GASIFICATION: A SUSTAINABLE TECHNOLOGY FOR CIRCULAR ECONOMIES

Scaling up to reach net-zero by 2050

November 2021

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EXECUTIVE SUMMARY

Climate protection is one of the political priorities of the European Union. In December 2019, EU leaders committed to the goal of climate neutrality by 2050. The European Commission's Green Deal sets a target to reduce greenhouse gas emissions from 40% to 55% by 2030 and is included in the 12 legislative proposals of the 'Fit for 55' package. This goal, like the one set out in the Paris Agreement at COP21, to limit global temperature increase to "well below 2 degrees Celsius compared to pre-industrial levels", requires deep decarbonization and a commitment to a circular economy.

The United Nations Industrial Development Organization (UNIDO) describes the circular economy as "a new way of creating value, and ultimately prosperity, through extending product lifespan and relocating waste from the end of the supply chain to the beginning – in effect, using resources more efficiently by using them more than once." Sustainable gasification turns out to be one of the technologies that can fulfil those requirements. With first applications starting in the 18th century, the industry sits on a robust background that is increasingly transferred onto modern and clean applications. By offering other ways of valuing solid waste biomass and other resources than applying direct heat through combustion, gasification is increasingly recognized as a complementary solution to meet the challenges we are increasingly facing in the energy transition. Syngas resulting from the gasification process, is the raw mixture of chemical elements that contains and can generate a large spectrum of low carbon or renewable final products: gaseous fuels (methane, hydrogen, ammonia), liquid fuels (Fischer-Tropsch, mixed alcohols, methanol / DME) and direct conversion into heat and/or power.

Today's applications are implemented from tailormade and commercial solutions including small to medium scale Combined Heat and Power, large scale co-firing and a number of plants producing fuels and chemicals. The rationale is either to produce bioenergy with negative, no or low impact on greenhouse gas emissions or to operate infrastructure with a more efficient waste-to-energy solution as opposed to the existing older widespread methods. With the rapid development of and changes within the gasification sector, we expect projects to be operating at even higher efficiency, lower emissions profiles and lower costs in the near future. Additionally, when using a sustainable woody biomass, the by-product of biochar or CO2 provides an extra and unique benefit from gasification as a net Negative Emission Technology (NET).

Gasification is a highly promising and already commercialised technology - one that is ready to scale-up. It has many benefits to our planet:

- a low greenhouse gas and a low or no toxic emissions profile
- high energy efficiency
- versatility to create valuable, cleaner applications from many types of solid fuels
- operates as a circular economic model
- allows development of net negative value chains

Its success and ability to scale to become the waste-to-energy/fuel method of choice depends on the levels and type of political, policy, economic and commercial support, in order to reduce costs and raise awareness of its strong potential to accelerate the net-zero responsibilities of the waste, energy and fuels markets.

CHAPTER 1: FUNDAMENTALS – WHAT IS GASIFICATION?

Gasification, or – more precisely thermochemical gasification – is capable of converting dry, organic solid substances like ligno-cellulosic biomass (including plants, crops and wood), waste or coal at elevated temperatures and with a controlled deficiency of oxygen and/or steam into a hydrogen- and carbon monoxide-containing gas (called 'syngas', 'producer gas' or 'wood gas') and – depending on technology – also char (called 'biochar' when using biogenic raw materials). Aside from gasification, other existing technologies that produce usable gases from organic material include:

- Biogas produced from anaerobic digestion, liquid and/or wet biodegradable biomass is converted into a methane-containing gas at low temperatures with the help of microorganisms.
- Two other thermochemical processes can convert wet biomass into hydrogen-containing gas: hydrothermal carbonization (HTC) and supercritical water gasification (SCWG).

This Whitepaper deals exclusively with thermochemical gasification of dry, solid biomass and waste into syngas and (bio-)char.

1.1. Brief historical background

The history of solid fuel gasification (wood and coal) starts in the late 18th century. The syngas was mainly used as a burning gas for direct heat use or the use in steam engines. With the further development of the chemical industry in the 19th century, the hydrogen-rich gas became interesting for several synthesis processes (e.g. producing ammonia and liquid fuels). In the beginning of the 20th century, most developed cities established gas distribution networks which were operated with syngas produced from coal or wood. The automotive sector started to develop wood gas operated vehicles, which were very common in the time of the second world war due to the lack of liquid fuels. Coal gasification had the next renaissance in the 1970s as a consequence of the oil crisis. In this time, the technology was used for power production as well as for the production of liquid fuels by means of Fischer-Tropsch synthesis. With decreasing prices for liquid and gaseous fossil fuels, the importance of gasification technologies faded at that time.

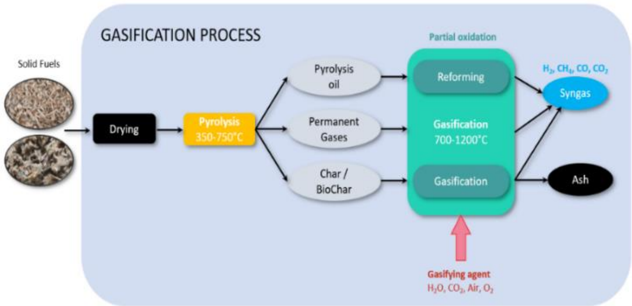
In recent years, the increasing global awareness and understanding of the link between fossil CO2 emissions with climate change acceleration has given waste gasification a new boost as a part of the green energy transition.

Today, gasification uses renewable raw materials to close the CO2 cycle at high efficiency with no toxic emissions or pollutants resulting in. If, additionally, enough biochar is produced in the process from biomass waste and is used for soil remediation, modern biomass gasification plants can be defined as a carbon sink.

1.2. Sustainable gasification explained

The conversion process consists of four main steps resulting in the production of syngas:

- Drying
- Pyrolysis
- Partial oxidation and;
- Reforming and/or gasification (see *Figure 1: Syngas generation*).



The whole process is called 'Gasification'. Depending on the type of gasification technology, the single process steps can be performed in one single reactor or be separated in staged processes. The energy required to maintain the gasification reactions can be provided by partial oxidation using air, pure oxygen or enriched air. On the other hand, the gasification process can be indirectly heated. In this case, the gasification agent can include steam, carbon dioxide or a mixture of the two.

Five principal types of gasification reactors are commonly used in today's market. They offer a modular range of capacity from kW to GW and for various types of feedstock:

- Fixed bed (updraft, downdraft, twin fire and fixed-floating bed)
- Fluidized bed (bubbling, circulating)
- Dual fluidized bed
- Entrained flow and;
- Plasma reactors.

