Bio energy

Overview of Bio energy technologies

1. Basic definitions

Bioenergy is one of the most important renewable energy industries, based on the transformation of various types of biomass into a variety of useful energy products. Biomass includes natural organic materials of plant or animal origin, as well as specially grown energy crops, agricultural or forestry waste, food waste, wastewater and other industrial organic matter. Biomass is the oldest energy source known to mankind, and the heat and light generated from the combustion of biomass were fundamental in shaping human society. The vast majority of biomass energy on Earth is concentrated in green vegetation but is also found to a much lesser extent in terrestrial and marine living organisms.

Bioenergy is a renewable resource capable of replacing fossil fuels at a significant scale. Moreover, modern methods of converting biomass without direct combustion make it possible to switch to carbon-free energy; these methods also help to dispose of numerous organic wastes that release methane into the atmosphere during uncontrolled decomposition, which is the most aggressive source of the greenhouse effect.

Currently, bioenergy is a highly developed technology that has advanced in many countries around the world. However, the centuries-old tradition of using biomass for heat production, which continues today, does not correspond to modern ideas of energy efficiency and requires improvement. The practice of using food vegetation for energy purposes when the problem of hunger has not yet been universally solved has also been subjected to harsh criticism from various organizations. Other negative factors include the widespread use of agricultural land for biomass cultivation, resulting in competition for land; fossil-fueled farm vehicles, used, for example, for harvesting do not make this technology 100% green. In this regard, the most promising technologies in the development of bioenergy are second-generation biofuel production that use raw materials from non-food biomass/non-food crops, for example, from algae or wood; and deeper biomass processing technologies - gasification and pyrolysis, as opposed to incineration [1,2].

According to [3], in 2018, the share of traditional biomass as a percentage of total energy consumption was around 7%, with the share of more modern or advanced types accounting for a little more than 5%.

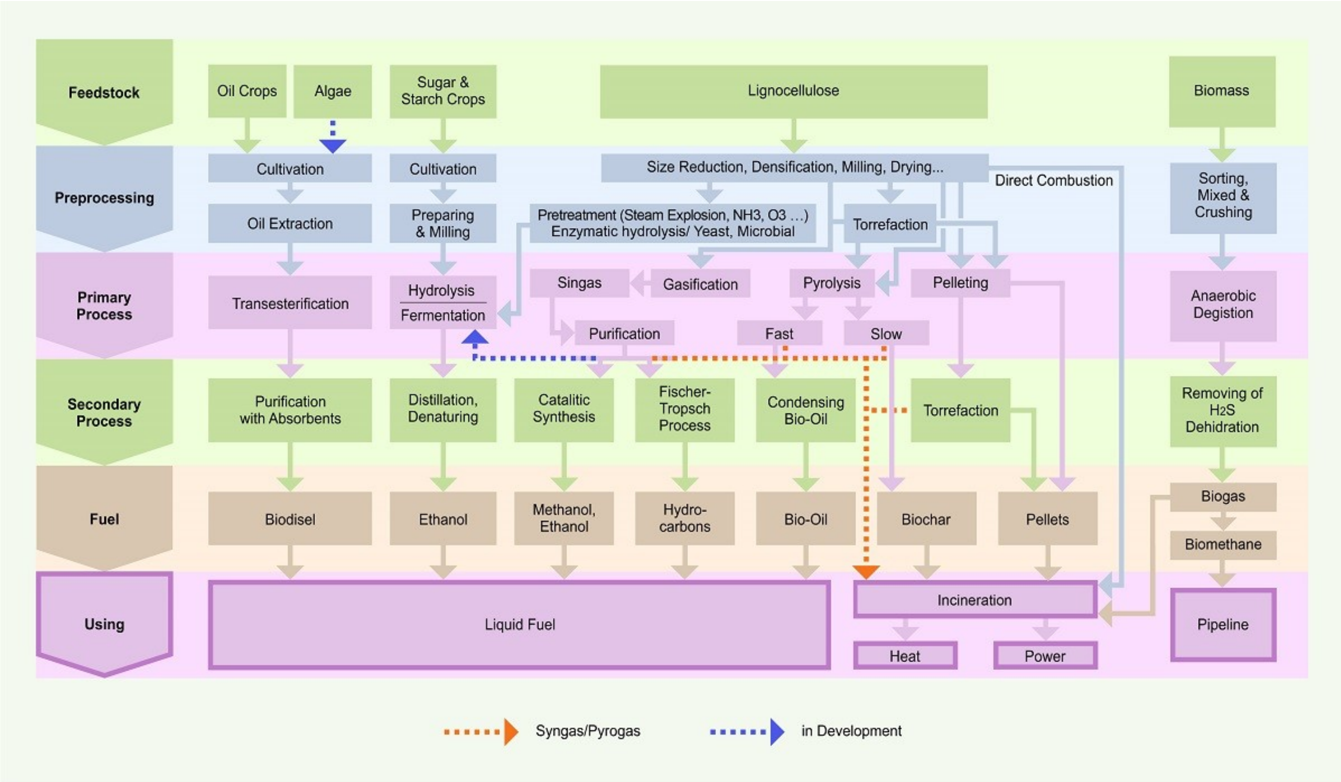
A huge advantage of bioenergy is it allows for the possibility of obtaining a wide range of energy products in solid, gaseous and liquid form, which contributes to the satisfaction of various energy needs in electricity, heat supply or transport. In addition, by-products of bioenergy can be used as feedstock for the chemical, construction and agricultural industries. Another equally important advantage of bioenergy is that many of its products can be accumulated, stored long-term and easily transported, which at this stage of technological development is practically impossible in the case of solar and wind energy.

Bioenergy has a relatively modest share in global power generation, its total generation capacity is slightly over 5%, which is insignificant when compared to other renewable energy sectors, including hydropower. At the same time, bioenergy is dominant in the production of heat energy and vehicle fuels. As a result, the share of bioenergy in the global consumption of energy from renewable sources is about 50% [4], taking into account the consumption of traditional biomass. Moreover, today more than 70% of processed biomass is used for thermal energy production, while the share of transport and electricity accounts for about 20 and 8%, respectively [3].

There are a large number of different technologies for the conversion of biomass into energy products, which take into account the characteristics of the feedstock and are mainly based on three types of technological impact - chemical, biochemical or thermochemical.

Fig. 1 shows a simplified diagram of biomass processing options that are either most widely used industrially or are at the design stage. It should be noted that due to the wide variety of technological processes it is difficult to simultaneously arrange them on a small diagram in accordance with the main stages of production. As a result, certain processes can be considered as preliminary processing, and others, as main processing, etc. Nevertheless, in general the diagram reflects the main types of feedstock and final products, as well as the dominant technological processes for direct biomass conversion.

Fig. 1. The main methods of processing biomass for energy production.



Technological applications of biomass processing begin with the collection of raw materials, for example, in the form of agricultural waste, or special energy crops, such as rapeseed, corn or sugarcane. The biomass feedstock is then pre-treated. This process includes the following stages: drying, size reduction, crushing and milling, densification, and sorting. For certain types of raw materials, mixing, washing, exposure to steam, torrefaction, etc. are used. It should be noted that these procedures are expensive and largely determine the effectiveness of the subsequent stages of biomass processing. Unlike other types of raw energy materials including liquid and gaseous hydrocarbons or coal - biomass is a technologically complex substance, often unsuitable for efficient subdivision or transportation. Therefore, increased attention is paid to methods of preliminary treatment of biomass, as well as the development of the methods themselves.

The choice of technology for biomass processing is primarily determined by the feedstock type, the desired end product and the availability of the necessary infrastructure. The commitment of manufacturers to modern environmental and social standards will also play a factor. For example, bioethanol can be obtained from wheat, corn, sugarcane or other food plants via traditional acid hydrolysis and fermentation technologies. Bioethanol can also be obtained from more complex biomass, based on lignocellulose, using more complex second generation technologies such as, enzymatic hydrolysis or high-temperature gasification followed by catalytic synthesis .

Today, the most prevalent end products of biomass conversion are biodiesel and bioethanol, which are used as liquid fuel; and other products, such as biogas, wood chips and pellets. Biodiesel and bioethanol are predominantly obtained using first-generation technologies. Biogas is produced from agricultural waste, and fuel chips and pellets from woodworking industry waste, i.e. not from food products. Therefore, in this sense, they can be classified as second generation technologies. However, these products are then still subjected to traditional and often ineffective incineration. As a result of additional purification of biogas to biomethane or processing of pellets by special torrefaction, high-quality fuel can be obtained. This fuel can be considered a product of modern bioenergy.

First generation diesel fuel is produced from vegetable oil, most often obtained from rapeseed, or oil and fat production waste, by reacting fats with methyl alcohol with the addition of a catalyst. This process is called transesterification. As a result, diesel and glycerin are formed. Due to the simplicity of the production cycle and the low temperature conditions, this method was popularity with the agricultural sector, and even gained state support in some countries. However, the intensive use of agricultural areas for rapeseed cultivation provoked protests, and the high sensitivity of economic indicators of production to external market conditions significantly restrain the development of this technology. According to one estimate [3], 47 billion liters of biodiesel were produced globally in 2020, primarily in Europe, the USA, Brazil, Argentina, Indonesia and Thailand.

Over the last decade new technologies for the production of second-generation biofuels in cooperation with oil refineries have become very widespread. For example, OMV has launched a “Bio CRACK plant” pilot project for the production of biodiesel in Schwechat which uses wood waste and heavy mineral oil produced at a local refinery as feedstock. The processing of raw materials include liquid-phase pyrolysis at a temperature of 420°C, which makes it possible to obtain diesel fuel with a 20% biogenic content [5].

Fig. 2 and 3. Biodiesel production plants. Left - Bio-Venta plant in Ventspils, Latvia, first-generation biofuels; Right - Neste Oil NExBTL plant, Rotterdam, second-generation biofuels

Finnish Neste Oil has launched facilities to produce diesel fuel using the NExBTL technology at several of its own refineries. Any kind of vegetable oil or animal fat can be used as raw materials in this process. Hydrogen, which is widely used in oil refining, is used here for hydrocracking and hydrogenation of feedstock, instead of the traditional esterification method [6]. In 2019, the annual production of HVO (HVO-hydrotreated vegetable oil) reached 6.5 billion liters globally [3].

One of the most promising prospects for the production of biodiesel lies in the processing of certain types of microalgae, as lands unsuitable for agricultural production can be used for algae cultivation and their oil content per unit mass exceeds that of many food crops. This technology will be presented in more detail below. Bioethanol is another popular first-generation biofuel produced worldwide on an industrial scale.

The report by the American association RFA states that in 2019 the production of bioethanol was mainly concentrated in the USA (about 60 billion liters) and Brazil (about 33 billion liters). Other countries and regions accounted for about 16%, including other large producers - the European Union, China and India [7]. According to [8], by 2027 the production of bioethanol in the world will reach 130 billion tons. The volumes of production of second generation bioethanol from cellulosic biomass are still small. For comparison, in 2019 the production of cellulosic ethanol in Brazil was estimated at 45 million liters, and in Europe in 2017 at 85 million liters [9-10]. The annual list of ethanol producers in the United States in 2019 included only 11 enterprises out of almost 250 use cellulosic biomass as feedstock [7]. The main crops for the production of first generation ethanol are sugarcane/beets and maize. The first generation ethanol technology is based on a fermentation processes that breaks down glucose molecules under anaerobic conditions. More complex technologies for the production of ethanol from cellulosic biomass are discussed in a separate chapter.

One of the main areas of bioenergy is the production and use of wood chips and pellets as raw materials for the generation of heat and electricity. According to [11], about 500 million m3 of various sawn wood and 37 million tons of pellets were produced in the world in 2018. The main pellet producers are the USA, Canada, Vietnam, Latvia and

Russia, and the largest consumers are Great Britain, Denmark, South Korea and Italy. Drying is almost always included in the list of technological operations for the pretreatment of woody biomass, since further processing of wet wood would be impossible. Wood chips are usually produced by mechanically shredding forestry waste in chippers and shredder machines. To produce pellets the feedstock is finely ground in a Hammer Mill and then passed through a wood pellet machine where the ground biomass is configured into dense granules. This raw material is consumed widely both by large enterprises and households.

Fig. 4 and 5. Wood chips CHP plants. Left - Tolkkinen CHP Plant, Finland, right - Brista CHP plant, Sweden

Recently, woody biomass has been replacing part of the coal feedstock at thermal power plants, potentially reducing carbon dioxide emissions. Further, after reforestation it is hypothesized that emissions from biomass combustion will be offset, leading to zero emissions. However, this approach has been increasingly subjected to criticism [12]. There is a significant time gap between biomass combustion and reforestation and, in addition, owing to the significantly lower calorific value of biomass compared to fossil fuels with the same mass (as well as the low density of the finished raw material - wood chips or pellets), their transportation over long distances leaves a serious ecological footprint, which reduces the attractiveness of this particular area of bioenergy.

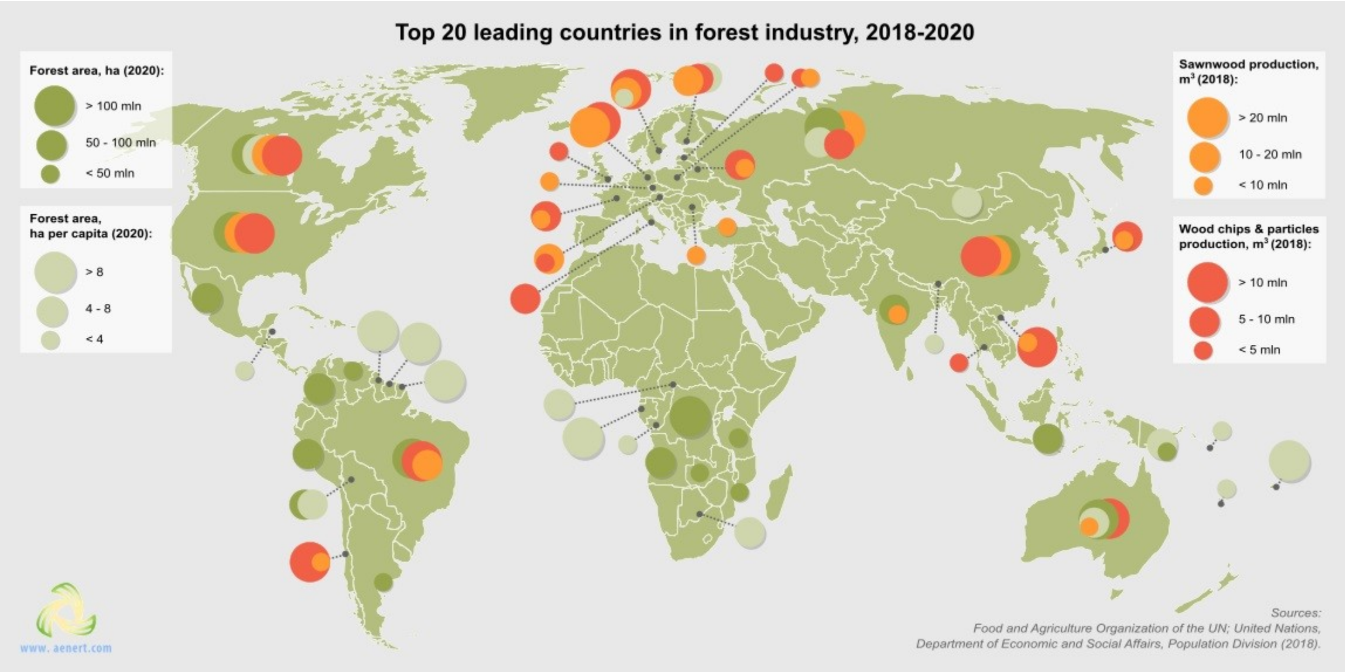
Therefore, in modern bioenergy more efficient thermochemical methods of using biomass are being intensively developed, such as gasification and pyrolysis, which, like biogas production, will be discussed in more detail below.

2. Biomass Resources

As noted above, the progressive development of bioenergy benefits by relying on the use of non-food biomass. These primarily include agricultural and forestry waste. Direct indicators of bioenergy resource supply can be specific quantitative data; for example, the volume of municipal organic waste or biomass burned, the volume of sewage, the volume of wood chips production, etc. Indirect indicators such as agricultural production, arable land area and forest area also provide useful auxiliary material for assessing biomass resources in a particular region. Figures 6 and 7 show maps of the resource potential of the biomass of agricultural activity and forestry for the 20 most advanced countries of the world for each of the detailed indicators shown on the maps. The information is based on data from [13, 14].

Clearly, with an increase in the size of farmland or livestock the level of organic waste also increases. This can provide extensive raw material for bioenergy, although, this of course largely depends on the level of applied technologies and the specific type of agricultural products. As follows from the data in Fig. 6, countries with large territories are not always among the leaders in terms of agricultural land or arable land per capita. For example, large countries such as Algeria, the Republic of Congo, Libya, Egypt, and Pakistan are not included in the top 20 list. Canada is in the second half of this list in terms of total agricultural land area, but among the leaders in terms of arable land per capita. The largest areas of agricultural land are in the United States, Russia, China, Kazakhstan, Australia and Brazil. The leading countries in terms of arable land per capita are Canada, Kazakhstan and Australia. Many types of animal waste can be used as raw materials for the production of biodiesel or biogas, which is directly related to the livestock population. Countries such as the United States, Brazil, India and China have the largest livestock population. Pakistan, Nigeria, Ethiopia and Australia also have significant livestock resources. In [14] data is

Fig. 6. Top 20 countries in the world in terms of agricultural activity

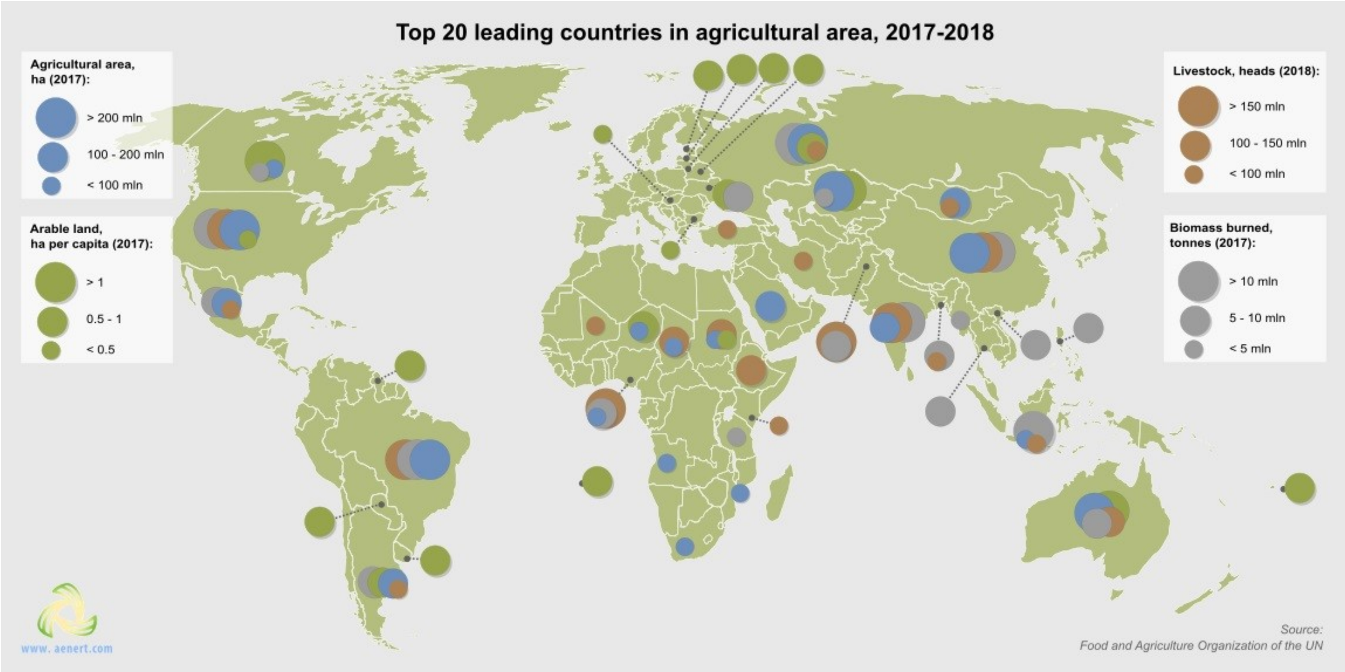


[Top 20 leading countries in agricultural area, 2017-2018 [0.55 MB]]

provided on the direct combustion of biomass; according to the source, the USA, Brazil, India, Russia, Indonesia and China annually burn more than 10 million tons of biomass each.

A somewhat different picture emerges when analyzing the countries of the world in terms of forest area and the level of timber processing. The absolute leader based on the four indicators shown in Fig. 7 is Canada. Each of these indicators (Forest area, Forest area per capita, sawn wood production, Chips and Particles production), to a certain

Fig. 7. Top-20 countries in the world in terms of forest area and level of timber processing



[Top 20 leading countries in forest industry, 2018-2020 [0.56 MB]] degree demonstrates the resource potential of biomass from waste from the forest and timber processing industries. Among the leaders, as in the previous example with agricultural indicators, are the countries with the largest forest area: the USA, Russia, China, Australia, and Brazil.

However, with regard to timber processing, the following European countries play a significant role: Germany, Sweden, Finland, as well as Chile and South Africa.

The most valuable bioresources for biomass production factoring in agricultural activity, forest area and level of timber processing are to be found in the USA, Russia, Canada, China, Brazil and Australia. Such densely populated and industrialized countries as Japan, Great Britain, South Korea, France, and Germany have entered the top 20 list solely due to the high level of timber processing. The northern countries of South America, belonging to the Amazon basin, have unique forest resources. The Baltic countries have high per capita arable land and a high level of timber processing. The countries of Southeast Asia, where biomass combustion prevails, have relatively limited resources in both categories. The same applies, largely, to India, which is among the leaders in livestock and has good indicators in terms of forest area and the level of timber processing.

A more extensive and detailed analysis of indicators of agricultural activity and the state of forests and timber processing for most countries of the world can be found in the following sources [13, 14].

Bio energy. References

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3. Biogas

3.1. Production and application of biogas

Biogas is a gaseous product of processing bioorganic material by anaerobic microorganisms in the absence of oxygen, and consists of methane (50-70%) and carbon dioxide (30-50%), as well as a certain amount of various impurities, for example, hydrogen sulfide and water [1]. Today, biogas production is an intensively developing area of biomass processing in all regions of the world, although it is significantly inferior to modern methods of using solid biomass and liquid biofuel, and many times inferior to traditional wood combustion. According to [2], in 2018 a little more than 33 Mtoe (about 36.5 Bcm) of biogas was produced in the world. Smaller, but comparable values for biogas production are given in other sources, for example, in [3]. More than half of the total biogas is produced in Europe, with China and the United States being other important producers. The total capacity of biogas production in Europe in 2018, according to [4], exceeded 11GW. A higher value of European production in 2018 was given by IRENA [5] - 12.8 GW (18.3 GW globally). However, it should be borne in mind that the production of biogas in China and other Asian countries is mainly concentrated in small households, so it is difficult to account precisely for the total capacity, and especially the volume of biogas production. Germany is the world leader in this technology by a significant margin; however, after a peak in 2016, biogas production in this country has stabilized and even slightly decreased. ,

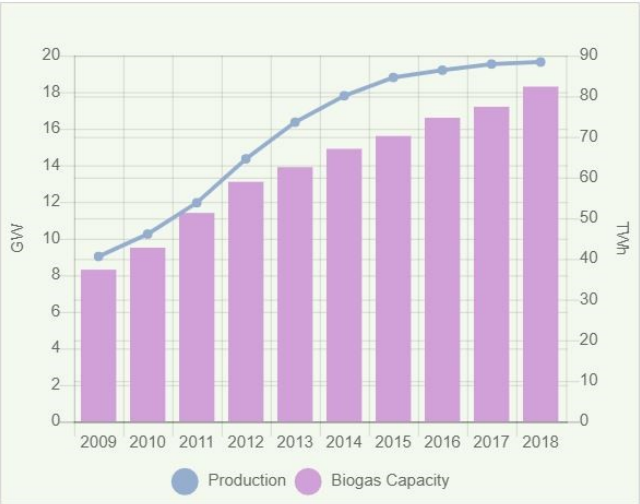
Figures 1 and 2. Biogas plants. Left - Jordberga Biogas Plant, Sweden. Right - BTS Biogas plant, Tuscany, Italy

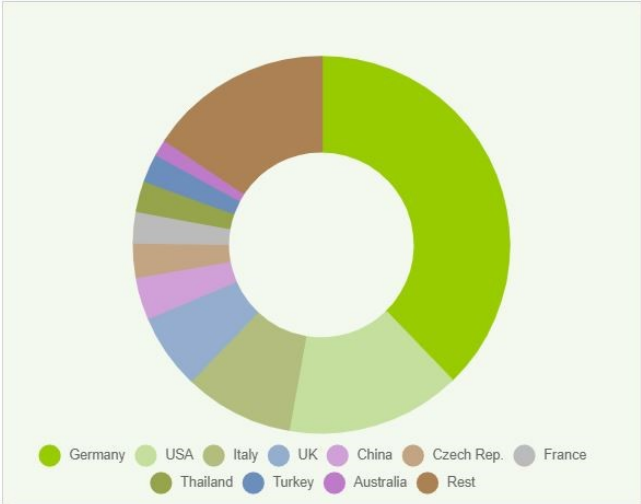
Considering that the total volume of natural gas production in the world in 2018 amounted to 3325.8 Mtoe or approximately 3868 Bcm [6], then the share of biogas currently covers approximately 1% of this amount. Of course, this is an insignificant contribution to the total energy consumption; however, it is necessary to take into account several important components related to biogas production - firstly, it is the implementation of a useful transformation of a permanently renewable resource, and not the irreversible extraction of fossil fuels; secondly, when utilizing biomass in the process of biogas production the release of methane into the atmosphere, as the most aggressive greenhouse gas, is prevented; thirdly, the potential for biogas production that has not yet been realized is many times higher, which is especially important for some densely populated regions of the world. For example, according to calculations made in [7] and [8] only in China is the potential for biogas production between 150 and 350 Bcm. According to [1], in the USA, the potential for methane production using lignocellulosic biomass resources can reach 4.2 Tcf (about 120 Bcm) per year, which will replace 46% of natural gas in the power sector and 100% in the transport sector. At the same time, in 2018, according to estimates [9], only 270 Bcf (7.65 Bcm) was collected at 352 gas landfills in the United States (which is the main resource for biogas production in the country).The global potential for energy crops and organic waste is estimated at 36-48 EJ (860 - 1146 Mtoe) [10]. In [11], the potential for the use of biogas (agriculture and waste) on a global scale is estimated at 1000 Bcm, for China at 274 and for EU-27 at 78 Bcm. In [2], the global potential of biogas is estimated at a volume significantly exceeding 550 Mtoe. In the same paper, as well as in [12], detailed data on the potential for biogas production in the world are given, depending on the type of feedstock and by region. Thus, even according to the most conservative estimates, biogas obtained from various types of biomass in the future can compete with conventional and unconventional types of natural gas.

Biogas is used to produce heat and electricity, as well as biomethane, which is enriched biogas by removing most of the hydrocarbon dioxide and harmful impurities, and which is the most promising environmentally-friendly transport fuel. Most often, biogas is sent to Combined Heat and Power (CHP) units. This process achieves 40% electrical efficiency and 50% heat efficiency, 10% energy losses with exhaust gases [13].

Figures 3 and 4 show the data on the growth of the total capacity for biogas production in the world and the growth in electricity generation, as well as the top 10 countries for the production of electricity from biogas.

Figures 3 and 4. Left - Biogas capacity growth and electricity production in 2010 – 2018; Right - Top-10 countries by biogas electricity production in the world, 2018, GWth





Source: Based on Data from IRENA (2020), Renewable Energy Statistics 2020, International Renewable Energy Agency (IRENA), Abu Dhabi

The raw material for biogas production is a wide range of bioorganic waste - agriculture residues, sewage sludge, animal manure from Livestock Operations, municipal waste, as well as special energy crops (energy crops). Each of these raw materials has its own energy value. The greatest yield of biogas after anaerobic treatment can be obtained from cereals, rapeseed and molasses [12]. Among various types of manure, fresh chicken manure has the highest energy value, and to a lesser extent cattle and pig manure. The variety of raw materials for biogas production is a great advantage of this technology and allows production to be organized relying solely on local raw materials and taking into account the characteristics of local infrastructure. For example, in Europe - Austria, Slovakia, Slovenia, Latvia, Czech Republic and Croatia, the main raw materials for biogas production are energy crops, in Belgium, Finland, Romania and the UK - organic waste, and in Greece, Estonia and Portugal - sewage sludge [13]. The leading biogas producers in Europe, Germany and Italy have less advantage of one or another type of raw material. Energy crops, sewage sludge and Animal manure from Livestock Operations are widely used here.

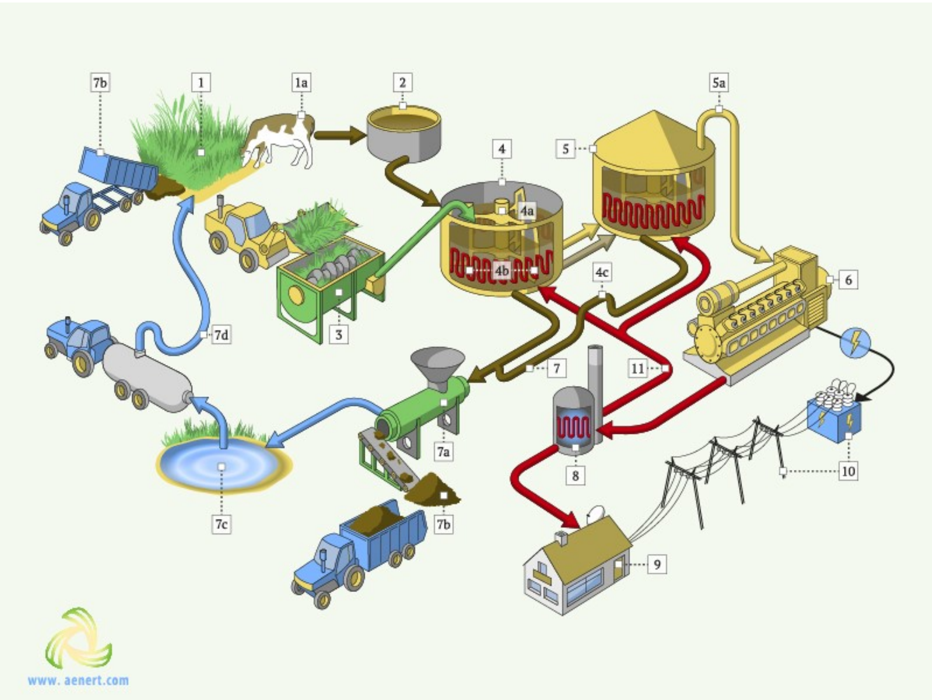
The main method of biogas production is anaerobic decomposition. The process includes a multistage digestion of biomass by means of anaerobic bacteria without oxygen in a special reactor, mainly in two temperature ranges – between 35 - 40ºC and 55 - 60ºC. During this process, several complex biochemical reactions occur, such as hydrolysis, acidogenesis, acetogenesis, and finally, metanogenesis, which actually produces biogas [12]. The degree and rate of decomposition of organic matter depends on its "digestibility" and can be enhanced by the combined use of specially-selected species [14].

There are several types of industrial reactors for biogas production [15], differing in scale, degree of centralization, configuration, level of consumption of methane-generating sources, methods of mixing, heating, substrate loading, etc. There are also two main processes of anaerobic fermentation - wet-type and conditionally dry. The Continuous Stirred Tank Reactor, with side heating, and where mixing of the substrate is provided by mixers, has become widely used on farms. Above the reactor there is a sealed gas-holder made from gas-tight polymer materials, which can be conical or spherical. In some cases, gas-holders are installed separately and made of steel. The decomposition of biomass occurs in the mesophilic mode at temperatures of 33°C - 40°C with a degree of decomposition of 70-75% [16].

Figures 5 and 6. Biogas plants with cone gas-holder. Left - Sweden, right – Austria

A schematic diagram of the wet process for biogas production is shown in Fig. 7. The diagram shows the joint use of manure and energy crops as a raw material. The supply of the substrate to the reactor is provided by an inclined auger. Tubular heaters are displayed on the walls of the reactor, in the upper part there is a cone-shaped gasholder for collecting gas. The option of mixed tanks in series, as well as the combined production of heat and electricity from the obtained biogas, is presented.

Figure 7. Schematic principle of biogas production



1. *Energy crops 1****a****. Animal manure* ***2.*** *Preliminary pit* ***3.*** *Chopper* ***4.*** *Primary digester* ***4a.*** *Mixer* ***4b.*** *Heating units* ***4c.*** *Pipes (gas and liquid)* ***5.*** *Secondary digester* ***5a.*** *Gas holder* ***6.*** *Gas generator* ***7.*** *Fermented residues* ***7a.*** *Separator* ***7b.*** *Transportable dry fermented residue (fertilizers)* ***7c.*** *Water reservoir* ***7d.*** *Water for irrigation* ***8.*** *Heat exchangers* ***9.*** *Heating system* ***10.*** *Electricity supply* ***11.*** *Heat supply for heating elements*

Some countries, for example China, have adopted special programs for the construction of small reactors for households in rural areas, taking into account the characteristics of the local resource base, climatic conditions and available options for operation [17].

The main regulating technological factors that determine the efficiency of anaerobic decomposition in a reactor are primarily the type of raw material, the degree of its preparation, temperature, humidity, acidity level, and the presence of provoking additives.

In addition to the wet method of production, the dry method has become widespread, in which the biomass placed in a metal container is not mixed, but only irrigated with a techno-solution that seeps through the substrate layer, providing anaerobic decomposition of the biomass. Loading of raw materials is carried out by conventional loaders or even by trucks, then the container with biomass is sealed and irrigation and heating are turned on. Anaerobic bacteria digest biomass and produce biogas. Once used, the solution is pumped into a special container for reuse. The biogas generated is accumulated in a gas-holder and is purified. The main processes of biogas production, including the dry method, can be seen in more detail in the Zorg Biogas advertising video [16].

Figures 8 and 9. On the left - communications for collecting biogas and mixing the substrate. On the right is a biogas electricity generator. Gussing, Austria

Recently, due to the improvement or new application of previously known technologies, it became possible to use lignocellulosic biomass as a feedstock, which opens up unprecedented opportunities for biogas production in terms of the resource base. However, the feedstock must undergo a steam explosion. This process includes saturation of the crushed lignocellulosic biomass with water while heating under pressure until conditions for the formation of superheated steam are created. After rapid depressurization, the resulting steam grinds the fibres to a state suitable for use in biogas reactors [17]. Steam explosion has previously been used in the production of cellulosic ethanol. Of course, this process requires serious additional costs and is not always justified.

The final stage of biogas processing usually involves the removal of hydrogen sulfide, moisture and other contaminants. However, for biomethane production, biogas is subjected to deeper purification and enrichment, i.e. reduction of CO_2 content to the level corresponding to natural gas. The most commonly used methods are water scrubbing, chemical scrubbing, and pressure swing adsorption [19]. Membrane technologies have proven themselves well, when the gas is passed through materials with selective permeability, for example, through special polymers, which allows for the separation of carbon dioxide and methane. Cryogenic separation is also possible.

The main advantage of the applied technologies for biogas production is their sufficient diversity, which allows the use of available local raw materials in regional climatic conditions. Biogas reactors can be extremely simple for small households, designed for limited production of thermal energy and the simplest digestates or, conversely, large-scale and centralized for the production of electricity or biomethane. The variety of end products is also an important advantage for operating in an ever-changing commercial market.

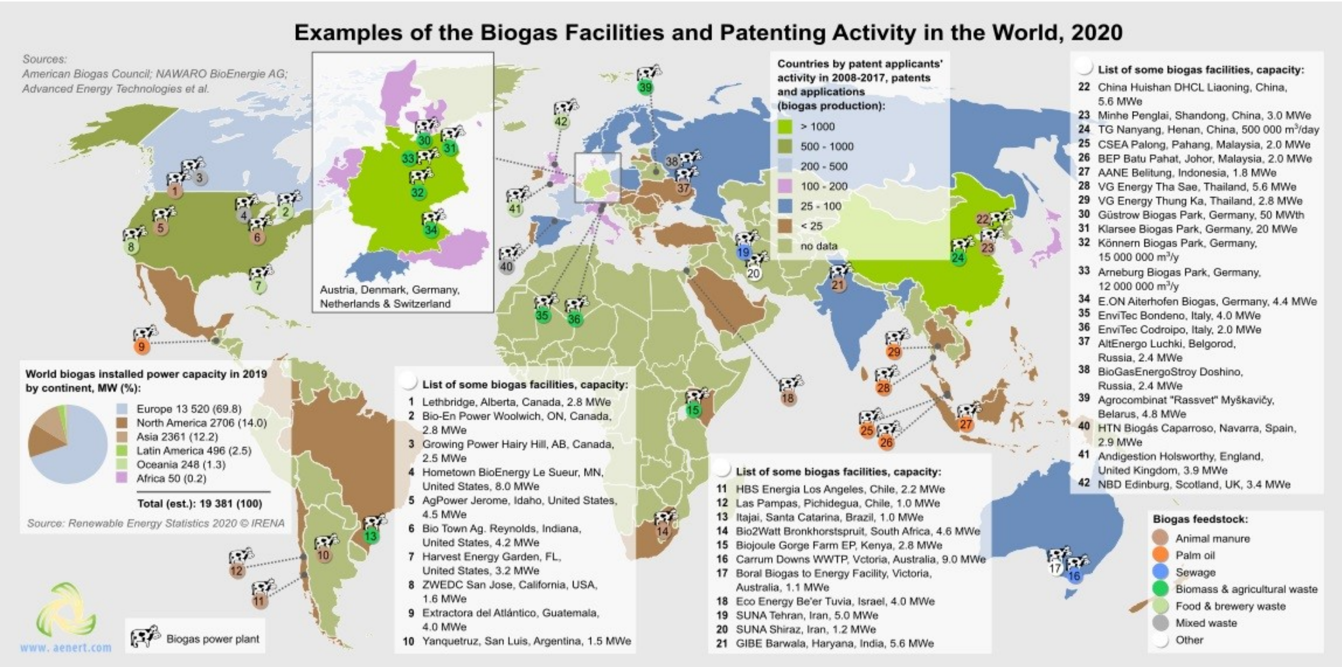
Figures 10 and 11. Jordberga Biogas Plant, Sweden.

In [13], the main barriers to increasing biogas production are noted, among which, first of all, the "Existence, stability and reliability of the framework and support scheme (s)" stands out. At the same time, it is emphasized that the need for such a support scheme is associated with relatively high investment costs, which according to [13], may amount to 2,700 €/(Nm3/hr). With operating and maintenance costs of 270 €/(Nm3/hr) per year, the payback period of projects can be quite long. Other important barriers to the development of biogas production include administrative procedures and access to finance.

3.2. Biogas plants

According to estimates [12], there are about 50 million biogas enterprises in the world, of course, primarily in the form of micro-scale. Most of them are concentrated in China (over 40 million) and India - about 5 million. There are several hundred thousand micro biogas plants in Nepal and Vietnam, and more than ten thousand in many Asian countries, including Indonesia, Bangladesh, Cambodia[17]. Fig 12 shows a map with the largest enterprises with a division by the type of raw materials used, as well as with a display of the patent activity of countries by the number of patents received and patent applications filed by their residents for 10 years from 2008 to 2017.

Figure 12. Examples of the largest biogas production facilities with a display of patent activity of countries in the field of biogas technologies



[Examples of the Biogas Facilities and Patenting Activity in the World, 2020]

The largest biogas farms are concentrated in Germany, such as Klarsee Biogas Park with a capacity of 20 MWe. A list of biogas production facilities in the United States with accompanying information can be found in [20], and biomethane production facilities in Europe on the map presented in [21]. According to the latest research, in 2020 the number of biomethane plants in Europe exceeded 700, of which more than 30% are concentrated in Germany. France and Great Britain are among the major biomethane producers.

Figures 13 and 14. Left - Delivery of biomass for processing, Jordberga Biogas Plant, Sweden. Right - biomethane filling station, Norrkoping Biogas Plant, Sweden

Detailed information on the state of biogas production in different countries of the world can be found in [22].

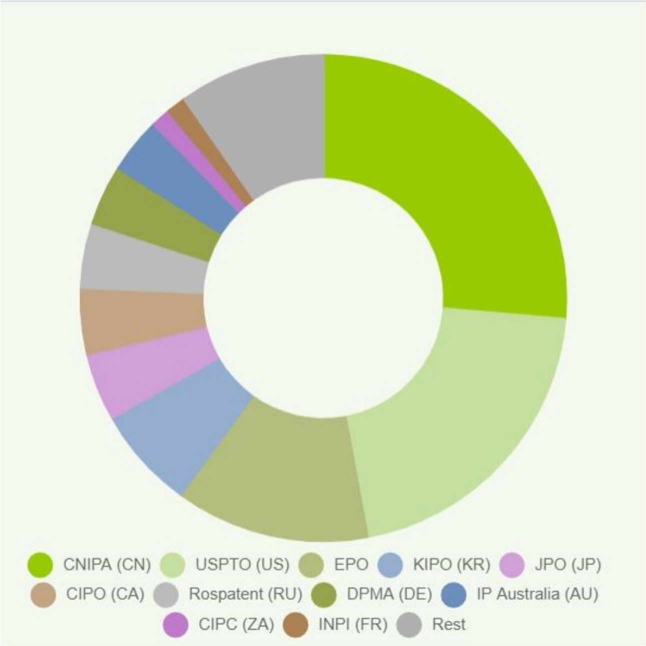
3.3. Biogas. Research and innovations

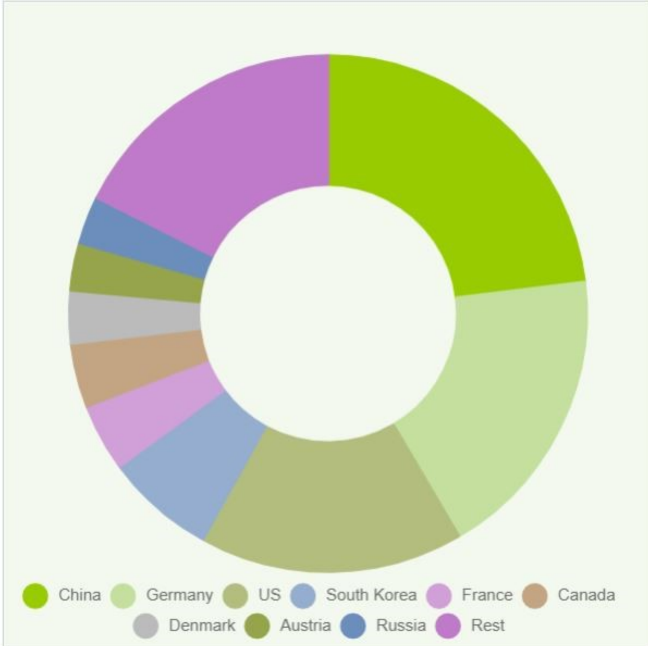
Biogas and biomethane production is the subject of intensive scientific and engineering research. Below is a brief statistical analysis of inventive activity in the field of biogas production over the past 10 years (2010 -2019), based on a patent selection of nearly 2,000 patents prepared by residents of 46 countries and issued in 46 patent offices worldwide.

During the period under review, the largest number of patents was granted by the Chinese Patent Office CNIPA, as well as by the American USPTO. In total, these two offices have issued about 50% of the patents. Other popular patent jurisdictions, included in the top 10 included Korean, Japanese, Russian, German, Australian, South African and French. The share of other offices was less than 10% (Figure 15).

Residents of China, Germany and the United States dominated the intellectual property register, having received more than 1100 patents together, or 60% of the total number of patents (Fig. 16).

Figures 15 and 16. Top 10 patent offices in the world by the number of patents issued in 2010-2019 (left) and top 10 countries whose residents received the largest number of patents in 2010-2019 (right), %





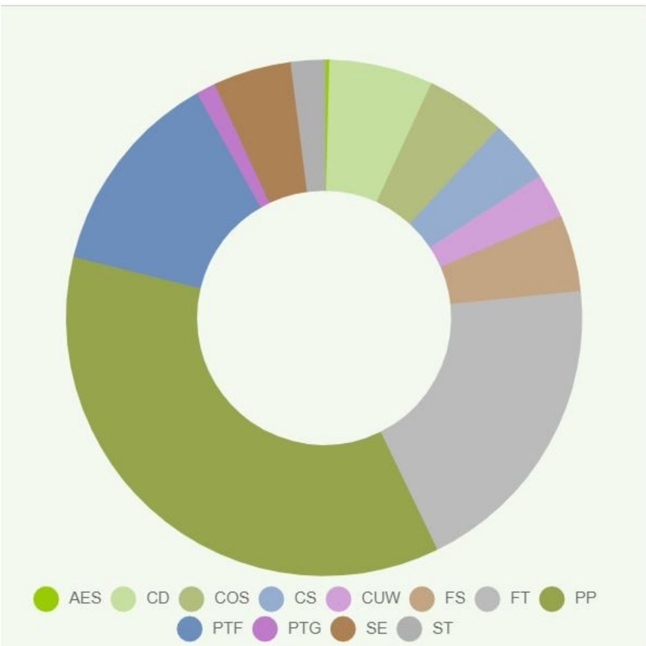
Source: Advanced Energy Technologies

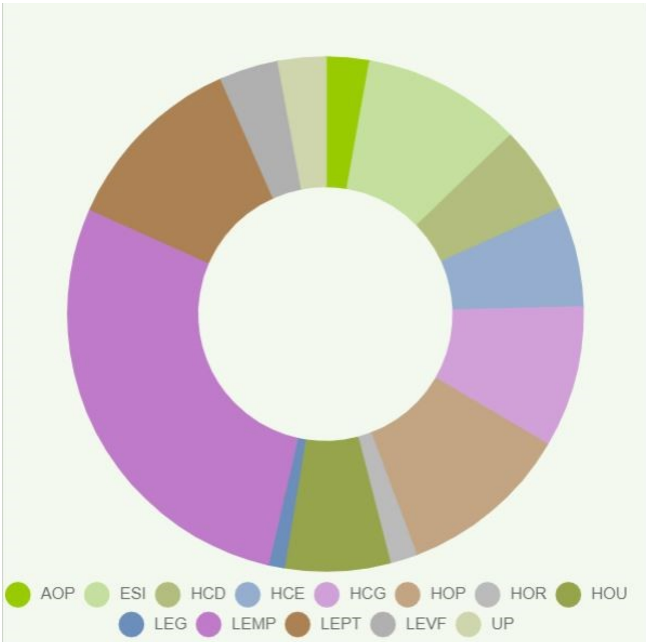
***CIPO (CA)** - Canadian Intellectual Property Office; **CIPC (ZA)** - Companies and Intellectual Property Commission; **CNIPA (CN)** - National Intellectual Property Administration; **DPMA (DE)** - German Patent and Trade Mark Office; **EPO** - European Patent Organization; **INPI (FR)** - National Institute of Industrial Property; **JPO (JP)** - Industrial Property Office (Japan); **KIPO (KR)** - Korean Intellectual Property Office; **Rospatent (RU)** - Federal Service for Intellectual Property (Russia); **IP Australia (AU)** - IP Australia; **USPTO (US)** - United States Patent and Trademark Office*

The largest number of patents was aimed at technical solutions for primary processing, as well as operations for pre-treatment of feedstock and finishing treatment (Fig. 17).

Figure 18 shows the distribution of patents by the number of technical, organizational and environmental problems mentioned in them, the solution of which was addressed by the inventors. Other inventors were interested in the problems of low efficiency of main processes and low efficiency of product treatment, problems of high operating costs (OPEX/Poor performance) and problems of environmental and social impact of biogas production technologies.

Figures 17 and 18. Distribution of patents by technology elements (left) and problems (right), %





Source: Advanced Energy Technologies

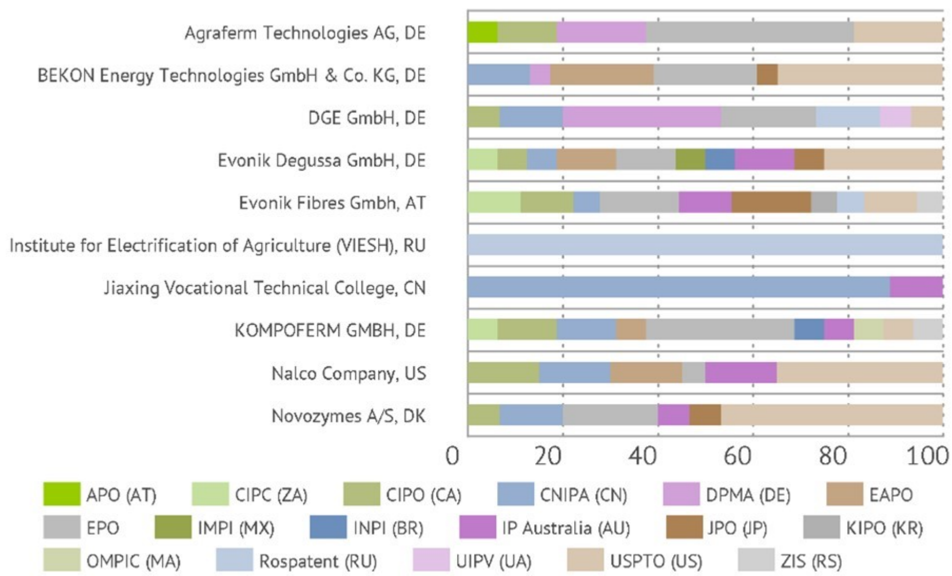
***AES** - Additional equipment, substances; **CD** - Methods of control and diagnostics; **COS** - Chemistry and other substances; **CS** - Capture and separation; **CUW** - Capture, utilization of solid, liquid and gaseous wastes; **FS** - Feeding systems; **FT** - Finishing treatment; **PP** - Primary processing; **PTF** - Pre-treatment of feedstock; **PTG** - Processing technologies in general; **SE** - Secondary equipment; **ST** - Storage & transportation*

***AOP** - Administrative and organizational problems; **ESI** - Environmental and social impact; **HCD** - High CAPEX / Development; **HCE** - High CAPEX / Equipment; **HCG** - High costs in general; **HOP** - High OPEX / Poor performance; **HOR** - High OPEX / Repair and replacement; **HOU** - High OPEX / Utilization; **LEG** - Low efficiency in general; **LEMP** - Low efficiency of main processes; **LEPT** - Low efficiency of product treatment; **LEVF** - Low efficiency / Variety of feedstock; **UP** - Unclear problem*

The top 10 leading applicants who received the largest number of patents during the period under review included BEKON Energy Technologies GmbH &Co. (Germany), KG, Evonik Degussa GmbH (Germany), Agraferm Technologies AG (Germany), KOMPOFERM GMBH (Germany), DGE GmbH (Germany), Nalco Company (USA), Evonik Fibres Gmbh (Australia), Novozymes A/S (Denmark), and two research organizations – Jiaxing Vocational Technical College (China), and the Institute for Electrification of Agriculture (VIESH) (Russia). Each of these applicants received between 15 and 23 invention patents.

Figures 19 and 20 show the interests of these applicants in terms of the regions of patenting and elements of the technological chain of biogas production.

Figure 19. Distribution of patents of the leading applicants among patent offices of the world, %

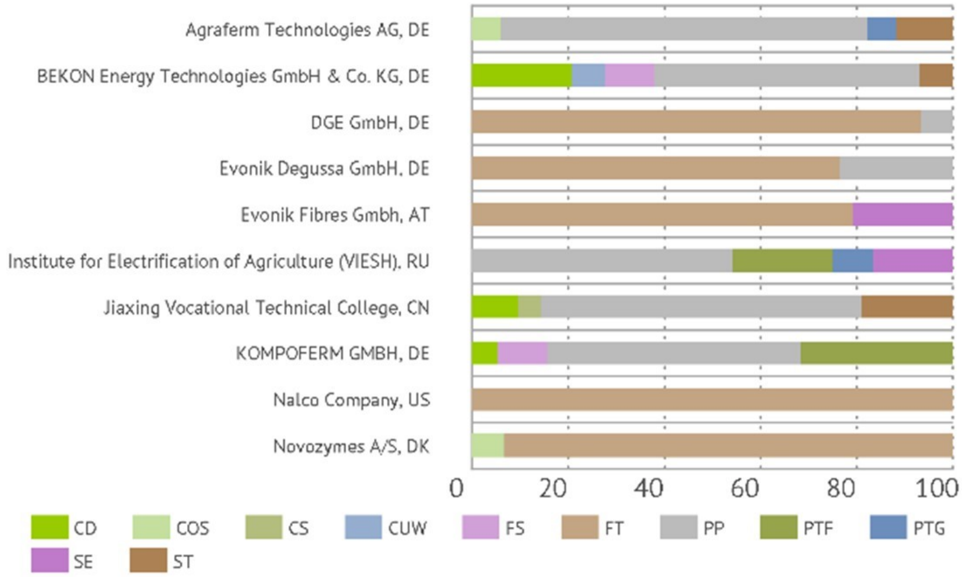


Source: Advanced Energy Technologies

***CIPO (CA)** - Canadian Intellectual Property Office; **CIPC (ZA)** - Companies and Intellectual Property Commission; **CNIPA (CN)** - National Intellectual Property Administration; **DPMA (DE)** - German Patent and Trade Mark Office; **EPO** - European Patent Organization; **INPI (FR)** - National Institute of Industrial Property; **JPO (JP)** - Industrial Property Office (Japan); **KIPO (KR)** - Korean Intellectual Property Office; **Rospatent (RU)** - Federal Service for Intellectual Property (Russia); IP **Australia (AU)** - IP Australia; **USPTO (US)** - United States Patent and Trademark Office; **IMPI (MX)** - Mexican Institute of Industrial Property; **APO (AT)** - The Austrian Patent Office; **EAPO** - Eurasian Patent Organization; **INPI (BR)** - National Institute of Industrial Property; **OMPIC (MA)** - Moroccan Industrial and Commercial Property Office; **UIPV (UA)** - Ministry of Economic Development and Trade of Ukraine; **ZIS (RS)** - Intellectual Property Office of the Republic of Serbia*

Each of the top 10 patent applicants focused mainly on the technological operations of finishing treatment (including the processing of biogas to biomethane) and the primary processing.

Figure 20. Distribution of patents of the leading applicants by technological element, %



Source: Advanced Energy Technologies

AES *- Additional equipment, substances;* ***CD*** *- Methods of control and diagnostics;* ***COS*** *- Chemistry and other substances;* ***CS*** *- Capture and separation;* ***CUW*** *- Capture, utilization of solid, liquid and gaseous wastes;* ***FS*** *- Feeding systems;* ***FT*** *- Finishing treatment;* ***PP*** *- Primary processing;* ***PTF*** *- Pre-treatment of feedstock;* ***PTG*** *- Processing technologies in general;* ***SE*** *- Secondary equipment;* ***ST*** *- Storage & transportation*

The largest number of patents - 117 - was found in groups of identical unified indicators, including "Low efficiency of main processes" and "Primary processing" and "device" as a type of technical solution.

The most popular International Patent Classification (IPC) index groups were: C12M01 - Apparatus for enzymology or microbiology; B01D53 - Separation of gases or vapors; Recovering vapors of volatile solvents from gases; Chemical or biological purification of waste gases and C02F11 - Treatment of sludge; Devices thereof. Their combined share was over 38%.

3.4. Biogas. Trends of development

Most of the forecasts for the development of biogas production are optimistic and assume a significant increase in this production over the next two decades. Thus, according to the restrained Stated Policies Scenario, [2] an increase in biogas production is predicted in the world by 2040 to a level exceeding about 150 Mtoe, and according to the optimistic Sustainable Development Scenario up to 300 Mtoe. On the other hand, in [13] in 28 EU countries it is assumed that biogas production will increase by 2030 according to different scenarios to a relatively modest range of 28-40 Mtoe, which is interesting given that Europe is currently the main biogas producer. Another study [19] examined the prospects for biomethane production in the countries of the European Union. Here, the authors were less constrained in their assessments - they predicted an increase in biomethane production almost 10 times higher than the current level - up to 18 Bcm, which will be about 10% of the projected imports of natural gas

Biogas. References

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4. Biomass Thermochemical Conversion

4.1. General information

Thermochemical conversion of biomass is the most widespread technological aspect of bioenergy, since it includes several different technologies from simple combustion to the most modern gasification and fast pyrolysis, and also allows obtaining a wide range of useful products. It should be noted that biomass combustion dominates in the modern industry, while more advanced technologies account for only a few percent of the world bioenergy production [1].

At the heart of each of the technological processes are fundamentally different options for the chemical transformation of organic raw materials, determined primarily by the presence of oxygen or the nature of interaction with it. In the most uncompromising cases, the combustion of biomass occurs in the free presence of oxygen (air), during gasification of biomass there is a limited and controlled presence of oxygen, while pyrolysis is carried out in the absence of oxygen [2].

Of course, in practice, deviations in the options for using oxygen, as well as combinations of the processes mentioned, are possible .

The combustion between oxygen and other main participants in the process - carbon, hydrogen and methane, results in water and carbon dioxide:

$C + O_2 = CO_2$

$H_2 + 1/2O_2 = H_2O$

$CH_4 + 2O_2 + CO_2 + 2H_2O$

The main product of biomass incineration is heat, which is used for industrial or residential buildings, as well as for generating electricity.

Figures 1 and 2. Left - biomass CHP plant in Simmering, Vienna, Austria (24.5 MW electrical and 37 MW of thermal energy, 200000 tons of biomass annually). Right -Igelsta CHP plant in Södertälje, Sweden (circulating fluidized bed boiler, thermal output: 240MW, electricity production: 83MW, wood chips and recovered fuels)

Gasification makes it possible to obtain syngas, i.e. a mixture of predominantly carbon monoxide and hydrogen, which can be used both as a fuel and as a chemical raw material to obtain a wide range of various valuable products, including synthetic natural gas or liquid fuels. The main reactions during gasification are[3]:

$C_6H_{12}O_6 + O_2 + H_2O \rightarrow CO + CO_2 + H2$ + other species
$CO + H_2O \rightarrow CO_2 + H_2$ (+ small amount of heat)

During pyrolysis, depending on the temperature conditions and the duration of the process, liquid, gaseous and solid reaction products can be obtained. Another important feature of using biomass as an energy raw material is its high heterogeneity, moisture content, low density and extreme non-technological, especially when grinding, transporting and dispensing, which is especially noticeable when comparing biomass with the traditional type of solid energy raw material - coal. The most stringent requirements for bioenergy raw materials are imposed by more complex technologies, primarily gasification. It also does not contribute to their competitive distribution.

Any technologies for thermochemical processing of biomass inevitably lead to significant emissions of carbon dioxide and the formation of other hazardous gases and solids. Combustion of biomass in this part is the least safe. However, thermochemical biomass conversion is often regarded as a zero-emission option, since after its equivalent reproduction in wildlife, for example, in the form of forest planting, complete absorption of the produced carbon dioxide is expected. Nevertheless, this interpretation raises reasonable doubts, taking into account the time range of these events .

Table 1. Main technologies of thermochemical conversion of biomass

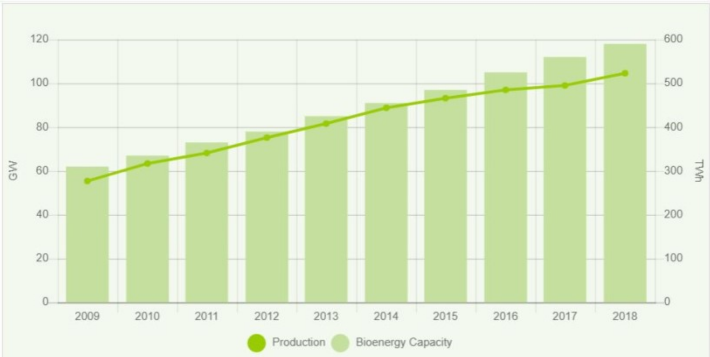
Process	Particle size requirements	Types of Reactor	Temperature/residence time	Energy Product, %		
				Gas	Liquid	Char
Slow Pyrolysis (Carbonisation)	Small or Large Sizes	Rotating drum reactors Auger reactors Rotary kiln reactor	400 - 500°C/hours-days	35	30	35
Torrefaction	Particles depending on Type Reactor	Screw reactor Rotary drum reactor Moving bed reactor Torbed reactor	250 - 300 (400)°C/ 30-40 min	18	-	82
Fast Pyrolysis	1-2 mm	Bubbling fluidised bed Circulating fluidised bed Rotating cone reactor Auger or screw reactor	500 - 650°C/1-5 sec	13	75	12
Gasification	3-30 mm	Fixed Bed	700 (550) - 900°C /min	85	5	10
	1-5 mm	Fluidized Bed	800 - 1100°C /few min	90 - 95	-	5 - 10
	0.1 mm	Entrained Flow	1350 - 1600°C /few sec	Up to 98 - 99.5	-	0.5 - 2

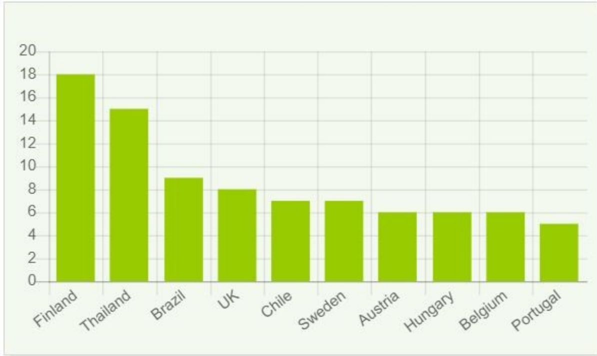
Sources: [2,4,5,6,7,8,9,10, 11]

As follows from the data in Table 1, the percentage composition of the final energy product largely depends on the temperature conditions and time of the process, and also, as noted above, on the degree of oxygen or air use. To ensure uniform and timely heating, the biomass is preliminarily subjected to grinding, down to millimetre particles and even smaller. Different types of process reactors are used depending on the composition of the feedstock and the requirements for the finished product. First of all, they are characterized by the degree of biomass mobility (fixed-bed, fluidized bed, entrained flow), the way of heating the biomass (autothermal gasifiers or direct gasifiers, and allothermal or indirect - external heating), the type of heat carrier (solid heat-carriers, gaseous heat- carriers)

The main types of final products resulting from thermochemical conversion of biomass are thermal and electrical energy, much less often syngas, biochar or bio-oil. Statistical data on the production of electricity from biomass are shown in Fig.3 and 4. In total, according to [12], in 2018, the total capacity of bioenergy plants in the world approached 120 GW, and electricity generation was about 523 TWh. At the same time, bioenergy, which uses solid biomass and renewable waste as a feedstock, accounted for more than 80% of the total capacity - 101.4 GW, with electricity generation exceeding 425 TWh .

Fig. 3 - 4. Left - Bioenergy capacity and electricity production in 2009 - 2018. Right - Top 10 countries rated by bioenergy electricity generation to total production, 2018, % (for countries with an annual electricity production of at least 10 TWh)





Sources: Based on Data from IRENA (2020), Renewable Energy Statistics 2020, International Renewable Energy Agency (IRENA), Abu Dhabi; BP Statistical Review of World Energy, June 2020

The leading countries using biomass for electricity generation in 2018 were Finland and Thailand, where the share of this type of feedstock in the total electricity generation balance reached or exceeded 15%. It should be emphasized once again that throughout the world electricity production in most cases is carried out using biomass combustion technologies, especially in combination with coal.

More detailed statistical information on the production and consumption of heat and electricity from bioenergy raw materials can be found in [13}.

4.2. Torrefaction and Fast Pyrolysis

Torrefaction is an example of slow low-temperature pyrolysis, which effectively removes moisture and a significant part of volatiles from biomass and leads to a significant improvement in its properties, including an increase in calorific value and embrittlement.This, among other things, allows the combination of biomass subjected to such a treatment with other types of raw materials, such as pulverized coal, for further joint combustion. According to [6], the calorific value of different solid fuels of wood chips and wood pellets is 9-12 and 15-16 MJ / kg, respectively, and after torrefaction pellets already have 20- 24 MJ / kg, which is comparable to the heat output of coal. At the same time, torrefied pellets have a power density similar to coal and significantly lower moisture content [7]. In this sense, torrefaction makes it possible to obtain a new type of bioenergy product called bio-coal. In addition, torrefaction provides a decrease in the ability to absorb moisture and a decrease in the volume of the original biomass, which is very important during its transportation and storage.

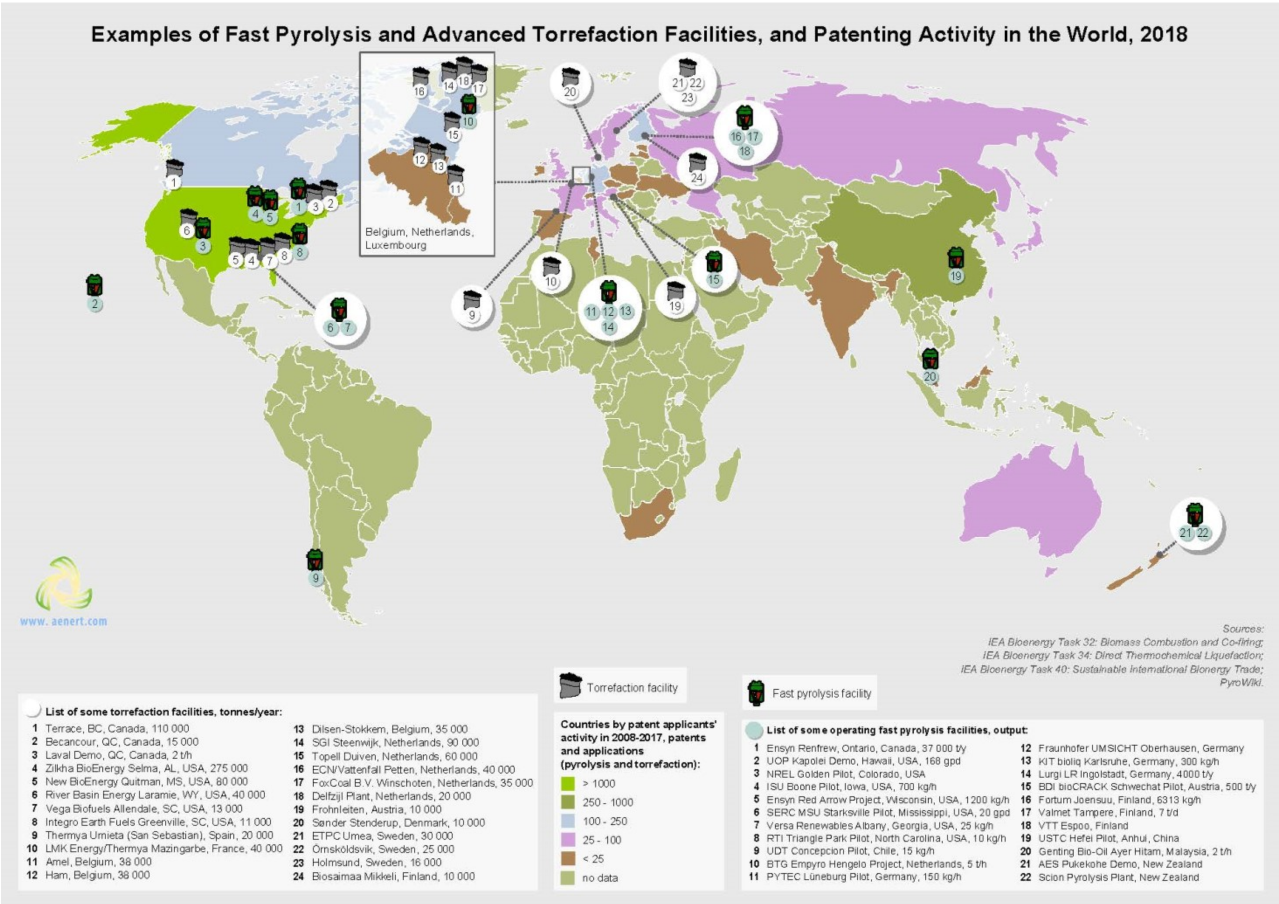
Torrefaction is usually carried out in the temperature range of 200-300°C [4,6,14,15], however, some sources report that the upper temperature can be even higher up to - 400°C [10]. Wood chips are most often used as raw materials; less often other woodworking products, including wood pellets. For pelletizing wood chips after torrefaction, a higher compaction pressure is required to ensure the required pellet strength. Among the types of torrefaction reactors, proven technologies include, first of all, the screw reactor and the rotary drum reactor. Also used are a fluidized bed reactor, a moving bed reactor, a microwave reactor, a torbed reactor, and others. Reactors can be continuous reactors, with direct or indirect heating (directly or indirectly heated), in the latter case, heating is carried out most often due to flue gas.

The Screw reactor and Rotary drum reactor allow for the best possible process and optimum temperature control. Mixing of fuel is possible in the Rotary drum reactor and Fluidized bed reactor. The moving bed reactor and the Fluidized bed reactor have good potential for upscaling. Finally, the reactor with the lowest conversion costs is the moving bed reactor [6].

The economic value of torrefaction pellets in comparison with the basic version of the production of conventional pellets is discussed in detail in [7]. Despite the need for significantly higher capital and operating costs in the case of torrefaction (capital investments, electricity consumption, etc.), the final cost of the product can be about 30% lower due to significant savings in logistics operations.

Figure 5 shows the location of the largest regional enterprises for torrefaction of biomass, as well as data on patent activity of countries over the past decade (including fast pyrolysis technologies). Torrefaction has become widespread in the United States and Western Europe; in other regions of the world, this technology has not yet been implemented.

Figure 5. Examples of large factories and patent activity of countries around the world in the torrefaction and fast pyrolysis sector

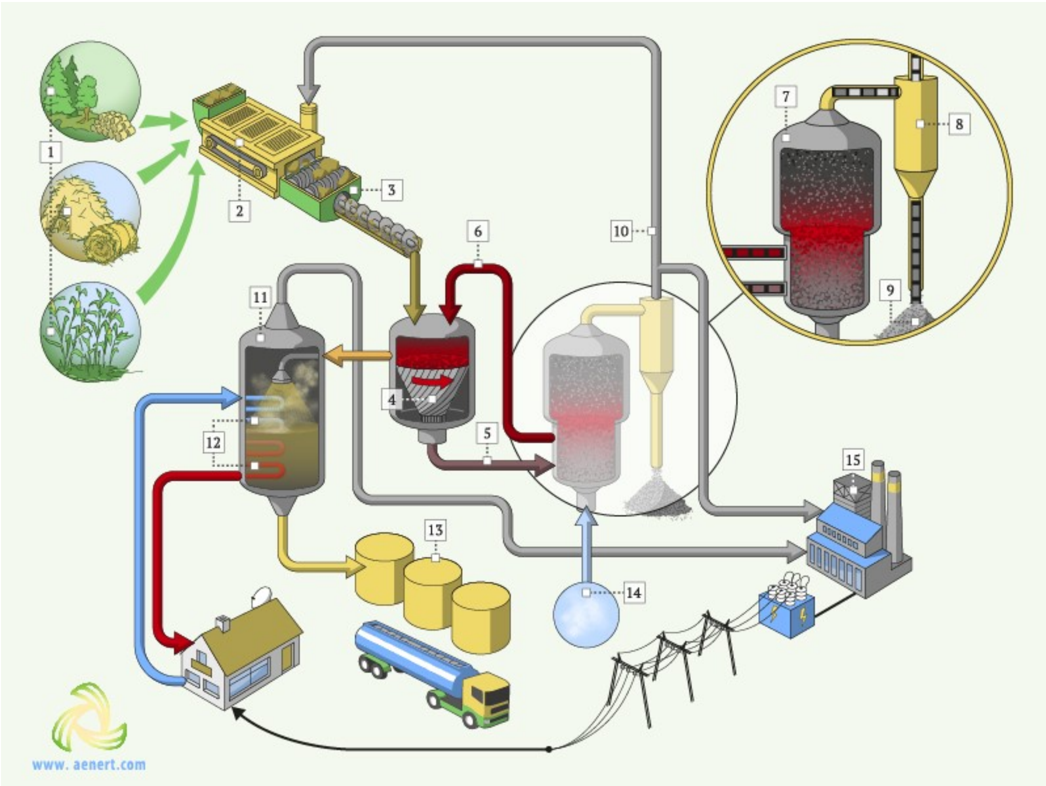


[Examples of the Torrefaction and Pyrolysis Facilities open full format (PDF, 1.3 MB)]

Fast pyrolysis is another promising area of thermochemical biomass conversion that has gained commercial acceptance in recent years. This technology is implemented at moderate temperatures, usually at 500°C, in the absence of oxygen, and a very short residence time of several seconds (Table 1). As a result of this treatment, the biomass decomposes with the formation of a relatively small amount of charcoal, combustible gases and oily vapour, from which, after subsequent cooling and condensation, about 75% of a bioenergy liquid called bio-oil can be obtained. The peculiar qualities of this technology inevitably require fine preliminary grinding of the biomass and the provision of severe conditions for uniform and, in essence, instant heat transfer from the coolant to the biomass particles inside the reactor.

In general, the sequence of technological operations of fast pyrolysis includes (Figure 6): reception and storage; drying and grinding; preparation and loading of the heat transfer agent; biomass feed and fast pyrolysis; removal of pyrolysis products; condensing of pyrolysis gas and liquids collection; separation of flue gas and ash. Pyrolysis by-products in the form of flue gas can be used in the drying stage or transferred through heat exchangers in the form of heat to other consumers. A very important advantage of the fast pyrolysis technology is the possibility of obtaining bio-oil, which can be stored or transported over a long distance using traditional infrastructure, as well as used as a fuel or chemical raw material to obtain more valuable products, including automobile fuel .

Figure 6. Basic technological operations of fast pyrolysis

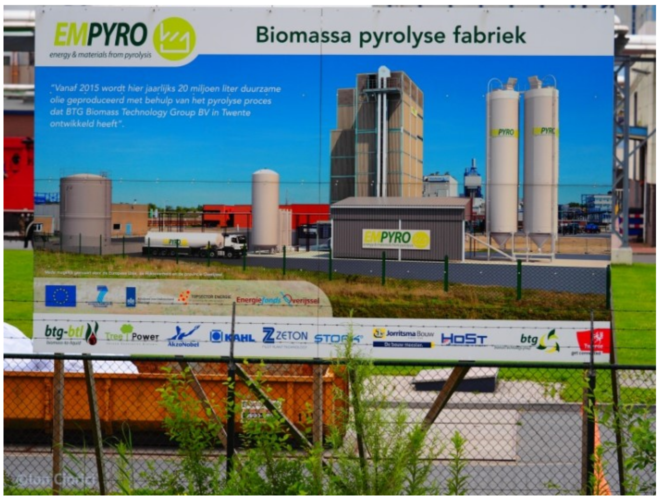


1. *Raw materials biomass* ***2.*** *Drying system* ***3.*** *Chopper* ***4.*** *Rotating cone* ***5.*** *Sand and biomass particle* ***6.*** *Hot sand* ***7.*** *Fluidized bed boiler* ***8.*** *Ash and gas separator* ***9.*** *Ash* ***10.*** *Non condensable gases for biomass drying* ***11.*** *Bio oil steam condenser* ***12.*** *Heat exchange tubes with water* ***13.*** *Bio oil stock* ***14.*** *Air blower* ***15.*** *Electricity generation plant*

The factors that determine the efficiency and composition of fast pyrolysis products are [4] - reaction temperature, feedstock characteristics, reactor design, additives and catalysts, hot vapour and solids residence time, pressure. Wood is most often used as a raw material for pyrolysis, although, according to [16], many other types of biomass, including agricultural waste, can be used. The most critical part of the fast pyrolysis technology is the reactor, despite the fact that the cost of its construction is only 10-15% of the total capital costs [4].

Among the various reactor options for fast pyrolysis, there are bubbling fluidized bed reactors, circulating fluidized bed reactors, rotating cone reactor, auger or screw reactor [2,11]. Bubbling fluidised bed reactors allow for good temperature control, and easy scaling; the technology is well studied, but requires small particle sizes [2]. Circulation

Figure 7 and 8. The Empyro fast pyrolysis plant in Hengelo, the Netherlands



reactors of this group allow the use of larger particles, allow for large-scale production, but have more complex hydrodynamics of the process. The main auger or screw reactor is the presence of moving parts in the hot zone, heat transfer at larger scale may be a problem and lower bio-oil yields [2].

BTG-BTL has developed a commercial fast pyrolysis technology based on its own patented technology [17]. They applied the design of a rotating cone reactor and sand as a circulating heat carrier material; combustion of solid reaction products and heating of sand is carried out in a combustion chamber with a fluidized bed combustor. The resulting excess heat can be used, among other things, to generate electricity (Figures 7 and 8). Fortum in 2013 in Joensuu, Finland put into operation one of the world's first industrial Integrated pyrolysis oil production technology and combined heat and power plant [18]. The plant uses Valmet technology with a circulation fluidized bed boiler reactor and uses sand as a heat transfer medium. Low-temperature heat from condensation is used to dry biomass before pyrolysis [19]. The annual production of bio-oil in Joensuu is 50,000 tons, with processing from 300,000 to 450,000 m^3 of wood [18]. Examples of plants for the conversion of biomass using fast pyrolysis technology can be seen in Fig. 5.

Among the main disadvantages of bio-oil production are [2] - high cost, in some cases significantly higher than fossil fuel; incompatibility with conventional fuels; lack of standards; limited supplies for testing. Figure 5 shows examples of plants for the conversion of biomass by fast pyrolysis and data on patent activity of the countries around the world over the last decade (including torrefaction technologies). Table 2 lists the main patent holders which have received patents in the torrefaction and fast pyrolysis technology sector over the last 10 years between 2009 and 2018. In total, about 1100 patents were selected for consideration, in which the authors directly indicated that the proposed technical solutions belong to these technologies. Data on the shares of patent holders in the general register of intellectual property are also shown below.

Table 2. Leading patent holders related to torrefaction and fast biomass pyrolysis over the past 10 years (2009 -2018) and their shares in the intellectual property register in relation to all patent holders

Status	Country	Name	Volume, %	Ownership ratio,%	Market involnement, %
Company	US	Xyleco Inc.	5.27	94.55	4.98
Company	US	UOP LLC	4.41	81.43	3.59
Company	US	Kior Inc	4.12	71.12	2.93
Organization	US	Gas Technology Institute	2.49	91.99	2.29
Company	US	ENSYN Group, Inc	2.3	81.32	1.87
Company	FI	Metso Power Oy	1.72	76.85	1.32
Company	IT	Eni S.p.A.	1.44	80.22	1.16
Organization	CN	Sunshine Kaidi New energy Group Co. Ltd	1.44	100	1.44
Organization	CN	SEU Southeast University	1.25	92.31	1.15

Volume ratio - share of applicant documents in total number of documents
Ownership ratio - applicant's participation share in total number of documents
Market involvement ratio (bubble size) - volume ratio multiplied by ownership ratio

Source: Advanced Energy Technologies

The list is dominated by American companies, with Xyleco Inc. an absolute leader, with a share of about 5% of the total number of patents issued worldwide between 2009 and 2018 in the bioenergy technology sector under consideration.

4.3. Biomass Gasification

Gasification is a process of high-temperature conversion of biomass with the formation of producer gas or synthesis gas (syngas) as the main product, as well as thermal energy, biochar, and useful mineral residues. Biomass gasification is a more advanced technological process compared to combustion in terms of biomass conversion efficiency, variety and value of the finished product.

Wood is primarily used as feedstock for gasification, but agricultural, municipal and industrial waste, marine biomass, etc. can also be used. The properties of the feedstock can have a serious impact on the gasification process. These primarily include: its physical characteristics, including moisture content, particle size, density and porosity, and some others; and also, to the same degree of importance, chemical indicators, for example, the content of lignin, cellulose and hemicellulose content, the content of gases, solids, metals - carbon, oxygen, nitrogen, hydrogen, sulfur, chlorine, alkali and other metals. Variations of the noted indicators for different types of biomass can be significant. For example, Rice straw can contain 50.0–80.0% moisture, and Wheat straw only up to 20%. Softwood contains 41% Cellulose, 24% Hemicellulose, 28% Lignin, and Birch wood 35.7%, 25.1%, 19.3%, respectively [20]. It is also very important that the oxygen content in carbohydrates from biomass is quite high, while the amount of the main fuel elements - carbon and hydrogen, is significantly lower compared to fossil fuels.

All gasifiers are divided into two large groups - autothermal and allothermal. In the first, heat for the conversion of biomass is produced due to its partial oxidation in the reactor with a controlled supply of air or oxygen. However, in this case it is necessary to ensure the possible uniformity of heating through intensive heat transfer. In addition, when air is used as an oxidizer, the resulting syngas will contain higher nitrogen concentrations than when oxygen is supplied, which makes it unsuitable for the subsequent production of energy products. On the other hand, the use of oxygen requires the construction of expensive facilities for its production.

In indirectly-heated gasifiers, heat is supplied to the reactor from an external heat source. Most often, sand is used for these purposes, which is heated in a separate reactor and circulated between it and the gasification reactor. In addition, the heat of the hot flue gas is used for indirect heating. In recent years, numerous unconventional technologies of indirect heating with the use of electric heaters, microwave generators, and solar reflectors have been encountered in patent documents. There are two initial drivers pushing developers for such innovations - firstly, the use of such heating options dramatically improves the environmental performance of the gasification process while significantly reducing the cost of technical equipment for cleaning flue gases, and secondly, indirect heating makes it possible to obtain syngas with a permissible nitrogen content without using oxygen. The main chemical reactions during gasification with an agent in the form of water vapour are (steam reforming) [20]:

$CH_4 + H_2O \rightarrow CO + 3H_2$

$CH_4 + ½O_2 \rightarrow CO + 2H_2$

and water-gas shift reaction:

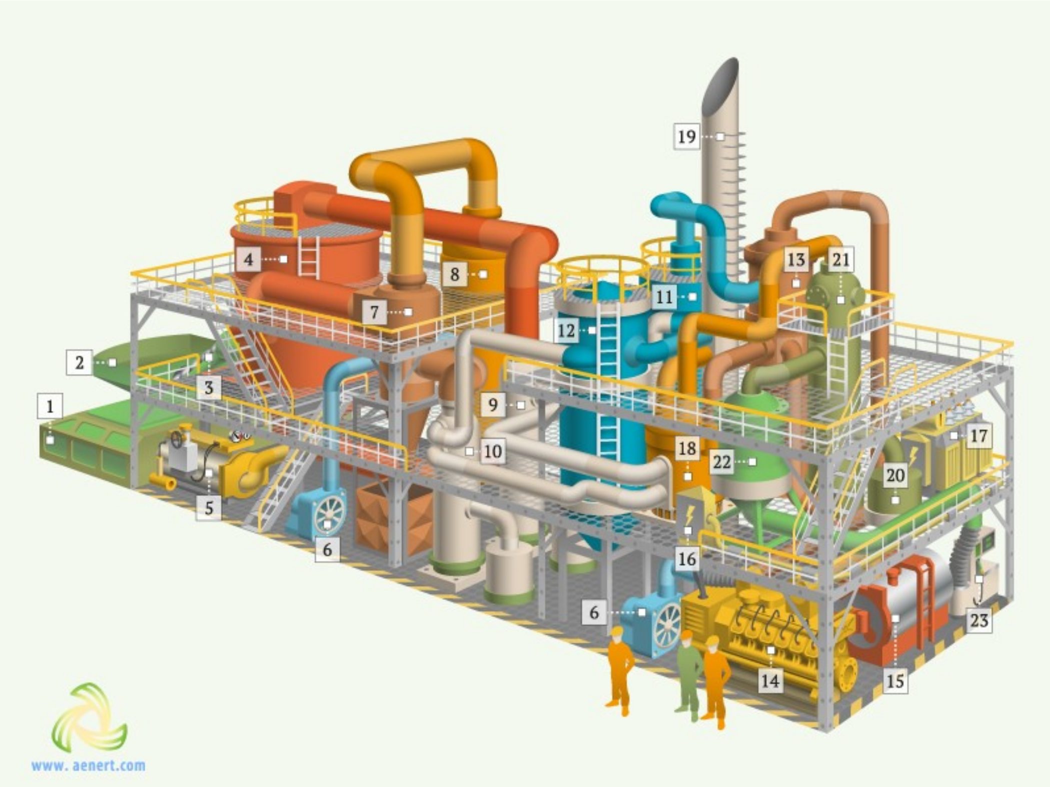
$CO + H_2O \rightarrow H_2 + CO_2$

Depending on the type of reactor, gasification is usually carried out in a temperature range from 700 to 1600^oC, although, for example, in [5,23], lower temperatures are indicated, and in some patent documents, in contrast, upper temperature conditions can reach up to 2000^oC.

The general design of an autothermal plant for biomass gasification with steam reforming is shown in Figure 9. A significant share in the total metal consumption of the plant is taken up by equipment elements related to the treatment of off-gases - a purge gas cooler, a flue gas cooler, a purge gas filter, a flue gas filter, and a gas scrubber. Conventionally, the installation in the figure includes useful syngas consumers - a gas generator, a hotwater boiler, an electricity transmitter from the generator, an electric transformer to the power grid, and a peak load boiler. The details of the equipment are shown in the figure in proportion to the real dimensions.

The main types of gasification reactors are: fixed bed; moving bed; fluidized bed; circulating fluidized bed; entrained flow [2,5,21,22,23,24,25]. In reactors with a fixed bed, there is a small movement of biomass in the direction of flow, therefore, an alternative name is used - moving bed [9,25].

Figure 9. General design of a biomass gasification plant



1. *Pretreatment hopper* ***2.*** *Biomass hopper* ***3.*** *Feeding screw* ***4.*** *Gasifier 5. Steam generator* ***6.*** *Air blower* ***7.*** *Cyclone* ***8.*** *Combustion chamber* ***9.*** *Producer gas cooler* ***10.*** *Flue gas cooler* ***11.*** *Producer gas filter* ***12.*** *Flue gas filter* ***13.*** *Producer gas scrubber* ***14.*** *Gas engine* ***15.*** *Hot water boiler* ***16.*** *Power generator electricity transmitter* ***17.*** *Electricity transformer to power grid* ***18.*** *Peak load boiler* ***19.*** *Stack or chimney* ***20.*** *Synthesis reactor* ***21.*** *Synthesis gas filter* ***22.*** *Gas conditioning unit* ***23.*** *Methane fuel station*

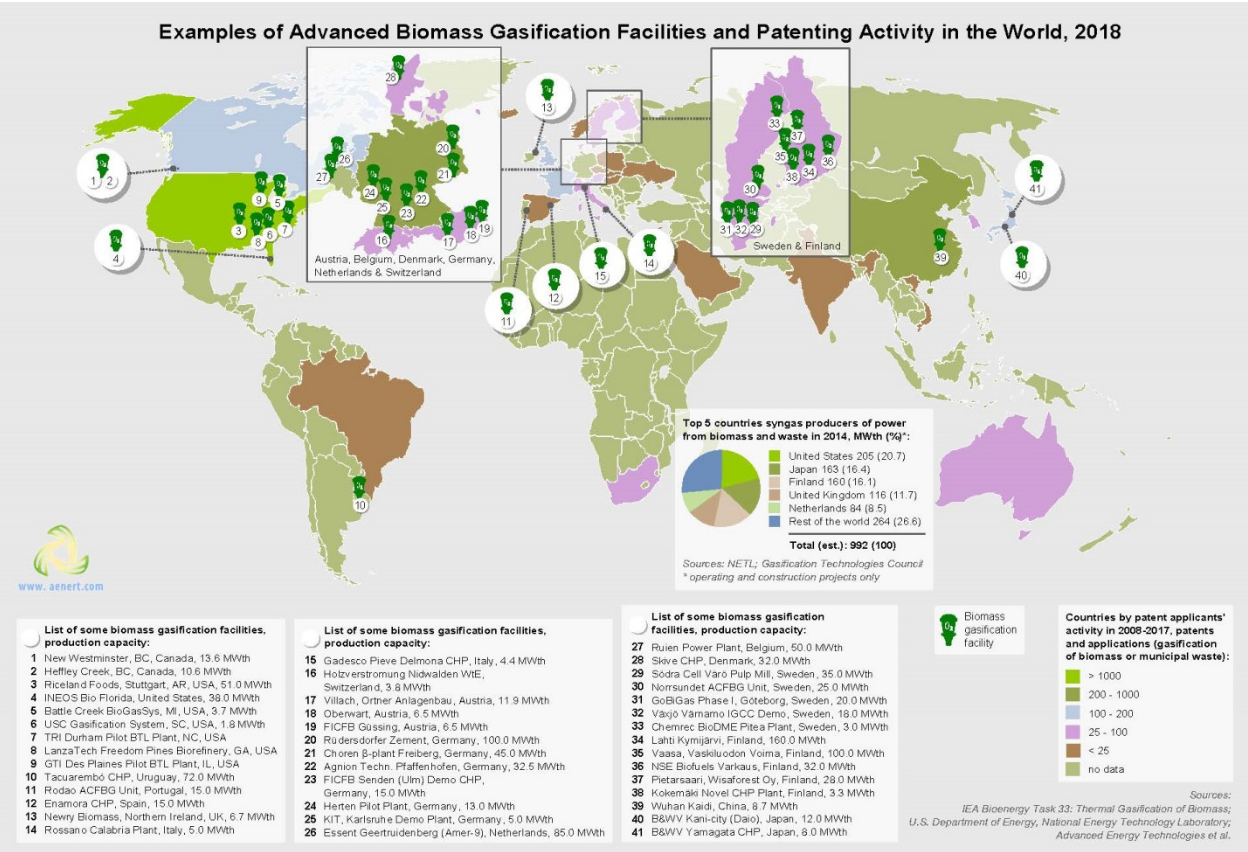
In moving bed reactors, biomass is loaded from above and oxidizing agents from below. Gaseous reaction products are removed from the reactor at the top, and slag and ash at the bottom. Due to the resulting counterflow of biomass and oxidizer, the upper layers of the loaded raw material are preheated due to the heat of gasification from the lower layers. Reactors of this type are characterized by a relatively long gasification time, up to several hours, low oxidant requirements, a high methane con-tent in the produced gas, significant restrictions on the use of small particles [24], and significant contamination of the product with tars forming during gasification [25]. The main feature of fluidized bed reactors is to ensure good mixing of already gasified and new particles, which contributes to uniform heating of the biomass. Fluidization here means the floating of particles in the bed due to the gases supplied to the reactor; however, without the removal of these particles from the bed until they become noticeably lighter as a result of gasification [24]. There are several types of these gasifiers, including bubbling fluidized bed, circulating fluidized bed and dual fluidized bed. The circulating fluidized bed gasifier consists of two main units: a gasification unit and a circulation unit. Double fluidized bed gasifiers consist of two separate fluidized beds that are used for the pyrolysis process and the combustion process [25]. Gasification temperature for these types of reactors usually varies in the range of 800-1100ºC, and the particle size is 1-5 mm [5]. Entrained flow reactors use vertical or horizontal feed of biomass and oxidizer. The gasification temperature can reach 1600ºC; oxygen is used as an agent, the gasification time is several seconds. As a result of this process, the yield of syngas can be very high, close to 99% [9]. However, to implement the process of involving biomass particles in a gas flow, the particle size should be no more than 0.1-0.4 mm [5.25], which is extremely difficult to ensure for most types of biomass. The central challenge for biomass gasification is to minimize and remove the resulting tar, which can cause serious operational problems. In addition, there are strict standards for the maximum permissible limits of contaminants in synthesis gas. For example, the content of tars in synthesis gas for Fischer-Tropsch processes should not exceed 1 mg/Nm^3 [20]. The best results are achieved with entrained flow reactors, where tars and other organic by-products are almost completely decomposed at high temperatures [9]. In other cases, special catalysts are used to decompose the tars inside the gasifiers. The formation of tars is also significantly influenced by the size of the particles, since in this case, due to the better thermal conductivity, the conversion is carried out more uniformly in the space of the reactor. In addition, it was found that open-top gasification systems produce the lowest amount of tar and particulates vis-a-vis other gasification systems [20]. Outside the gasifiers, resins are removed using the Mechanical method, Thermal cracking, Catalytic cracking, Plasma method [20].

Figures 10-12 show examples of gasification plants in the world in relation to biomass.

Figures 10-11. Lahti Energia's Kymijärvi II power plant in Lahti, Finland

Lahti Energia'sKymijärvi II power plant in Lahti, Finland is one of the world's largest gasification waste and wood conversion plants. The plant was intended to replace a thermal coal station. The power plant has a capacity of 50 MW of electricity and 90 MW of thermal energy, making it one of the largest in the world. The plant uses a Valmet circulating fluidized bed gasifier, as well as a special cleaning and cooling system, steam boiler and environmental protection system [26].

Figure 12. Examples of the largest biomass gasification plants in the world



Examples of the Biomass Gasification Facilities open full format (PDF, 0.7 MB)

Most of the large biomass gasifiers are located in Germany, USA, Finland and Sweden. More detailed information on various designs of reactors for gasification of biomass, as well as on production facilities, can be seen in the following scientific papers and databases [27-31].

Table 3 below lists the top ten patent holders for biomass gasification over the past 10 years (2009 -2018), as well as their shares in the intellectual property register in relation to all patent holders. About 1,500 patents were selected for analytical evaluation, in which the authors indicated that the proposed technical solutions belong to biomass gasification technologies at any stage of the production process, including raw material preparation, waste gas treatment, sludge removal, etc.

Table 3. Leading biomass gasification patent holders from 2009 to 2018 and their shares in the register of intellectual property in relation to all patent holders

Status	Country	Name	Volume, %	Ownership ratio,%	Market involnement, %
Organization	CN	Wuhan Kaidi Engineering Technology Research General Institute Co., Ltd.	6.72	97.38	6.54
Company	NL	Shell Internationale Research Maatschappij B.V.	2.72	98.68	2.68
Company	US	General Electric	2.58	82.38	2.13
Organization	CN	Sunshine Kaidi New Energy Group Co. Ltd	2	100	2.00
Company	JP	IHI Corparation	1.93	88.4	1.71
Company	US	Rentech Inc.	1.93	84.57	1.63
Organization	FR	IFP (École Nationale Supérieure du Pétrole et des Moteurs)	1.79	75.05	1.34
Company	US	RES USA LLC	1.79	65	1.16
Organization	FR	Commissariat à l'énergie atomique et aux énergies alternatives	1.57	53.54	0.84

Source: Advanced Energy Technologies

The presence of representatives of five countries in this list indicates a significant interest of inventors in biomass gasification technologies in different countries around the world. A comparative analysis of the costs for the production of electricity from biomass by various methods is given in [32]. It is established here that the levelised costs (LCOE) for fairly popular fixed bed and fluidized bed gasifiers is 0.07 - 0.21 USD/kWh, and the investment cost is 2 140 - 5 700 USD/kWh. Undoubtedly, the upper values of the indicated intervals are uncompetitive, and the lower ones are relatively feasible. For example, according to [33], in 2019 the average LCOE of biomass for electricity production was 0.066 USD/kWh, noticeably inferior only to hydropower and offshore wind energy, but being on a par with photovoltaics and geothermal energy. In this case it is necessary to take into account the efficiency of utilization of the generated thermal energy in detail; however, in any case, the high cost of gasification processes is one of the main barriers to the promotion of this technology. Other problems include ensuring the required purity of syngas, utilization of carbon dioxide and solid gasification products, problems of preparing feedstock, and optimizing the design of reactors to ensure the specified parameters of heat and mass transfer.

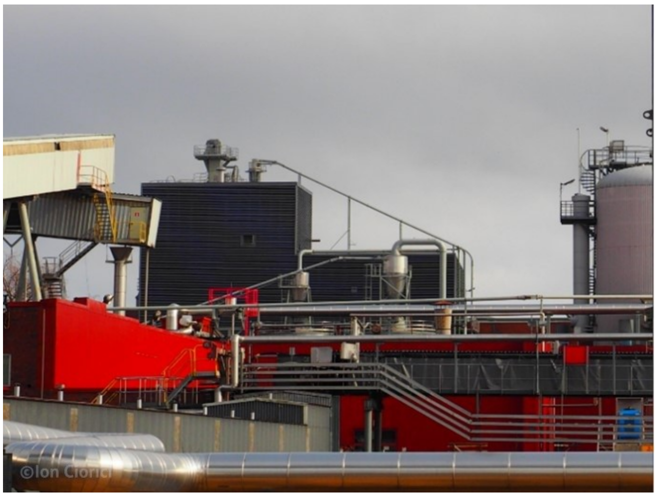
In recent years, biomass reforming in supercritical water biomass technology has attracted considerable interest. This technology ensures the maximum yield of hydrogen in the syngas composition, and also does not require expensive preliminary biomass drying operations. The conversion requires temperature and pressure conditions not lower than the following - 374°C and 22.1 MPa. According to the technology developed by BTG, the operating temperature of the reactor is usually from 600 to 650°C, and the operating pressure is about 300 bar, the moisture content of the raw materials is 70-95%, and the process time is up to 2 minutes [34]. These modes allow for the preferential oxidation of high-density carbon to CO_2, the formation of low CO concentrations and the active release of H2 from water. The industrial application of this technology can significantly change the balance of clean fuel production in favour of hydrogen and strengthen the position of biomass among renewable energy sources. .

4.4. Production of synthetic fuels from biomass syngas

Syngas (synthesis gas), which is predominantly a mixture of hydrogen and carbon monoxide, is the most important chemical raw material for the production of liquid and gaseous environmentally-friendly fuels. There are several methods for the synthesis of simple syngas molecules into long fossil fuel molecules. Since these processes occur at the intermolecular level, very stringent requirements are imposed on the purity of syngas, which was mentioned above, when considering the gasification processes. Therefore, purification of syngas prior to synthesis processes is of paramount importance. The most common method for producing synthetic fuels from syngas is the Fischer-Tropsch process (FT), first developed about 100 years ago and named after its creators. Typical parameters of the process are a temperature in the range 150-300°C pressure - up to several tens of atmospheres, catalysts - mainly cobalt and iron [36]. The Fischer-Tropsch conversion of biomass to liquid (BTL), has much in common with related processes, gas to liquid (GTL) and coal to liquid (CTL). However, there is a significant difference due to the fact that syngas obtained from biomass has a lower hydrogen to carbon monoxide ratio and a greater number of pollutants in comparison with syngas produced from natural gas [37]. If we also take into account that natural gas and coal are more technological types of raw materials, it becomes clear why GTL and CTL have received larger development in comparison with BTL technologies. For example, the world's largest power plants - Pearl GTL and Oryx GTL in Qatar have capacities of 140,000 and 130,000 barrels per day (bpd), respectively, and the total capacity of all BTL factories in the world is much lower. For comparison, the capacity of one of the largest plants in the world for the production of second generation bioethanol run by a Canadian company, Enerkem, in Alberta (using syngas obtained from municipal waste and biomass as feedstock), is only 38 million litres per year [38].

The formation of multidimensional hydrocarbon molecules during the implementation of the conditions for the Fischer-Tropsch reaction occurs on the surface of catalysts, while the nature of this process and, moreover, the creation of its rigorous mathematical model is the subject of numerous and longstanding research. But it is well known that this reaction is exothermic, creating conditions for overheating of catalysts, therefore the creation of a stable temperature in reactors is of paramount importance [39]. The most common are four types of reactors - fixed-bed multitubular reactors, fluidized-bed reactors, slurry-bed reactors, microchannel reactors [37]. Each of these has its own advantages and disadvantages. For example, fixed-bed multitubular reactors are quite simple to operate and easily scalable, however they require long downtime when replacing catalysts [39]. Slurry-bed reactors and microchannel reactors ensure the best use of catalysts [37], etc.

Figures 13-14. The demonstration facility at Stora Enso Varkaus Mill, Finland



As a result of the technology of conversion of syngas by the FT method, various types of products can be obtained - diesel fuel, paraffins, gaseous fuels, wax. Regulation of the percentage yield of products can be ensured by temperature conditions, by choosing the optimal type of reactor and catalysts [39]. The hydrocarbons obtained, if necessary, are subjected to additional processing - separation, purification, and hydrocracking.

One of the biomass to liquid plants was launched in Finland in Varkaus in 2009 [40] (Figures 13-14). The demonstration unit has a capacity of 12 MW and includes a drying section, a gasifier, gas purification and catalyst testing units (including drying of bio-mass, gasification, gas cleaning and testing of Fischer-Tropsch catalysts). FT biomass to liquid technology is more capital intensive than other biomass-to-fuel conversion methods. A detailed technical and economic analysis of the production of various types of liquid fuel by thermochemical conversion methods is given in [41]. The cost of diesel fuel produced by the FT method is estimated here as the highest - 4.29 - 4.85 USD / gallon. To reduce the cost of the process, both technical and organizational improvements are made. In [42], a new BTL concept is described, aimed at reducing the cost of the final product by up to 35%. The concept provides for the conversion of biomass by the FT method in medium-sized plants, integrated with third-party facilities through heat supply. At the same time, according to this concept, FT units should mainly produce synthetic oil, distillates and wax, which are then sent to nearby refineries for the production of final types of standardized fuels. Another area of production of various fuels from syngas is the intermediate production of methanol and its derivatives, as well as methanation.

Methanol is obtained from synthesis gas at temperatures from 220°C to 300°C, pressure from 50 to 100 bar and with a catalyst of copper and zinc oxide [28, 39, 43]. The main reactions in the conversion of syngas to methanol are:

$CO + 2\ H_2 \rightarrow CH_3OH$

$CO_2 + 3\ H2 \rightarrow CH_3OH + H_2O$

Methanol is used in various forms, both as an additive to traditional fuels and as a feedstock for the production of gasoline, diesel, and dimethyl ether (DME).

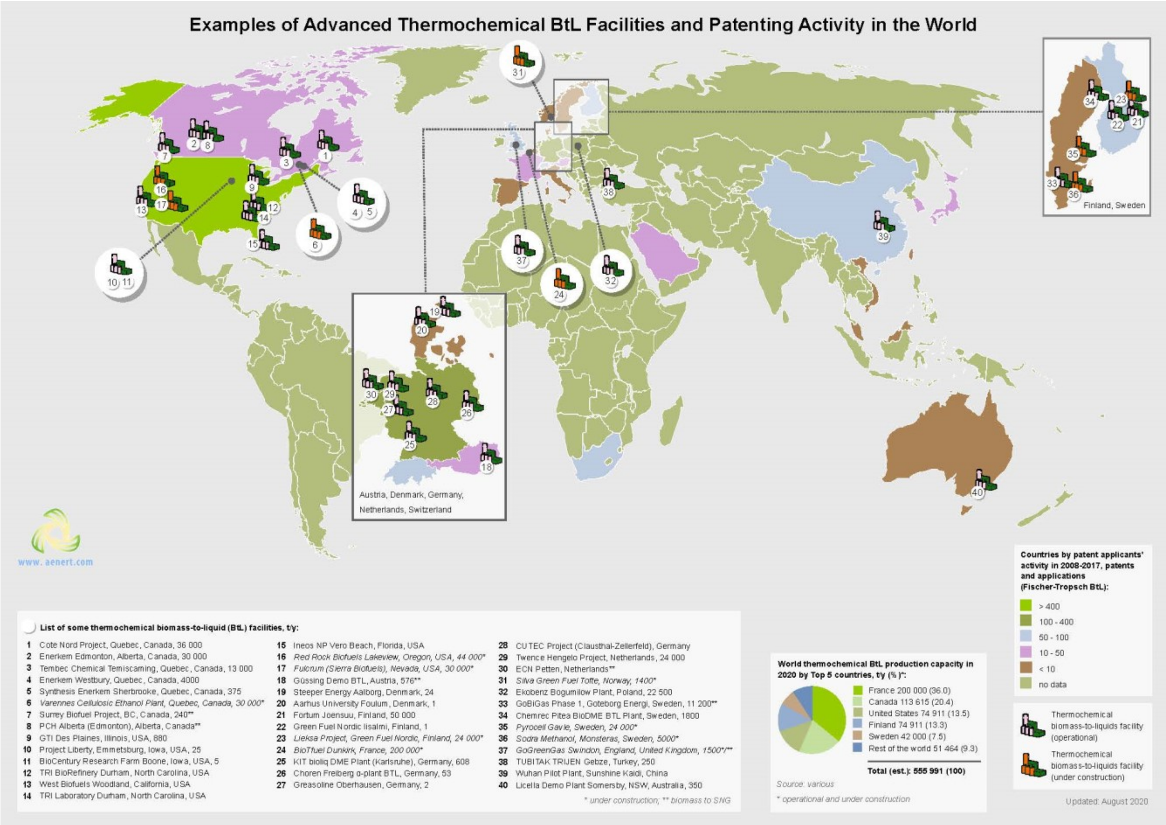
Figures 15-16. Gussing gasification plant, Austria

Methanation is carried out at temperatures from 700°C to 1000°C, nickel is used as the catalyst material. The main reaction [44]:

$CO + 3H_2 \rightarrow CH_4 + H_2O$

The process was first implemented in Güssing, Austria. The demonstration methanization unit was combined with an existing commercial biomass gasifier and has been successfully operating for several years (Figures 15-16). Examples of the largest facilities for the production of synthetic fuels from synthesis gas obtained from biomass gasification are shown in Figure 17.

Figure 17. Examples of objects of thermochemical processing of biomass and patent activity of the countries of the world in the BTL area



[Examples of Advanced Thermochemical BtL Facilities and Patenting Activity in the World (0.9 MB)]

Table 4 shows the leading BTL technology patent holders that were issued by world patent offices in 2009-2018, as well as their shares in the intellectual property register in relation to all patent holders. For the analysis, about 500 patents were selected, in which the authors unambiguously expressed the applicability of the proposed technical solutions in the field of BTL. The undisputed leader in this area is Shell Internationale Research Maatschappij B.V., from the Netherlands, whose share in the general register of intellectual property was almost 13%.

Table 4. Leading patent holders of BTL technologies between 2009 and 2018 and their shares in the register of intellectual property in relation to all patent holders

Status	Country	Name	Volume, %	Ownership ratio,%	Market involnement, %
Company	NL	Shell Internationale Research Maatschappij B.V.	12.71	100	12.71
Company	ZA	Sasol Technology (Pty) Ltd	4.79	94.93	4.55
Company	US	Shell Oil Company	4.58	74.32	3.40
Company	US	Rentech Inc.	4.17	86.87	3.61
Organization	FR	IFP (École Nationale Supérieure du Pétrole et des Moteurs)	3.96	54.32	2.15
Company	US	RES USA LLC	3.33	60.31	2.01
Company	FI	UPM-Kymmene Oyj	2.92	89.29	2.61
Organization	FR	Commissariat à l'énergie atomique et aux énergies alternatives	2.29	20.62	0.47
Company	IT	Eni S.p.A.	2.29	50	1.15

Source: Advanced Energy Technologies

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5. Cellulosic ethanol production

Global ethanol production for energy purposes is currently around 30 billion gallons per year. Among the leaders in this industry are two countries - the United States, which accounts for more than half of world production and Brazil, whose share in world production is about 30% [1,2]. However, with an overwhelming preponderance, these statistics demonstrate the production of first generation ethanol, the raw material for which is food grade agricultural plants - wheat, corn, sugar cane, etc. This raw material characteristic of ethanol production is at the heart of the ongoing criticism of first-generation technology and is driving the development of second-generation technologies that use non-food biomass as raw materials, such as agricultural, forestry or municipal waste.

Second-Generation bioethanol production statistics are still not uniform and are mostly based on information from manufacturers, which makes it difficult to assess the development of this industry. For some countries, generalized information can be found, for example, in [3,4]. In this section, it has already been noted that the production of second generation bioethanol from cellulosic biomass in China in 2018 was estimated at about 20 million litres, and in Brazil in 2017 at 85 million litres [4]. These are certainly insignificant volumes and do not correspond to the importance of cellulosic ethanol as a separate type of renewable energy fuel. Several problems of a different nature hinder the further development of the industry. First, the biochemical conversion of cellulosic biomass is a much more complex technological process than the processing of first generation raw materials; secondly, large-scale investments are required for the large-scale development of the production of second-generation bioethanol; thirdly, bioethanol ranks among other different types of fuel, including fossil fuels, and depends on them, competes with them, not always successfully; Finally, the industry, having an opportunity to produce fuel, based on simpler and more proven technologies, should be able to rely on understandable financial and legislative incentives for organizing more complex and costly production, which is not everywhere and not always the case.

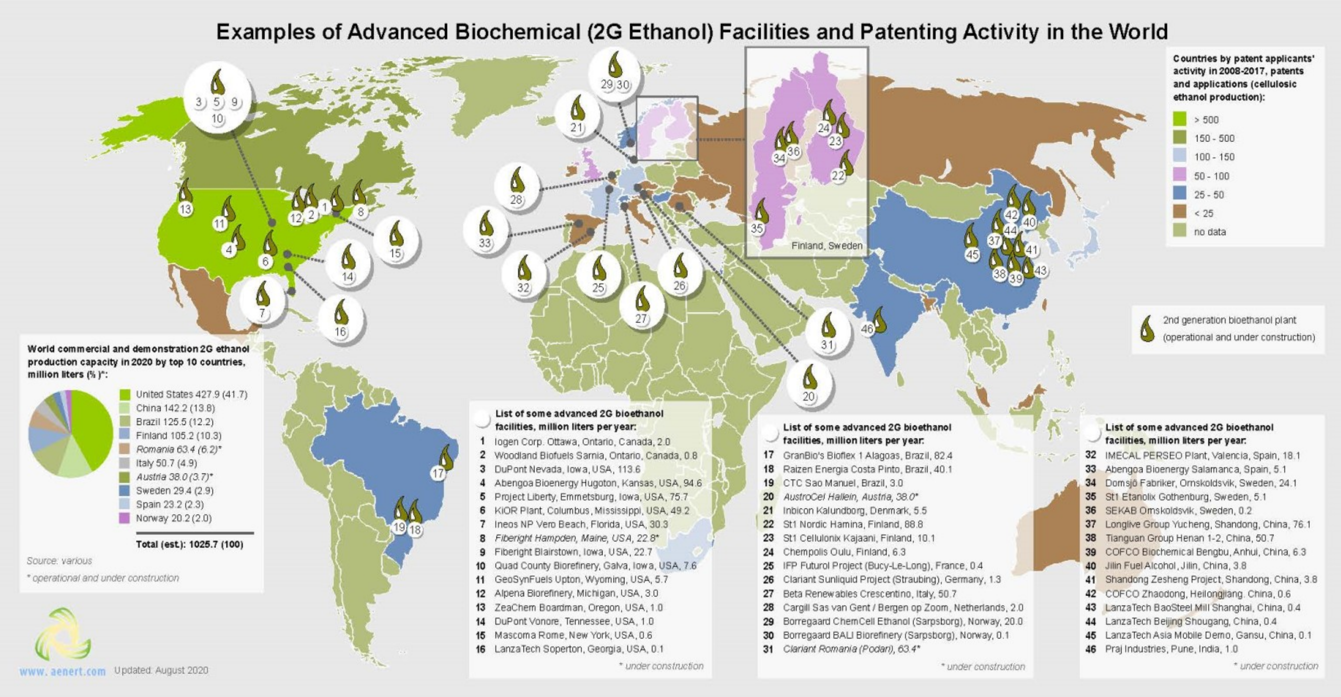
Second-generation ethanol production refers to biochemical conversion methods based on enzymatic or microbiological processes. If conventional bioethanol is obtained as a result of alcoholic fermentation of biomass with a high sugar and starch content, then for the conversion of cellulosic biomass it is necessary to first isolate carbohydrates from cellulose and hemicellulose and only then ferment them into ethanol. Since cellulose is a very stable substance that is difficult to destroy even by acid hydrolysis; special enzymes have been developed, and the process itself is called enzymatic hydrolysis. The nature of these processes and the search for effective enzymes are the subject of serious and numerous studies carried out by chemical and energy companies and research institutes. Among the most popular fermentation methods are yeast fermentation, microbial fermentation via acetic acid, and microbial fermentation via farnesene [5]. In addition, methods of pre-treatment of cellulosic biomass have found wide application, including steam explosion, ozone oxidation, ammonia treatment, etc. Detailed information on the physicochemical bases of processing and conversion of cellulosic biomass can be seen in [5-7]. Today, there are several dozen commercial and demonstration projects for the production of second generation bioethanol in the world, some of them are shown in Fig. 1. The leader in this area is the United States, although in recent years a significant number of enterprises have appeared in China. In Europe, this technology is receiving special attention in Finland, Italy, Austria and Sweden.

More detailed information on projects for the production of liquid biofuels from biomass, including Bioethanol 2G, can be found in [8-10].

Since the choice of the optimal biochemical conversion technology, including pre-treatment and fermentation methods, is largely determined by the properties of the feedstock, most companies are guided by their own technologies. In addition, bioethanol 2G units are often part of larger conventional bioethanol plants. Unfortunately, many companies are experiencing serious difficulties in the commercial production of bioethanol 2G, even to the point of bankruptcy. Moreover, these difficulties are typical for several manufacturers .

In 2015, DuPont commissioned one of the largest second generation bioethanol plants in the state of Iowa, US with a capacity of 30 million gallons per year. The company has developed a wide range of original enzymes for different stages of production of SPEZYME®, OPTIMASH®, DISTILLASE® and others. Generally, DuPont technology includes pre-treatment of the feedstock (remnants of corn plant stems and leaves) - grinding and additional splitting; then the first stage of fermentation is carried out — saccharification to break down complex carbohydrates into simple sugars for fermentation; then the next stage of fermentation by means of patented strains of microorganisms; finally, during

Figure 1. Examples of Advanced Biochemical (2G Ethanol) Facilities and Patenting Activity in the World



[2G Ethanol Facilities and Patenting Activity in the World (2.3 Mb)]

distillation, ethanol vapours are captured and condensed into liquid ethanol [11-13]. Despite the successful launch of the enterprise, two years later DuPont sold the plant in Iowa to the German company VERBIO, which announced its conversion to produce synthetic methane, and the fermentation technology was sold to Petron Scientech [14-15]. According to [3], there is no information on ethanol production by VERBIO in 2019. Thus, this project has apparentlyc eased to exist.

According to [16], Abengoa Bioenergy Biomass sold its Hugoton cellulosic ethanol plant in Kansas, USA to Synata Bio. As the buyer specializes in gas-to-liquid conversion, there is reason to believe that the plant will also be refurbished. At least [3] Synata Bio has no data on ethanol production. This loss may be most significant as the plant was built under US government guarantees and was seen as a flagship 2G bioethanol plant.

Beta Renewables, one of the largest cellulosic ethanol plants in Europe, was launched in 2013 in Crescentino, Italy. The raw materials for the production here are wheat and rice straw, as well as the local flower cane Arundo donax. The technology is based on the patented Proesa™ technology and enzymes from Novozymes [9,17]. In 2018, following bankruptcy, the owner of the Beta Renewables plant, Mossi & Ghisolfi Group, sold it to a subsidiary of the Italian oil and gas giant Eni [18].

Perhaps a more stable situation has developed in Brazil, where the production of cellulosic ethanol in large quantities is established by GranBio and Raízen using their own technologies on parallel lines of plants producing conventional ethanol. In particular, Raízen's technology includes the full chain of ethanol production and use, from growing sugar cane to selling ethanol at city gas stations.

Figures 2-3. Sugarcane cultivation (left) and harvesting (right), Brazil

After the raw materials are transported by trucks to the receiving and unloading point, a quantitative assessment of the sugar content is analysed, and then the sugar cane is crushed, heated in containers to 105ºC and the juice is separated from the pulp. Following this, the components are separated into two streams - raw materials with a high sugar content, which are sent directly to fermentation, and the bagasse, which is subjected to additional hydrolysis. In addition, part of the bagasse is burned to generate electricity. After fermentation, the first and second generation ethanol is distilled, purified, and then distributed through the distributor network [19].

Figures 4-5. Raízen 2G Ethanol Plant in Piracicaba, Brazil

Information on other technologies for the production of ethanol 2G can be found in [20-22]. Table 1 lists the top ten patent holders for cellulosic ethanol production over the past 10 years (2009 -2018), as well as their shares in the intellectual property register in relation to all patent holders. About 1650 patents prepared by 1011 applicants from 40 countries and issued in 33 patent offices around the world were selected for analytical assessment. Patents were selected where the authors indicated that the proposed technical solutions belong to technologies for the production of cellulosic ethanol at any stage of the production process, including the preparation of raw materials, fermentation, hydrolysis, distillation, etc.

Table 1. Leading patent holders on the subject related to the production of bioethanol 2G for the period from 2009 to 2018 and their shares in the register of intellectual property in relation to all patent holders

Status	Country	Name	Volume, %	Ownership ratio,%	Market involnement, %
Company	US	Xyleco Inc.	28.75	98.17	28.22
Company	DK	Inbicon A/S	2.32	92.34	2.14
Company	NL	DSM IP Assets B.V.	2.2	79.6	1.75
Organization	FR	IFP (École Nationale Supérieure du Pétrole et des Moteurs)	1.95	61.86	1.21
Company	US	Verenium Corporation	1.82	85.98	1.56
Company	NL	Shell Internationale Research Maatschappij B.V.	1.57	98	1.54
Company	US	Cargill Incorporated	1.44	82.28	1.18
Company	US	Poet Research, Inc.	1.26	76.25	0.96
Company	US	BASF Enzymes LLC	1.19	91.23	1.09

Volume ratio - share of applicant documents in total number of documents
Ownership ratio - applicant's participation share in total number of documents
Market involvement ratio (bubble size) - volume ratio multiplied by ownership ratio

Source: Advanced Energy Technologies

As follows from the data above, the American Xyleco Inc. is the undisputed leader in this area, with American companies dominating among the first ten applicants.

It is obvious that cellulosic ethanol technology has a difficult history, and the prospects for further development are still unclear. Much here will depend on future breakthrough technical solutions if they contribute to the commercialization of the technology by reducing the cost of processes. The level of state support for projects will certainly play an important role. A detailed review of barriers to the development of cellulosic ethanol can be found in [23].

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6. Biofuels from algae

Biofuel from algae is another feasible 2nd generation biomass processing industry. The advantages of this type of product include: the possibility of obtaining significant volumes of biofuel in relatively small areas, even unsuitable for agricultural production; when growing algae, there is no acute need for fresh water; microalgae can contain a record high oil level - up to 60-80%; these plants are classified as fast-growing, and some species in favourable conditions can double their weight within a few hours; during their growth, microalgae assimilate carbon dioxide from the atmospheric air.

The term algae means a large number of bio organisms with more than 100,000 genetically diverse strains [1]. Some of them belong to macroalgae, which are multicellular plants. Another part refers to microalgae, which unlike the first group, have a unicellular structure [2]. Most microalgae exist through photosynthesis, absorbing carbon dioxide and water and converting them under the influence of sunlight into organic matter and oxygen. Comparing potential of oil yields demonstrates the amazing properties of microalgae. For example, the extraction rates of palm oil, which is also used for the production of biodiesel, are 635 oil yield gallons/acre, and in the case of the simplest microalgae it is about twice as high [3].

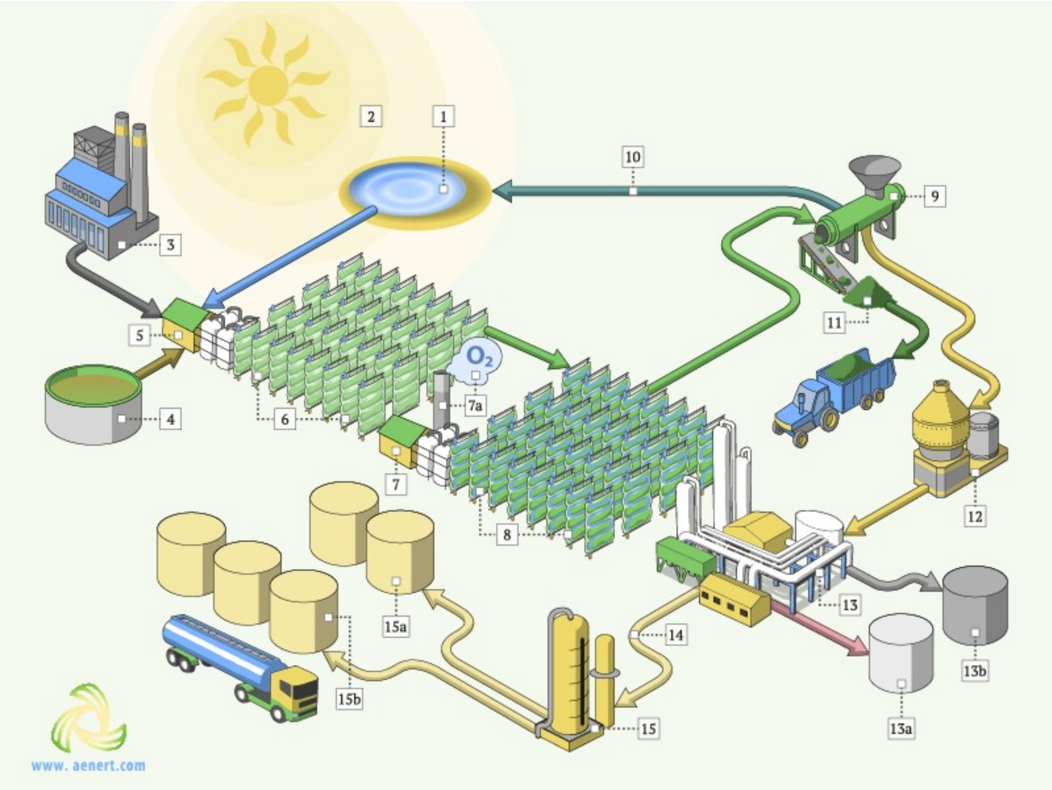
Microalgae contain several important chemicals that determine their beneficial properties - lipids, proteins, carbohydrates, and other residues (ash). Proteins are the main components of most microalgae, and their concentration ranges between 30%-7%, for carbohydrates, the range of possible concentration is from 4% to 58% of dry weight [2]. From the point of view of extracting liquid oil from microalgae, the most important substance in microalgae is lipids, the content of which can vary within wide limits - from 5% to 58% (Chlorella vulgaris) of dry weight [2]. The concentration of lipids in microalgae depends on their species, growing conditions, and nutrients. The accumulated knowledge about the vital activity of microalgae has made it possible to construct a process flow diagram [4]. In general terms, this diagram includes:

- Algae species selection (Algae species, Nutrients, Pathogens, predators);
- Siting (Land, CO_2, Facilities, Primary Energy, Water);
- Cultivation (Closed systems, Open systems, Hybrid systems, Wastewater Photoautotrophic & Heterotrophic; Co-generation, Biological Assist);
- Harvesting/De-watering, Flocculation & settling, Airlift flocculation, Filtering, Centrifuge, Biological Assist Harvesting (shrimp, fish excrement, etc.);
- Extraction & Separation (Lipids, Carbohydrates, Proteins, Other metabolites);
- Conversion to Biofuels;
- Conversion to Co-products.

The centrepiece of this diagram is the cultivation of microalgae. There are three principal ways: phototrophic cultivation, with light and CO_2; heterotrophic cultivation, when there is no light, but a special organic substrate is additionally supplied; mixotrophic cultivation - where the growth of microalgae can take place under both of the above conditions [2]. The process of growing microalgae is carried out either in open (Open Raceway Pond (ORP) or closed systems (PBR). Open systems are natural or artificial reservoirs where microalgae are grown. Closed systems can be placed both outdoors and indoors under artificial light. Open systems have the following advantages - simple cleaning and maintenance, low energy consumption; however, at the same time, this system is characterized by low productivity, requires large areas of land, but a limited number of algae strains. Closed tubular systems require a large illumination area, but there is good biomass productivity. Limiting factors include active fouling, the need to control gradients of pH dissolved oxygen and CO_2 along the tubes, and others [2].

A schematic diagram of the production of biodiesel from microalgae may look like this (Figure 1).

Figure 1. Possible scheme of biofuel production from microalgae



***1.** Water **2.** Sunlight for algae grewth **3.** Facility emitting carbon dioxide **4.** Nutrients **5.** Gas, water and nutrient conditioning unit or incubation tank **6.** Bioreactor network(microalgae ponds) **7.** Second conditioning unit **7a.** Oxygen **8.** Algae harvesting reactors **9.** Screw process unit **10.** Recycled water **11.** Algae biomass **12.** Algae hexane solvent mixer **13.** Transesterification unit **13a.** Sodium hydroxide **13b.** Methanol **14.** Fuel conditioning **15.** Biodiesel fuel combined with a glycerol **15a.** Glycerol **15b.** Algae biodiesel*

The production of biodiesel from microalgae is costly, which is one of the main obstacles to industrial deployment of this technology. The largest part of expenditure falls on material resources (material cost), including nutrients, carbon source (carbon source), energy costs (energy), catalysts (catalyst) [5].

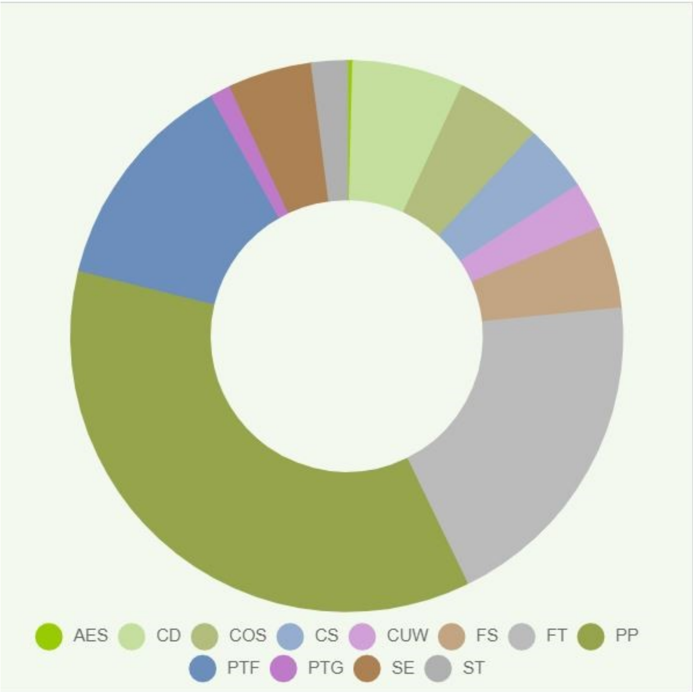
In addition to biodiesel, modern technologies for processing microalgae make it possible to obtain Biohydrogen, Bioethanol, Biomethane.

Currently, there are several research and demonstration projects for the production of biofuels from microalgae, as well as special programs to facilitate this process [1,6], but there is no industrial production. The latest news, research results, and basic concepts can be found on the website [7].

Below is a short list of indicators of patent activity of inventors in the field of biofuel production from microalgae. More than 1600 patents were selected for analysis, issued by 41 patent offices around the world in 2009-2018. More than 1,250 applicants from 42 countries took part in the creating of patents.

The largest number of patents was granted by the US Patent Office - about 42%. 5% to 10% of the total patents were also granted by Australian, Chinese, European and Japanese offices. 60% of patents were created by US residents. The most popular among inventors were technological issues related to the new aspects of Chemistry and other substances, Primary processing and the Pre-treatment of feedstock (Figure 2).

Figure 2. Distribution of technological elements identified among patents, 2009-2018, %



AES *- Additional equipment, substances;*

CD *- Methods of control and diagnostics;*

COS *- Chemistry and other substances;*

CS *- Capture and separation;*

CUW *- Capture, utilization of solid, liquid and gaseous wastes;*

FS *- Feeding systems;*

FT *- Finishing treatment;*

PP *- Primary processing;*

PTF *- Pre-treatment of feedstock;*

PTG *- Processing technologies in general;*

SE *- Secondary equipment;*

ST *- Storage & transportation*

Source: Advanced Energy Technologies

A list of leading patent holders and their shares in the intellectual property register is presented in Table 1.

Table 1. Leading patent holders for the production of biofuels from microalgae between 2009 and 2018 and their shares in the register of intellectual property in relation to all patent holders

Status	Country	Name	Volume, %	Ownership ratio,%	Market involnement, %
Company	US	Xyleco Inc.	5.24	100	5.24
Company	US	Solazyme, Inc.	4.87	70.38	3.43
Company	US	Heliae Development LLC	4.37	74.52	3.26
Company	US	ExxonMobil Research and Engineering Company	2.31	68.93	1.59
Person	US	KALE ANIKET	2.06	50	1.03
Company	US	Terravia Holdings Inc	1.75	87.5	1.53
Company	IT	Eni S.p.A.	1.69	88	1.49
Person	US	FRANKLIN SCOTT	1.5	14.7	0.22
Organization	AU	Commonwealth Scientific and Industrial Research Organization (CSIRO)	1.44	82.61	1.19

Volume ratio - share of applicant documents in total number of documents
Ownership ratio - applicant's participation share in total number of documents
Market involvement ratio (bubble size) - volume ratio multiplied by ownership ratio

Source: Advanced Energy Technologies

Representatives of the US clearly dominate among patent holders, while the total share of the first five American companies in the intellectual register exceeds 15%.

Biofuels from algae. References

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