. **Hydrothermal Carbonisation (HTC):** involves heating biomass in water at high pressures and moderate temperatures (180 °C to 250 °C) for several hours. Biomass undergoes hydrothermal reactions that convert it into a coal-like substance known as hydrochar (a form of biochar). This process is effective for wet biomass, reducing the need for drying. Hydrochar is used for soil improvement, waste management and as a solid fuel.
5. **Torrefaction:** involves heating biomass to moderate temperatures (200 °C to 300 °C) in an inert atmosphere for a short period. This process improves biomass properties for combustion and gasification, and also produces biochar that can be used for soil enhancement (under specific condition) or carbon sequestration.
6. **Carbonisation in Kilns:** involves the carbonisation of biomass by heating it in an oxygen-limited environment. Slow heating leads to the production of biochar, along with gases and vapours that can be captured or flared. This process is a simple and scalable method for producing biochar from various biomass feedstocks.

Additional policy context for soil enhancement (restricted to some biochar)

Table A4. Requirements to be fulfilled according to CMC 14

	CMC 14 – Pyrolysis and gasification materials
Input materials allowed	• **living or dead organisms** or parts thereof, which are unprocessed or processed only by manual, mechanical or gravitational means, by dissolution in water, by flotation, by extraction with water, by steam distillation or by heating solely to remove water, or which are extracted from air by any means (except materials originating from mixed municipal waste, sewage/industrial/dredging sludge and animal by-products or derived products within the scope of Regulation (EC) No 1069/2009) • **vegetable waste from the food processing industry and fibrous vegetable waste from virgin pulp production and from production of paper from virgin pulp**, if not chemically modified • **processing residues** within the meaning of Article 2, point (t) of Directive 2009/28/**EC from the production of bioethanol and biodiesel**, derived from materials referred to in sub-points (a), (b) and (d) • **bio-waste** within the meaning of Article 3, point 4 of Directive 2008/98/EC resulting from separate bio-waste collection at source, other than animal by-products or derived products within the scope of Regulation (EC) No 1069/2009 • **pyrolysis or gasification additives,** which are necessary to improve the process performance or the environmental performance of the pyrolysis or gasification process, provided that those additives are consumed in chemical processing or used for such processing and that the total concentration of all additives does not exceed 25% of the fresh matter of the total input material, with certain exceptions[6]. • **category 2 or category 3 animal by-product materials or derived products** thereof, in accordance with the conditions set out in Article 32(1) and (2) of Regulation (EC) No 1069/2009, provided that their end point in the manufacturing chain has been determined[7]. The input materials may have been processed by manual, mechanical or gravitational means, by solid-liquid fractionation using biodegradable polymers, by dissolution in water, by flotation, by extraction with water, by steam distillation or by heating solely to remove water, by composting or by anaerobic digestion.
Plant requirement	Separated production lines
Thermochemical conversion process	Shall take place under oxygen-limiting conditions in such a way that a temperature of at least 180 °C for at least two seconds is reached in the reactor.
Criteria for the pyrolysis and gasification materials	• A molar ratio of hydrogen (H) to organic carbon (H/Corg) < 0.7, with testing to be performed in the dry and ash-free fraction for materials that have an organic carbon (Corg) content < 50%. • ≤ 6 mg/kg dry matter of PAH16 • ≤ 20 ng WHO toxicity equivalents (20) of PCDD/F (21)/kg dry matter.
Additional criteria for the EU fertilising product containing or consisting of CMC 14	• the chlorine (Cl-) content shall not be higher than 30 g/kg dry matter • the thallium (Tl) content shall not be higher than 2 mg/kg dry matter, in case more than 5% of pyrolysis or gasification additives relative to the fresh weight of total input material have been applied.
Additional criteria	• All substances incorporated into the EU fertilising product, on their own or in a mixture, except polymers, must be registered under REACH regulation.
Applicable conformity assessment procedure[8]	Module D1 – Quality assurance of the production process and certification by Notified Body

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[6] Cf. CMC 14, 1 e).

[7] According to Commission Delegated Regulation (EU) 2023/1605 of 22 May 2023 supplementing Regulation (EC) No 1069/2009 of the European Parliament and of the Council as regards the determination of end points in the manufacturing chain of certain organic fertilisers and soil improvers.

[8] More information on the procedures for Module A and D1 to be found in Part II of Annex IV.

Table A5. Requirements to be fulfilled according to PFC 3(A)

	PFC 3(A) – Organic soil improver
Function of the product	Improve or protect the physical or chemical properties, the structure or the biological activity of the soil to which it is added.
General composition	Material 95% of which is of solely biological origin. + may contain peat, leonardite and lignite
Carbon content	Organic carbon > 7.5% by mass
Dry matter content	20% or more of dry matter
Limit values for contaminants	• cadmium (Cd): 2 mg/kg dry matter • hexavalent chromium (Cr VI): 2 mg/kg dry matter • mercury (Hg): 1 mg/kg dry matter • nickel (Ni): 50 mg/kg dry matter • lead (Pb): 120 mg/kg dry matter • inorganic arsenic (As): 40 mg/kg dry matter • copper (Cu) < 300 mg/kg dry matter • zinc (Zn) < 800 mg/kg dry matter
Pathogens limits	• Absence of Salmonella spp • Escherichia coli or Enterococcaceae ≤ 1,000 CFU/g

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