The gasification reactors can be operated on an autothermal (a part of the introduced fuel is burned internally for the heat supply) or on an allothermal (the necessary process heat is transferred from an external source into the gasification reactor) basis. The single process steps can be performed in one of the named reactors, but also combinations of different reactor types in staged processes are possible.

The resulting syngas consists of a mixture of hydrogen, carbon monoxide, carbon dioxide and lower quantities of light hydrocarbons, and in the case of air gasification, also nitrogen. The concentration of the components can vary in a broad range, depending on the:

- Gasification technology used
- Gasifying agent
- Type of feedstock and;
- Process parameters

1.3. Feedstock base

A broad range of solid fuels are proven to create syngas from thermochemical conversion methods:

- Woody biomass from forestry (conventional forestry, short-rotation crops) and waste wood
- Residues from the agricultural sector (including straw, vine and branches, grape marc, olive pomace) as well as dried sewage sludge or dried livestock manure and;

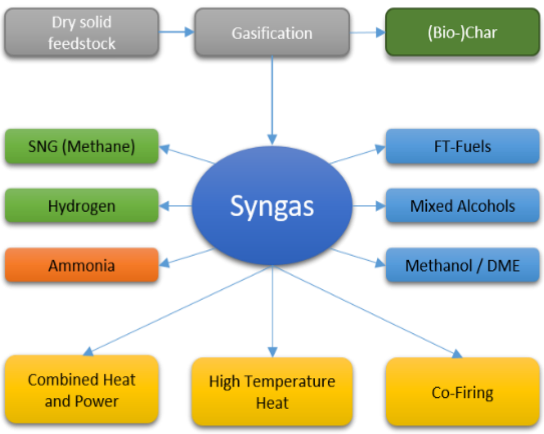
- Non-recyclable solid waste in the case of low carbon or Recycled Carbon Fuels production: Refuse Derived Fuels (RDF) and Solid Recovered Fuels (SRF), mainly composed of plastics, wood, foam and textile.

1.4. Products output

Syngas can be used in various applications including:

- From the direct use of the gas for high-temperature heating for local applications
- The use in gas engines for combined heat and power generation and;
- The use as a source for several chemical synthesis like Fischer-Tropsch, Synthetic Natural Gas (SNG), Hydrogen or Methanol.

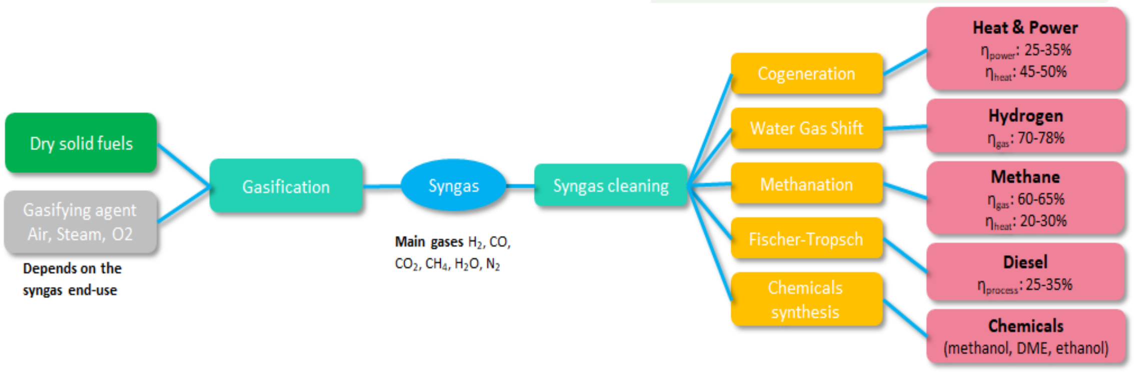
Figure 2: The possible uses of syngas



In Figure 2, different pathways for syngas utilizations are shown. On the left-hand side, gaseous fuels (SNG, hydrogen and ammonia) and on the right-hand side liquid fuels (Fischer-Tropsch fuels, mixed alcohols, methanol and DME). It should be emphasized that multiple productions are possible.

Depending on the use and the degree of post-treatment of the products, the achievable energy efficiencies span by a broad range. Some examples of efficiencies are shown in Figure 3.

Figure 3: Technological pathway to produce energy and chemicals products from solid fuels



A final separation and upgrading step ensures the product is compliant with the final end usage. For hydrogen and methane, an overall gas efficiency of between 60% and 78% can be achieved with the technologies currently available on the market.
Additionally, the direct use of the gas for industrial heating for local applications achieves efficiencies of 90% and higher.

CHAPTER 2: BENEFITS OF SUSTAINABLE GASIFICATION

2.1. Sustainable Gasification is a key enabler to decarbonize EU's energy consumption

Gasification technologies allow the production of non-intermittent renewables with a great versatility: they are suited for a wide range of resources and for the needs of many regions, allowing the development of new circular economy models, the implementation of decentralized production of fuels, and for renewable and low-carbon gases to be stored and transported in existing gas infrastructures.

To date, sustainable gasification is mainly used and widely developed to produce renewable heat and power (CHP / co-firing) by recovering local biomass and various carbonaceous wastes which are often lacking better ways to dispose of it. In the last 15 years, a new generation of gasification units has been emerging, aiming to produce biomethane, hydrogen and biofuels. These second-generation gasification plants operate at a higher efficiency, have a lower environmental impact on emissions than other waste-to-energy processes and are capable of transforming a broad spectrum of feedstocks into a variety of outputs.

For instance, gasification of Solid Recovered Fuels, standing within the energy recovery stage of the waste hierarchy, is one of the most energy efficient waste-to-energy processes. According to the European Commission, this best proven technique would increase the amount of energy recovered from waste by 29%, using exactly the same amount of waste as a feedstock[1]. As a lower emissions profile in its own right, and when combined with increased energy efficiency, gasification offers an even better solution for the local and global environment.

Combining CCS[2] and developing biochar uses with second generation gasification plants would result in negative emissions, which are required to meet the global net-zero carbon level by 2050.

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2.2. Gasification is a versatile technology that meets a variety of current global challenges

Thanks to their great versatility, whether in terms of inputs, capacities and outputs, gasification processes can be integrated into various industrial settings. They are appealing to various stakeholders: from resource managers looking for outlets for their by-products (agricultural residues

[1] https://publications.jrc.ec.europa.eu/repository/bitstream/JRC104013/wte%20report%20full%2020161212.pdf.
[2] Carbon Capture and Storage: process of capturing waste CO2, transporting it to a storage site, and depositing it where it will not enter the atmosphere.

or waste wood, Solid Recovered Fuel, etc.) to industries looking for solutions in order to replace their fossil uses in high temperature processes.

Unlike conventional combustion or incineration processes, gasification transforms solid biomass or waste into energetic products (syngas, oil, (bio)char) using temperatures in excess of 700°C and a highly controlled supply of oxygen or steam (without using combustion). This thermochemical decomposition of the feedstock allows these products to be purified before using or transforming them, resulting in a drop of pollutant and greenhouse gases emissions, and it opens the way to new uses such as SNG, hydrogen or biofuel production.

▪ Circular economy

Generally, the emergence of facilities recovering local waste resources is expected, encouraging the energy independence of local communities, industries and creating new circular economy models. Respecting the cascading use principle is a pillar of the development aimed by the gasification sector. As a result, only inputs that cannot be directly recovered in the form of food or material are targeted, in particular: residual biomass from various activities (forestry, agriculture, etc.) and solid waste that cannot be recycled using currently available techniques (including SRF, waste furniture, non-recyclable and complex plastics).

▪ Gasification's contribution to reducing carbon emissions as part of the global Net Zero roadmap

Gasification technologies and the facilities in which they are central within, offer the opportunity of being low carbon, neutral or even negative carbon emissions. Whether a plant is negative, neutral or positive in emissions depends on a combination of factors:

- The feedstock chosen
- The exact specification and combination of technologies used; and
- The offtake(s) specified by the project owner-operator.

A carbon life cycle assessment is required to precisely measure the positive impact on the environment.

Combining CCS and developing biochar uses with second generation gasification plants would result in negative emissions, which are required to meet the global net-zero carbon level by 2050.

CHAPTER 2: BENEFITS OF SUSTAINABLE GASIFICATION

As the emitted CO2 has been previously fixed by the biomass growing, producing heat and power, SNG, hydrogen or liquid biofuels from sustainably-grown biomass[3] feedstocks is considered carbon neutral or with a very small impact on CO2. And when combined with a Carbon Capture Utilization or Storage with the separated CO2 stream, it results in negative emissions. Capturing the CO2 released by bio-based processes or using and storing it in, for example geological formations, results in negative CO2 emissions and contributes to the targeted carbon sinks of 850 Mt of CO2eq.

▪ Biogenic carbon and carbon sinks as by-products

Biochar co-generation can modify the carbon cycle in a way that bioenergy power plants store more carbon in the soil and materials than they emit into the atmosphere, making them net negative emission technologies (NET).

✓ Biochar and carbon sinks

Biochar is a carbon-rich material that is produced by biomass heating in a low oxygen environment, a process called pyrolysis. Organic substances are broken down at temperatures ranging from 350°C to 1000°C, producing a gaseous, a liquid and a solid phase. They can be used either for energy generation or as commodity materials. While the gaseous and liquid fractions are generally used for energy production, the solid fraction represents a valuable and highly versatile product.

As long as the biochars are not thermally used (burnt or combusted), the carbon is conserved over hundreds to thousands of years[4]. Instead, through the process of photosynthesis, plants capture carbon dioxide (CO2) from the atmosphere and incorporate the carbon (C) while emitting oxygen (O2). By the conversion of biomass to biochar, parts (30-70%) of this carbon are made recalcitrant.

As a result, gasification plants have the potential to produce not only renewable energy, but also carbon-rich materials that can serve as stable carbon sinks.

✓ Quality of biochar

While all pyrogenic carbon from pyrolysis or gasification processes can provide a carbon sink, differences in quality have to be considered based on adequate uses: while some chars can undoubtedly be used for a variety of applications ranging from materials to agricultural uses, others may contain concentrations of pollutants that make them unsuitable for certain applications. For some of the latter, uses have yet to be developed.

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[3] The EU Renewable Energy Directive (RED II) defines and imposes various sustainability criteria to ensure that, despite the growing demand for forest biomass, harvesting is carried out in a sustainable manner in forests where regeneration is ensured, that special attention is given to areas explicitly designated for the protection of biodiversity, landscapes and specific natural elements, that biodiversity resources are preserved and that carbon stocks are tracked.

[4] Lehmann et al. (2015). Persistence of biochar in soil. In Biochar for Environmental Management: Science, Technology and Implementation (S. 233-280).

CHAPTER 2: BENEFITS OF SUSTAINABLE GASIFICATION

The European standard for quality biochar is defined by the European Biochar Certificate (EBC). It regulates possible input materials (feedstocks) and contaminant thresholds for different grades of biochar like biochar feed additive, soil applications and biochar-based materials[5]. For such quality biochars, the business case is evident: a market already exists and access to it is relatively easy due to high demand. This can further improve the business case for gasification plants.

✓ Biochar uses and markets

Common uses for biochars are found in agriculture where they serve as feed amendment, stable bedding, for slurry stabilization, in biogas plants or directly in soils, e.g. as a carrier matrix for nutrients. New applications of biochars include their use in building materials such as concrete or asphalt, in plastics or in high-tech where they can replace fossil resources.

✓ Biochar potential to reach climate neutrality in the EU

In order to achieve climate neutrality by 2050, the creation of carbon sinks in the magnitude of 850 Mt of CO2eq p.a. will need to be made available. Biochar can provide a third of this amount by mid-century if the respective regulations are set. It can do so by optimizing resource flows and closing local and regional material cycles. Biochar can help agriculture adapt to climate change and serve as the basis for a circular economy, producing goods that are endlessly recyclable.

[5] www.european-biochar.org.

CHAPTER 3: GASIFICATION OF BIOMASS AND WASTE – MARKET POTENTIAL

It is widely accepted that initiatives are needed and should be implemented in order to reduce greenhouse gas emissions, limit global temperatures and create more circular, sustainable economies. Gasification of biomass and wastes can have a real impact on all three of these goals, by reducing the amount of waste in the world and generating energy, heat, biofuels, biochar and other products with value. It should take place after reducing, re using and recycling in the waste management hierarchy.

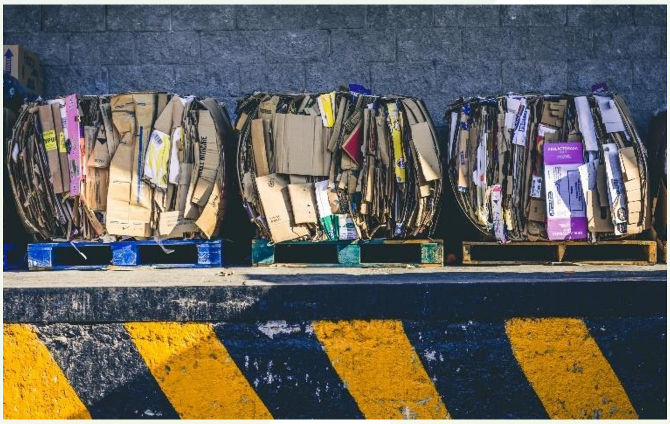
As the European Commission Circular Economy package states: "The new legislation strengthens the 'waste hierarchy', i.e. it requires Member States to take specific measures to prioritize prevention, re-use and recycling above landfilling and incineration, thus making the circular economy a reality."

The market for gasification of fossil, biomass and waste resources was valued $479bn in 2019 and is projected to reach $901bn by 2028[6]. Today, the share of biomass and waste is limited to a few percent in this well-developed market but it is expected that it will play an important role in the future. This chapter examines the feedstocks needed and applications from gasification.

3.1. Feedstock potential of biomass and waste

Sustainable gasification has the potential to turn waste disposal into revenue streams for forest wood owners and producers, for collectors and producers of other waste types, including biomass, municipal and non-hazardous industrial and commercial waste, and for investors. Additionally, through gasification, industrial, commercial and municipal wastes become feedstocks for chemical valorization and do not have to be disposed of at a cost. Finally, gasification can divert waste from other less environmentally-friendly methods and can also save valuable landfill space.

Over 2.1 billion tonnes of municipal solid waste (MSW) are generated globally each year, yet only 16% (323 million tonnes) of this is recycled each year and 46% (950 million tonnes) is disposed of unsustainably[7]. By 2050, municipal waste production could increase by 70% to reach 3.75 billion tons[8]. Moreover, due to the growing volumes of waste recycled, Refuse Derived Fuels will be an ever-increasing feedstock in the future. The industrialization of gasification will provide an additional method for addressing the wastes in more environmentally and community-friendly ways. In 2018, the municipal waste feedstock segment of the global gasification market was valued at 541.4 million USD and estimates predict that this market share will be worth 800.0 million USD in 2024[9].



[6] Fortune Business Insights (2020).
[7] Verisk Maplecroft, Waste Generation and Recycling Indices 2019 report.
[8] Boundless Impact Investing, FullCycle report, World Bank data (2019).
[9] Meticulous Research (2019) Global Opportunity Analysis and Industry Forecast (2018-2024).

CHAPTER 3: GASIFICATION OF BIOMASS AND WASTE – MARKET POTENTIAL

Increasing energy consumption and the demand for clean energy in the light of the billions of tons of waste produced by agroforestry, municipal and industrial sectors will continue to drive the gasification market in the future[10].

Biomass waste is expected to grow in the coming years, as an environmentally-friendly energy source, supported by government policies and regulations, as well as the abundant nature of the feedstock. As described before, solid biomass gasification sustainably converts wood processing by-products, storm or damaged wood into various energy and chemical products.

The use of solid biomass and waste already accounts for 530 million tons of oil equivalent (6163 TWh) worldwide, which is almost 40% of the renewable energy demand[11].

Gasification has the potential to turn waste disposal into revenue streams for forest wood owners and producers, for collectors and producers of other waste types, including biomass, municipal and non-hazardous industrial and commercial waste, and for investors.

451 million solid cubic meters 'wood equivalent'[12] of woody biomass from both primary and secondary sources were used for bioenergy production in Europe in 2015[13]. Primary wood, which includes stemwood, treetops, branches, etc. harvested from forests, contributed to at least 37% (166 Mm3) of the total wood used for energy. Secondary woody biomass, which includes by-products from the wood processing industry, contributed 222 Mm^3 or at least 49% of total wood for energy, making it the largest source of wood-based bioenergy[14]. It increased by just over 20% from 2009 to 2015.

The electricity and commercial heat sectors in particular underpinned the more recent biomass growth worldwide. For example, the generation of heat and electricity from solid biomass and renewable waste increased by more than 4% per year[15]. Reasons for this can be found in emerging Asian economies, namely the 23-gigawatt target in China's 13th Five-Year Plan, increasing waste combustion in China, and improving availability of feedstocks in India and Southeast Asia.

In the 2020 IEA's STEPS scenario[16], solid biomass and waste will increase by one-third to 700 Mtoe in 2030. China alone will be responsible for almost one third of this growth. The scenario states that the use of solid biomass and renewable waste in power and heat generation will exceed the use in industry in the mid-2020s. This is driven by the introduction of energy-from-waste (EfW) projects in China, national renewable energy targets in the European Union, and the continued development of co-generation in the agriculture and food sectors in India. According to STEPS, by 2040, solid biomass and renewable waste will account for more than a quarter of renewable energy demand, making it the largest source of low-carbon fuels[17].

[10] Fortune Business Insights (2020).
[11] IEA 2020: World Energy Outlook 2020, IEA, 2020.
[12] 1 million solid cubic meter approximately equals 0.5 TWh thermal energy (https://stat.luke.fi/en/wood-energy-generation-2020_en).
[13] Camia, A. et al. (2020).
[14] Camia, A. et al. (2020).
[15] IEA 2020.
[16] The International Energy Agency (IEA) figures presented in the text are figures within the Stated Policies Scenario (STEPS) only, in which Covid-19 is gradually brought under control in 2021 and the global economy returns to pre-crisis levels the same year. This scenario reflects all of today's announced policy intentions and targets, insofar as they are backed up by detailed measures for their realisation. (IEA 2020).
[17] IEA 2020.

CHAPTER 3: GASIFICATION OF BIOMASS AND WASTE – MARKET POTENTIAL

There is both the abundance of waste feedstocks and an increasing demand for the variety of applications that the production of syngas is ideally placed to provide.

3.2. Potential of Gasification by output / demand by application

The energy transition cannot be achieved without the shift to cleaner gas, power, heat and transportation. This section examines these sectors and the opportunities they offer from the gasification of solid biomass and renewable waste.

▪ Electricity

Renewable electricity growth averages about 5% per year from 2019 to 2030[18]. According to the 2020 IEA's STEPS scenario, electricity from renewable sources will increase by two-thirds from 2020 to 2030, replacing coal as the primary form of electricity generation. In 2025, global electricity demand will exceed 26,000 TWh, 10% higher than in 2019. A steady increase in electricity demand will provide nearly 29,000 TWh in 2030. By 2030, hydro, wind, solar PV, bioenergy, geothermal, concentrating solar and marine power between them provide nearly 40% of electricity supply.

> *The energy transition cannot be achieved without the shift to cleaner gas, power, heat and transportation.*

▪ Heat

In 2019, renewables accounted for 10% of total global energy consumption for heating. In the STEPS scenario, this share increases to 14% by 2030. Modern bioenergy with gasification of solid biomass and renewable waste accounts for nearly 40% of the increase in renewable heat, thanks to biomethane, which is suitable for process heat at high temperatures and can be fed into existing natural gas grids[19]. This is mainly due to policy measures in China and the European Union. These are, for example, the introduction of new renewable energy standards and emission reduction targets.

In emerging and developing countries, low-level industrial heat is often provided by solid waste biomass. In this context, the use of solid biomass in these countries is expected to maintain its share in the supply of industrial heat.

Driven by the growth in industry, demand for biogas and biomass for heating will double by 2030[20]. Increased blending of biomethane into natural gas networks will increase the share of bioenergy in district heating systems and in the building sector.

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[18] IEA 2020.
[19] Ibid.
[20] Ibid.

CHAPTER 3: GASIFICATION OF BIOMASS AND WASTE – MARKET POTENTIAL

In this sector, an increase in use of renewable heat by 2030 and according to the STEPS scenario with 35% will be largely through electrification, mainly through heat pumps. Bioenergy will account for 30% in this context. By blending biomethane into existing natural gas networks, the use of biogas in the building sector will grow by 5 % per year into the 2020s. The use of bioenergy in district heating systems, according to STEPS, will also increase in the future, mainly driven by the switch from coal to gas, especially in China.

Transport

Above all, policy measures are the key precondition for a steady increase in low-carbon fuels that are produced using solid biomass, liquid biofuels and biogases.

The IEA's STEPS scenario forecasts strong annual growth of 5% per year for biofuels in the transportation sector over the next decade. The key growth markets are expected to be the United States, China and Europe. The Renewable Fuel Standard in the USA for example requires the introduction of higher-blend fuels after 2022. The European Commission's Renewable Energies Directive II mandates a 14% share of renewable energy in transportation by 2030.

In emerging and developing countries, the importance of biofuels is especially increasing. According to the STEPS scenario, around 40% of global growth for biofuels will come from these countries, particularly those where biofuel production also supports agricultural policy goals[21]. India, for example, has adopted the ambitious goal of achieving a biofuel blending quota by 2030.

Renewable Natural Gas

Renewable Natural Gas (RNG) is methane created from renewable sources and compliant with traditional natural gas usages. RNG originates from processes such as SNG thermal gasification and upgraded biogas. For Europe as a whole, the RNG share is expected to reach about 8% by 2030, which is roughly equivalent to 35 bcm of RNG[22]. IHS estimated the technical potential of gasification for SNG generation to be around 120 bcm in Europe, representing half of the total RNG potential[23].

RNG demand is ramping up quickly, and growth is accelerating. The global market is called for an exponential growth in this decade and could reach more than 100 bcm by 2030 (all technologies, including gasification). This would represent close to 3% of global gas demand, and much more in some regions.[24] And RNG as a transportation fuel is leading global demand growth, reaching 1.5 bcf in this sector in 2019, up 40 % from 2018[25].

Biochar

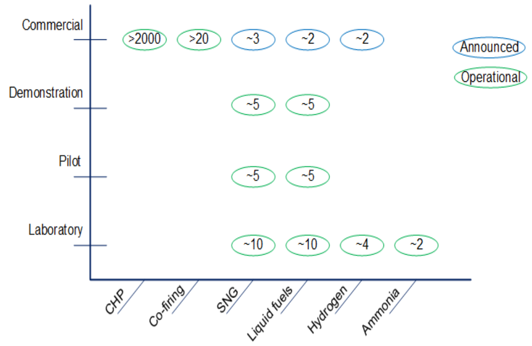
Biochar is a material produced from the gasification process when using biomass materials and can be used either for energy generation, as a soil re-fertiliser or as a commodity material for sale. The biochar market is growing exponentially. A recent market analysis of the European Biochar Industry Consortium (EBI) shows a 5-year CAGR of 38% and a 3-year CAGR of even 42%. In 2020, the growth rate was 70% and in 2021 even higher rates are expected.

[21] Ibid.
[22] CEDIGAZ (2021).
[23] Biomethane in Europe: Estimating the potential resource, IHS Markit, October 2019.
[24] Global Biomethane Market 2021 Assessment, CEDIGAZ, March 2021.
[25] CEDIGAZ (2021).

CHAPTER 4: GASIFICATION AS A STATE OF THE ART TECHNOLOGY

The approximate number of operational and known gasification facilities, also known as plants, can be seen in Figure 4. The production of power and heat (CHP) as well as co-firing are very well-established technologies, still far fewer plants which produce synthetic biofuels and biochemicals.

Figure 4: Number of global gasification facilities



The proven implementation of CHP facilities is the most widespread and successful.

4.1. Power and combined heat and power (CHP)

The proven implementation of CHP facilities is the most widespread and successful. In 2021, there are over 1,700 operational facilities all over Europe, most of them in Germany, Italy and Austria. The well-known producers are Burkhardt GmbH, Spanner Re2 GmbH, SynCraft and Urbas. These types of gasification facilities are able to cover the energy demand (power and heat) of hospitals, schools and hotels, they are often used also for district heating or in saw mills, food production facilities or farms, where the feedstock is easily available. Most of them are small scale gasifiers with output up to 500 kWel / 800 kWth. There are also a few examples of larger plants with an average total capacity of 5-6 MWe (e.g. EQTEC).

The gasification technology uses biomass or waste, which is converted into syngas and after cleaning, it is moved into one or more gas engines for the production of electric power. The process can be combined with heat production which makes it more economically beneficial.[26]

Biomass gasification integrated with a gas turbine based combined cycle (Biomass Integrated Gasification Combined Cycle or BIGCC) is the most efficient biomass energy conversion technology for power production and it can also be applied to organic residues from any source.[27]

4.2. Co-firing for heat/steam production

Gasification can play an important role in the production of high temperature heat, where typically only fossil fuels (natural gas, or oil) are used for combustion. Co-firing of product gas for heat/steam production is mostly used in industrial processes or for district heating to substitute fossil fuels and instead using biomass or waste. Most of those facilities are found in Finland, Sweden, the Netherlands and Germany.[28] An example is the refused paper reject gasifier built at Sappermeer in the Netherlands to displace natural gas that was used to produce steam in their cardboard making process. All the advantages of this application are highlighted in a full report.[29]

[26] The reference facilities can be found in IEA Bioenergy Task 33 database. Further details regarding CHP producers can be found in Branchenguide, which is regularly published by FEE.
[27] Francesco Fantozzi, Pietro Bartocci, Biomass feedstock for IGCC systems in Integrated Gasification Combined Cycle (IGCC) Technologies, 2017.
[28] More information here: http://task33.ieabioenergy.com/?database=true).
[29] Industrial Process Heat: Gasification of paper reject to displace natural gas usage in a pulp and paper process, S. Grootjes, B. Vreugdenhil, B. Bodewes.

4.3. Fuel synthesis

The 'low hanging fruit' for gasification applications is in CHP or the co-firing context. The next step is to process the syngas, creating a variety of end products and replacing fossil-based equivalents. Typically, these developments require a larger scale than the previously described routes. The following biofuels and biochemicals could be produced from syngas through different synthesis process: synthetic natural gas (SNG), hydrogen, ammonia, liquid biofuels based on Fischer-Tropsch (FT) synthesis (diesel, kerosine, petrol), mixed alcohols, and methanol/DME (see Figure 3).

▪ Synthetic natural gas (SNG)

Synthetic Natural Gas (SNG) composed mostly of methane is gained from a direct chemical reaction called methanation between the syngas components hydrogen and carbon monoxide. The resulting gas can be fed into existing natural gas grids. Injecting synthetic methane (SNG) produced through gasification into existing gas networks decarbonizes the gas system, which itself contributes to balancing the electricity grid. SNG is suitable as a long-term energy storage.

It is established that renewable natural gas is very well placed to play a key role in the EU's energy transition. Natural gas is widely used as feedstock in industrial processes, to supply households, as a transportation fuel (like in liquid form – LNG), or for power generation (CCGT). This highly efficient process (65 – 70% on an energy basis, ca. 80% including heat recovery) is developed up to TRL 8 and needs full scale deployment.
Several routes have been developed in Europe, in particular: GoBiGas in Sweden[30]; Synova, Torrgas and SCW Systems in the Netherlands; Gaya platform in France[31]; Advanced Biofuel Solutions in the UK.[32]

SNG production through gasification is ready to be upscaled and fully deployed but faces issues such as competition with an actual low fossil natural gas price. Subsidies or incentives have not yet proven to be sufficiently supportive to these technologies.

▪ Hydrogen

Hydrogen is obtained within a so-called water gas shift reaction after gasification. Carbon monoxide reacts with additional water molecules (steam) to hydrogen and carbon dioxide. In this way, high concentrations of hydrogen can be reached. Today, hydrogen is predominantly produced from fossil fuels and mostly used in industrial processes. In the future, renewable hydrogen will replace fossil fuels in industry (feedstock and high temperature heat), heavy transport, power and centrally heated buildings.[33]

[30] The GoBiGas Project: Demonstration of the Production of Biomethane from Biomass via Gasification.
[31] Gaya platform in France, visit website.
[32] More information: https://absl.tech/.
[33] More information regarding production of hydrogen through gasification can be found in IEA Bioenergy Task 33 Special report 'Hydrogen from biomass gasification'.

CHAPTER 4: GASIFICATION AS A STATE OF THE ART TECHNOLOGY

At the moment there are no commercial plants operating at scale in the EU for hydrogen through gasification, however a number of these have been announced and are being developed. This is an area of expected innovation with plants due to be constructed, as the market demand and investment case for hydrogen is established.

▪ Ammonia

Ammonia is commonly produced via steam methane reforming to produce H2 and it is, after adding N2 from an air separation unit, converted to ammonia. To make it fossil free, a gasification-based hydrogen plant can be the first step towards an ammonia synthesis.

Since 2003, the Ebara Gasification facility in Japan has been producing hydrogen from non-recyclable plastic waste (approx. 70 000 t/year) for the manufacturing company Showa Denko K.K.[34], which uses it as a raw material for the synthesis of ammonia.

▪ Liquid biofuels (biodiesel, biokerosene, biopetrol)

Biodiesel, bio-kerosene and biopetrol can be produced from syngas using the Fischer-Tropsch (FT) synthesis process. The quality of those products is even higher than fossil based fuels. Furthermore, only the particular addition of renewable FT fuels into fossil ones ('drop-in') improves the combustion process in motors and decreases emissions. There are currently no commercial facilities for production of FT fuels in operation. However, there are several demonstration projects showing the techno-economic feasibility of the process (e.g. BioTfuel project[35]).

▪ Mixed alcohols

Mixed alcohols mainly consist of C1–C4 alcohols (mixture of methanol, ethanol, propanol, isopropanol, butanol and isobutanol). They are of great importance because mixed alcohols are valuable additives to gasoline to increase the octane number and reduce the environmental pollution. Furthermore, the great benefit of the mixed alcohol synthesis is the high resistance of the catalysts against sulphur poisoning and the fact that the gas cleaning facilities can be simpler than by other synthesis. Mixed alcohols can be also converted to high quality fuels over dehydration and oligomerization.[36]

▪ Methanol and Dimethyl ether (DME)

DME has promising features as a fuel candidate with both the Otto and the diesel engine. With adaptations to the engine and fuel system, DME can be used in diesel engines, leading to higher fuel efficiency and lower emissions. In Otto engines, DME can be used with LPG. Since DME is as easily reformed as methanol, it has potential for fuel cell vehicles. DME has similar physical properties as LPG and can be handled as a liquid, using the same infrastructure as LPG (e.g. the bioliq® process[37]). The route to methanol is very similar to DME and there are processes being developed to directly convert methanol to DME in one synthesis step[38].

[34] https://www.sdk.co.jp/english/news/2019/37672.html.
[35] https://www.total.com/energy-expertise/projects/bioenergies/biotfuel-converting-plant-wastes-into-fuel.
[36] R. Rauch, J. Hrbek, H. Hofbauer: Biomass gasification for synthesis gas production and applications of the syngas, July 2014, Wiley Interdisciplinary Reviews: Energy and Environment 3(4) DOI: 10.1002/wene.97.
[37] Further detail can be found in Country Report Germany as well as in IEA Bioenergy Task 33.
[38] J. van Kampen, J. Boon, J. Vente, M. van Sint Annaland: Sorption enhanced dimethyl ether synthesis for high efficiency carbon conversion: Modelling and cycle design, April 2020, Journal of CO2 Utilization (37).

CHAPTER 5: DEVELOPMENT OF COSTS

This chapter focuses on the net production costs now and in the future. For a totally viable business case, the availability and quality of the feedstock, the production costs and the forecast revenues from the products created from gasification, like heat and biochar, are all important. Production mainly depends on three cost streams: feedstock (gate fees in some cases), gasification process (Capex & Opex) and product-specific costs. It is also important to distinguish between the various production processes.

Figure 6: Summary of production costs

Product	Production costs[1]
Electricity	99 - 109 €/MWh_{el}
Heat / Steam	21 - 44 €/MWh_{th}
Synthetic Natural Gas (SNG)	37 - 90 €/MWh
Hydrogen	42 - 101 €/MWh (1.40 - 3.35 €/kg)
Ammonia	47 - 105 €/MWh (0.25 - 0.55 €/kg)
Fischer-Tropsch Fuels	40 - 113 €/MWh (0.30 - 0.85 €/kg)
Mixed alcohols, DME	No reliable information available
Methanol	37-90 €/MWh (0.21 - 0.50 €/kg)

Figure 6 shows the future production costs ranges per product.

5.1. CHP and co-firing

As described in Chapter 2, the main application of gasification is currently in CHP and, to a smaller degree, co-firing. The main costs for CHP are capital costs and feedstock costs. Mostly, CHP plants are small plants. Depending on the size of a CHP plant, costs range from 21 to 44 €/MWh(th) and from 99 to 109 €/MWh(el) (IEA Bioenergy (2015)).

5.2. Synthetic natural gas (SNG)

In order to produce SNG, hydrogen or other fuels, further syngas processing is needed. This can be done in large scale plants, enabling the production of substantial volumes in an economically feasible way. Besides the Gobigas plant, some relatively small plants have been developed. These plants provide valuable information about capex, opex and product specific costs, albeit that cost information relates to relatively small production locations. As a consequence, the opex and capex costs per MWh are relatively high. With the further development and upscaling of this second generation gasification plants, costs per MWh will reduce.

Production mainly depends on three cost streams: feedstock (gate fees in some cases), gasification process (Capex & Opex) and product-specific costs.

According to various sources, the projected costs per MWh to produce SNG varies between 48 and 112 €/MWh[39], based on a plant size of 20-40 MW. These costs include feedstock costs, capex and opex, and relate to the final product (including both gasification and product specific costs).

[39] Excluding outdated sources, outliers and liquefaction costs.

Figure 7: Current and future costs for the production of Synthetic Natural Gas[40]

Biomethane cost price values

Gasification costs (€/MWh)	Current low	Current mid	Current high	Future (2030-2050) low	Future (2030-2050) mid	Future (2030-2050) high	Remark
Gassner&Meréchal (2009)	79*	*(111)*	142*				refer to CE Delft (2020)
Billig (2016)	66*	*(119)*	172*				refer to CE Delft (2020)
Ecofys (2018)					37		
Held (2018a)					90		Based on Gobigas; 100 MW plant; Include revenues of 5 €/MWh.
Held (2018b)				65	*(68)*	70	70 = based on Gobigas, 100 MW plant; Include revenues of 7 €/MWh; 65 = based on METDRIV project, 200 MW pressurised oxygen-blown gasifier.
Göteborg Energi (2018)					73		Based on GoBiGas
Navigant (2019)					47		88 = based on GoBiGas, 20MW phase 1
Thunman (2019)					60		Based on Gobigas; 200 MW plant
Guidehouse (2020a)(2020b)	90	*(95)*	100	47	*(52)*	57	
IEA Bioenergy (2020)	62	*(87)*	112	42	*(72)*	102**	Methane/methanol - biomass
IEA Bioenergy (2020)	48	*(69)*	89	29**	*(55)*	80	Methane/methanol - waste
Range	48	-	172	29	-	102	
Range excl outliers, outdated sources	48	-	112	37	-	90	
Mid excl outlayers, outdated sources		84			59		

** Interpreted as outdated sources*
*** Interpreted as outlier*

A current average cost value for the production of SNG would be around 85 €/MWh.

Several studies have assessed the expected future costs for gasification. Thunman (2019)[41], Held (2018a)[42], Held (2018b)[43] and Göteborg Energi (2018)[44] have based their analyses on lessons learned from Gobigas[45], extrapolating 'current' costs onto a 100-200 MW plant. Ecofys (2018)[46], Navigant (2019)[47], IEA Bioenergy (2020)[48], Guidehouse (2020a)[49] and Guidehouse (2020b)[50] have taken a broader view based on various techniques. All the studies estimate future costs for a well-developed and upscaled future gasification plant. Although the year for which these costs apply is not always specified, here it is assumed that full development and scaling will take place before 2030. Reported future costs show a wide range. Aside from the main outliers in the data set, a net production cost range for SNG is between 37 and 90 €/MWh seems realistic. An average value has been assumed of 59 €/MWh. Feedstock accounts for approximately 30% of total costs.[51]

There are two factors that will improve the competitive position of SNG:

[40] CE Delft (2020): Availability and costs of liquefied bio- and synthetic methane, The maritime shipping perspective; Billig (2016): Billig, E., 2016. Bewertung technischer und wirtschaftlicher Entwicklungspotenziale künftiger und bestehender Biomass-zu-Methan-Konversionsprozesse, Leipzig: Universität Leipzig; Gassner (2009): Gassner, M. & Maréchal, F., 2009. , Thermo-economic process model for thermochemical production of Synthetic Natural Gas (SNG) from lignocellulosic biomass. Biomass and bioenergy, 33(11), pp. 1587-1604.
[41] Thunman (2019): Thunman, H. et al., Economic assessment of advanced biofuel production via gasification using real cost data from GoBiGas, 2019.
[42] Held (2018a): Held, J., Biomass Product Gas Reforming Solutions – BioProGReSs. Renewtec Report 007:2018. ISSN 2001-6255. Renewable Energy Technology International AB, 2018.
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[44] Göteborg Energi (2020): Anton Larsson, Ingemar Gunnasrsson, Freddy Tengberg, The GoBiGas Project Demonstration of the Production of Biomethane from Biomass via Gasification, December 2018.
[45] Ecofys (2018): The Gothenburg Biomass Gasification (GoBiGas) project was first-of-its-kind demonstration plant for the production of 20 MW biomethane via the gasification of biomass. The plant was decommissioned in 2018.
[46] Ecofys (2018): Gas for Climate, How gas can help to achieve the Paris Agreement target in an affordable way, Feb. 2018.
[47] Navigant (2019): Gas for Climate, The optimal role for gas in a net-sero emissions energy system, March 2019.
[48] IEA Bioenergy (2020): Advanced Biofuels – Potential for Cost Reduction, IEA Bioenergy Task 41, 2020.
[49] Guidehouse (2020a): Gas for Climate Market Trends Report, 2020.
[50] Guidehouse (2020b): Gas Decarbonisation Pathways 2020-2050, Gas for Climate, April 2020.
[51] Ecofys (2018); Guidehouse (2020b).

- Despite the fact that in some jurisdictions, with current gate fee regimes and energy prices, waste-to-energy gasification is already a profitable activity, further development of technology and upscaling would bring down the costs for gasification by more than 30% and;
- The need to bring down CO2 emissions by 55% in 2030 and by 100% in 2050 (compared to 1990 levels) which will increase the costs for utilization of fossil gas, amongst others, through the EU Emission Trading System (ETS).

At the lower end of the production costs range, SNG is already competitive with natural gas at an ETS price of 84 €/tCO2 and higher[52]. Forecasts and recent developments clearly indicate that a break-even price of 84 €/tCO2 can already be reached in a short period of time. The break-even price at average SNG costs of 59 €/MWh would be 193 €/tCO2, which is relatively high but should not be ruled out beforehand for 2030. Those figures clearly indicate that stimulation of further development and scale up is necessary to quickly bring down the cost price of SNG to economical levels.

Three aspects must also be taken into account for grid injection: (1) biomethane must be 'on spec' for injection, (2) compression costs might apply, and (3) grid connection costs might apply. Upgrading and compression costs have been analysed by various sources[53] and are reported to vary between 8 and 12 €/MWh for anaerobic digestion. In the case of SNG production, upgrading and compression costs are expected to be lower. Grid connection and injection costs have been assessed by Guidehouse (2020b) at 2€/MWh. It is to be noted that it is not always clear whether the studies in Figure 7 include upgrading costs. Grid connection and injection costs are not included. The assumption is to include up to 5 €/MWh for the injection of produced SNG into the gas grid.

Further development of technology and upscaling will bring down the costs for gasification by more than 30%.

5.3. Hydrogen

The production process for hydrogen via gasification is more or less similar to the production of SNG. However, most studies do not assess future hydrogen costs by. An exception is IEA Bioenergy (2018)[54], which calculates the future cost of hydrogen at 2.70 €/kg. These costs are based on a dual fluidized bed (DFB) Gasification plant of 50 MW. Current costs are calculated at 5.49 €/kg based on a 1 MW sorption enhanced reforming plant. Considering the studies assessing the future costs for SNG, a relatively high downward potential for hydrogen is assumed to be possible as well as limited upward risk on costs. This leads to a cost range of 1,40 – 3,35 €/kg (42 – 101 €/MWh) depending on the unit size.

[52] Assuming a natural gas price of 20€/MWh.
[53] Navigant (2019), CE Delft (2020).
[54] IEA Bioenergy (2018): Hydrogen from biomass gasification, IEA Bioenergy: Task 33: December 2018.

5.4. Ammonia

Ammonia produced from hydrogen via the Haber-Bosch principle will account for an additional 10-15 €/MWh to the costs of hydrogen production through gasification, resulting in 47-105 €/MWh.

5.5. Liquid biofuels

In relation to the future costs of producing Fischer-Tropsch-biofuels, an assessment is based on IEA Bioenergy (2020), with the future costs for FT-biofuels at 40-113 €/MWh (302 - 854 €/kg) on the following basis:

- IEA estimates the future costs for SNG from biomass or waste at 42-102 and 29-80 €/MWh respectively, which are at the higher end compared to other studies
- IEA estimates the future costs for FT-fuels from biomass or waste at 56-125 and 32-94 €/MWh respectively
- As IEA estimates for future SNG costs are at the higher end, it is assumed estimates for future FT-biofuels are relatively high too
- The difference in cost estimates by IEA for SNG and FT-biofuels have been taken as a basis. The difference is 14-23 €/MWh for biomass and 3-14 €/MWh for waste. Combined: 3-23 €/MWh
- In this paper it is estimated that the costs of SNG at 37-90 €/MWh based on multiple sources; and
- The cost of FT-fuels is estimated at 3-23 €/MWh higher, resulting in 40-113 €/MWh.

5.6. Mixed alcohols

For the production of mixed alcohols no reliable sources on costs were found.

5.7. Methanol and Dimethyl ether (DME)

IEA Bioenergy (2020) assesses the costs for production of Methanol and SNG to be identical. Therefore, it is assumed that future costs for production of methanol through gasification will be on the same level as the costs for producing SNG. As with DME, no reliable sources on costs were found. Based on the relatively simple additional step, additional costs of a few euros per MWh are assumed.

For a totally viable business case, the availability and quality of the feedstock, the production costs and the forecast revenues from the products created from gasification, like heat and biochar, are all important. Production mainly depends on three cost streams: feedstock (gate fees in some cases), gasification process (Capex & Opex) and product-specific costs.

CHAPTER 6: ROAD TOWARDS COMMERCIAL SCALE

6.1. Challenges

The European Union is de-fossilizing its energy industry for important reasons. But that doesn't just mean changing fuels and technologies. It also means creating an energy market that operates according to completely different principles. A particular challenge is managing the volatile feed-in of wind energy and photovoltaics. This is where gasification comes into play.

Today's application of gasification technology relates to tailormade solutions like small scale CHP (around 2000 plants operational), large scale co-firing (around 20 plants operational) and a few plants producing fuels and chemicals Its greatest success and impact, so far, comes from its use in CHP-plants. It is precisely these plants - in conjunction with storage facilities - that can cover the residual load in the electricity market. In this way, gasification contributes to grid stability and make it possible for there to be such a large proportion of volatile electricity feed-in in the power market in the first place.

For the second generation, with many plants of this kind currently in development, to reach its commercial scale, the production process of each possible product must be optimized and upscaled - and each route needs specific support.

As shown in this paper, several demonstration second generation gasification plants in Europe have proven the technical feasibility of the production of biomethane, hydrogen, biofuels or other chemicals – and there are already commercial waste-to-energy plants that are profitable with current support regimes. This process of further evolving and product-specific optimizing of the gasification technology is already underway. More support is needed and still pending, to allow more mature, impactful and extended commercial scale which encourage companies to invest in the technology through, for instance, capital investments, off-take support or operational subsidies.

Its success and ability to scale and become the waste-to-energy/fuel method of choice depends on the levels and type of political, policy, economic and commercial support, in order to reduce costs and raise awareness of its strong potential to accelerate the net-zero responsibilities of the waste, energy and fuels markets.

6.2. European stakeholders are committed to develop gasification although public support is still pending due to lack of awareness of the benefits

The sector needs concrete public and political support policies to demonstrate confidence as well as further widen and scale up in its current commercial phase.

Bioenergy and biofuels produced through gasification will end up playing a valuable role in an integrated sustainable energy system. To enable that transition companies and communities all over Europe are committed to supporting the sector. The main challenge is to stimulate the upscaling of second generation gasification plants, which operate under different conditions than the first generation and therefore require new support mechanisms to quickly reach a commercial scale. In reaching that scale, they will be ready to take over from less environmentally beneficial waste management infrastructure, an estate with many plants quickly reaching their useful end of life in the EU.

This support is also key as the production of sustainable energy through gasification needs upscaling to become competitive compared with fossil fuels and therefore needs to be promoted, supported and enabled in the same way that large-scale renewables such as solar and wind power have been for the last 15 years,keeping an eye on the subtleties of gasification technologies. It is self-evident that a supportive scheme should take into account the system value of bioenergy and biofuels, in addition to acknowledging the importance of energy storability, in a future coupled energy and circular system.

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About the EBA

The EBA is the voice of renewable gas in Europe. Founded in February 2009, the association is committed to the active promotion of sustainable biogas and biomethane production and their use across the continent. The EBA today counts on a well established network of over 200 national organisations, scientific institutes and companies from Europe and beyond.

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