PAST, PRESENT AND FUTURE OF THERMAL GASIFICATION OF BIOMASS AND WASTE

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Abstract
The thermal gasification has been used for nearly 200 years. At the beginning coal or peat were used as a feedstock to produce gas for cooking and lighting. Nowadays, the coal gasification is still actual, anyway, in times without fossils the biomass and waste gasification becomes more important.
In this paper, the past, present and future of the biomass and waste gasification (BWG) is discussed. The current status of BWG in Austria, Denmark, Germany, Italy, the Netherlands, Sweden and USA is detailed described and the future potential of the technology is outlined.

Keywords
gasification, syngas, biochemicals, biofuels, CHP, hybrid systems

Introduction
This year, 2020, the EU aims to reduce greenhouse gas emissions by at least 20% (compared to 1990). The share of renewable energy should be significantly increased. In transport sector, all EU countries should achieve at least 10% share of renewables. [1]

It seems that the energy transition should start in transport sector, followed by industrial one. One of the possibilities, how to reduce CO_2 emissions in transport sector is the implementation of electro cars. One could argue, that the electricity to power the vehicles will come from renewable sources, like wind power or PV and it seems that the problem could be solved in this way. However, what about aviation, marine or heavy-duty trucks? What about the material costs and energy demanding production process of batteries? Even if we skip the safety factor by batteries– explosion danger, we should mention that their life cycle is not as long as it should be. Producers suggest to use the battery for 500-1 200 charge cycles, it means a life span of an electro car of 5 to 10 years. Probably it is not necessary to point out, that the battery price contributes significantly to price of the electrical vehicle.
Another way, how to power the cars is the utilization of biomethane. This way seems to be more reasonable; the biomethane could be used as natural gas. Its properties are similar or even better as by its fossil-based "brother" and the infrastructure for it exists already. The significant advantage is for sure that biomethane is based on renewable resources. The idea to use biomethane in cars is not new, but demonstration of production in large scale was missing. Thus, the project with the aim to produce biomethane from biomass started in Sweden (GoBiGas) and will be described later in this paper.

In the period 2021-2030, a strong signal should be sent to the market by EU to encourage and support private investment in low-carbon technologies [2].
The strategic long-term vision ("2050 Energy Strategy) shows how Europe can lead the way to climate neutrality and Paris Agreement objective to keep the global temperature increase to well below 2°C and pursue efforts to keep it to 1.5°C.
To rich all these goals, the complete transformation of our energy policy and framework will be necessary. It is clear, that new political acts in many areas, e.g. industry or transportation sector could not be avoided. And, in this case, the massive support of renewable energy by the political acts will be the right way to the future. Not the reduction of energy use, but efficiency increase as well as search for new and advanced technologies and their synergies based on renewables and waste utilization will be the right direction how to save the environment for the next generations. It is also clear that not just one renewable energy source will be able to cover our energy demand, but technologies combination and share of renewable sources will be the right way.

In this paper, one of these technologies, which is based on bioenergy will be described and discussed. Thermal gasification of biomass and waste is a thermochemical process, which enables the conversion of the feedstock (biomass or waste) into product gas and by-products. From the product gas, after cleaning and upgrading, the

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synthesis gas, containing mostly hydrogen and carbon monoxide, will be produced. There are many ways of utilization of synthesis gas. It could be used for production of power and heat, liquid or gaseous biofuels, chemicals or for fuel cells. The by-products from the gasification process e.g. bio-char became very popular on the market and because of its purity it could be used in many ways, either for material use or carbon storage, which is of a great benefit.

History of gasification

The gasification process is not new. The process has been used nearly 200 years for energy production. At the beginning coal or peat were used as a feedstock to produce gas for cooking and lighting. During the World War II, the search for new feedstock because of fossil fuels shortage was necessary. The wood gas generator was developed, which was used to power motor vehicles, such as agricultural machines, trucks, buses and cars.
After the WWII, when the fossil fuels were available and cheap again, it was only Sweden, which continued working on gasification technology, furthermore, after 1956 (Suez Canal crisis), the gasifiers were in Sweden included in Swedish strategic emergency plants.
An overview on gasification applications in different time periods is shown in the table below. As can be seen, gasification technology was utilized already in pre-industrial time, anyway, the considerable development of biomass gasification can be observed in 20. and 21. Century, especially the boom of small-scale gasification units in Europe.

Table 1. Overview on gasification application in different time periods. *Source: [3]*

	preindustrial	1900-2000	2001 - today
Coal to Gas	-	Yes	Yes
Coal to liquid	-	Yes	Yes
Crude oil to liquid	-	Few	Yes
CHP IGCC with NG/Coal	-	Yes	Yes
Small scale biomass CHP		No	Yes
Large scale biomass CHP	-	No	Yes
Co firing BM	-	Yes	Yes
MSW		No	Yes
BM to syngas	Yes, for smoking food	Yes, short time mobile application	Yes
BM to liquid	Yes, for tars and chemicals	No	No
Biomass CHP with IGCC	-	Demonstrated	No
BM to SNG	-	No	Demonstrated

Following figure offers an overview on output of small-scale biomass gasification plants between 2009 and 2016 in Germany and worldwide.

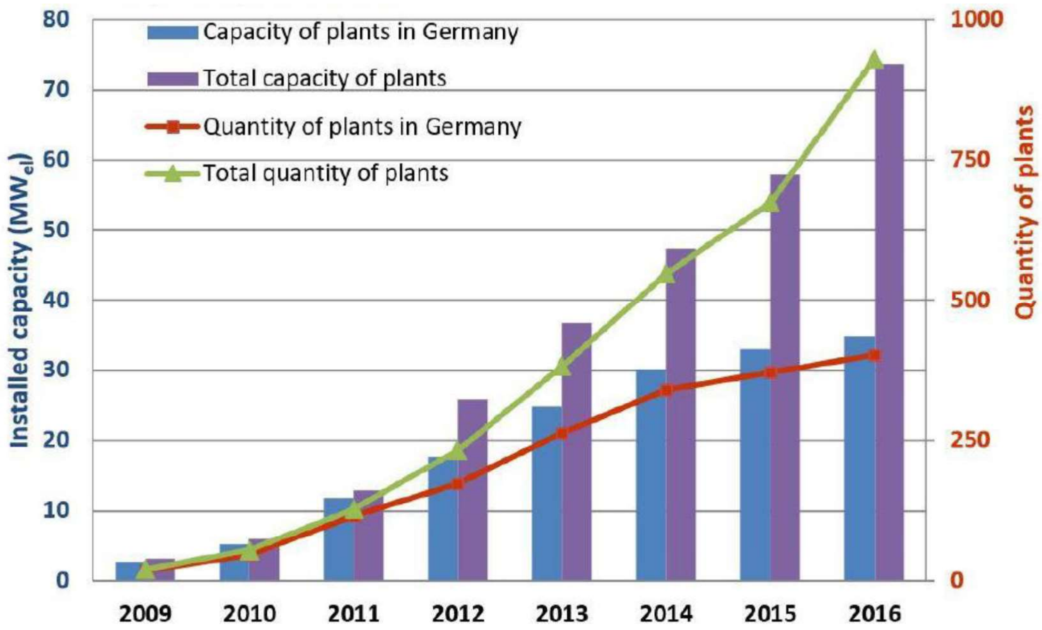

Fig. 1. Installed capacity of small-scale biomass gasification units in Germany and worldwide. *Source: [4]*

