Impact of (bio)-LNG on the environment

Report on the impact of installation, production, transport, storage, distribution and use of (bio)-LNG powered transport means on the broadly understood environment.

The positives and the dangers

2021

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Content

1. Introduction

Fulfilling the growing global demand for energy, while counteracting climate change and environmental pollution, is the most important challenge facing societies.

Air quality is a particularly pressing problem in the world, as smog significantly affects the quality of life and health of people in cities, and is often the cause of death. Pollutant fuels, used in unsustainable household heating, industry, energy and transport, can be a major source of air pollution.

The European Union (EU) aims to fully decarbonise its economy, which requires a complete overhaul of the energy system and its infrastructure by 2050. The Green Deal, as announced by the European Commission (EC) in December 2019, aims to achieve at least a 55% reduction in greenhouse gas (GHG) emissions by 2030 compared to 1990 levels. In July 2021, the EC adopted a package of proposals to make the EU's climate, energy, land use, transport, and taxation policies fit to meet its 2030 GHG reduction goals and put Europe on track to becoming the world's first climate-neutral continent by 2050 - making the European Green Deal a reality [Gas for Climate 2021].

In the process of burning natural gas, less hazardous to the atmosphere (environment) components of exhaust gases are created, such as nitrogen oxides, sulfur oxides, solid particles, etc. Natural gas is a fuel with a very low sulfur content. The emission of carbon dioxide is about 30% lower from energy devices with the same efficiency. It is due to the higher calorific value of natural gas compared to liquid fuels and the greater share of hydrogen in the gas [Herdzik 2011, Herdzik 2012]. When natural gas is used as a fuel in marine diesel engines, they meet the emission standards in Emission Control Area (ECA) and, as a result, there is no need for additional installations limiting the emission of harmful substances into the atmosphere [Herdzik 2013].

According to the International Energy Agency, gas used to generate electricity, emits 45% to 55% less greenhouse gases than coal. The displacement of coal-fired power plants and diesel generators, combined with gas-based electricity generation and renewable energy sources, appears to be a fast and cost-effective way to reduce greenhouse gas emissions in the energy sector while ensuring a reliable electricity supply. Nevertheless, the transport of combustible gases is associated with a high risk of failure due to the physical properties of the transported medium, such as low boiling point, flammability, formation of flammable mixtures with air in a short time.

Natural gas as well as LNG play a crucial role in the energy transformation in the industrial (e.g., light industry) and transport sectors, which can significantly reduce costs, greenhouse gas emissions and improve air quality.

Also, a renewable fuel such as biogas produced from biological waste is used more and more. The production process not only produces electricity, heat and gaseous fuel, but also the fermented material that is used as fertilizer (Figure 1).

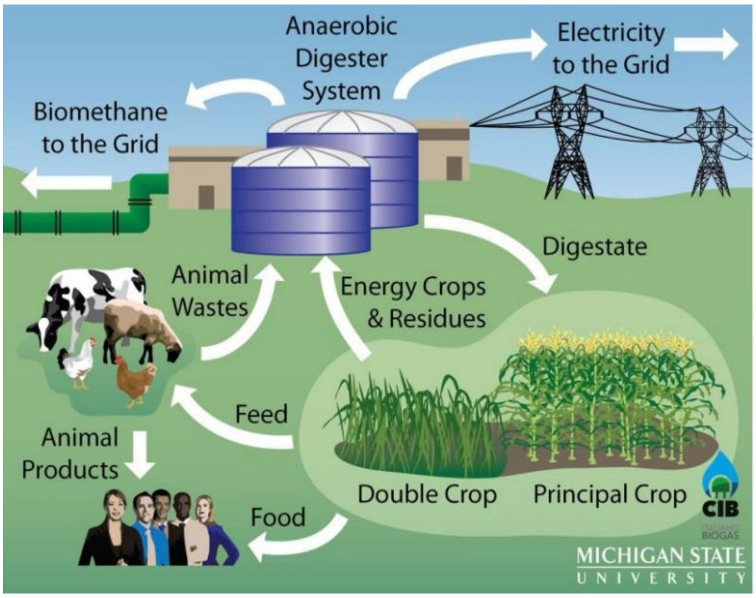

Fig. 1. Feed and biogas circulation
[https://www.cnhindustrial.com/PublishingImages/top_stories/biogas/feed-and-biogas-feedstock-sequential-croppingccib_high.jpg]

2. Purpose of the report

The aim of the report is to analyse the environmental impact of the increasingly widely used LNG, biogas and biomethane as fuels. It is used for internal combustion engines, heating boilers for the production of energy and heat and for supplying gas networks. In the report, we will analyse all the pros and cons of using this alternative fuel, the risks associated with it and its impact on the widely understood environment.

3. Natural gas, CNG (Compressed Natural Gas) and LNG (Liquid Natural Gas)

Natural gas – non-renewable natural fuel

Natural gas is an organic origin type of fossil fuel. It can occur in various forms of concentration: natural gas, liquid natural gas (LNG) and compressed natural gas (CNG). Nevertheless it is still the same gas with the same composition.

Under natural conditions, gas accumulates in deposits that fill empty spaces in the Earth's crust. The gas deposits may be under high pressure. Natural gas is extracted by drilling. Natural gas resources can occur independently or are located in the vicinity of crude oil or hard coal deposits. The composition of a specific gas depends on the place where it is extracted, as well as the technology of the so-called gasification. The basic component of natural gas is methane. It is even up to 98% in the case of high-methane gas.

The methane content in the gas prevents the production of dust or solid waste during the combustion process. In natural gas also small amounts of ethane, propane, butane and other mineral and organic compounds may be present. Natural gas is by its nature odourless, hence it must be specially odorized before it is released into the gas installation. It is in order to facilitate detection of its possible presence in the air.

Natural gas is relatively harmless to the environment, it can be seen in comparison with other energy sources. The emission of carbon dioxide from gas combustion is up to 30% lower compared to crude oil and approx. 60% lower than in the case of coal. The release of other chemicals such as mercury, sulfur and nitrogen dioxide is also significantly reduced. Natural gas is a colourless substance with a density less than air. It creates an explosive mixture by reacting with air. In its natural deposits, gas is under high pressure and therefore it comes out to the earth's surface by boreholes. The extracted raw gas is mostly contaminated by the presence of solids such as crushed sand or clay, or liquids such as petroleum residues (liquid hydrocarbons and water). For this reason, the gas is subjected to a purification process before it is introduced into the transmission pipeline. It should be emphasized that during the extraction of gas and then its transport, all rules regulating activities for the protection of the natural environment must be followed.

Due to its calorific value, natural gas states a very good source of energy. Natural gas reaching the end user is high-methane gas significantly different from the extracted gas. Water vapor, sulphur and hydrogen sulphide, helium, carbon dioxide and petroleum residues are present in the extracted raw natural gas. This usually happens when gas accompanies petroleum extraction. Raw gas is separated from other hydrocarbon fractions and purified before entering the pipeline. The hydrocarbons present in raw gas such as ethane, butane, propane, are very valuable products, but cannot be transported through gas pipelines as they tend to condense.

Due to the content of hydrocarbon components, the following gas is distinguished as:

- Dry (low content of propane and higher hydrocarbons),
- Wet (propane and higher hydrocarbons in amounts of 5-10%).

Due to the nitrogen content:

- Nitrogen-free gas (nitrogen content below 1-3%),
- Low nitrogen gas (nitrogen content between 3-10%),
- Nitrogen-rich gas (nitrogen content over 10%).

Due to the content of hydrogen sulphide (sulphur):

- Low sulphur gas (hydrogen sulphide content below 0.3%),
- Sulphur gas (hydrogen sulphide content within 0.3-3%),
- High-sulphur gas (hydrogen sulphide content over 3%).

Natural gas is the only fossil fuel for which the global demand continues to grow. It is estimated that natural gas will overtake crude oil in this regard around 2030. In the future, it is estimated that by 2030 gas consumption will be even higher and will amount to approximately 4,831 billion $m^3 \cdot year^{-1}$, which will of approximately 25% of global energy consumption. Then natural gas will become the second source of energy after crude oil. Today it ranks third after crude oil and coal [Kardasz 2017].

3.1 Physio-chemical properties of LNG

A typical composition of natural gas is:

- methane 94%,
- ethane 4.7%,
- propane 0.8%,
- butane 0.2%,
- nitrogen 0.3%.

The properties of liquefied natural gas (LNG) are shown in Table 1.

Table 1. Properties of liquefied natural gas [Safety Data Sheets in accordance with the model specified in REACH as amended by Regulation 830/2015 Date of update 29.05.2017 version 1.9]

No.	Property	State of
1	Molecular weight	16,4
2	Aggregate state at 20°C	gas
3	Colour	clear
4	Odour	odourless
5	Fluid density (-161.5°C)	430 kg·m^{-3}
6	Gross calorific value	39.21 MJ·m^{-3}
7	Calorific value	35.36 MJ·m^{-3}
8	Boiling point (1013 hPa)	-161.5°C
9	Melting point (1013 hPa)	-182.6°C
10	Auto-ignition temperature	580°C
11	Solubility	in ethyl ether
12	Solubility in water	poor
13	It's dangerous to react with	chlorine, fluorine, nitrogen trifluoride, oxygen difluoride, liquid oxygen

Liquefied natural gas is a liquid lighter than water with density 430–470 kg·m^{-3}. The density of methane (gas) at low temperature, close to condensation, is higher than that of air and is approx. 1.751 kg·m^{-3}. While spreading, methane can accumulate just above the ground and is easily subject to ventilation processes as the temperature rises to the value of approx. -110°C [Bralewski & Wolain 2019].

The quantitative composition of LNG depends on the composition of the source natural gas and the liquefaction method used, whereas the qualitative composition depends on the place of extraction and way of loading [Bralewski & Wolanin 2019, GIIGNL 2019].

The comparison of the properties of different types of gas is shown in Table 2.

Table 2. Composition of biogas, landfill gas and natural gas [Papacz 2011, Pomykała & Łyko 2013]

Parameter	**Biogas** [Papacz 2011, Pomykała & Łyko 2013]	**Biomethane** [Pomykała & Łyko 2013]	**Landfill gas** [Papacz 2011]	**Natural gas (Danish)** [Papacz 2011]	**Natural gas (Nederland)** [Papacz 2011]
Methane (vol-%)	47-70	94-99.9	35-65	89	81
Other hydro carbons (vol-%)	0	0	0	9.4	3.5
Hydrogen (vol-%)	0	traces	0 - 3	0	-
Carbon dioxide (vol-%)	25–40	0.1-4	15–50	0.67	1
Nitrogen (vol-%)	~0.2-3	<3	5–40	0.28	4
Oxygen (vol-%)	0-2	<1	0 - 5	0	0
Hydrogen sulphide (ppm)	0–4000	<10	0–100	~3	-
Ammonia (ppm)	~100	traces	~5	0	-
Lower heating value (kWh·Nm^{-3})	6.5		4.4	11.0	8.8

3.2 LNG distribution

In a very simplified way natural gas can change its state of aggregation to liquid after cleaning of heavy hydrocarbons, carbon dioxide and water, and under the influence of high pressure and temperature (-161°C). As a result of this process, its volume will decrease by about 600 times without losing its energy content. Thanks to this, the costs of transporting the same portion of energy are much lower.
Development of the natural gas liquefaction process created completely new possibilities when it comes to storing and transporting. Typically, LNG is transported in cryogenic road and rail tankers, as well as in special ships - called gas carriers or methane carriers. 1 m^3 of LNG is equal to 600 Nm^3 (cubic meters under normal conditions) of natural gas, which provides a considerable storage capacity (Figure 2). Thus, a large amount of energy can be concentrated with a relatively small storage capacity.

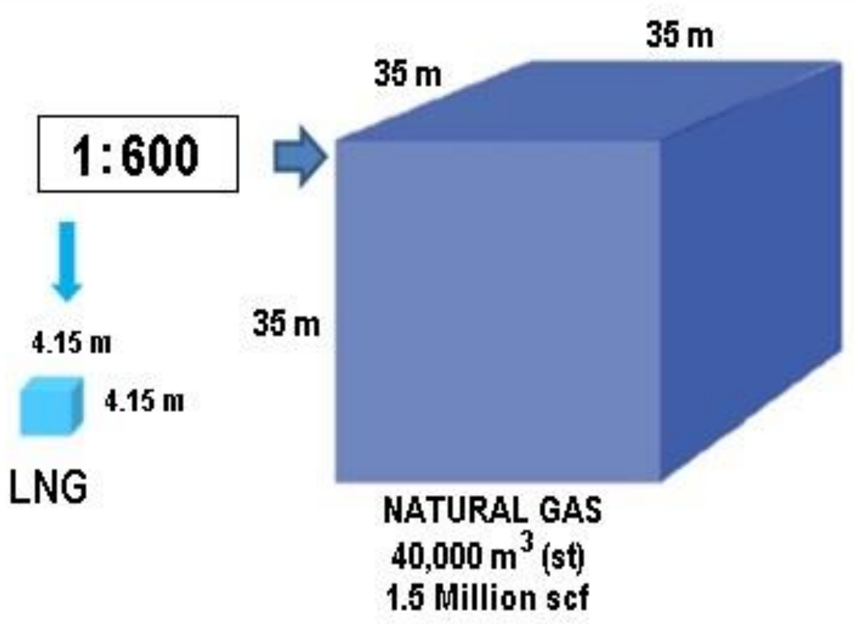

Fig. 2. The volume of LNG in liquid and gaseous states [https://www.eiaa.gov/energyexplained/natural-gas/deliveryandstorage.php]

Depending on the source of origin, natural gas can be collected and distributed using the following methods (Figure 3):

- LNG transported by sea is stored in tanks in gas ports. After evaporation, it is pumped into pipelines and delivered to customers or transported in liquefied form by rail and road tankers;
- The gas produced in the country can be stored in underground gas tanks, from where it is pumped to the gas network or liquefied and transported to customers in liquid form.

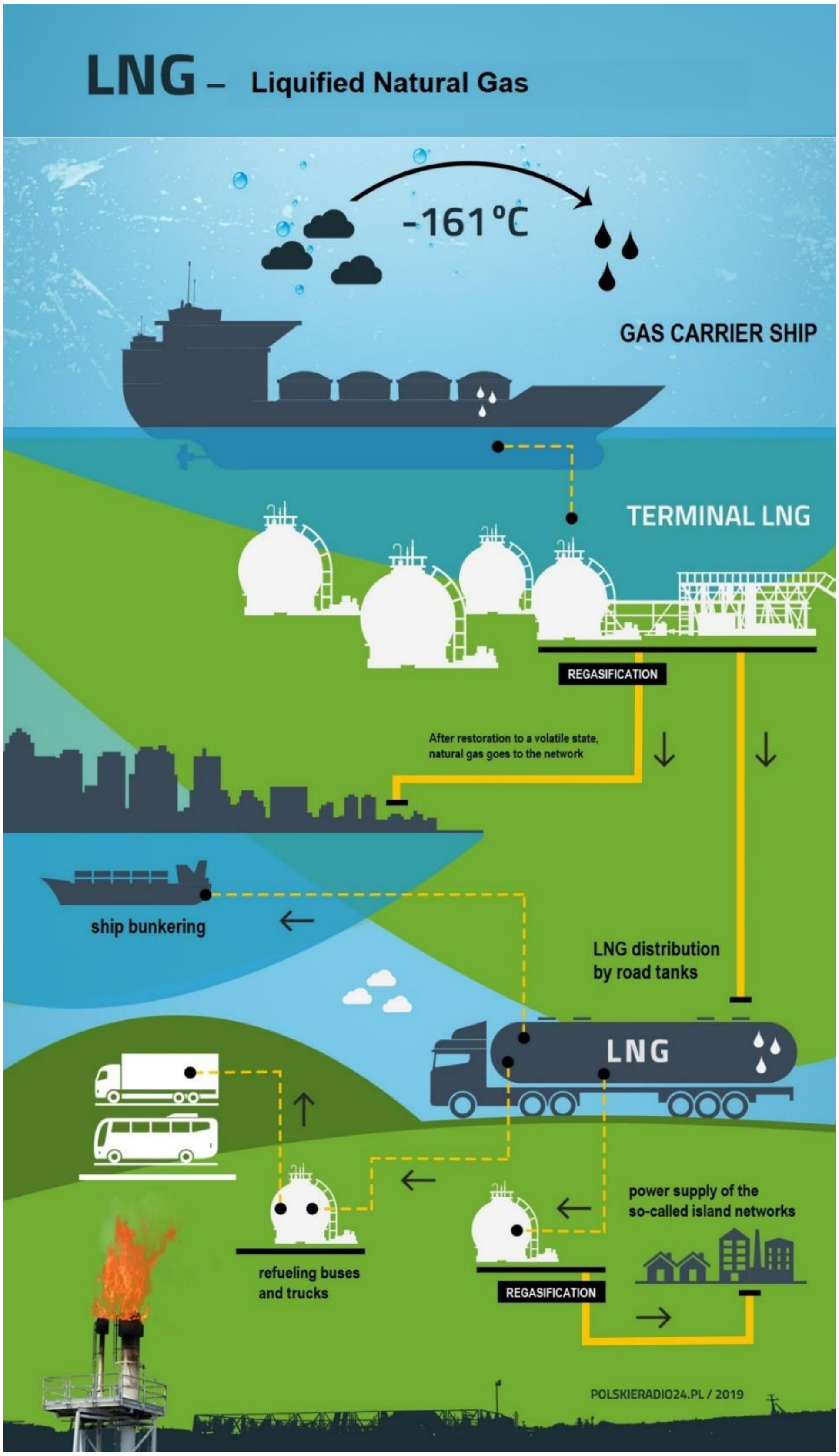

Fig. 3. Methods of transport, distribution and redistribution LNG [https://polskieradio24.pl/13/53/Artykul/2363783,Sprawdz-jakie-sa-roznice-miedzy-LNG-CNG-i-LPG]

3.3 Application of LNG

Examples of possible applications of liquefied natural gas (LNG) are as follows [https://www.polskielng.pl/terminal-lng/lng-w-pigulce/zastosowanie-lng/]:

- Supplying end users with natural gas. LNG is used as an alternative to gas supplied through traditional pipelines. For some countries, this is a way to diversify gas supply sources and ensure energy independence
- Covering short-term peak gas demand for 3 to 4 weeks per year with installations liquefying natural gas from pipelines or installations supplied from external sources, e.g. from installations to denitrification plants or from transportable complex installations. This solution is used in Europe (Germany, Great Britain, the Netherlands and Belgium) and also commonly used in the USA, where there are several dozen installations for liquefying natural gas and regasification, as well as LNG storage
- Gas supply gas to customers who have not been connected to the gas transmission (distribution) network so far (the so-called white spots). Most often, one or more large industrial customers are connected to the LNG stations, and the rest are relatively smaller consumers subject to the municipal government
- Gas supply to small and medium-sized towns to which fuel is supplied from the so-called LNG satellite installations, which in turn obtain liquefied natural gas from larger condensing installations. Examples of such solutions can be found in Germany and Great Britain
- Fuel for driving motor vehicles: buses, locomotives, helicopters and supersonic planes. The interest in liquefied natural gas as engine fuel is particularly high in densely populated countries. This is due to the need to protect the atmosphere against toxic components contained in car exhaust fumes. This solution is used in France, Great Britain and also in Japan
- Fuel for power plants. Powering the plant with LNG is widely used in Japan - the Yokohama plant is fired with liquefied natural gas supplied by tankers from fields in Alaska
- Gas supply to customers temporarily cut off from gas supplies from pipelines, for example as a result of the need to repair or maintain the transmission network. The use of LNG makes it possible to supply customers with gas without interrupting supplies. The solution used, among others in France
- Cooling source - LNG is sometimes used for cooling purposes and for air separation, for example in magnetogasdynamics generators for cooling magnets or in the refinery and petrochemical industry in installations for low-temperature fractionation of hydrocarbon gases. Often, the cold generated during LNG regasification is also used in low-temperature installations, e.g. for the production of oxygen by rectifying liquefied air. The solution used, among others in Fos-sur-Mer, France
- Powering fuel cells that generate electricity and / or heat. Examples of such an application can be found in France.

4. Biomass and Biogas

Biogas, biomethane – renewable natural fuel

The Directive 2009/28/EC of the European Parliament and of the Council of April 23, 2009 *on promoting the use of energy from renewable sources*, amending and consequently repealing Directives 2001/77/EC and 2003/30/EC (Official Journal of the European Union L 140 of 05.06.2009, p. 16, as amended) establishes a common framework for the promotion of energy from renewable sources. It sets mandatory national targets for the overall share of energy from renewable sources in gross final consumption of energy and for the share of energy from renewable sources in transport. It lays down rules relating to statistical transfers between Member States, joint projects between Member States and with third countries, guarantees of origin, administrative procedures, information and training, and access to the electricity grid for energy from renewable sources. It establishes sustainability criteria for biofuels and bioliquids and the following definitions:

- **biomass** - means the biodegradable fraction of products, waste and residues from biological origin from agriculture (including vegetal and animal substances), forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste;
- **bioliquids** - means liquid fuel for energy purposes other than for transport, including electricity and heating and cooling, produced from biomass;
- **biofuels** - means liquid or gaseous fuel for transport produced from biomass.

In addition to the above definition, biomass is primarily biodegradable organic matter derived from plants and animals. It is also left over from production and forestry as well as industrial and municipal waste. For energy purposes from the so-called solid biomass is used for wood and waste from its processing, plants from crops for energy purposes, agricultural products and organic waste from agriculture, some municipal and industrial waste. The denser the biomass is used, the greater its fuel value. Briquette made of highly shredded wood waste is an extremely valuable fuel. The enriched fuel, i.e. briquettes and wood pellets, are produced by drying, grinding and pressing the biomass. Biogas is produced around the sewage treatment plant as well as in landfills, which is a mixture of mainly methane and carbon dioxide. It is produced in the process of anaerobic fermentation of organic substances. It can be used in the process of:

- electricity generation in spark engines and turbines,
- generation of thermal energy in boilers,
- generation of electricity and heat in the so-called associated systems.

The use of methane, which is one of the greenhouse gases, prevents unnecessary emissions into the Earth's atmosphere. Liquid biomass is of the greatest importance as a raw material for the production of alcohols produced from plants with a high sugar content, as well as biodiesel produced from oilseeds. As a result of the fermentation process, pyrolysis and the hydrolysis of corn and sugar cane, we obtain methanol and ethanol, i.e. biofuels, which later become an addition to traditional liquid fuels. For the production of biomass to be economically justified, it is necessary to take into account certain limitations related to the use of arable lands and the impact of the use of certain plant products on the formation of food prices. This mainly includes the production of liquid fuels. Simple combustion of biomass is not the best solution. From biomass of the type: straw and wood chips and other bio-raw materials, it is possible to produce noble energy carriers such as: bioethanol, biogas, biobutanol, biodiesel, as well as use vegetable oils as biofuel or produce wood gas, i.e. holtzgas. Bioethanol itself is now a fuel additive used in many countries. The biofuel technology is available to countries with different, also not very high, levels of development. It is worth adding that the investment costs related to this area are not high. Biomass is a raw material that is basically harmless to the environment, because the amount of CO_2 emitted to the atmosphere in the process of its combustion balances the amount of carbon dioxide absorbed by the plants themselves, regenerating biomass in the photosynthesis process. The use of biomass also allows for better management of wastelands and waste [Kardasz 2017].

A diagram of the biofuel production technology for transport is presented below (Figure 4).

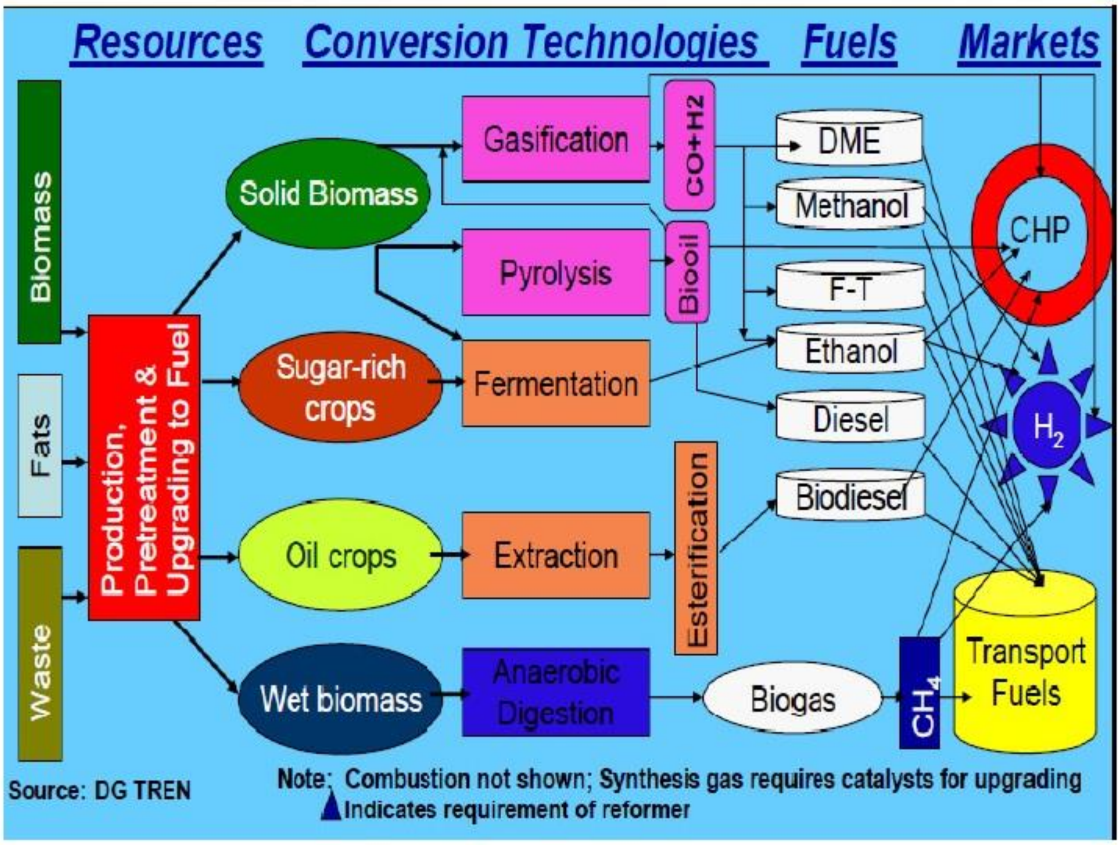

Fig. 4. Technologies of production of fuels for transport [Merkisz et al. 2011]

The term biomethane is not defined in the Directive 2009/28/EC. However, the term is used to describe biogas with high methane content. Such biogas is prepared for use as transport fuel and / or for injection into the natural gas grid. The following terms are also used:

- CBG (compressed biogas) - compressed biogas, presumably high-methane, i.e. biomethane
- LBG (liquid biogas) or (bio-)LNG- liquefied high-methane biogas, i.e. liquefied biomethane
- (bio-)CNG (compressed natural gas) - a mixture of natural gas and biomethane, usually formed as a result of injecting biomethane into the natural gas network [Pomykała & Łyko 2013].

The main advantages of biofuels are that they are renewable fuels derived from biological resources, offer many technical and environmental benefits, reduce greenhouse gas emissions (CO_2 and methane), diversify the energy and fuel market, and are biodegradable.

In recent decades, there has been a dynamic development of biogas technologies in various countries and regions of the world (the United States, Germany, Sweden, South-East Asian countries), the goal of which is to produce energy from renewable sources.

During the anaerobic fermentation of biomass from agriculture or other sources, biogas is released, i.e. a mixture of methane and carbon dioxide, also containing small concentrations of hydrogen sulphide, ammonia, hydrogen, oxygen, water vapor (usually in the range of 45-85% CH_4, 14-48% CO_2 , 0.05-0.8% H_2S, 0.005-0.04% NH_3, 0.2-1% H_2, up to 2% O_2 and 2-7% H_2O), traces of siloxanes and other substances. The content of individual components of biogas obtained in the biomass fermentation processes is not constant, but depends on the specificity of the technological process and the type of input material. However, the supply of raw materials for biogas plants, the process of their fermentation, and the acquisition and purification of biogas can be a potential source of a number of nuisances and threats to the environment, especially if there are errors in the design of the installation or its implementation, inadequate health and safety procedures, as well as generally low technical culture in the company [Klemba 2015].

While the biogas is used to produce heat in boilers or to generate electricity, it is more cost-effective - to remove sulphur compounds and other pollutants harmful to the operation of the plant,. This process has a lower efficiency and is proceeded without the separation of carbon dioxide. Whereas in the case of gas injection into the gas installation or its use as a transport fuel, it is necessary to convert biogas to biomethane, i.e. to remove also carbon dioxide. This requires the construction of additional biogas treatment plants.

The process of generating biogas can be divided into four closely related stages. A diagram of the anaerobic digestion process is shown in Figure 5.

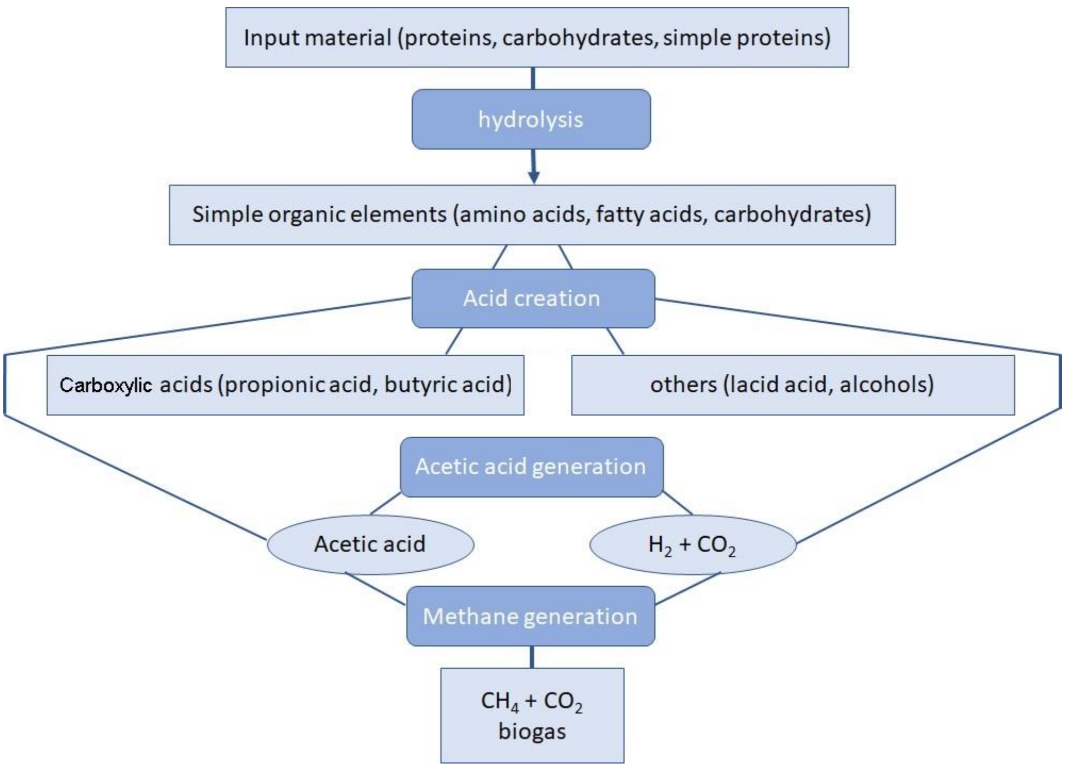

Fig. 5. Scheme of basic process of anaerobic digestion [Wiącek & Tys 2015]

The biogas production process is carried out through many stages. Hence it is essential to use a large amount of microorganisms, which are capable to use energy deposited in carbon hydrates, fats and proteins in process which is followed under anaerobic conditions. 30% of the known species use hydrogen and carbon dioxide for their metabolism. Whereas almost 70% of the methane bacteria use acetic acid. Depending on the type of bacteria settings of the process should be regulated . Temperature of 55 to 60°C for thermophilic bacteria, and 30-40°C for mesophilic bacteria. It is recommended to adjust the e pH-value. It should range from neutral up to low alkaline There is strong dependency between every degradation stage of bacteria. It is because the metabolism products of one group can have an impact on other group Depending on the number of contained bacteria at a time there is a probability that different groups of bacteria can inhibit other groups. The production of biogas starts after 4 to 6 weeks after starting the fermentation process. It is a result of occurring order of the processes. The diagram of biogas production technology is presented in Figure 6.

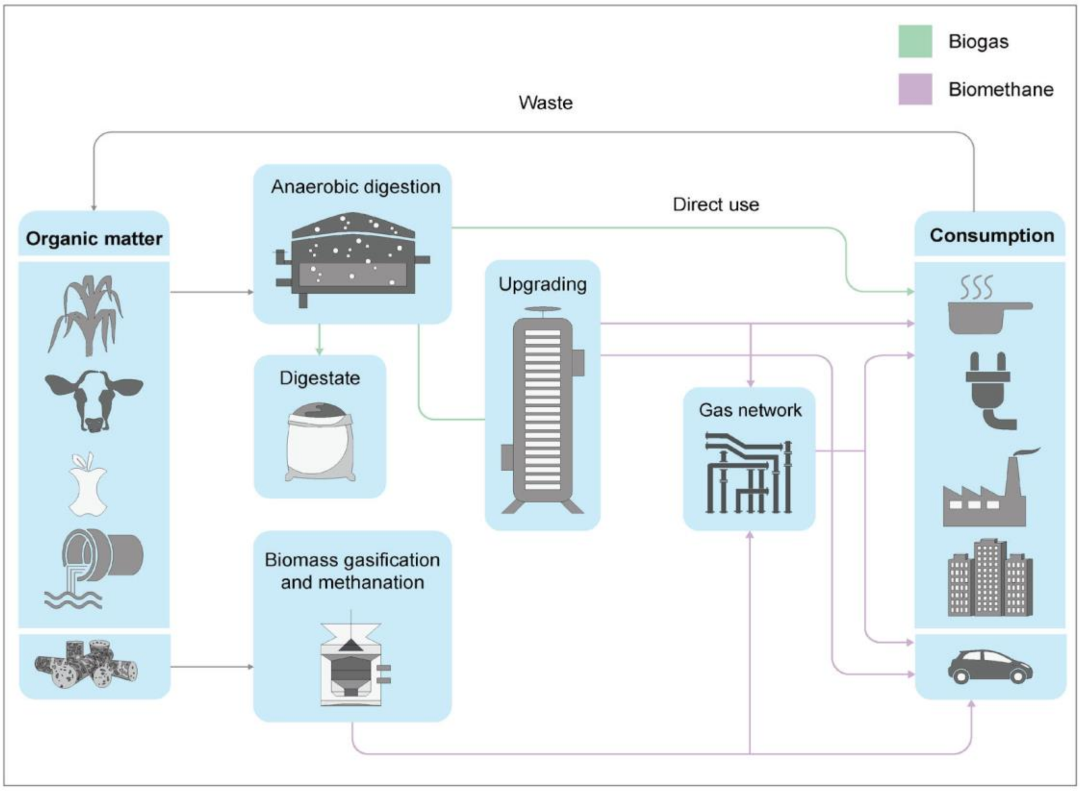

Fig. 6. Biogas and biomethane production pathways
[https://www.euneighbours.eu/sites/default/files/publications/202003/Outlook_for_biogas_and_biomethane.pdf]

It is recommended to use biogas plants on livestock farms and crops. Due to the production of biogas, electricity and heating needs can be covered. Exceeded amount of produced biogas, electricity and heat can be directed to meet the needs of local residents, or sold to external customers. Furthermore digestate from the biogas plant can be used as a fertilizer in agriculture. Examples of the described capabilities are presended in Figure 7.

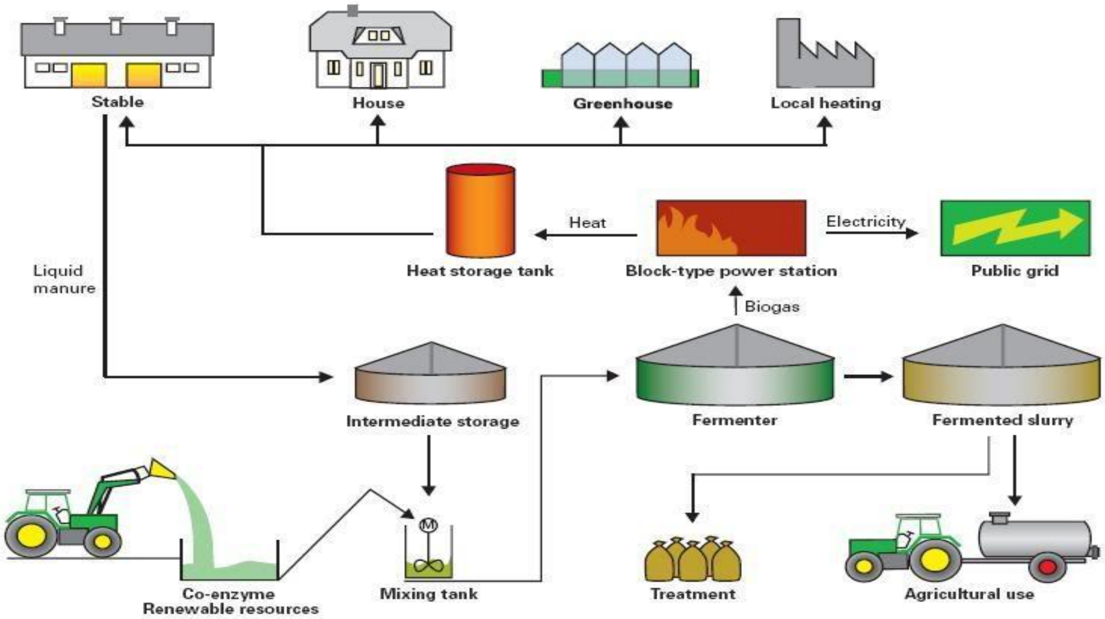

Fig. 7. Biogas plant concept, distribution of generated energy and digestate
[https://www.bioenergyconsult.com/wp-content/uploads/2013/04/biogas_applications.jpg]

4.1 Biogas and its physio-chemical properties

The biogas produced by the decomposition of organic matter by methane fermentation contains 50–75% methane (CH_4) and 25–50% carbon dioxide (CO_2) and small amounts of ammonia, hydrogen sulphide, hydrogen, mercaptans and other gases. Anaerobic digestion is a complex biochemical process that occurs under anaerobic conditions. Organic substances are broken down by bacteria into simple compounds - mainly methane and carbon dioxide (see Table 2).

From an ecological point of view biomass is more favourable than coal. It emits less SO_2 than coal when it is burned. Furthermore while biomass is burned, carbon dioxide emission balance is zero: burning biomass emits the same amount of carbon dioxide to environment as the plants absorbed form the atmosphere. In terms of energy, 2 tons of biomass is the same as 1 ton of hard coal.

5. Environmental impacts

In the twentieth century, there was a rapid development of modern modes of transport, such as road, rail, air, sea, inland, special and pipeline. Highways, sea ports, airports and railroads are built. These activities are detrimental to the natural environment.

The pollutants that contribute to lowering the level of air quality, originating in transport, are gases emitted from systems installed in cars, trains and maritime units. Airborne nitrogen oxides, sulphur dioxide, carbon dioxide, metals and organic compounds are the main pollutants generated by the transport sector.

In order to protect the natural environment and human health, the emission of pollutants is constantly reduced due to the use of solutions reducing the release of toxic compounds, e.g. the use of exhaust gas catalysts in road vehicles. The type of used fuel is crucial in solving the problem. Liquefied natural gas is an ecological fuel characterized by high demand in sea and road transport , as well as many other areas of the economy. Its specificity is due to the low level of sulphur that is released into the atmosphere in relation to other fuels used.

Air pollution

The level of air pollution in the world is constantly increasing. In particular, this phenomenon is noticeable in developing countries. Contamination is primarily evidenced by the presence of gases, liquids or solids in the air composition that are not its natural components. This also applies to an emerging concentration that does not correspond to the natural composition of the Earth's atmosphere. It is the most dangerous type of pollution because it cannot be confined to a specific area. Due to its mobility, it covers a considerable range of environmental contamination.

The increasing demand for energy causes gas and dust pollutants to enter the atmosphere: PM10, CO, PM2.5, NO_2, SO_2. The main factors contributing to this are coal-fired power plants, the increase in the number of road vehicles, improper use of energy in residential buildings and the use of biomass for heating or cooking, etc.

Due to the presence of SO_2 in the air and other, previously mentioned pollutants, there is a constant effort to reduce the level of harmful compounds generated in the combustion process of fuel used as a drive for road and sea units, etc. An alternative to the previously used fuels in various areas of the world economy is the use of "blue fuel". Due to its ecological properties, natural gas is commonly referred to as "blue fuel" and could be one of the many solutions to reduce pollution. Due to in order to protect the natural environment, the demand for natural gas is constantly increasing.

In the sea areas this demand results from the introduced in 2015 legal regulation on the content of sulphur and other harmful compounds in fuels used in the areas of strict sulphur emission control SECA (Sulphur Oxide Emission Control Area). Directive 2012/33/EU of the European Parliament and of the Council has limited the sulphur content of the fuel used by marine vessels operating in the Baltic Sea, the North Sea, the English Channel and coastal waters of North America to 0.1%. and the following Directive (EU) 2016/802 of the European Parliament and of the Council of 11 May 2016 relating to the reduction of sulphur content in certain liquid fuels [Chłopińska & Nowakowska 2017].

5.1 The transport and LNG reloading stations impact on the environment

Potential fire and explosion hazards related to the transport, storage or use of LNG result mainly from three properties of this substance, in particular:

- at atmospheric pressure, depending on its composition, LNG has a boiling point of around –162°C. At this temperature, LNG vapours are much heavier than air,
- small amount of the LNG liquid phase transforms into a large volume gas cloud. One unit by volume of the liquid phase of LNG produces about 600 units by volume of gas,
- natural gas, like other hydrocarbon gases, is a flammable gas, so it forms an explosive mixture with air. In order to catch fire, LNG must first be vaporized (heated and brought to a vapor state), mixed with 5% to 15% air, and brought into contact with an ignition source.

Fig. 8. A ship with liquefied natural gas at the LNG terminal in Świnoujście [https://portalstoczniowy.pl/wiadomosci/pgnig-trzeci-statek-ze-skroplonym-gazem-ziemnym-z-usa-w-gazoporcie-w-swinoujsciu/ access on 23.07.2020]

When LNG is released, e.g. from a tank onto the ground, as a result of a failure, it evaporates rapidly until the evaporation rate reaches a constant value, which largely depends on the thermal characteristics of the substrate and the heat obtained from the air.

If LNG is released above the water surface during shipping, the evaporation rate will be constant due to the high heat transfer due to convection in the water.

In the first stage, the gas released during the rapid evaporation of LNG has almost the same temperature as condensation temperature. At this time, the relative density of LNG is greater than that of air. When spreading, this gas accumulates just above the ground. Then, as the temperature rises to about - 110°C, it becomes lighter than air. If LNG leaks from pressurized equipment or pipelines, it will be released in a stream into the atmosphere. This process is associated with intensive, physical mixing of LNG with air. In this situation, a large part of the LNG will be contained in the released cloud. Initially in the form of an aerosol, and then as a result of mixing with air, the LNG will gradually evaporate [Łaciak & Nagy 2010].

Hence, the basic problem of LNG transport is its very low temperature during transport and the negative impact on the environment as a result of spillage (e.g. the so-called low-temperature brittleness of steel) [Herdzik 2017].

When exposed to air, LNG evaporates and dilutes in the air. Therefore, it is a much less harmful and dangerous fuel than, for example crude oil.There is no possibility of contamination of the environment (sea water, soil) in the event of an LNG leak. Modern technologies for the construction of LNG tanks ('full-containment', "tank in a tank"), special procedures and security systems ensure an exceptionally high level of security for regasification terminals [https://www.polskielng.pl/terminal-lng/lng-w-pigulce/znaczenie-i-zalety-lng/].

Nevertheless, there are dangers resulting from the physicochemical properties of LNG. The threats that may arise in the LNG supply chain are related to the properties of this fuel [Bralewski & Wolanin 2019; Herdzik 2017]. Sedlaczek [2010] points to three types of threats that result directly from the physicochemical properties of LNG and are related to the storage and transport of this substance. These are: fire and explosion hazards; "rollover" and the Rapid Phase Transition (RPT) phenomenon [Sedlaczek 2010, Łaciak & Nagy 2010, Zabrzeski et al. 2017]. Other authors also indicate the possibility of such phenomena as: pool fire, jet fire, explosion of expanding vapours of boiling liquid (BLEVE) [Pitblado & Woodward 2011, SIGTTO 2012], flash fire and vapor cloud fire [Dalaklis 2015, Havens & Spicer 2007].

5.2 The ecological results of the use of LNG, CNG and biogas (biomethane) in public transport

The composition of natural gas, which determines its physicochemical properties, makes it an excellent engine fuel and does not require major modifications and processing. Compressed natural gas engines emit much smaller amounts of harmful substances into the atmosphere than engines powered by traditional liquid fuels. The emission of harmful substances is so low that CNG buses meet current and future European environmental standards [Bogusz 2014].

The noticeable difference in the air quality and effect of less frequent painting of the external facades of buildings can be caused of unmanufactured smoke while using CNG as fuel. Therefore, the use of CNG initiates a secondary ecological effect consisting in reducing emissions from paints used to paint buildings. When refuelling a car with natural gas, no fuel is emitted into the atmosphere. In addition, the gas exchange effect of natural gas tanks does not occur when the car is stationary, as is the case with traditional fuel tanks. Although it is a greenhouse gas, it cannot contaminate the ground and groundwater like spilled liquid fuels. The composition of CNG and the lack of carcinogenic substances extends the life of the engine. Therefore, it positively contributes to the process of utilization and recycling of waste [https://cng.auto.pl/ekologia-cng/].

The natural gas engine runs smoothly, which contributes to noise reduction by an average of 5 dB compared to diesel engines Due to small amount of sulphur in the composition of natural gas it emits a small amount of this element to the environment. It causes low particulate matter (PM) emissions (-95% compared to a diesel engine) and nitrogen oxides (-35%), as well as low carbon dioxide emissions (from 10% even to 100% - if biomethane is used) [https://cng.auto.pl/ekologia-cng/].

Vehicles powered by liquefied natural gas must be equipped in cryogenic tank that stores fuel at a very low temperature. Due to the significant energy storage in one litter of liquefied gas, fuel tanks are three times smaller than compressed gas tanks. While maintaining the advantages of CNG gas (high purity of exhaust gases, low fuel price), the LNG drive eliminates the problem of large tanks on the vehicle roof and longer refuelling time.

LNG is also a safe fuel. As in the case of CNG, almost pure methane escapes from the damaged tank of the vehicle, which under normal pressure and relatively high ambient temperature begins to boil into a gaseous state. Being a gas lighter than air, methane dissipates quickly, rarely forming an explosive cloud. It may be controversial that in the first moment of methane transition from a liquid to a gaseous state, gas has a very low temperature. Until the gas temperature rises, i.e. in the first seconds, very cold methane is a gas heavier than air and may accumulate in depressions of the ground. This effect is very short and is important in the event of damage to large LNG tanks or pipelines. There are worldwide known cases of the formation of large clouds of cold methane, which would ignite, causing great damage. In the case of small fuel tanks installed in passenger vehicles and buses, the safety of using LNG can be considered almost identical to that in vehicles with compressed gas [Bogusz 2014].

LNG is practically free of contamination with sulphur compounds, and consequently no sulphur oxides emissions in the exhaust gas can be noticed. Additionally, reduction of CO_2 emissions by approx. 25%, NOx by approx. 85% compared to traditional fuels, and elimination of SOx emissions can be noticed [http://pgnig.pl/o-lng].

The effect of using biogas (biomethane) is similar to that of compressed natural gas (CNG). However, it comes from renewable sources.

Biogas is more expensive to produce than natural gas, but its use has the advantage of reducing CO_2 emissions. In addition, according to EU law, biological waste must not be stored due to uncontrolled methane emissions, which has a 22 times greater negative impact on the greenhouse effect than the aforementioned carbon dioxide.

The test results show that:

- currently, methane-powered buses that meet the EEV standard (Enhanced Environmentally Friendly Vehicle) clearly outperform EEV diesel engines for NOx and PM emissions,
- methane-powered vehicles have true EEV properties,
- all methane-powered vehicles have very low PM emissions,
- stoichiometric vehicles are characterized by lower NOx emissions and lower fuel consumption,
- clear benefits for methane also in terms of unregulated emissions (particle number, aldehydes, PAH, NO_2 emissions, etc.),
- the main disadvantage of methane fuelled spark ignition engines compared to compression ignition engines is the higher energy consumption.

However, it should be remembered that biomethane is a renewable fuel and thus the CO_2 emission for well to wheel is close to zero [Nylund 2010, Merkisz et al. 2011].

5.3 The biogas plants impact on the environment

Agricultural biogas plants above 0.5 MW have been classified as projects that can potentially have a significant impact on the environment. The construction and operation of an agricultural biogas plant may affect:

- the state of air pollution in the scope of standard substances such as nitrogen dioxide, sulphur dioxide, carbon monoxide, dust, aromatic hydrocarbons and non-standard odour substances (hydrogen sulphide),
- ground and water environment in terms of water intake, water pollution with sewage and rainwater, especially with nitrogen compounds,
- acoustic climate through noise emission from technical devices and means of transport.

Table 3 presents the environmental hazards of an agricultural biogas plant.

Fig. 9. Example of a biogas plant in Boleszyn [photo by S. Ostrowski. https://ro.com.pl/wp-content/uploads/2014/01/boleszyn1.jpg / access on 23.07.2020]

Table 3. Environmental hazards of an agricultural biogas plant
[https://wios.rzeszow.pl/cms/upload/edit/file/BIOGAZOWNIA.pdf]

Process	Danger
Supply and intake of substrates	Exhaust emissions, traffic noise, odours from transported loads, emergency spills, escape mass being transported onto the road and adjacent land with the possibility of water pollution
Preparation of substrates	Cracking of the tanks and the release of the prepared mass with possible water contamination, odours. