Synthetic fuels

Overview of synthetic fuels technologies

Basic definitions

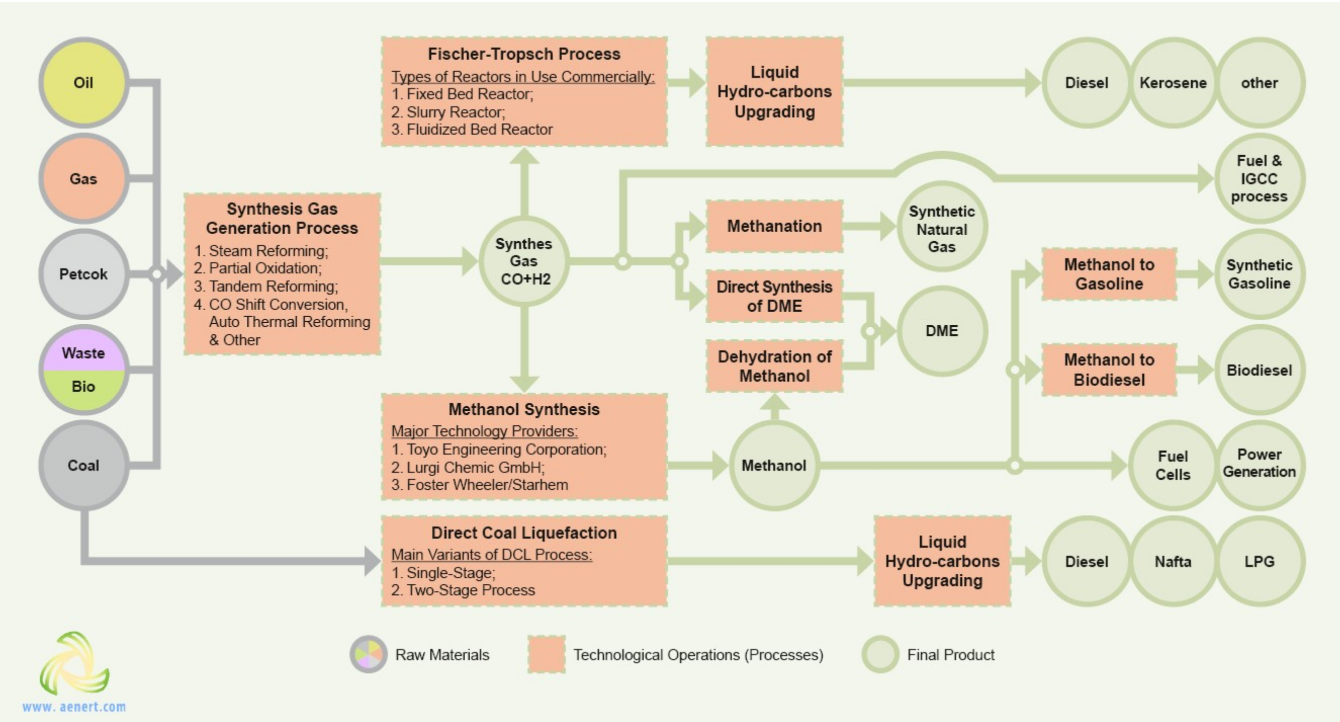
Production of synthetic fuels, i.e. man-made fuel, obtained as a result of the deliberate synthesis of the initial components, is one of the promising areas of the modern energy industry and the subject of increased scientific and technological interest. In most cases, synthetic fuels are liquid or gaseous fuels obtained from syngas - a mixture of hydrogen and carbon monoxide. Syngas, in turn, can be obtained by thermochemical methods from almost any hydrocarbon feedstock, including oil, natural gas, coal, biomass or municipal and industrial waste. Since syngas contains the main components of any organic matter - hydrogen, oxygen and carbon (the latter in the form of carbon monoxide), it is potentially possible to form long organic molecules with a high molecular weight, which are the material basis of hydrocarbon fuel. Thus, the production of synthetic fuels from syngas involves at least a two-stage process. At the first stage, syngas is produced, and in the overwhelming majority of cases this is by means of the steam reforming method, using natural gas as a raw material. In addition, the use of the gasification method of coal and biomass is gaining popularity. In the second stage, syngas is converted into final synthetic products. There are a wide variety of technologies, but the most prevalent are the Fischer-Tropsch method and Methanol synthesis followed by the production of various derivatives (Fig. 1).

In addition to the methods mentioned above, there are other methods for the production of synthetic fuels, in particular the direct coal liquefaction by hydrogenation, i.e. heating coal in the presence of hydrogen.

The Fischer-Tropsch method makes it possible to obtain a variety of liquid hydrocarbons, including diesel fuel, kerosene, as well as paraffins, wax, etc. The syngas-methanol-based technological chain is the most common, since methanol is widely used as a feedstock for the chemical industry or for the production of various fuels (energy applications), and as a final product used, for example, as an additive to petroleum products (direct methanol blending).

The expediency of producing synthetic fuels is not as straightforward as it seems at first glance. Historically, this feasibility was determined by the need of individual countries (Germany, South Africa) for liquid hydrocarbon fuel. At the same time, the lack of sufficient natural resources of oil and various international restrictions stimulated the development of technologies for the production of liquid fuel from available local raw materials, primarily from coal. Today, the idea of using surplus local hydrocarbons of one type to produce synthetic fuels of another type still exists,

Fig.1 Basic Variants of the Production of Synthetic Fuels



Source: [1-6]

but increasingly it is driven by market levers and environmental regulations. For example, Qatar, having a rich resource base of natural gas, produces a relatively large amount of liquid fuel by the Fischer-Tropsch method, some of which is exported. This allows manufacturers to significantly diversify the range of products and make more efficient use of market conditions. China has, on the one hand, a serious shortage of natural gas and oil, but on the other hand, significant reserves of coal, and directs its efforts to create a developed infrastructure for coal gasification with the subsequent production of liquid fuel to meet domestic demand. Gas to liquid (GTL) and coal to liquid (CTL) plants in South Africa and some other countries operate on similar principles. Biomass to liquid (BTL) technologies are also used in a number of countries for the production of syngas and derivatives. This is especially true for the Scandinavian countries (Finland, Sweden), where there are significant resources of biomass and great experience in its processing.

This approach removes some of the risks for countries dependent on fuel imports, and also solves fuel supply issues in regions lacking the necessary transport infrastructure.

Another advantage of synthetic fuel is its high environmental friendliness and, above all, the minimum content of sulphur and other harmful impurities. Other advantages of synthetic fuel are also considered to be more economical and technologically convenient conditions for its transportation, compared to liquefied gas or biomass due to the higher energy density, as well as the possibility of obtaining a more demanded and cost-effective range of end-products.

Nevertheless, despite a number of advantages of synthetic fuel, its production has not received large-scale development, which does not allow to assert its unambiguous expediency, at least at the current level of technology development and in the current conjuncture. In general, this is due to a number of significant shortcomings of the technologies used, economic problems, as well as low competitiveness. First, the production of synthetic fuels is characterized by the presence of a large number of intermediate operations, including feedstock preparation, basic processes, cleaning and disposal of waste gases and waste. The technology for the production of syngas and subsequent products requires adherence to the highest technological discipline, the use of high-tech equipment, and the availability of qualified personnel. Secondly, these technologies have a high capital intensity, long payback periods, and significant operating costs. In addition, these processes require a large amount of energy, water and related materials, in particular expensive catalysts. Thirdly, the environmental benefits of synthetic fuel are largely offset by serious greenhouse gas emissions during its production, pollution of the surrounding area and underground aquifers. Given these shortcomings, the current competitiveness of synthetic fuel production seems unconvincing, especially in the current market environment.

The assessment of the prospects for the deployment of synthetic fuel plants depends on specific conditions, and in some cases may even be the most preferable. At the same time, there are several applications for which the use of these technologies is quite competitive and sometimes irreplaceable. An example is the utilization of associated petroleum gas at remote oil fields, which can be carried out using microchannel GTL units. Gasification of biomass waste also has significant advantages over other technologies. Plasma gasification of municipal solid waste (MSW) and industrial waste, despite high energy consumption, has undeniable advantages in terms of requirements for feedstock and product quality .

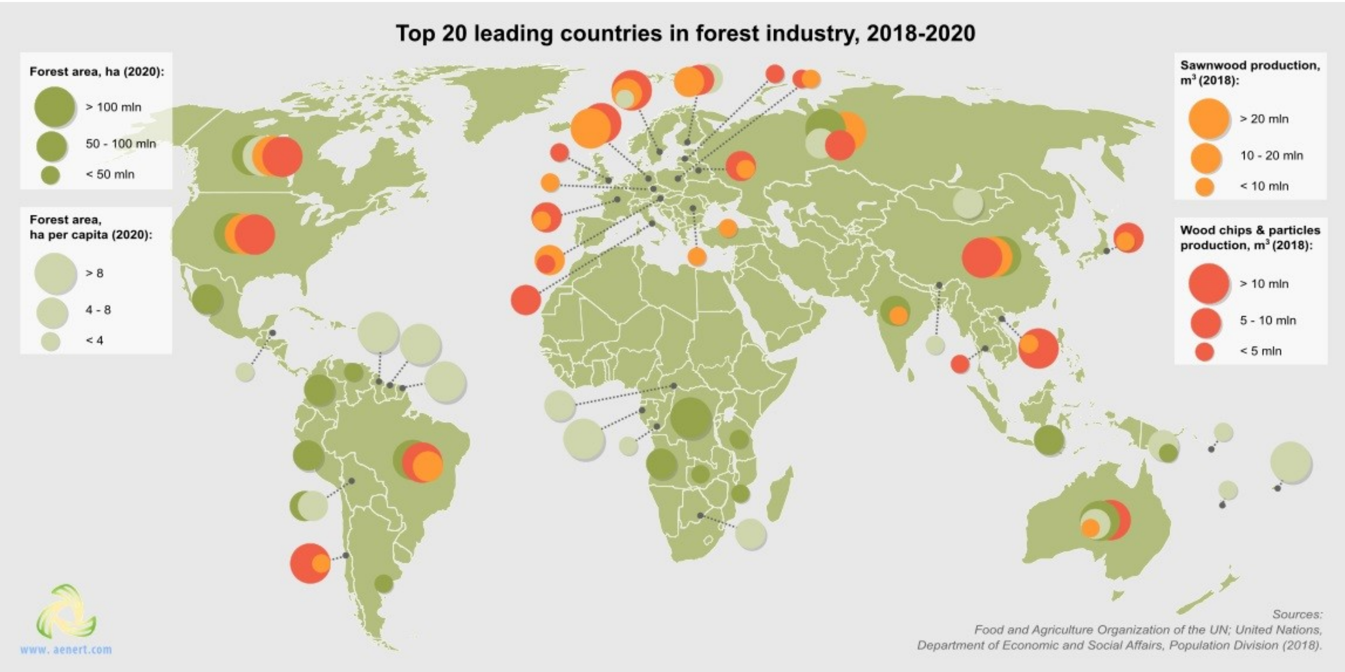
Thus, the production of synthetic fuel, as one of the areas of modern energy, includes several mature, industrially approved technologies, and has a number of applications with competitive advantages. On the other hand, the current volumes of synthetic fuel production do not have a noticeable effect on the energy balance for the vast majority of countries, and even more so on a global scale. However, one should also take into account the fact that the technologies for the production of synthetic fuel are constantly being improved, and the conditions on the hydrocarbon market are changing, which can promptly affect the current trends.

Synthetic fuels resources

As noted above, any hydrocarbon fuel, biomass, municipal and industrial waste can serve as a raw material for the production of syngas. Thus, countries with hydrocarbon resources in excess of domestic needs can be potential producers of synthetic fuels with sufficient market demand. Currently, the major global and regional exporters of natural gas, are the USA, Russia, Trinidad and Tobago, Norway, the countries of the Middle East (Qatar, Oman, United Arab Emirates), some African countries (Nigeria, Algeria) and the countries of the Asia-Pacific region (Malaysia, Indonesia, Australia, Brunei) [7]. The largest coal producers are China, Indonesia, USA, India, Australia, Russia, South Africa, Colombia, Kazakhstan, Poland [7]. All these countries simultaneously possess significant coal reserves. Petroleum resources can also serve as feedstock for the production of syngas, although to a significantly lesser extent compared to natural gas and coal. However, given that conventional petroleum products are the main competitors for synthetic fuel, it is their shortage that is the main reason for the local development of technologies for the production of syngas and its derivatives. According to [7], the largest importers of oil and oil products are the EU, USA, China, India and Japan. More detailed information on the reserves and production of hydrocarbon fuels can be found, for example, in [7-9].

BTL technologies are suitable for the beneficial disposal of forest and agricultural waste, the volumes of which are very significant. In most cases they are simply burned, but the production of syngas and synthetic fuels is a much more efficient process. Below is an information map of the world's leading countries in terms of the availability of forest resources [10], as well as the level of wood processing, which is an excellent raw material for biomass gasification.

Fig. 2. Top-20 countries in the world in terms of forest area and level of timber processing

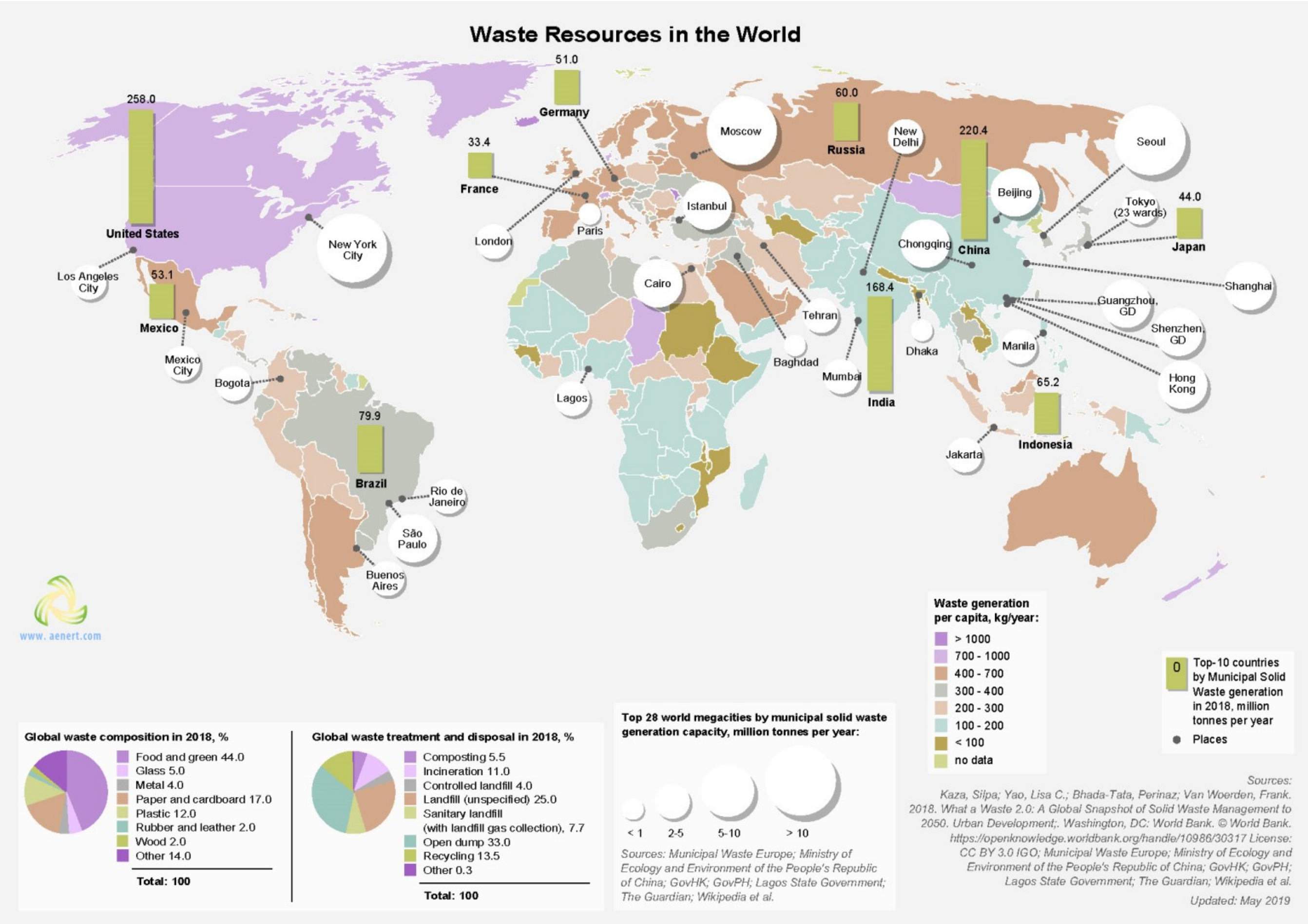


Source: on the map

[Top 20 leading countries in forest industry, 2018-2020](#)

Another type of raw material that can be used in the production of synthetic fuels is municipal solid waste. Below are data on the level of municipal waste in individual countries and large cities [11], as well as statistical data on their type and methods of treatment.

Fig.3. Waste Resources in the World



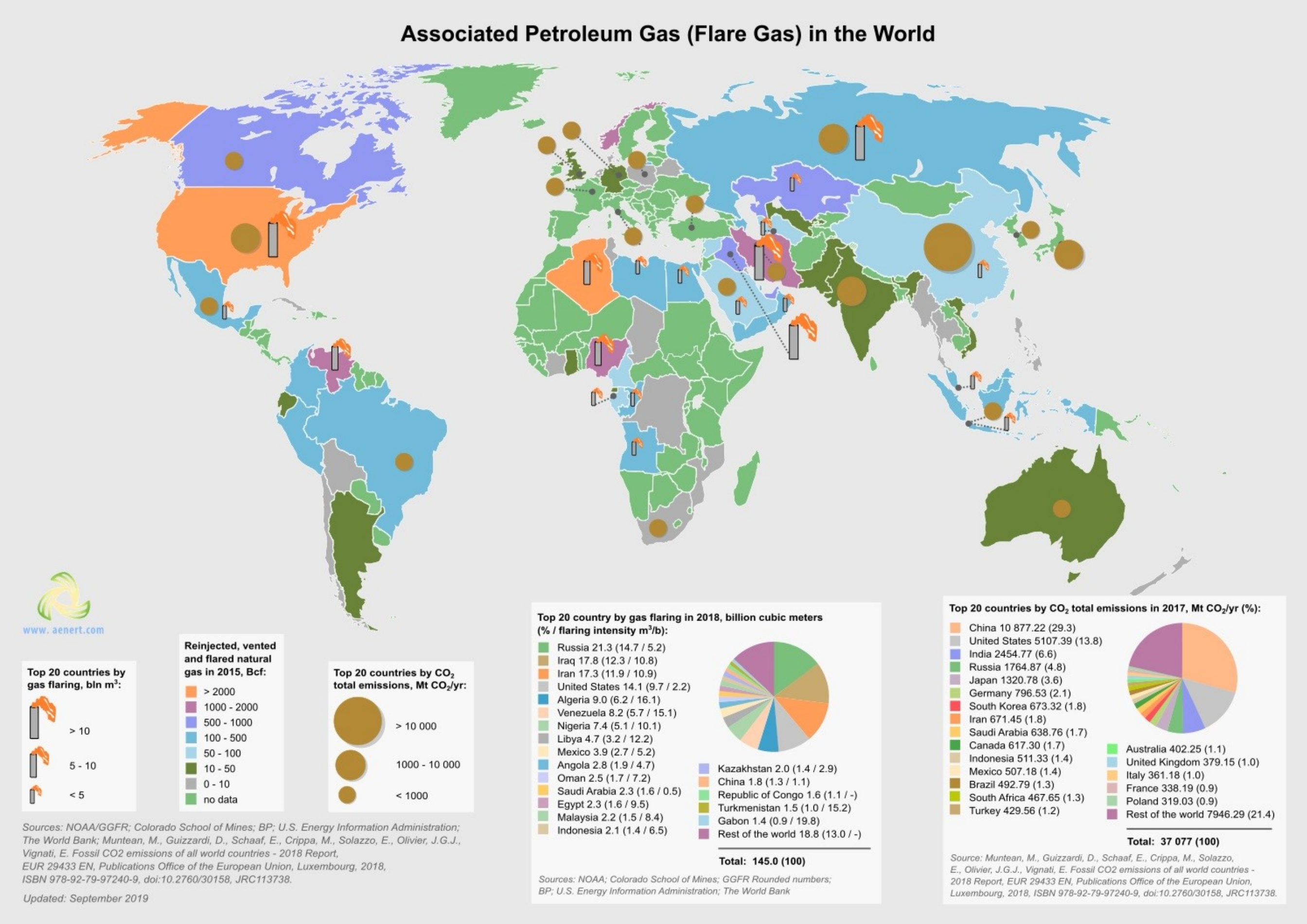
Source: on the map

[Waste-resources_in_the_world]

A key factor that determines the efficiency of municipal waste processing is its careful sorting, which determines the choice of processing technology and the level of environmental impact. The list of various gasification technologies includes the plasma gasification technology, which makes it possible to subject almost any hydrocarbon feed to full high-temperature decomposition into elementary components, which significantly reduces the stringent requirements for expensive sorting and preliminary preparation of the feedstock.

Associated petroleum gas (APG), which is obtained in the process of oil production, is another significant feedstock for GTL technologies. The primary processing and transportation of this gas from remote fields or from offshore platforms to gas processing plants is an expensive and technologically difficult task. Therefore, a large amount of gas is injected back into the reservoir, or simply flared, which is accompanied by emissions of greenhouse gases into the atmosphere. Figure 4 shows data on associated gas flaring and CO_2 emissions for leading oil producers.

Fig. 4. Associated Petroleum Gas (Flare Gas) in the World



Source: on the map

[Associated Petroleum Gas (Flare Gas) in the World]

As follows from the above data, the total potential of associated petroleum gas as a feedstock for microchannel GTL technologies is large and widespread.

Mainstream technologies

Synthesis gas production

Most synthetic fuel technologies are based on the synthesis of hydrogen and carbon monoxide, i.e. syngas components. In turn, to obtain syngas, various hydrocarbons and municipal waste are used in the form of feedstock, coupled with special technologies. The main ones are [1,13]:

- Steam-Methane Reforming
- Auto-Thermal Reforming
- Partial Oxidation
- Coal Gasification
- Biomass Gasification
- Waste to Energy Gasification, including Plasma Gasification

The most popular is the Steam-Methane Reforming technology, although it is best suited to meet hydrogen needs, since it allows the production of syngas with a hydrogen to carbon monoxide ratio of up to 5: 1 [13]. Natural gas is used as a feedstock. The reforming process is two-stage. At the first stage, the heated gas mixture of methane and water vapor is passed through a tubular reactor, usually with a nickel catalyst, at a temperature of 700–1100°C and with a relatively low pressure of 3–25 bar [15] and decomposes into hydrogen and carbon monoxide in compliance with a strong endothermic reaction:

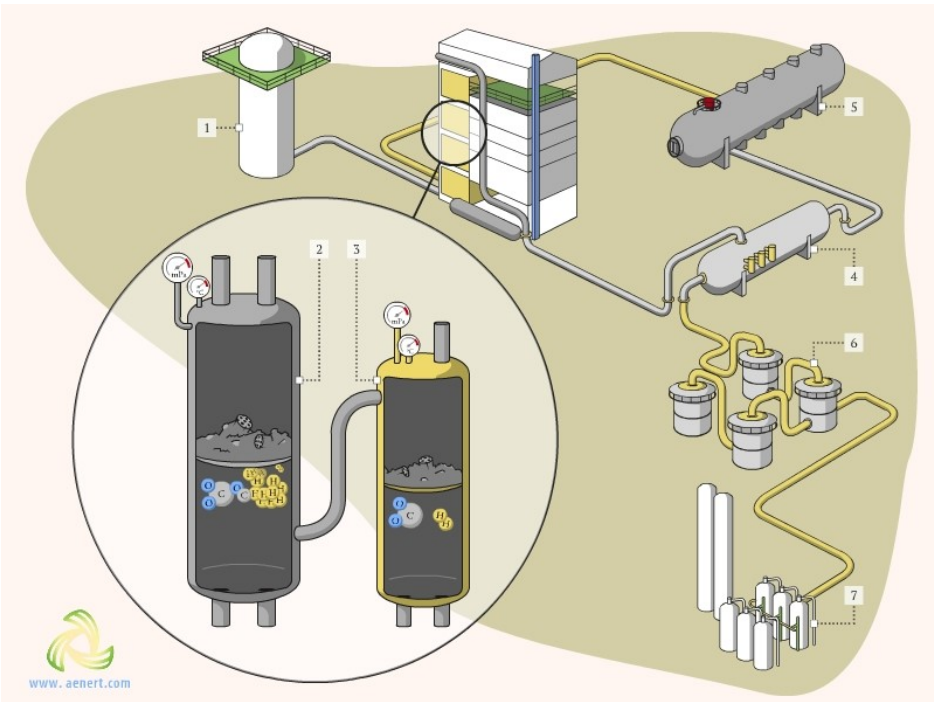
$CH_4 + H_2O \rightarrow CO + 3H_2$

At the second stage, to increase the efficiency of hydrogen production, a water-gas shift reaction or CO-shift conversion is implemented, which results in the carbon monoxide interacting with water vapour to produce heat by reaction:

$CO + H_2O \rightarrow H_2 + CO_2$

and in the temperature range 200–450°C (400° F and 900°F) [15]. In the low-temperature version of the process, CuO -based metal oxide catalysts are used, and in the high-temperature - Fe_2O_3-based catalysts [16].

Fig. 5. Hydrogen production as a part of synthesis gas through steam reforming in combination with the reaction of carbon monoxide and water vapor to form carbon dioxide and hydrogen



1. *Feed pretreatment*

2. *Steam reformer 850°C*

3. *CO-shift conversion 350°C*

4. *Gas cooler*

5. *Steam drum*

6. *Pressure swing adsorption (PSA)*

7. *Desulphurization*

Like all technological processes for the production of synthetic fuel, Steam-Methane Reforming is highly dependent on strict adherence to the specified temperature regimes inside the reactor, which in turn is largely determined by the conditions for supplying or removing heat and reaction gases.

Another popular process for producing syngas is gasification of solid raw materials. This process is carried out in a special reactor called a gasifier, where, under the influence of high temperature, pressure and oxygen (or air, steam), the carbon-based raw material is converted into syngas. During gasification, coal, biomass or other raw materials are sequentially subjected to dehydration and pyrolysis, which leads to the breaking of weaker chemical bonds, the release of volatile gases and the formation of an intermediate substance - a high molecular weight char. The resulting products partially combust, reacting with oxygen and form carbon oxides, as well as a significant amount of heat, which contributes to the passage of the next stage - the actual gasification. In this case, char interacts with carbon dioxide, oxygen or steam to form syngas in the form of a mixture of H_2 and CO [1]. Depending on the type of oxidizer (oxygen, air, water vapor), the main gasification reactions are [1,13,15]:

$C + 1/2O_2 \rightarrow CO$

$C + H_2O \rightarrow CO + H_2$

$CO + H_2O \rightarrow CO + H_2$

In this regard, the gasification process is often referred to as a partial oxidation process. By adjusting the feed volume of raw materials and oxidants, it is possible to achieve a different composition of syngas. The typical ratio is H_2/CO in the range 1.6 - 1.8 [13]. The percentage composition of syngas usually varies within the following limits [1]:

Table 1. Syngas percentage composition

Gasifier Gas Composition	Vol, %
H_2	25-30
CO	30-60
CO_2	5-15
H_2O	2-30
CH_4	0-5
H_2S	0.2-1
N_2	0.5-4
Other	0.2- 1.4

Source: [1]

Any gasification complex consists of a gasification reactor, a feedstock pre-treatment unit (crushing, grinding, mixing), a feeding system, a plant for the production of oxygen or steam, equipment for cooling and purification of waste gases (gas coolers, cyclones, filters, scrubbers), removal of resins and solid particles, separation of components, waste disposal, storage of raw materials and products, etc.

Gasifiers differ in terms of the type of reactor, the methods of heat delivery (direct or indirect); the methods of heating (including electricity, microwaves Plasma, other Plasma, Solar); the type of coolant (using solid heat-carriers, using gaseous heat-carriers); the type of gas-forming agent (without oxygen - by reaction of gaseous or liquid organic compounds with gasifying agents, eg. water, carbon dioxide, air; with oxygen - using oxygen or mixtures containing oxygen as gasifying agents); the degree of waste processing; and the level and efficiency of gas cleaning (purifying combustible gases), etc.

There are several options of gasification reactors; however, almost all of them correspond to three main types [1]:

- Fixed-bed gasifiers
- Entrained-flow gasifiers
- Fluidized-bed gasifiers

The design of each of these reactors is determined by the particle size of the feedstock; the conditions for feeding the feedstock and reagents into the reactor; the features of heat and mass transfer inside the reactor; and the presence and characteristics of the functional zones of the reactor (Table 2).

Fixed-bed gasifiers receive relatively coarse feedstocks at the top of the reactor and reaction gases are fed at the bottom. As the raw materials and reagents move towards each other, several functional zones are formed in the reactor - a drying zone, a carbonization zone, a gasification zone, and finally the hottest zone - a combustion zone, at the very bottom of the reactor [1].

Table 2. Main parameters of gasification

Process	Particle size requirements	Types of Reactor	Temperature/ residence time	Energy Product, %		
				Gas	Liquid	Char
Gasification	3-30 mm	Fixed Bed	700 (550) - 900oC /min	85	5	10
	1-5 mm	USA	800 - 1100oC / few min	90-95	-	5 - 10
	0.1 mm	Germany	1350 - 1600oC / few sec	Up to 98 - 99.5	-	0.5 - 2

Sources: [1, 17, 18, 19, 20]

The advantages of this type of reactor are: relative simplicity and efficiency of the equipment; complex preparation of raw materials is not required; low process temperatures, as a result of which there is no need for expensive equipment for significant cooling of exhaust gases. Among the main disadvantages of this type of reactor are increased safety requirements; high content of methane and liquid resins in finished products. The latter is especially important for the production of synthetic fuels from syngas, since, for example, Fischer-Tropsch processes are very sensitive to the purity of syngas. The most famous among Fixed-bed gasifiers are commercial gasifiers from Lurgi GmbH in various configurations [1,21].

Fluidized-bed gasifiers operate with raw materials that look like a liquid mass (hence the name Fluidized-bed). This is achieved by mixing the particles of the feedstock of a regulated size with the supplied gas, and the feed of the feedstock into the reactor is carried out from the side, while the feed of the oxidant is carried out into the lower part, and at a high speed. Due to the active mixing of particles, a uniform temperature distribution is achieved, which ensures a high degree of conversion of carbon-containing raw materials [1]. The most famous are Fluidized-bed gasifiers made by KBR Transport or U-GAS®.

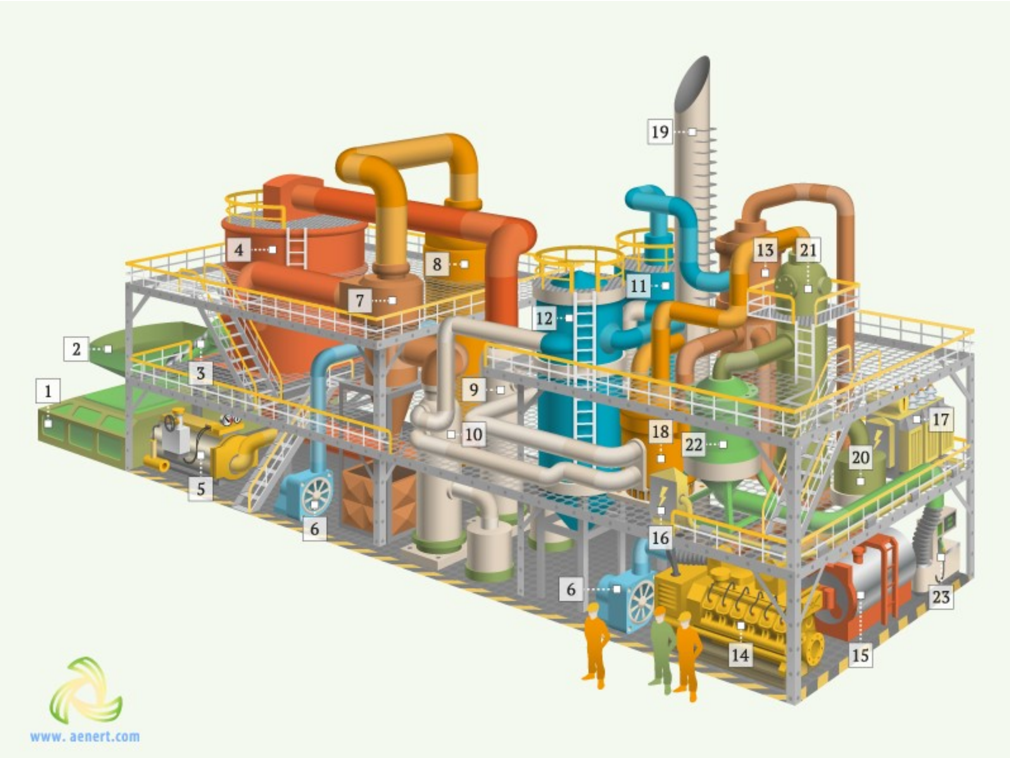
Entrained-flow gasifiers require finely dispersed feedstock, which is fed into the reactor together with oxidants and enters the turbulent flow. Under high temperatures and pressure, gasification reactions take place very quickly, within a few seconds, the process efficiency reaches its maximum values, while syngas has practically no tar, and slags are converted into glassy slag. Oxygen is most often used as an oxidizer, which requires a specialized unit for its production, and the high temperature of the exhaust gases also requires additional cooling and heat recovery [1,19]. This type of reactor is the most energy-consuming, in addition, grinding the feedstock to the required size is not always possible, especially in the case of biomass. Currently, commercial entrained-flow gasifiers by PRENFLO, ECUST, Shell, Texaco and others have gained the greatest popularity. More information on gasification and reactor types can be found in [1,13,19,21].

Currently, the most widespread technology is coal gasification, which has gained commercial success. The process of biomass gasification is also of considerable interest. However, biomass feedstock is much more diverse and less technologically advanced; in addition, biomass gasification has issues with obtaining high purity syngas. A general review of the biomass gasification plant is shown below.

The biomass gasification plant shown in the figure includes: a pre-treatment of feedstock unit; feeding system (biomass hopper, pre-treatment hopper, feeding screw); gasifier; oxidizer preparation and supply unit (steam generator, air blower); gas cooling unit (producer gas cooler, flue gas cooler); gas cleaning unit (cyclone, producer gas filter, flue gas filter, producer gas scrubber); useful syngas utilization unit (gas engine, hot water boiler, power generator electricity). In addition, a synthetic methane plant is shown on the right side of the figure.

Municipal solid waste gasification (MSW) is another area of the energy sector where gasification has a number of undeniable advantages over other disposal options, primarily over incineration [13]. Combustion produces heat that can be used for heating or electricity generation. Gasification makes it possible to obtain syngas, the scope of which is much wider. Despite the fact that modern incinerators have highly efficient systems for cleaning combustion products

Fig. 6. 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*

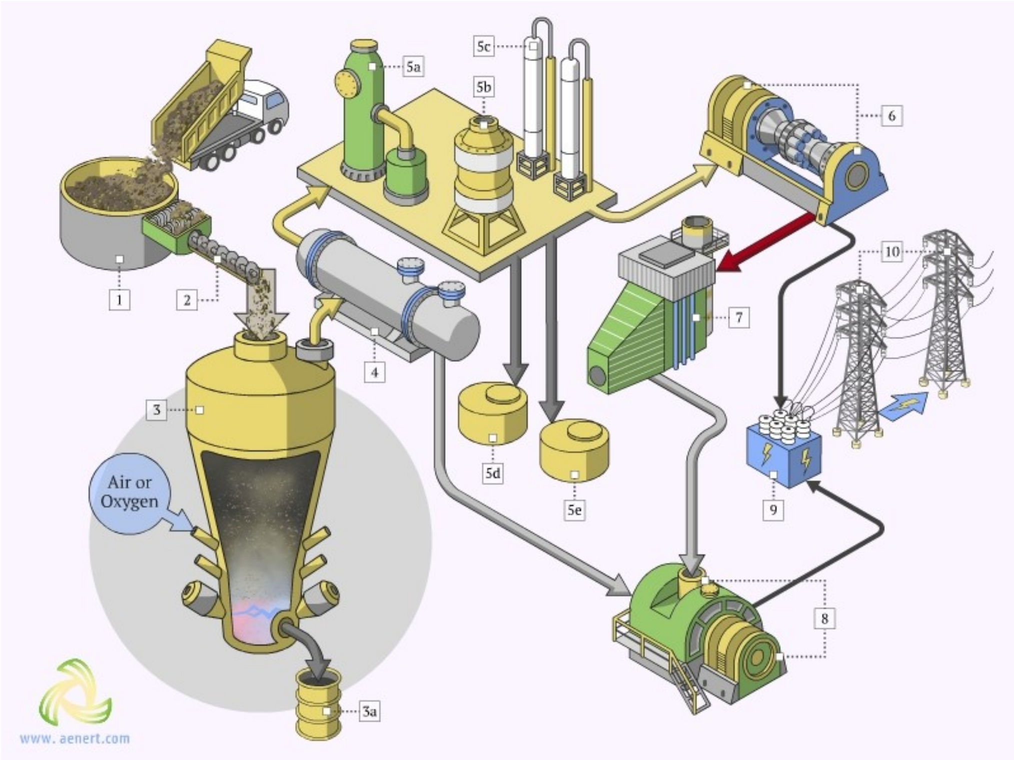
and slags, high-temperature gasification also allows similar and even better performance to be achieved. In particular, glassy slag, as a high-quality building material, has a wide and most importantly safe application [13]. Gasification makes it possible to process a wider range of waste, including plastics, industrial rubber waste, construction waste, etc.

Plasma gasification takes a special place among gasification technologies. The main distinguishing feature of this technology is the use of a plasma arc torch, which ionizes the gas in the reactor. The high temperature created by the plasma torch can reach several thousand degrees Celsius, and the syngas temperature is maintained above 1000°C [1]. These conditions contribute to very high decomposition efficiency of organic materials, including hazardous substances, and increase the yield of hydrogen and carbon monoxide to maximum values.

One of the design options for a plasma gasifier involves loading the feedstock in its upper part (Fig. 7). At the bottom of the reactor is a plasma torch to which oxygen-enriched gas is fed. In this case, gaseous gasification products are removed in the upper part, and the molten inorganic waste flows down to the lower part, where it is cooled and moved to the solid residue chamber. The walls of the gasifier are often lined with refractory materials or a cooling system. The requirements for the preparation of raw materials are essentially limited to uniform grinding, and in some cases the particle size can be quite large. For example, according to [13] OMNI Conversion Technologies Gasification crushes raw materials to sizes of no more than 10 cm. In addition, the plasma gasifier, as usual, includes a cooling system, gasification, chamber, cyclone separator, scrubber, and scrubber reservoir. Some options involve the use of plasma only for additional purification from syngas tars obtained by conventional gasification.

Syngas, as well as the heat generated during plasma gasification, can be used to generate electricity, as well as to provide heat for the syngas production process.

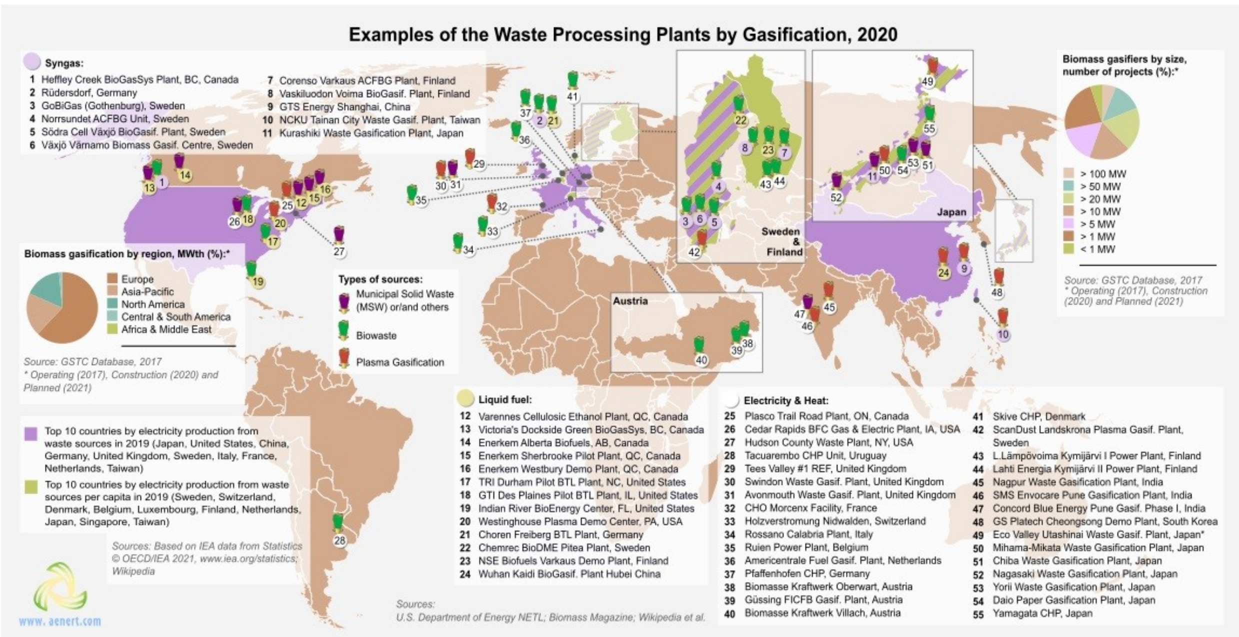
Fig.7. Plasma gasification of municipal solid waste



1. *Waste Storage* ***2.*** *Screw Feed* ***3.*** *Plasma Gasifier* ***3a.*** *Slag* ***4.*** *Heat Exchange* ***5a.*** *Gas Cooler* ***5b.*** *Gas Cleaner* ***5c.*** *Desulfurizator* ***5d.*** *Sludge* ***5e.*** *Sulphur* ***6.*** *Gas Turbine & Generator* ***7.*** *HRSG (Heat Recovery Steam Generator)* ***8.*** *Steam Turbine & Generator* ***9.*** *Transformer* ***10.*** *Electric Power Grid*

More detailed information on plasma gasification can be found in [1,13, 22, 23, 24, 25]. A list of the largest biomass and municipal solid waste gasification plants is shown in Figure 8, some of which operate in conjunction with installations for the production of liquid and gaseous synthetic fuels.

Fig.8. Examples of the Waste Processing Plants by Gasification, 2020



Source: on the map

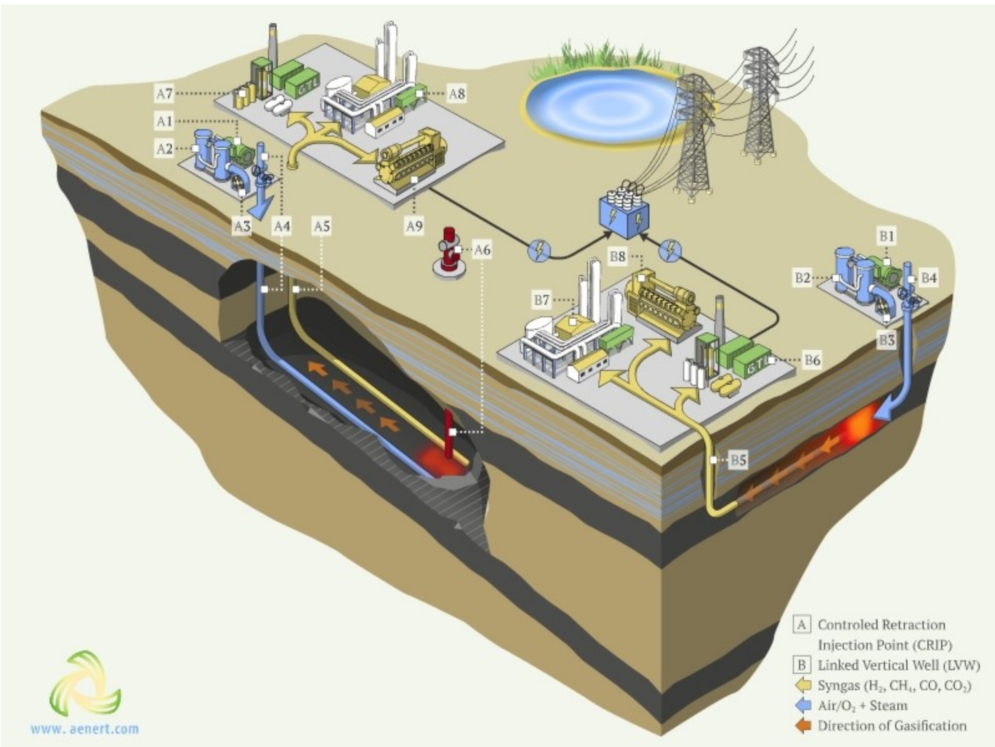
[*Examples of the Waste Processing Plants by Gasification, 2020*]

Lahti Energia's Kymijärvi 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].

Fig. 9-10. Lahti Energia's Kymijärvi II power plant in Lahti, Finland

Underground coal gasification is another option for gasification, which is not carried out in a stand-alone reactor, but directly underground in a coal seam. In this case, a less costly option for producing synthesis gas can be implemented. Technologically, underground gasification provides for the drilling of injection and production wells in undeveloped coal seams. The first of them is supplied with an oxidizing agent in the form of air or oxygen, after which a nearby layer of coal is ignited, which leads to its oxidation to supply syngas. After that, the next layer of coal, and the reaction products are removed through production wells [27-30]. Underground gasification is carried out at a depth of 100 to 1400 meters at a temperature of about 700-900°C [28].

Fig.11. The underground coal gasification technologies



***A1**. Steam generator*

***A2**.Oxygen generator(PSA)*

***A3**. Blower*

***A4**. Injection well*

***A5**. Production well*

***A6**. Ignition well*

***A7**. GTL technology*

***A8**. Gas processing*

***A9**. Gas generator*

***B1**. Steam generator*

***B2**.Oxygen generator(PSA)*

***B3**. Blower*

***B4**. Injection well*

***B5**. Production well*

***B6**. GTL technology*

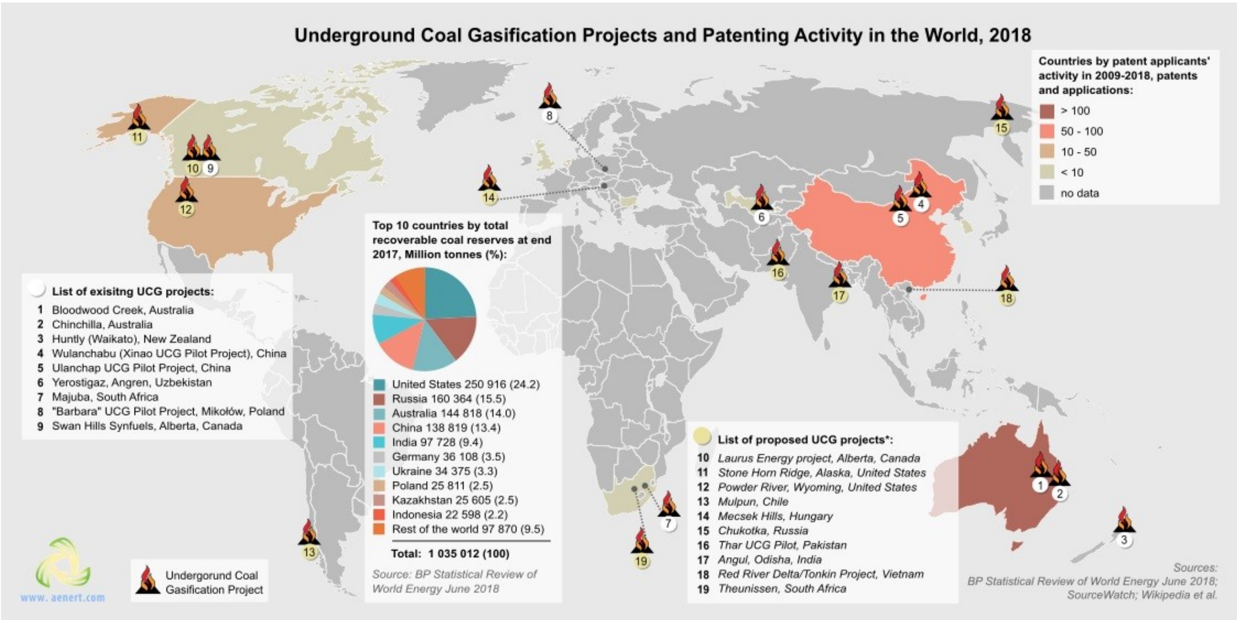
***B7**. Gas processing*

***B8**. Gas generator*

A number of technologies have been tested in practice and each has its own characteristics. The first method involves a moveable injection point that switches to new areas of unburned coal as combustion progresses (Figure 11). This technology is known as controlled retraction injection point (CRIP). In another case, a linced vertical well and reverse firing is used. The publications [27, 30] also mention such methods as Steeply dipping coal seams and Biological Underground Coal Gasification.

A serious advantage of underground gasification is the possibility of using unprofitable or inaccessible coal seams for traditional mining [27]. It is also argued that underground gasification makes it possible to obtain syngas with a lower content of tar and ash [27, 28]. On the other hand, possible underground gasification can cause critical subsidence of the ground, as well as contamination of groundwater. More detailed information on underground coal gasification can be found in [27-30]. Information on several projects can be seen in Fig. 12.

Fig.12. Underground Coal Gasification Projects and Patenting Activity in the World, 2018



Source: on the map and Advanced Energy Technologies

Underground_coal_gasification_projects_in_the_world_2018

Methanol synthesis

Methanol is an important syngas derivative as it is widely used in the chemical industry. Methanol is also used as a fuel or fuel additive. In addition, methanol is used as a raw material for the production of dimethyl ether or gasoline. The most common raw materials for methanol synthesis are natural gas and coal. Global methanol production exceeds 80 million tons per year [75].

According to most experts, the synthesis of methanol is based on the hydrogenation reaction [31,32] of carbon dioxide:

$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$

In addition, the following reactions are involved in the synthesis process:

$2H_2 + CO \rightarrow CH_3OH$

$CO + H_2O \rightarrow CO2 + H_2$

All of these reactions are exothermic. CuO and ZnO based on Al_2O_3 are used as catalysts. The process temperature is 250°C at a pressure of 50 to 100 bar [31]. There is a large number of methanol synthesis reactors on the market with a capacity of 2000-2500 tons/day; however, there has recently been a tendency to increase the capacity of up to

10,000 tons/day, which can significantly reduce the unit cost. Key developers and licensors include Toyo Engineering Corporation, Lurgi Chemie GmbH (Air Liquide), Foster Wheeler / Starchem, Air Products, Mitsubishi Heavy Industries, Johnson Matthey, Davy Technologies, Haldor Topsøe [32].

The synthesis of methanol from carbon dioxide is of particular interest, as it can help solve the problem of beneficial utilization of greenhouse gases. A commercial plant based on this technology with a capacity of 4000 t/a was launched by Carbon Recycling International (CRI) in Iceland [33]. The company commercially operates a liquid emissions treatment plant using CRI's Emissions-to-Liquid (ETL) proprietary technology with a capacity of 50,000-100,000 tonnes of methanol per annum.

Fig.13-14. Carbon Recycling International, Emissions-to-Liquid plant, Iceland

The plant design includes several modules:

- CO_2 Capture & Cleanup. The exhaust gases are captured directly in the chimneys and sent to a purification unit to remove impurities. At a plant in Iceland, Carbon Recycling International uses emissions from the nearby Svartsengi Geothermal Power Station;
- Generation of hydrogen. Hydrogen using ETL technology is obtained by electrolysis or processed from by-products of specialized industries;
- Compression. Mixing of components in the form of hydrogen and CO_2;
- Methanol Synthesis. The synthesis is carried out in a catalytic conversion unit by reactions between hydrogen, carbon dioxide and water;
- Purification of methanol. Purification is carried out in a distillation column, the water can be reused or disposed of.

The proposed technology essentially allows the synthesis of green renewable methanol, which the company offers under the brand name Vulcanol ™, which "can achieve carbon emissions reduction by more than 90% compared to fossil fuels") [33]. The implementation of this technology in the face of serious competition requires the availability of cheap electricity and fresh water resources, which is exactly what Iceland has.

Another option for bio methanol synthesis was implemented by the Canadian company Enerkem. The company's plant in Alberta (Edmonton, Canada) can produce 38 million litres of liquid bio methanol and ethanol per year. Municipal waste is used as raw material [34]. The company's patented technology includes Feedstock preparation, which includes sorting, drying, feeding; bubbling fluidized bed gasification); scrubbing, separation; catalytic conversion of syngas to liquid methanol, as well as ethanol and their final purification.

Fig.15-16. Enerkem, Waste to Biofuels facility, Canada

Methanol to gasoline (MTG)

Conversion of methanol to gasoline (MTG) is an independent technology as opposed to the Fischer-Tropsch process. The technology is developed and implemented by ExxonMobil at their factories in New Zealand and China. In China, coal is used as a feedstock, which is converted into syngas through gasification. MTG technology is a complex and multistage process of sequential synthesis of methanol, then dehydration of methanol to dimethyl ether and obtaining an equilibrium mixture of methanol, dimethyl ether and water, dehydration of the mixture and release of olefins, and finally the synthesis of hydrocarbons to gasoline. The main MTG reactions are as follows [32,35]:

$2CH_3OH \rightarrow CH_3CH_3 + H_2O$

$CH_3OH \rightarrow$ Light Olefins + H_2O

Light Olefins $\rightarrow CH_5$ + Olefins

CH_5 + Olefins $\rightarrow$ Paraffins, Naphthenes, Aromatics $\rightarrow$ Gasoline

DME synthesis

Dimethyl ether (C_2H_6O) is a colorless gas with a melting point of 141°C [36]. Recently, dimethyl ether has been considered as a potential substitute for liquefied propane as a fuel for both domestic needs and industry [31, 36]. For the dimethyl ether storage, a technology similar to the storage of liquefied petroleum gas (Liquefied Petroleum Gas LPG) can be used. The big advantage of dimethyl ether is the low content of sulfur and other combustion products, which makes it an equivalent to other environmentally friendly fuels, such as biofuels.

There are two key technologies for dimethyl ether production - direct synthesis from syngas and indirect production from methanol (indirect route DME). The indirect conversion technology of the Toyo Engineering Corporation has become widespread in the market [37]. The technology includes two stages. First, methanol is obtained from syngas, and then dimethyl ether is obtained by methanol dehydration reaction. As an advantage of this process, the company notes "… the enabling selection of the most optimum reactor type and operating conditions for each reaction step, and becoming easy to remove the reaction heat from the reactor due to less reaction heat against the direct route…". Similar processes have been developed by other companies, such as Mitsubishi Gas Chemical in cooperation with JGC.

The technology for direct production of dimethyl ether from syngas includes (Fig. 17) pre-treatment, reforming, gas cleaning-recycles, DME synthesis, and separation and purification of DME sections. Direct synthesis of dimethyl ether is carried out at a temperature of 200-300°C, a pressure of 30-70 bar, a H_2/CO ratio of 1-2 and with copper-zinc catalysts $Cu - ZnO - Al_2O_3$ [31]. The main reactions of the process:

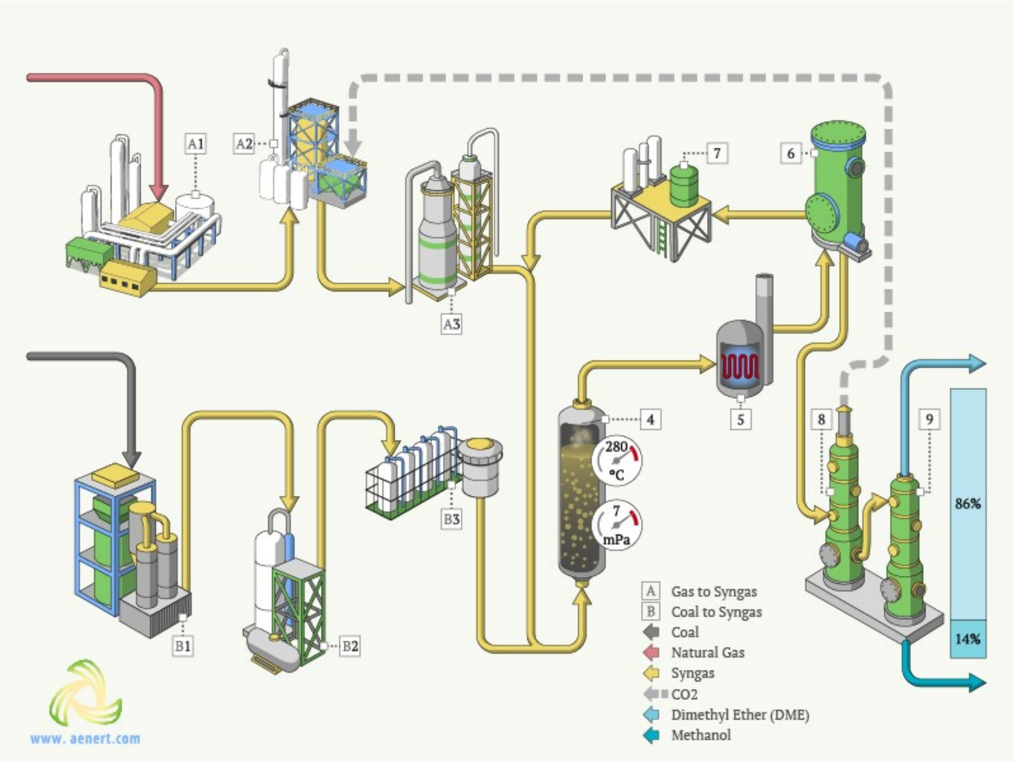
Methanol synthesis: $CO + 2H_2 \rightarrow CH_3OH$

Methanol dehydration: $2CH3OH \rightarrow CH3OCH3 + H2O$

Water-gas shift reaction: $CO + H2O \rightarrow CO_2 + H_2$

Overall reaction: $3CO + 3H_2 \rightarrow CH_3OCH_3 + CO_2$

Fig.17. DME synthesis



***A1.** Gas purification* ***A2.** Primary reforming* ***A3.** Autothermal reforming(ATR)*

***B1.** Coal gasifier* ***B2.** Sour shift* ***B3.** Syngas purification*

***4.** DME synthesis reactor* ***5.** Heat exchanger* ***6.** Liquig/gas separator*

***7.** Compressor* ***8.** CO_2 *separation* ***9.** DME purification*

Fluidized-bed, slurry phase, fixed bed reactors are best suited for this technology. Heat removal and temperature control are essential and are best achieved in fluidized-bed reactors.

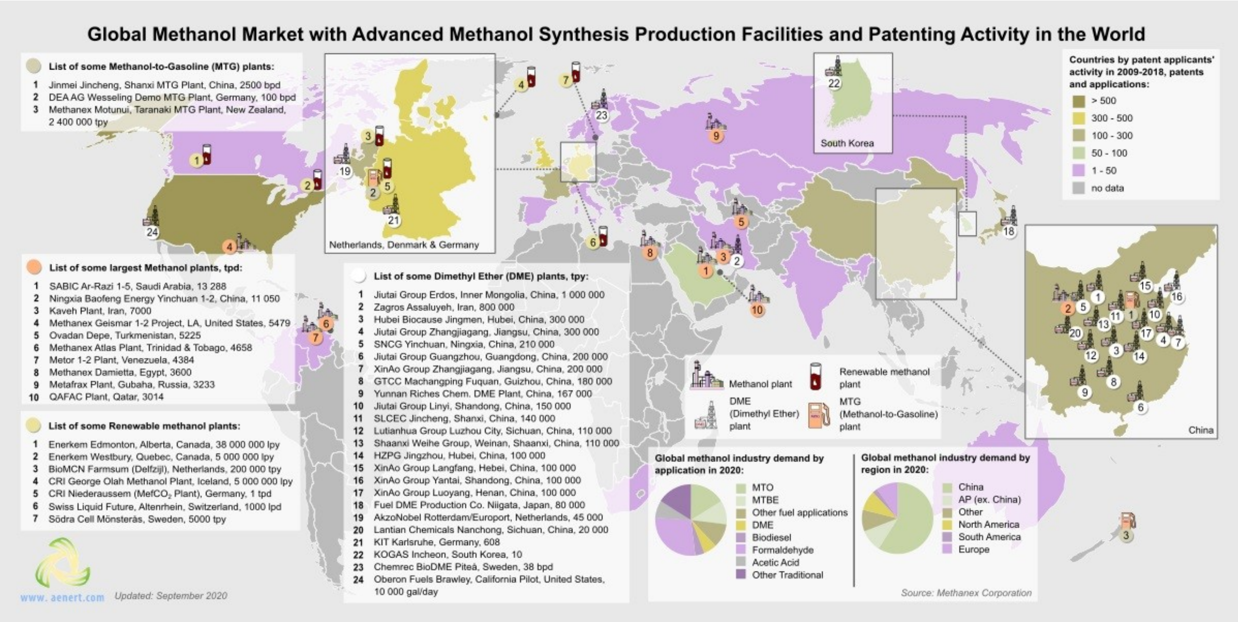
A technology for entrained flow gasification of black liquor for production of biofuels from syngas was launched in Piteå, Sweden in 2010 [38-41].

Fig.18-19. Chemrec BioDME Pitea Plant and BioDME refueling, Sweden

Black liquor is one of the waste paper production and is an excellent raw material for gasification, thus the Black liquor gasification and biofuels plant was erected next to the main production. For several years, the company supplied BioDME to the local market; however, several years later the production was shut down due to financial issues. This once again proves that competition in the fuel market is quite tough and any blunders, even in the presence of favourable conditions for the supply of raw materials, can lead to critical situations.

Fig. 20 shows a map listing some of the significant projects for the production of methanol and its derivatives, as well as related data.

Fig.20. Global Methanol Market with Advanced Synthesis Production Facilities and Patenting Activity



Source: on the map and Advanced Energy Technologies

[Global_methanol_market]()

In addition to technologies for the production of dimethyl ether, which are based on syngas, there are other production options on the market, for example, direct synthesis of hydrogen obtained by electrolysis and biomass processing products [42].

Fischer–Tropsch synthesis

Fischer-Tropsch synthesis is one of the most studied and industrialized options for converting syngas into liquid fuel and other hydrocarbon products. The majority of factories use natural gas as feedstock and steam reforming as their syngas production technology. Primary coal gasification has been developed in China, while biomass gasification has been developed in Europe and the United States. Syngas usually has a H_2/CO ratio in the range of 2–2.2 [31]. The actual Fischer-Tropsch synthesis is most often carried out on an Fe or Co catalyst at temperatures of 160–350°C [31]. In the process of the synthesis, syngas components are converted into long hydrocarbon molecules in accordance with the reaction [32]:

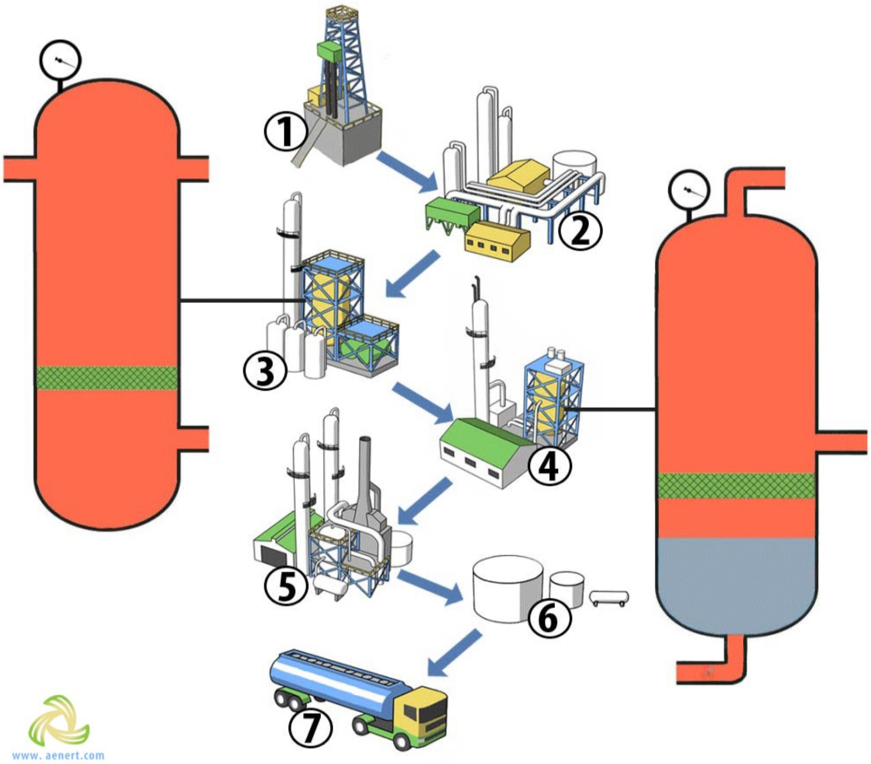
$(2n+1)\ H_2 + nCO \longrightarrow Cn\ H(2n+2) + nH_2O$, where n is an integer.

Depending on the conditions and type of catalyst, various types of hydrocarbons can be obtained from methane to high molecular weight compounds.

Commercial converter designs include Fixed bed, Slurry bed reactor, Fluidized bed, and Circulating fluidized bed. For Fixed bed and Slurry bed reactors, the process temperature is 220-240°C, at a pressure of 20-25 bar, with Fe or Co as catalysts. Fluidized bed, as well as Circulating fluidized bed, require higher temperatures of about 320-350°C [31].

Currently, there are several large enterprises for the production of hydrocarbon fuel using the Fischer-Tropsch method in the world, the main ones are shown in Fig. 22.

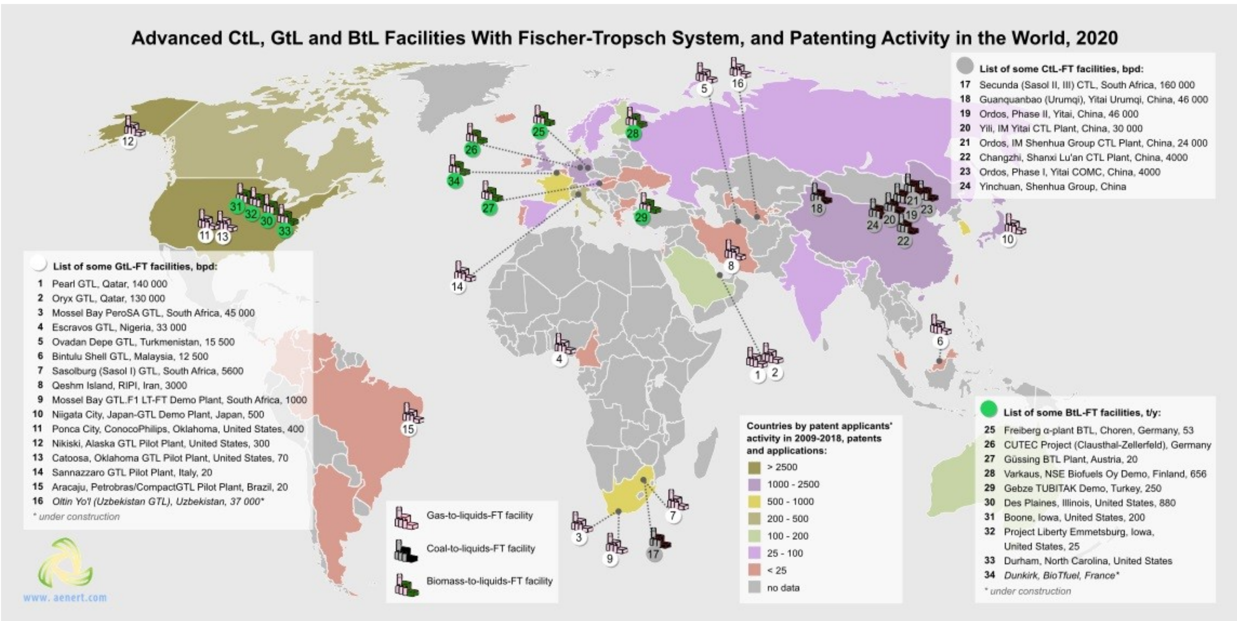
Fig.21. Gas to liquid production (Fischer–Tropsch synthesis)



Depiction legend:

***1.** Natural gas production well (raw material for processing); **2.** The gas purification from sulfur impurities or metals: **3.** synthesis reactor (synthesis gas with the addition of water vapor). **4.** Fischer-Tropsch reactor (short hydrocarbon chains form a long series of liquid hydrocarbons water goes into the sediment. **5.** Liquid hydrocarbons upgrading in to the final products. **6.** Product storage (both liquids and gases); **7.** Transportation of products*

Fig.22. Advanced GTL, CTL, BTL facilities with Fischer-Tropsch system and Patenting Activity



Source: [43-52], Advanced Energy Technologies

[*Advanced CtL, GtL and BtL Facilities With Fischer-Tropsch System, and Patenting Activity in the World, 2020*]

The largest GTL plants are Pearl GTL in Qatar, (140,000 bpd); Oryx GTL, Qatar, (130,000 bpd) and Mossel Bay PeroSA GTL, South Africa, (45,000 bpd). In addition, smaller plants in Nigeria, Malaysia, the United States and other countries are successfully operating. CTL plants are most represented in China and South Africa. The largest of them are Secunda (Sasol II, III) CTL, South Africa with a capacity of 160,000 bpd; Guanquanbao (Urumqi), Yitai Urumqi, China, (46,000 bpd); Ordos, Phase II, Yitai, China, (46,000 bpd) [43,44].

Fig.23-24. Sasol, CTL Refinery, Secunda and Fuel Jet, South Africa

Biomass to Liquid Fuel (BTL) plants are significantly smaller in capacity compared to those of GTL and CTL, and are mainly located in Europe and the USA.

Synthetic natural gas (SNG)

The production of synthetic natural gas has several important applications. First of all, this technology allows abundant coal or biomass resources as well as solid waste to be converted into natural gas, and then feeding it into existing gas distribution networks or gas storage facilities. In addition, this gas can be used as transport fuel. The traditional production line of synthetic natural gas includes feedstock gasification, resulting syngas cleanup and its subsequent methanation. As a result of the methanation reaction, carbon oxides interact with hydrogen, producing methane, water and large amounts of heat. In this case, nickel catalysts are most often used. The widespread diffusion of this technology is hampered by serious technical and economic problems, including those related to ensuring the thermal stability and durability of the catalyst, optimizing the design of reactors, the utilization of hydrogen sulfide and carbon dioxide, as well as those associated with the significant dependence of the final price of gas on the characteristics and cost of feedstock.

The main methanation reaction is the conversion of syngas components into methane, which is achieved by [54]:

$CO + 3H_2 \rightarrow CH_4 + H_2O$

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

Both reactions are highly exothermic. In addition to nickel, ruthenium and rhodium are used as catalysts, but their high cost severely hinders their practical application. According to [54], the following types of reactors are currently used for SNG production - Equilibrium-limited fixed bed reactors, Throughwall-cooled fixed bed reactor, and Slurry bubble reactor. The main companies active in the development of this technology are Lurgi, Haldor Topsoe, Air Products, Davy Process Technology [54].

There are several SNG manufacturing facilities, but most of them are demonstration projects. The Great Plains plant in the United States processes brown coal into SNG through gasification and subsequent methanation, and annually pumps more than 4 million m3/day into the country's gas pipeline system [55]. China is intensively developing this technology, where several large enterprises are under construction.

Great prospects are associated with the production of SNG from biomass, since in this case numerous plant resources can be used to obtain a valuable product with a developed infrastructure for storage, transportation and use. A good example of the practical application of this technology is the Bio-SNG project in Güssing, Austria. The 8 MW plant operated successfully from 2002 to 2016. Wood chips were used as raw material. The gasifier includes two lines with a fluidized bed, designed by the Pau-Scherrer Institute, and uses steam as an agent [56,57].

Fig.25-26. Gussing gasification and methanation plant, Austria

The methanation unit includes a Fluidized bed reactor and has the following operating characteristics: temperature - 300-350°C, pressure - 1-5 bar, capacity 10 Nm^3/h, catalyst - Ni [57].

Integrated gasification combined cycle (IGCC)

Integrated gasification combined cycle (IGCC) plants generate electrical power in a combined cycle by burning synthesis gas in gas turbines and superheated steam in steam turbines. Among the electricity generation technologies, the innovative Integrated Gasification Combined Cycle (IGCC) is considered to be a promising alternative for producing clean power from coal and other carbon-based feedstocks. IGCC uses both gas and steam turbines to generate electricity by burning synthesis gas (syngas), primarily a mixture of hydrogen and carbon monoxide produced by the gasifier.

For the production of synthesis gas, oxygen or air blown fluidized bed gasifiers or entrained flow gasifiers with pulverized feed are used. Using an entrained flow makes it possible to produce synthesis gas with minimal solid waste, but it needs significantly higher process temperatures. Oxygen blowing is more efficient in terms of synthesis gas quality, but requires higher energy use and special oxygen production. An important technological operation is cooling and subsequent cleaning of synthesis gas, which in turn occurs at relatively low temperatures requiring the use of large heat exchangers. In contrast, the efficiency of the gas turbine directly depends on the temperature of the incoming gas. These contradictory requirements are just a few of the problems restricting the development of this energy sector. In comparison to conventional power generation technologies, IGCC has advantages such as high generation efficiency due to greater carbon conversion, lower environmental impact, and less water usage. However, the widespread adoption of IGCC is hindered by high capital and operating costs and the complexity of construction, operation, and maintenance.

Integrated Gasification Combined Cycle (IGCC) plants generate combined cycle electricity by combusting syngas in gas turbines and superheated steam in steam turbines. Among power generation technologies, the innovative Integrated Gasification Combined Cycle (IGCC) is considered a promising alternative for generating clean energy from coal and other carbonaceous feedstocks. IGCC uses both gas and steam turbines to generate electricity by burning syngas (a mixture of mainly hydrogen and carbon monoxide) produced by the gasifier. For the production of syngas, fluidized bed gasifiers with blown oxygen or air, or entrainment gasifiers with crushed feedstocks are used. The use of entrained steam allows the production of synthesis gas with a minimum amount of solid waste, but this requires significantly higher process temperatures. Oxygen flushing is more efficient in terms of the quality of synthesis gas, but requires higher energy costs and special oxygen production. An important technological process is the cooling and subsequent purification of the synthesis gas, which, in turn, occurs at relatively low temperatures, requiring the use of large heat exchangers. On the other hand, the efficiency of a gas turbine is directly related to the temperature of the incoming gas. These conflicting demands are just a few of the challenges that are limiting the development of this energy sector. Compared to traditional power generation technologies, IGCC has the advantages of higher production efficiency through more carbon conversion, less environmental impact and less water use. However, the widespread adoption of IGCC is hampered by high capital and operating costs, as well as the complexity of design, operation and maintenance [58-60].

IGCC technologies have not yet become widespread, although in some countries, primarily in the United States, several plants are operating successfully. The largest IGCC plant in Europe is the Elcogas Puertollano IGCC Plant in Spain with a capacity of 335 MWe. The raw materials used are sub bituminous coal and petroleum coke in a 50:50 ratio, which are supplied from nearby mines and an oil refinery. The plant consists of three main units - an oxygen production unit by Air Liquide, a ThyssenKrupp's Prenflo gasifier and a steam production unit by Siemens. The gas turbine has a capacity of 182 MW and the steam turbine a capacity of 135 MW. The volume of emissions is 0.07 g/kWh for SO2, and 0.40 g/kWh for NO2, 0.02 g/kWh - particulate. The total cost of the IGCC plant is 27.32 €/MWh [19,58,61,62].

Fig.27-28. Elcogas Puertollano IGCC Plant, Spain

The entrained flow Prenflo gasifier with oxygen purge operates in the range 1200-1600ºC and a pressure of 25 bar. The syngas yield is 98%. After gasification, syngas is cooled to a temperature of about 165ºC and double purified to remove solid particles, ammonia and other components [19]. The actual average values of Raw Gas are about 59% of CO, 21% of H2, 4% of water, about 3% of CO^2, 13.3% of N_2 [62]. In general, this technology can significantly reduce emissions of sulphur dioxide, carbon dioxide, and nitrogen compounds.

Small-scale GTL plants

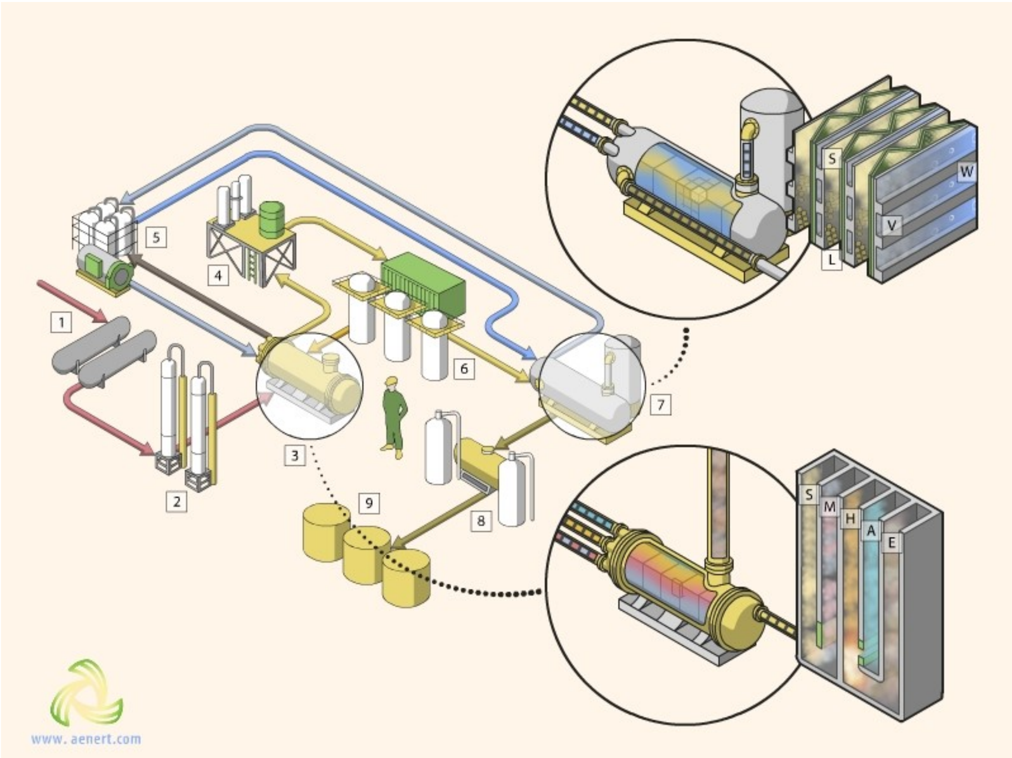
As already mentioned, GTL technologies in small configuration (microchannel GTL) may be the most viable option for the utilization of associated petroleum gas (APG). The issue of APG utilization is quite acute, since the volumes of its incineration are still high, despite administrative and organizational efforts worldwide. Efficient disposal of APG is only possible on site, so many researchers are making serious efforts to create compact installations for converting APG into useful products. One solution to this problem is to use the microchannel GTL.

Microchannel reactors are continuous flow reactors in which the reactor space is less than 1 mm in size. The main advantage of such reactors is a more accurate maintenance of the specified reaction modes, a high reaction rate, the possibility of using modular structures, compactness and mobility of installations.

The end product of GTL can be synthetic oil (syncrude), which can be pumped directly into the pipeline. However, it is also possible to produce more expensive products such as gasoline, diesel fuel, methanol or dimethyl ether.

So far, GTL technologies are the most expensive of those used for associated gas utilization. In addition, GTL processes are characterized by strict adherence to temperature conditions and pressure in reactors, as well as high requirements for catalysts. Nevertheless, these technologies are being improved and have significant prospects for the oil industry, given the relaxed requirements for the composition of the source gas compared to other technologies. The main suppliers of industrial equipment of mini-GTL are: Velocys (US), Infra Technologies (US, Russia), Primus GE (US), Verdis Fuels (Canada, UAE), Expander Energy (Canada), Greyrock (US), Advantage Midstream (US), CompactGTL (UK) [63-65].

Fig.29. Simplified GTL microchannel technology



1. *Gas treatment;* ***2.*** *Desulfurization;* ***3.*** *SMR microchannel reactor;* ***4.*** *Compressor station;* ***5.*** *Boiler & Cooling Water Unit;* ***6.*** *Hydrogen membranes;* ***7.*** *F-T microchannel reactor;* ***8.*** *Product separation unit;* ***9.*** *Stock of liquid hydrocarbons;*

S *- Syngas(H_2+CO);* ***L*** *- Liquid hydrocarbons;* ***V*** *- Vapor;* ***W*** *- Water cooling;* ***M*** *- Methane+Steam;* ***H*** *- Hydrogen;* ***A*** *– Air;* ***E*** *- Exhaust*

For example, Calvert Energy Group, offering modular mobile plants with the ability to produce 50 or 100 barrels per day (plant size 50 bbl/day and 100 bbl / day) of Diesel, Naptha, Jet fuel. Approximate Capex $47k - $52k / bbl, OPEX ~ $0.03 / litre of produced fuel. The expected life of the catalyst is three years.

For more information on research on these and other similar technologies, see [63-65].

Economics of Synthetic Fuel

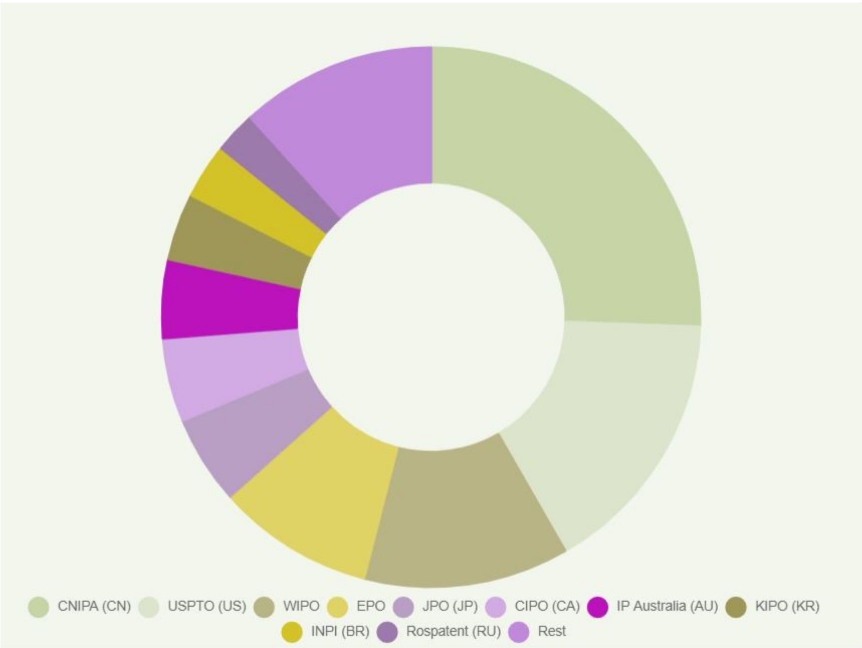
The economic indicators of synthetic fuel production are of decisive importance for the development of this direction in the energy sector. As noted above, at present, in most cases the technologies used are inferior in competitiveness to traditional technologies for the production of liquid and gaseous fuels. In addition, the large-scale expansion of renewable energy technologies and the global recession in many consumption sectors due to the covid-19 pandemic create an additional negative background for the implementation of synthetic fuels. In this regard, it should be borne in mind that many economic assessments of its production, made two or three years ago, and especially at a later date, require revision. Nevertheless, the links to some of these publications can be found in [66-69].

Research and innovations

The production of synthetic fuels has been the subject of increased scientific and engineering interest, especially in the last decade. Hundreds of research results are published annually in various scientific journals, and new patent applications for inventions are being registered in patent offices around the world.

This review presents the results of an analysis of about 17,000 patent applications published in the world over the past period (2010-2019). The analysis methodology can be found at the Advanced Energy Technologies website. Patent applications were submitted by almost 3,000 applicants from 57 countries to 59 patent offices worldwide. Below are some statistical results of the analysis, including comparative charts on the main indicators of patent applications.

Fig. 30. Top-10 patent offices registered the largest number of patent applications in 2010-2019 for synthetic fuels

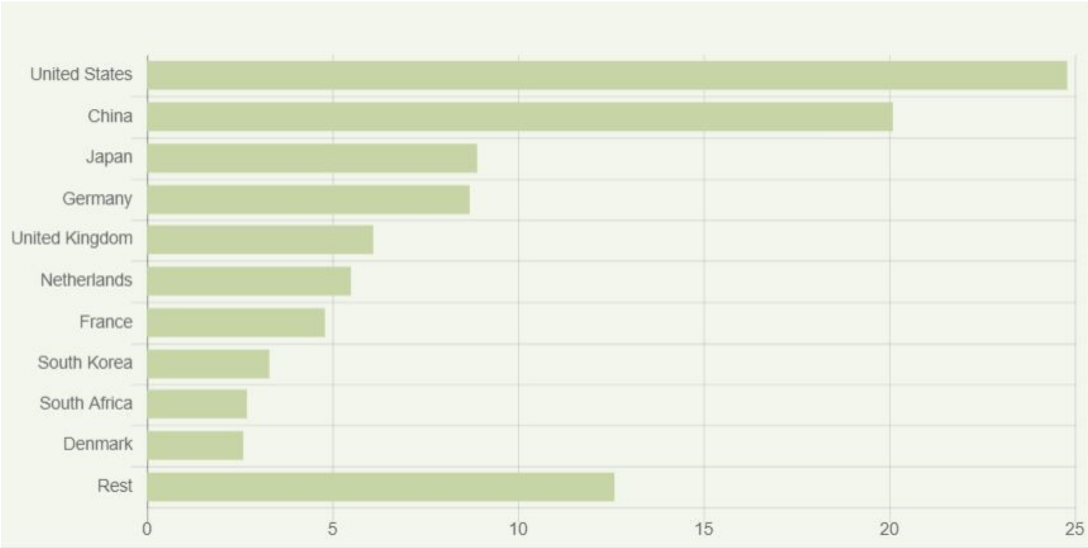


Source: Advanced Energy Technologies

The most popular offices for inventors were CNIPA (China), USPTO (United States) and EPO (European Patent Office). About 25% of applications were filed with China Patent Office (CNIPA), more than 15% in USPTO (United States). It should be noted that these three regions are currently the leaders in the number of installed synthetic fuels capacities (Fig. 30). About 12% of the total number of applications were registered with WIPO, and about 11% in other offices outside the top ten.

Inventors from the US registered the largest number of patent applications for this period –about 25% (Fig.31) – followed by representatives of China (a little over 20%) and Japan (9%). The top 10 countries also included Germany, the United Kingdom, the Netherlands, France, South Korea South Africa and Denmark. The remaining countries accounted for about 12.5%.

Fig. 31. Top 10 countries whose residents registered the largest number of patent applications in 2009-2018



Source: Advanced Energy Technologies

It is important to identify the main areas of research and engineering from the point of view of solving the existing technical, administrative or environmental problems in synthetic fuels. The result of such an assessment is shown in Table 3.

As follows from the data presented, the inventors were most concerned with the problems of "Low efficiency of main processes" (mentioned in almost 40% of inventions). In more than 16% of cases, patent applications offered solutions to the issues of "High OPEX / Maintenance & Repair and Replacement". In addition, the topics “Saving ecosystems” and “Low efficiency due to energy losses” were also popular among the inventors.

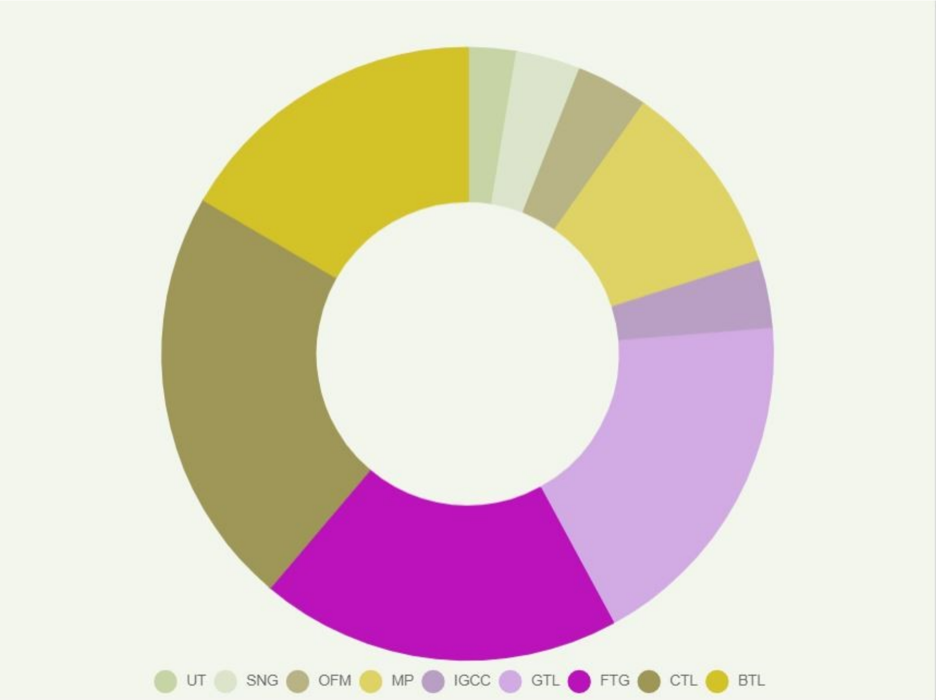
Table 3. Distribution of patent applications by the main problems

Problems	Patent applications, %
AOP - Administrative and organizational problems	0.4
HCD - High CAPEX / Development	5.1
HCE - High CAPEX / Equipment	3.2
HCG - High costs in general	3.7
HOM - High OPEX / Maintenance	8.1
HORR - High OPEX / Repair and replacement	8.3
LECR - Low efficiency due to catalyst replacement	0.8
LEEL - Low efficiency due to energy losses	6.4
LEFQ - Low efficiency due to feed quality	3.7
LEG - Low efficiency in general	2.6
LEMP - Low efficiency of main processes	39
LESP - Low efficiency of secondary processes	2.4
SE - Saving ecosystems	6.7
UP - Unclear problem	7.5
WEGC - Water, energy or gas consumption	2.2

Source: Advanced Energy Technologies

Four technologies were approximately equally present in patent applications - Coal-to-liquids (CTL), Fischer-Tropsch in general (FTG), Gas-to-liquids (GTL) and Biomass-to-liquids (BTL). Together they were mentioned in 76% of cases (Fig. 32).

Fig. 32. Distribution of patent applications by the main technology categories, %



UT *- Unspecified technologies;* ***SNG*** *- Synthetic natural gas;* ***OFM*** *- Other feed material;* ***MP*** *- Methanol & products;* ***IGCC*** *- Integrated gasification combined cycle;* ***GTL*** *- Gas-to-liquids;* ***FTG*** *- Fischer-Tropsch in general;* ***CTL*** *- Coal-to-liquids;* ***BTL*** *- Biomass-to-liquids*

Source: Advanced Energy Technologies

Table 4 shows the top 10 applicants by the number of patent applications in the field of synthetic fuels.

Table 4. Top 10 applicants by the number of patent applications in the field of synthetic fuels for 2010-2019

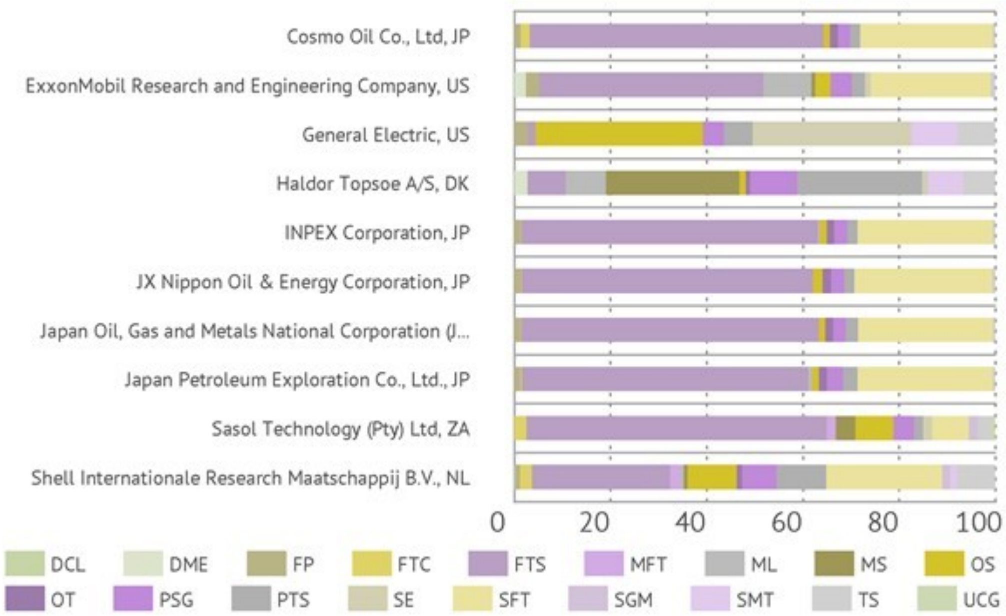
Status	Country	Name	Average rating	Total 2010 - 2019
Company	NL	Shell Internationale Research Maatschappij B.V.	10.6	620
Company	JP	Cosmo Oil Co., Ltd	13.6	549
Company	JP	Japan Oil, Gas and Metals National Corporation (JOGMEC)	13.7	529
Company	JP	INPEX Corporation	13.7	526
Company	JP	Japan Petroleum Exploration Co., Ltd.	13.7	514
Company	JP	JX Nippon Oil & Energy Corporation	13.5	510
Company	DK	Haldor Topsoe A/S	13	424
Company	ZA	Sasol Technology (Pty) Ltd	12.7	376
Company	US	General Electric	12.7	356
Company	US	ExxonMobil Research and Engineering Company	13.3	332

Source: Advanced Energy Technologies

Shell Internationale Research Maatschappij B.V. (the Netherlands) had largest share in the register of intellectual property during this period - more than 3%. Haldor Topsoe A / S (Denmark), Sasol Technology (Pty) Ltd (South Africa) and General Electric (the USA) also received more than 2%.

The technological priorities of the leaders of patenting are presented in Figure 33. All of the companies mentioned, to one degree or another, addressed the topic of improving “Primary technologies of syngas production”. For the majority of these companies, the share of mentions of this process exceeded 60%. Another popular topic was “Refining of products”. General Electric and Shell Internationale Research Maatschappij B.V. more than others paid attention to the technologies of “Fischer-Tropsch catalysts”.

Fig. 33. Technological elements of the top 10 applicants, %



DCL *- Direct coal liquefaction;* ***DME*** *- DME synthesis from syngas;* ***FP*** *- Feedstock preparation;* ***FTC*** *- Fischer-Tropsch catalysts;* ***FTS*** *- Fischer-Tropsch synthesis;* ***MFT*** *- Microchannel Fischer-Tropsch;* ***ML*** *- Methanol-to-liquids;* ***MS*** *- Methanol synthesis;* ***OS*** *- Other methods of syngas production;* ***OT*** *- Other technologies;* ***PSG*** *- Syngas production in general;* ***PTS*** *- Primary technologies of syngas production;* ***SE*** *- Syngas to electricity;* ***SFT*** *- Refining of products;* ***SGM*** *- Microchannel syngas production;* ***SMT*** *- Syngas to methane;* ***TS*** *- Treatment of syngas;* ***UCG*** *- Underground coal gasification*

Source: Advanced Energy Technologies

In addition, General Electric was the most active in the development of new engineering solutions in the field of “Syngas to electricity”. Haldor Topsoe A / S mainly focused on “Methanol synthesis” and “Fischer-Tropsch synthesis” technologies.

Synthetic fuel production trends

Since in most cases synthetic fuel is synthesized from syngas, the current volumes should be initially estimated, as well as forecasts of its production. It should be noted that it is rather difficult to obtain comprehensive and reliable data on this issue, this is due to the fact that a significant part of syngas is produced at chemical and oil refineries, where it is consumed for the production of methanol or hydrogen. The majority of the synthetic fuel plants, both using the Fischer-Tropsch method and the methanol chain, have steam reforming, coal gasification or MSW units; however, the actual production of syngas is not usually advertised. Therefore, estimates of production volumes by many authors differ significantly. In most cases, the market for "The Global Syngas & Derivatives in 2020" is estimated to be in the range of 180,000 - 250,000 MWth. At the same time, an average annual growth of 8% to more than 10% is forecasted for the next five to seven years [70-73]. Before the situation with covid-19 these estimates were more optimistic, but in 2021 they have become more restrained.

According to [74], about 70% of syngas is used for the production of ammonium, methanol and in oil refining. Approximately 11% is used for the production of liquid fuels and less than 2.5% for the production of synthetic natural gas (SNG). According to [75], the Global methanol industry demand is 80 million tons at a CAGR (Compound Annual Growth Rate) with an average annual growth of 6% and a forecast for the near future of 5%. Moreover, in 2016 the annual demand for methanol was estimated at 62 million tons. [76]. According to [77], in 2020, 4% of diesel fuel, 6% of DME, 11% of MTBE and more than 10% of other energy applications were produced from methanol. About 60% of methanol production capacity is located in China. Thus, until 2020, the production of methanol in the world has been rapidly increasing. Perhaps the 5% growth predicted in [75] will continue in the short term.

Currently, hydrogen, which is used in oil refining for fuel purification, is produced primarily by steam reforming. There is also no unanimity in assessing the production of syngas and hydrogen. For example, a comparative analysis of various estimates of the production and consumption of hydrogen in the world is given in [78]. These estimates range from 65 to 100 million tons per year of hydrogen production worldwide, of which about 70 million tons per year of "on-purpose" hydrogen. Previously, OPEC provided data on the capacity for the production of hydrogen at refineries in the amount of about 25,000 mscf/day [79]. However, this report could take into account the hydrogen capacity from the main oil refining processes. In [80] the following data are given - "… around 70 MtH_2/year is used today in pure form, mostly for oil refining and ammonia manufacture for fertilizers; a further 45 MtH_2 is used in industry without prior separation from other gases".

[74] gives various statistical assessments of global gasification. In particular, it is noted that in 2017 the total number of gasifiers in the world exceeded 2000 (Operating, Construction, Planned), of which the vast majority are located in the Asia-Pacific region and use coal as a raw material. The most popular are gasifiers designed by GE, Shell, ECUST, SEDIN, Siemens, Lurgi. It is assumed that biomass gasification will receive more intensive development in the next decade. Biomass Gasification is currently the most widespread in Europe, with over 60 gasification projects. Among them are gasifiers with a capacity of about 1 MW, and gasifiers with a capacity of more than 50 MW a little over 20. It is also planned to build more powerful gasifiers with an installed capacity of 10 MW and more.

One of the recent large projects for the production of synthetic fuels was implemented in June 2019 in Turkmenistan. The design and construction of the plant was carried out by the Japanese company Kawasaki Heavy Industries, Ltd. The plant is capable of producing 5,225 tonnes of methanol per day, as well as 600,000 tonnes per year of high-quality gasoline from natural gas using the Danish Haldor Topsoe SynCOR ™ - Autothermal Reformer technology, through an intermediate methanol synthesis (GTG process). In addition to gasoline, the plant produces up to 12,000 tons of diesel fuel and more than 100,000 tons of liquefied natural gas per year [81,82].

The Energy Information Administration (EIA) in [83] formulated a forecast for the implementation of new GTL projects until 2040. The outlook is largely restrained. The authors indicate that only two large projects will be completed in this rather long time period - the transformation of the CTL plant in Secunda (South Africa) into GTL by 2024 and the launch of a previously suspended project in Uzbekistan in 2021. In addition, the total production growth will be provided by the launch of small plants with a capacity of up to 5,000 bpd and less. Total global GTL production could rise from 230,000 bpd to 400,000. Further growth may be driven by high global oil prices.

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