Gasification growth from 1950 to 2018 can be seen also in the following figure. The expansion after 2010 is obvious in this figure. In the cake diagram, the global syngas output by feedstock can be seen. It is clearly showed, that the syngas is produced mostly from fossil fuels.

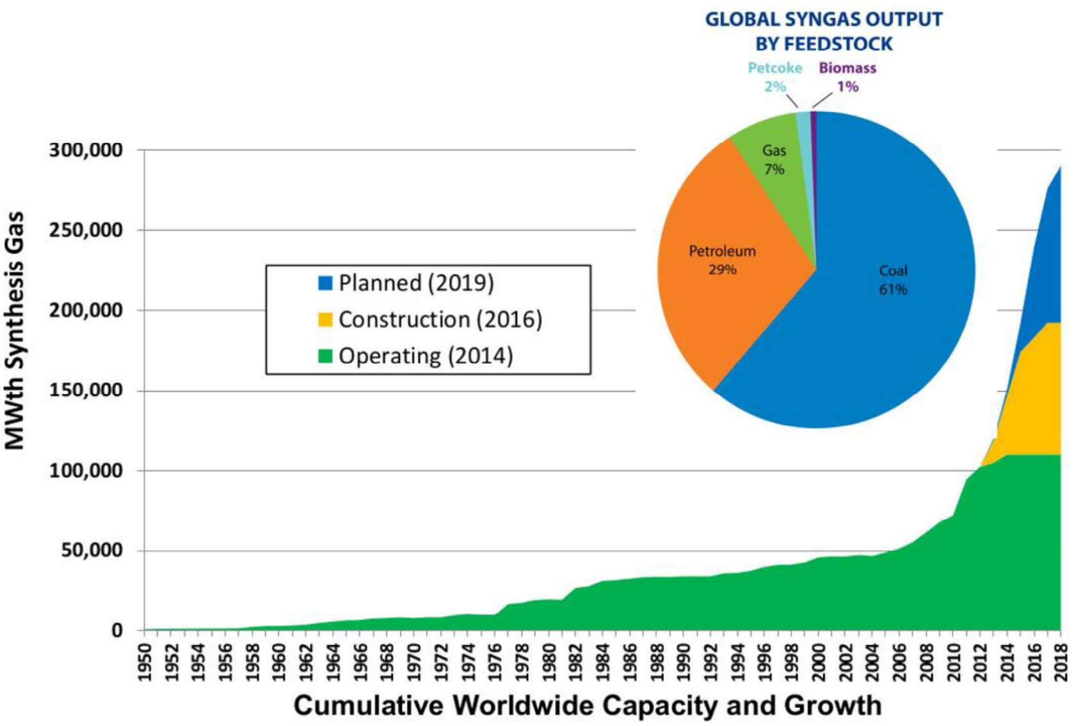

Fig. 2. Gasification growth between 1950 and 2018. *Source: [5]*

<u>Current status of biomass and waste gasification</u>

In this chapter, the status of thermal gasification in Austria, Denmark, Germany, Italy, the Netherlands, Sweden and USA will be described. All of these countries are/were the members in IEA Bioenergy Task 33: Gasification of biomass and waste (www.task33.ieabioenergy.com). The Task 33 is a working group of international experts with the aim to promote the commercialization of efficient, economical and environmentally preferable thermal biomass and waste gasification processes. The Task 33 works in 3-years periods. In actual triennium, the member countries are Austria, Germany, Italy, the Netherlands, Sweden, UK and USA. China will join the Task 33 probably in 2022, maybe earlier. It is also expected that Canada and New Zealand re-join the Task 33.

<u>Austria</u>

Research related to thermal gasification of biomass and waste takes place in Austria at Universities, research centres and private companies as well. The most important ones, which should be mentioned here are Vienna University of Technology (VUT), Graz University of Technology, University of Natural Resources and Life Sciences Vienna (BOKU), BEST (Bioenergy and Sustainable Technologies), MCI (Management Centre Innsbruck) and GET (Güssing Energy Technologies).

The research fields are very diverse. Starting with testing of different feedstock, through different gasification technologies to product gas and valuable by-products, which could be used in many different ways. The evaluations of the whole process chain are provided as well.

At Austrian Universities, two significant gasification technologies were developed during the last years, which after scaling up were very successfully implemented not only in Austria but also abroad.

The first one was FICFB gasifier (Fast Internal Circulating Fluidized Bed), which was developed at Vienna University of Technology and at the first time realized in Güssing (scheme 2001). The process will be described later in this publication.

The improved system called "G-volution" was built at VUT as the latest pilot plant for testing the whole gasification process in practice. The test plants development at VUT can be seen in the following figure.

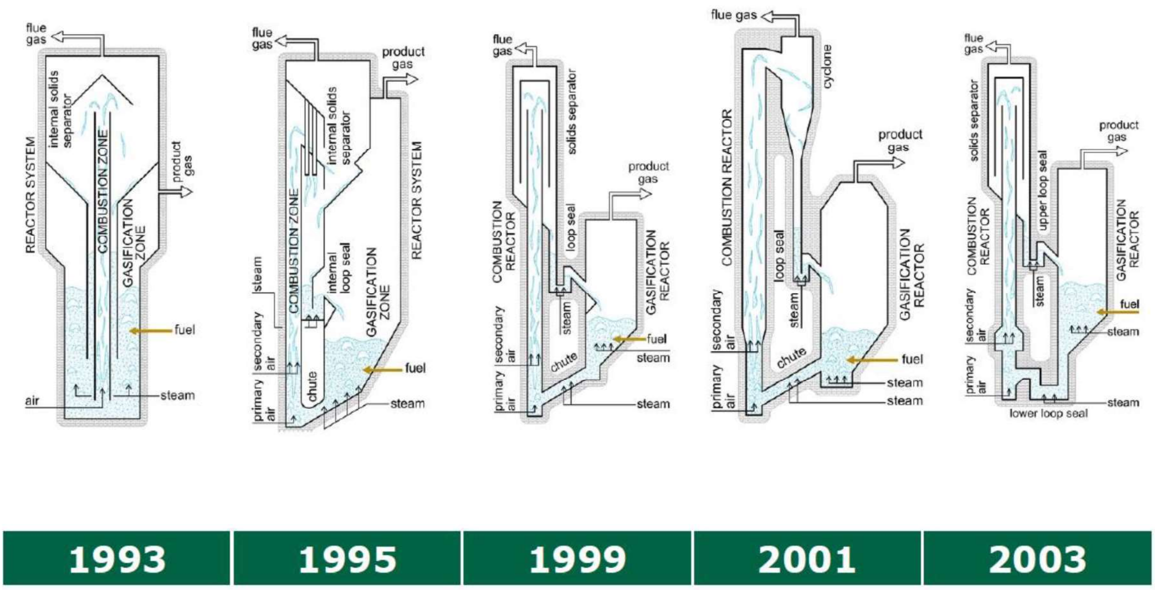

Fig. 3. Research at VUT - development of dual fluidized bed. *Source: [6]*

G-volution, a novel gasification process was developed in 2014 and since that time, many research projects were provided using this 100 kW test plant. The scheme of the reactor, which is divided into the gasification and combustion zones, can be seen in the figure below. The innovative is the gasification part of this set up, where the reactor includes several strictions. These strictions in reactor make the gas, together with fuel particles, to change their velocity several times and ensure the longer contact with bed material as well as longer remaining time in gasifier. This gasification system can be applied on bride spectrum of different feedstock such as wood, agricultural waste, coal, industrial residues etc. For improved product gas quality, the different bed materials, e.g. with catalytic effects can be used.

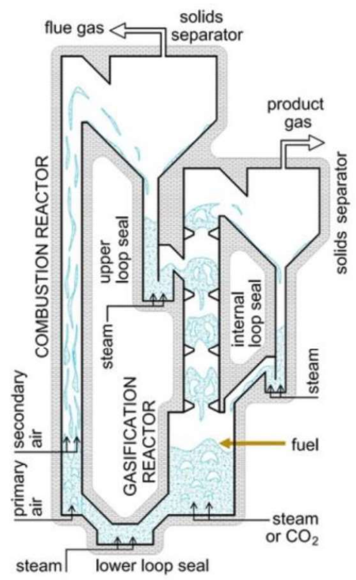

Fig. 4. Gasification system G-voution developed at VUT. *Source: [6]*

The second gasification technology, which should be mentioned here, is a staged gasification process with the floating fixed bed reactor, developed by SynCraft and MCI.

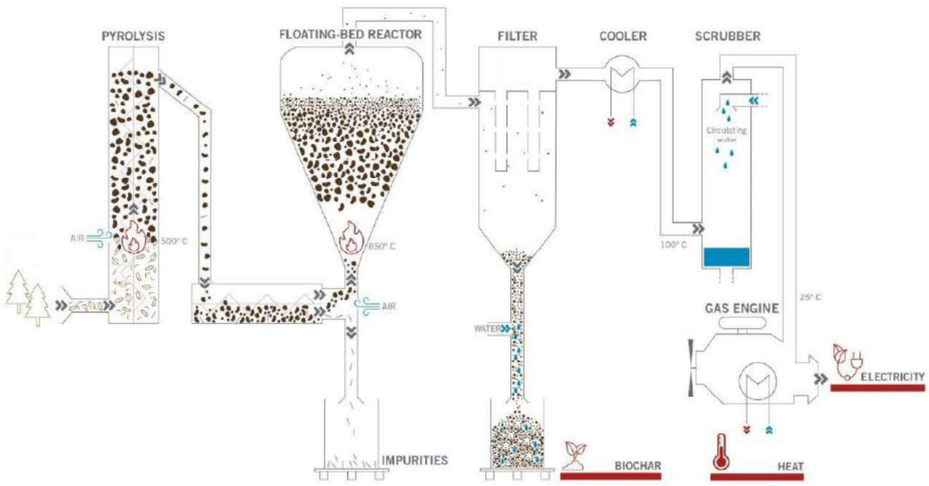

Fig. 5. Staged floating fixed bed gasification system by SynCraf. *Source: SynCraft*

The first step of the process is pyrolysis, where also the devolatilization takes place, fuel particles moves than to floating fixed bed reactor, where they are gasified. The gas, after the cleaning and cooling is used in gas machine for power production, the heat from the process can be used for district heating and drying of the feedstock. The valuable by-product is a premium quality charcoal, which is sold by company to the market. The system operates on low quality dry wood chips including bark and fine particles and overall electric efficiency due to high-tech gas engines is over 30%. At this time, there are 7 SynCraft facilities in operation and 8 further are planned/under construction. Nowadays, the implementation of many small-scale gasification projects can be observed in Austria. Opposite to this fact, it should be reported that the two biggest Austrian gasifiers in Guessing and Oberwart were shut down due to economic reasons. In Guessing, the concept of the fast internal circulating fluidized bed (FICFB) gasification system, developed at Vienna University of Technology was realised, the concept can be seen in the Figure 3 (scheme 2001). The technology of FICFB is based on circulation loop between two zones – gasification and combustion ones. The bed material acts as a heat carrier and circulates between those two zones. The gasification zone is fluidized by steam and combustion one by air, during the process remain steam and air as fluidizing agents separated. Both reactors operate under atmospheric pressure.

The feedstock coming into gasification zone is converted and nearly nitrogen free gas is produced. Not fully processed feedstock rest (char) together with ash move with the bed material (sand, olivine, dolomite etc.) into the combustion zone. Here the char is burned. In this way, the bed material is heated up and moves again into the gasification zone. The temperature in gasification zone is about 850°C, in combustion zone slightly higher, about 920°C. The scale up of the FICFB gasification process was at the first time realised in Guessing, Austria. Therefore, this demo plant can be seen as a reference plant for other facilities based on dual fluidized beds such as plants in Oberwart, Senden/Ulm, Göteborg etc. The Austrian facility was about 100 000 hours in operation and with end of October 2016 was shut down and mothballed. The reason was expiring of the feed-in tariff, supporting the economic operation of the plant.

In small scale, the main producers of gasification facilities in Austria are companies Urbas Energietechnik, SynCraft, Glock Oekoenergie, Hargassner and Froeling, which are successful in Austria as well as abroad. At the moment, many small-scale facilities are in operation in Austria, not only from domestic facilities producers, but also foreign ones.
The technology of Urbas Energietechnik, Glock Oekoenergie, Hargassner and Froeling is based on fixed bed gasification.

Urbas Energietechnik realizes CHP facilities with electric power up to 30 MWel. as biomass steam power plants. They offer also smaller units with output of 150 kWel. The feedstock are clean woodchips, with moisture content below 10%. The gasification plants are delivered as container type systems. It is a turnkey technology.

Fixed bed gasification technology based on Imbert principle offers the company **Glock Oekoenergie**. Wood chips are used as a feedstock. After drying (below 30 % moisture) and gasification the gas is cleaned and cooled down and ready for utilization in gas engines to produce electricity and heat. The company offers plants in two sizes, with output 18 kWel/44 kWth and 55 kWel/120 kWth.

Hargassner offers compact gasification units based on fixed bed technology as well. The electrical output is about 20 kW. The company was founded in 80ies of the last century and since that, time focuses of thermal conversion of biomass. They started with the biomass combustion, anyway, the gasification process is in focus now as well.

Froeling is relatively newly developed company, they first facility has been in operation since 2013. Since that time, they gasifiers can be found in Austria, Germany and Slovenia. The company is focusing on units with output 50 kWel/107 kWth.

SYNCRAFT® Engineering offers a quite unique technology, which is called floating fixed bed gasification process and was described above in this paper. Within this technology, an electrical efficiency of 30% and fuel utilization rate of 92% is possible. The company focuses not only on CHP production, but also char coal (bio char), which is of very high quality and it is therefore solved to the market, offering an additional income. The technology is a turnkey, the units are delivered with electrical output between 200 and 500 kWel.

All small-scale facilities utilize wood chips or pellets for the combined heat and power generation. In addition, the utilization of lower quality feedstock, such as waste wood could be of interest for small-scale gasification.

In Austria, also a large-scale gasification unit for waste materials (RDF) within the project **Waste2Value** will be built in 2020. The commissioning is planned for beginning of 2021. It will be a 1 MW dual fluidized bed gasification unit with improved reactor design as described above. The facility will be coupled with 300 kW Fischer-Tropsch synthesis pilot plant. A research laboratory will be a part of the side, where test rigs for production of mixed alcohols, H_2 separation, methanation will be situated.

<u>Denmark</u>
Talking about research in the field of thermal gasification, following research institutions and centres should be mentioned: Danish Technical University (DTU), Aalborg University (AAU), Danish Gas Technology Centre (DGC) and Danish Technological Institute (DTI).
Danish Technical University (DTU) aims to be leading the research within thermal gasification technologies in Denmark. The gasification group focuses on high efficient CHP as well as production of biofuels, such as bio-SNG or methanol.

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It worth to mention two gasification systems, developed at DTU. The first one is a two-stage gasification system called VIKING. Exactly it is a three-step conversion process if also the drying would be taken into account. The feedstock comes into dryer, where the moisture is reduced using superheated steam, then moves into the pyrolysis part and finally is gasified in the downdraft fixed bed reactor. The advantage is a high-energy efficiency, which is about 93% as well as clean product gas without tar. The technology is now owned by company Weiss.

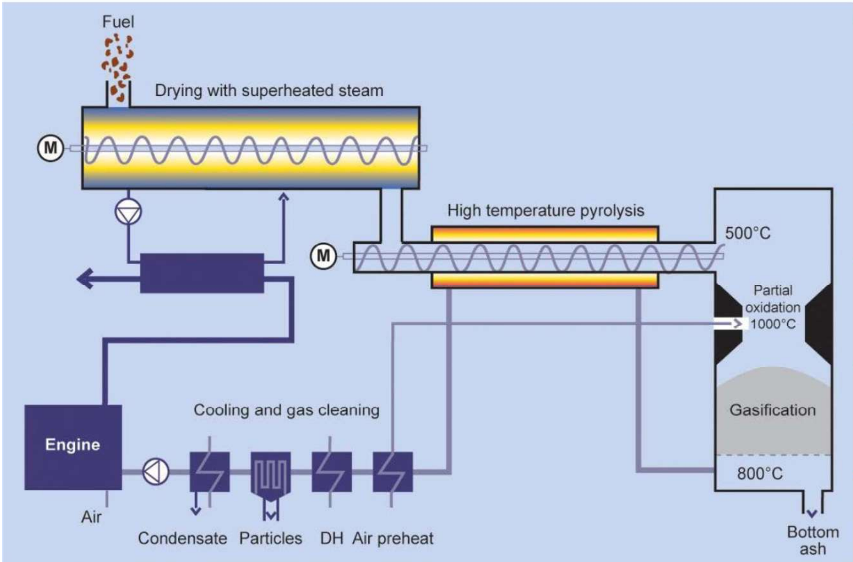

Fig. 6. VIKING gasification system developed at DTU. *Source [7]*

The second gasification system, which was developed at DTU, is called PYRONEER, which is a low temperature circulating fluidized bed technology. The advantage of this technology is the utilization of a bride spectrum of different feedstock, such as straw, manure, sludge, industrial waste etc. Furthermore, the ash from the process can be used as a fertilizer, because of lower temperature of gasification (below 730°C).
The scale up to 6 MWth was successful, the technology is owned by DONG Energy. Anyway, the facility is not in operation at the moment, it was mothballed at the end of 2015.

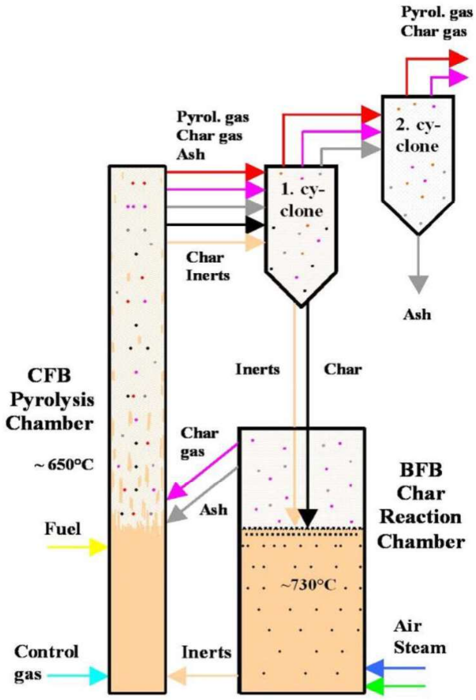

Fig. 7. Pyroneer gasifier. *Source: [7]*

Nowadays, following commercial gasification facilities are now in operation: in Harboøre, Sindal and Skive. The product gas is used for CHP applications. An overview on gasification technology, input and output, as well as utilization of the gas can be seen in the Table 2 below.

Table 2. Thermal gasification facilities in Denmark. *Source: [8]*

Project name	Technology	Input/ Feedstock	Output/ El./Th.	Usage/ Product	Start up
Harboøre CHP plant	Fixed bed - updraft	3,5 MW /forest wood chips	1 MW electric 1,9 MJ/s heat	CHP generation	1993 (CHP in 2000)
Sindal CHP plant	Staged updraft	5.5 MW /wood residues	0.8 MW electric 5 MJ/s heat	CHP generation	2018
Skive CHP plant	Bubbling fluidised bed	20 MW /wood pellets	6 MW electric 11,5 MJ/s heat	CHP generation	2008

A demoplant in **Harboøre,** which was based on developments of Babcock and Wilcox Vølund and university research, was established by Harboøre Varmeværk already in 1993.

Anyway, in 1997, after further developments, the gasifier was considered as commercial and in 2001 the plant was converted into CHP. The plant is since that in operation for 8 000 hours / year and supplies heat for the district heating and power to the net.

In Sindal, natural gas was used for district heating till 2018. To come out of the fossil fuels, the company **Sindal District Heating** searched for more environmental-friendly fuels and decided to build a Dall Energy biomass gasifier with an ORC turbine.

The technology is an updraft gasifier with partial oxidation, afterburner, thermal oil heater, scrubber system for recovery of heat and ORC unit. It is a third generation "Dall Energy Furnace".

In **Skive**, a bubbling fluidized bed (BFB) gasifier for CHP production was installed. As a feedstock, the wood pellets are used (20 MW input). Output is 6 MWel and 11.5 MWth. The heat is used in local district heating system and electricity comes into the grid.

<u>Germany</u>

There are many research institutions in Germany, focusing on thermal gasification of biomass and waste, such as The Karlsruhe Institute of Technology (KIT), The German Biomass Research Centre (DBFZ), Technical University of Munich, Fraunhofer Institute for Environmental, Safety, and Energy Technology (UMSICHT) and many others. Most of them are active in research of all thermal conversion processes and aim to develop an overall concept for the future energy mix, which could be employed in Germany in the near future.

KIT is a leading German research institution, where also a unique and nowadays already well-known bioliq process was developed. Research area at KIT is covering a wide range from characterization of materials to simulation of complex integrated systems.

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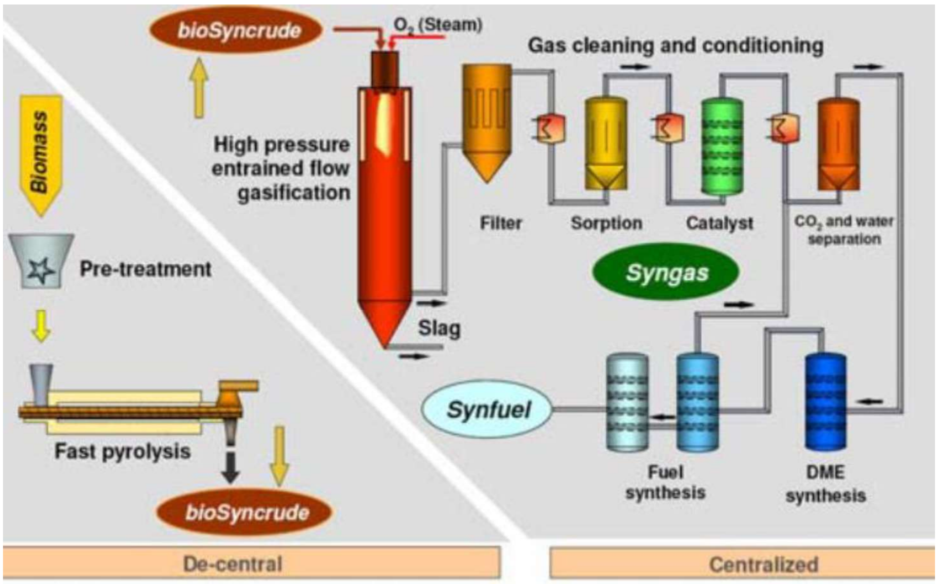

Fig. 8. The bioliq plant – process diagram. *Source: [9]*

The bioliq system, which is still in operation, consists of two different parts: de-central and central.
In de-central part a biomass (straw) is pyrolysed (2MW); in centralized part, the slurry gasification of biosyncrude takes place. The high-pressure entrained flow gasifier operates up to 8 MPa.
Both, the pilot plant for fast pyrolysis as well as a gasification unit were made in cooperation with AirLiquide E&C, Frankfurt. The hot gas cleaning in cooperation with MUT Advanced Heating GmbH, Jena and dimethylether and final gasoline synthesis together with Chemieanlagenbau Chemnitz GmbH.

The pilot plant providing a TRL level 6 is used to calculate mass and energy balances as well as practical experience with facility operation. The KIT tests there also fuel flexibility and its influence on the product quality [10]. In small scale, many companies are active in Germany. The product gas from gasification is mostly used for combined heat and power production.

On sewage sludge gasification focuses **Sülze Kopf SynGas**, a developer and producer of bubbling fluidized bed gasification systems for sewage sludge for heat, or combined heat and power applications. Their plants are fed with dried sewage sludge.

The technology of **Burkhardt GmbH**, which produces wood gasifiers since 2010, is based on co-current stationary fluidized bed. Three gasifier sizes for production of power and heat are offered by the company: 50 kWel, 165 kWel and 180 kWel. The feedstock are wood pellets. Nowadays, there are more than 240 Burkhardt operational units in Europe.

The gasification technology of **LiPRO Energy GmbH&CO.KG** is based on multi-stage gasification. The product gas is used for CHP applications, the output is between 30 – 50 kWel and 60 – 100 kWth respectively.

Spanner is well known producer of co-current fixed bed gasifiers using wood (wood chips, briquettes or pellets) as a feedstock. The output varies between 60 – 100 kWth and 30 – 50 kWel, using cascade combination it is possible couple more plants together. More than 700 operational plants could be found worldwide.

The next, well-known producer of counter- current fixed bed wood gasifiers is **REGAWATT.** In addition, here, the product gas is used for CHP applications. REGAWATT offers their gasifier from 300 – 2000 kWel and 600 – 4300 kWth respectively.

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Italy

Bioenergy research in Italy is split between seven Universities and research institutions, such as ENEA, CIRBE, CNR, Free University of Bozen, RE-CORD, SOTACARBO SPA and University of Capania "Luigi Vanvitelli". Detailed information regarding Italian research can be found in IEA Bioenergy, Task 33, Country Report Italy [11].

Research activities cover fixed bed and fluidized bed gasification technologies with facilities from laboratory scale up to pilot plants in range of MWth. Feedstock quality and analysis research focuses not only on woody biomass but also more difficult materials such as sludge, manure, rest waste etc. The next research field is a high temperature gas cleaning and conditioning, process simulations and modelling, biofuels production and life cycle and techno-economic assessment.

In commercial scale, the small-scale gasification is very popular in Italy. At the moment, there are more than 220 units in operational and further facilities are planned. The research in this field focuses also on gasification of non-woody biomass, e.g. chicken manure, rest waste etc. At the moment, there are no large-scale operational units in Italy.

An overview, how the small-scale gasification units are spread in Italy can be seen below.

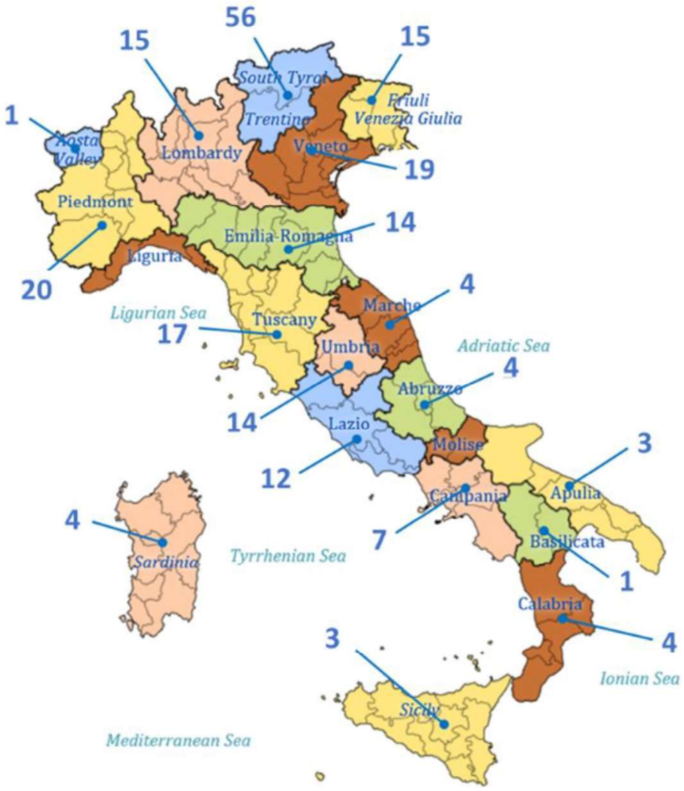

Fig. 9. Number of operational gasification facilities in each region of Italy (status 2019). *Source: [12]*

Most of the facilities are situated in northern part of the country, the power output is between 20 and 70 kWel.

In Italy, three commercial producers of the thermal gasification facilities can be found: CMD ECO20x, ESPE SRL and RESET SRL; the rest of the operational facilities come from foreign producers, mostly from Germany. An overview on Italian gasification facilities can be seen in the following table.

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Table 3: Technical data of Italian small-scale gasification facilities

	CMD ECO20x	ESPE SRL	RESET SRL
Technology	Micro Combined Heat & Power	Downdraft	Containerized biomass gasification and cogeneration systems.
Output	20 kWel/40 kWth	49 kWel/100kWth	50-200 kWel
Innovation	Trigenerative purpose (electricity, heat, cooling – absorption chiller)	Product gas extremely clean, no need for filters. Total efficiency 90%	High grade biochar production
Feedstock	Wide range of biomass	Clean wood chips	Woody biomass

The Netherlands

The research in the Netherlands takes place at Universities, research institutions and private companies as well. The technology, which should be pick out is a gasification system MILENA and tar removal OLGA. Both of them were developed at ECN, now part of TNO. MILENA is a CFB gasification technology consisting of two coupled reactors (gasification and combustion zones). It was designed for wide range of fuels, from woody biomass and straw to coal or industrial waste. The technology was licenced to Thermax and Royal Dahlman. The pilot plant using these technologies will be built in Alkmaar, producing 4 MW SNG.

In the Netherlands, many commercial projects in area of thermal gasification are ongoing [13]. Some of the most important ones will be mentioned here.

Essent/RWE is an owner and operator of Amer-9 – a waste wood gasifier, which is coupled with a coal-fired power station of 600 MWel output. The facility based on Lurgi circulating fluidized bed can be found in Geertruidenberg. The waste wood is gasified using steam and air and the gas is used for co-firing. The gasifier capacity is about 85 MWth. The wood is in coal plant co-fired in two ways; about 25% of energy comes from direct co-firing of wood pellets and about 5% indirectly through a gasifier.

The thermal gasification of biomass is used also in pulp and paper industry by **ESKA**. The CFB gasification replaces here natural gas. As a feedstock paper rejects are used, the product gas is fed into a boiler. The technology supplier is Leroux & Lotz. Since 2016, when the operation started, over 20 000 tons of reject were processed.

Mavitech Green Energy is a turnkey gasification plants producer. A downdraft fixed-bed technology is used to process various manure and sludge. The product gas is co-fired to produce heat for steam production or for CHP applications. The company is also a producer of biochar (EcoChar), which can be used in many different ways.

Synova, which started as the USA company received in 2017 the right on ECN technologies (MILENA, OLGA) and resides now in the US, Thailand and the Netherlands. The focus of the company is conversion of waste feedstock into power and heat. They plan to build a gasification plant in Thailand, where the waste wood will be converted into power and heat.

Synvalor focuses on gasification of difficult fuels (wood dust, chips, grass, straw, residues etc.) to produce low-tar gas for gas engines. The aim is to rich investment point below 2 500 Euro/kWel. The technology is called Synvator®. Pilot plant with 50 kWe was built.

Torrgas focuses on biomass-to-energy and biomass-to-chemicals projects. Their aim is to be a leading provider for syngas production from torrefied biomass. They specialize on plant scale between 10 and 100 MW.

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Between the largest suppliers of bioenergy facilities in Europe, focusing on technological development, the **HoSt** should be mentioned. Their portfolio spreads in many areas from anaerobic digestion and biogas upgrading to biomass CHP plants and boilers. Regarding the gasification technology, they offer CFB for boiler applications. The input is between 1-5 t/h but they offer also special plants with higher input.

Sweden

From Swedish research institutions focusing on thermal gasification following should be mentioned here: Chalmers Technical University, Royal Institute of Technology (KTH), Luleå Technical University of Technology and Lund University, where the gasification research started in 1975 focusing on oil shale gasification.

The Swedish Centre for Biomass Gasification (SFC) is a Centre of Excellence, created to coordinate and support established Swedish research in the area of biomass gasification. SFC is therefore an important national actor for developing new knowledge needed to reduce the country's dependence on fossil fuels and for reducing the net emissions of greenhouse gases to the atmosphere. [14]

Talking about the thermal gasification in Sweden, the **GoBiGas** project has to be mentioned. The project, which was initiated already in 2005 is described in detail in. [15]

The aim of the project was the demonstration of renewable biofuel (biomethane) production from biomass using thermal gasification and methanation processes. To reduce the investment risk, the project was split into two phases. It was planned to build a facility, where 20 MW of biomethane will be produced. This was the first step of the project and it should be mentioned, that this first phase was never intended as a self-sustaining project. As a second project phase, an upscaling to 80-100 MW output was planned.
As a gasification technology, an indirect atmospheric pressure gasification (DFB) from Austrian company Repotec (now Aichernig Engineering) was chosen and Finish company Valmet was selected to build up the gasification plant. Haldor Topsøe was responsible for methanation technology. The Dutch engineering company Jacobs was engaged as the EPCM contractor for the overall installation.

The mechanical completing was finished in December 2013 and the official opening of the plant was in March 2014. One month later started also the gasification process and in December 2014, the production of biomethane and its feeding into the grid began. With the continuous operation in autumn 2015, more than 90% of design capacity was achieved. Parallel to this first project phase the evaluation and preparation of the second project phase was ongoing. Anyway, in November 2015 the City Council of Gothenburg, which was the owner of the plant, decided to cancel the second phase.
In February 2018, over 1 800 operational hours were achieved and 100% of design capacity. Anyway, the sales values of biomethane had not followed the expectations, lower demand on biomethane caused by lower sales of compressed natural gas (CNG) vehicles and imports of cheaper biomethane from Denmark led to shut down and mothballing of the plant in May 2018. However, even if the facility was closed after only 5 years of operation, it was clearly demonstrated that the technology for production of biofuels from biomass works well and can be applied maybe in future, when better conditions for biomethane production will be set.

Another Swedish company focusing on production of gaseous biofuels is **Cortus Energy AB** and its WoodRoll® technology. This is a three steps integrated process, consisting of drying, pyrolysis and gasification. During this steps, the wet solid biomass can be converted into clean syngas. The process is fully allothermal and excess heat is used counter current the biomass processing. In 2011, the first plant was built in Stockholm. It was a 500 kWth gasifier, which was later moved to Nordkalk site at Köping. Based on the tests and experience with this unit a fully integrated unit has been built in 2015. It has been reported in [15] that the gasifier has been operated over 5 000 hours in September 2018, and the dryer and pyrolyzer over 2 000 hours each. Cortus Energy AB cooperates with many European companies and in 2018 a contract with Infinite Fuels GmbH was signed. The aim was to produce biomethane for the grid injection in Northern Germany. The realisation was planned in 2019. Cortus is focusing also on aviation fuels and in 2018 was it a grant from Swedish Sustainable Aviation fuel program awarded to study the integration of the WoodRoll system with a FT system producing aviation fuel.

The next player, focusing on innovative gasification technologies is Swedish company **MEVA.** They constructed a Vortex Intensive Power Process (VIPP-system) in 2012, based on developments at LTU. The technology consists of cyclone gasifier, which is the main core. The aim was to utilize the product gas in small-scale gas turbines. Based on the evaluation of the process a pilot plant with input of 500 kWth with included gas cleaning process and 100 kWe output was built at ETC.

The thermal gasification has a long history in Sweden and not only dried biomass is mentioned to be applied in gasification process. Thus, also the **black liquor gasification** was in focus of Chemrec Kraft Recovery. The technology was based on a refractory-lined entrained bed reactor, where the material was gasified at high temperature (1000°C) under reducing conditions. The product gas was used for DME synthesis in the FP 7 Bio- ME plant. The project for DME production started in 2008 and a 4 ton/day BioDME plant was constructed, based on Haldor Topsøe technology. In 2011, the fuel (DME) was produced and used in four locations in Sweden to power ten trucks. Nearly 400 tons of DME was produced for utilization in trucks for 80 000 kms. When the project ended in 2013, the plant was moved to LTU for further research in this field.

At this time, in Sweden some further gasification based projects are planned, e.g. biomass-to-methanol facility in Hagfors (VärmlandsMetanol AB) and production of bio methane (Bio2G) [16].

USA

Within the field of thermal biomass gasification in the US, the main focus is on production of biofuels based on renewable sources. At the moment, three American companies are working on projects regarding liquid and gaseous biofuels.

The conversion of biomass using the thermal gasification process coupled with FT technology is the purpose of **Red Rocks Biofuels** project. They are constructing a biofuels plant in Oregon to produce 15 mill. gallons/y of biofuels from 136 000 tons of wood. The gasification technology is licensed by TCG Global. Fluor is responsible for syngas cleaning and conditioning and FT technology provider is Velocys and EFT. Haldor Topsoe and other companies provide the hydrocracking and fractionation technology. 40 % of the product will be jet fuel, 40% diesel and the rest will be sold to the market as a gasoline blend. Red Rocks Biofuels has an offtake agreement with FedEx. At the moment, the plant is under construction, operation should start later this year.

On bioethanol production focuses **Aemetis**, which is partnering with InEnTec and LanzaTech. The goal is to produce 60 million gallons/y using the plant, situated in California. Syngas will be produced from biomass using plasma enhanced melter (PEM) technology, which is licensed by InEnTec. This will be coupled with microbial fermenter of Lanza Tech. Primarily; bioethanol will be produced. Construction is planned for 2020.

Conversion of MSW (municipal solid waste) into synthetic crude is the goal of the **Fulcrum Bioenergy's Sierra Biofuels.** The plant in Nevada should convert about 200,000 tons/y of MSW into more than 10 mill. gallons of syncrude. The three-step process should contain pre-processing, gasification and FT synthesis. The gasification technology is based on ThermoChem Recovery International's indirectly heated fluidized bed steam reformer. The product gas from waste gasification, which will be used for FT synthesis, should fulfil defined criteria, thus the cleaning and conditioning of the gas could not be avoided. It will be therefore treated using Praxair's Hot Oxygen Burner (HOB) technology to increase the quality of the gas. By this process, the hydrocarbons and tars will be partially oxidized. It was reported that the plant should start the operation in 2020.

Thermal biomass and waste gasification in other countries

In the field of thermal biomass and waste gasification there are also many other countries, which are active in this field, but were not described in this paper, e.g. France (e.g. Gaya, BioTFuel projects), UK (a MSW gasifier (KEW) will be taken into operation in 2020), Finland (lot of research in this field, company Valmet involved in many projects), Canada, China and India. The overall data are unfortunately not available at the moment.

Future of thermal gasification of biomass and waste

The technology of thermal gasification is still further developing.

Regarding the feedstock, wood alternatives, which are cheaper but for the gasification process more complicated such as waste materials (sludge, plastics, MSW) are in focus.

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Also the purpose and utilization of product gas changes. Whereas in small-scale gasification the heat or combined heat and power (CHP) production is still dominating, in the large scale more advanced cleaning and conditioning make it possible to produce gaseous or liquid biofuels and biochemicals, which could replace fossil ones in the near future.

The third issue, which have to be mentioned beside feedstock and gas utilization, is the integration of gasification into other processes and vice versa, other processes into gasification. There are many reasons to go this way, some of them are:

- the yield of the final products and efficiency could be maximised, e.g. combination of different technologies such as wind power or PV together with electrolysis and thermal gasification for increasing of amount of biofuels production (hybrid systems)
- in southern countries, the direct solar power could be employed in the gasification process to increase the efficiency and lower the production costs
- thermal gasification can be used as a technology for balancing the electrical grid
- use the gasification technology in concepts of bio- refineries

It would be too ambitious to state; which direction the thermal gasification will develop, because this depends on many factors, but primarily on policy framework, which could encourage investors to start more projects based on bioenergy.

Anyway, the author considers e.g. waste gasification in large scale as very reasonable for the future; in this way not only waste could be disposed, but also power and heat could be produced. Another issue is the production of biofuels and biochemicals through the combination of gasification with other technologies (hybrid systems). This way, as the author believes, should be supported to come out of fossils.

Impact

The thermal gasification of biomass and waste is a technology, which can utilize a wide spectrum of different feedstock materials: not only clean biomass and forest residues, but also waste materials such as sewage sludge, agricultural residues, municipal solid waste, waste wood, straw or chicken manure.

The technology can be applied for production of renewable energy (power and heat), biofuels and bio chemicals in refinery applications or even more as carbon storage technology (biochar).

In “2030 Energy Strategy” EU countries have agreed on a new framework for climate and energy, including EU-wide targets and policy objectives for the period between 2020 and 2030. These targets aim to help the EU achieve a more competitive, secure and sustainable energy system and to meet its long-term 2050 greenhouse gas reductions target.

The strategy sends a strong signal to the market, encouraging private investment in new pipelines, electricity networks, and low-carbon technology. And this act should be also the impulse for considerable implementation of technologies based on renewable sources, such as thermal gasification of biomass and waste.

Conclusions

The significant impulse for the thermal biomass gasification progress was the World War II, when the shortage of fossil fuels occurred. In that time, the wood gas generator became very popular. As a feedstock, wood was used to power vehicles or agricultural machines. With time, the applications of thermal gasification changed. Nowadays, the power and heat is produced using mainly small-scale gasification units; at the moment, there are more than 1 500 such operational applications over the Europe, mostly in central and southern parts.

Anyway, utilization of the syngas offers not only heat and power generation, but also many other applications, e.g. production of renewable biofuels and biochemicals. Many interesting projects with this purpose started or are under construction/commissioning in Sweden (GoBiGas), France (Gaya, BioTfuel) or USA (Redrocks Biofuels). Also a lot of research work has been done/is ongoing in this field. This way of syngas utilization shows also the greatest potential for future of thermal gasification, mostly in large scale. The majority of fuels and chemicals production nowadays is based on fossil feedstock; thus, it is necessary to find alternatives for the near future.

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Regarding the feedstock, waste disposal using the thermal gasification became also more interesting for investors, e.g. in the Netherlands (ESKA), in Finland (Lahti) or in the United Kingdom (KEW plant). The waste, which has a negative price seems to be of great benefit, which should be included into investment and operational costs. On the other hand, utilization of low value feedstock is still negative influencing the quality of the product gas, therefore also more expensive gas cleaning and upgrading should be taken into account. This could be anyway skipped by co-firing of the product gas, e.g. in lime kilns.

The integration of BWG into other technologies, such as paper industry, limekilns or biorefineries offers a new chance for the future. Furthermore, the combination of BWG with other technologies such as PV or wind energy (hybrid systems) provides the way of higher efficiencies and doubled amount of products [17].

The new way seems to be utilization of syngas for biochemicals production through bio-chemical conversion using specific bacteria. In this way, e.g. alcohols could be produced. Anyway, at the moment there are such application at the laboratory stage.

The great benefit offers also bio-char as a byproduct of thermal biomass gasification. There are many ways of biochar applications e.g. in agriculture as soil improver, as an addition of animal feed, or in industry as filter absorber or as energy carrier. In case, if the biochar is used as a soil improver and remains in soil for many years, we could talk also about carbon capturing, which is associated with negative CO_2 emissions.

The status of BMW in Austria, Denmark, Germany, Italy, the Netherlands, Sweden and USA was described in this paper. It can be seen that a lot of research has been done in this field. Anyway, the success and implementation of gasification projects depends on not only successful research, but also political frame conditions. The uncertain support of bioenergy from the policy nowadays does not really encourage investors, which are necessary for successful implementation of commercial projects.
The hope in this field should be the policy plan of the European Union between 2021 and 2030, so called „2030 Energy Strategy"; this could give green light to not only bioenergy, but also other renewables such as wind and solar power.

It is clear, that the thermal gasification of biomass and waste is not the only technology, which could save our world, but it should be considered as environmentally friendly, technologically proven technology, which worth to support, or to classify newly respectively. It is important to realize that e.g. the price comparison of biofuels and fossils could not be correct, if we would not take into account also the impact of the fossils to our environment.

Conflict of interest
There are no conflicts to declare

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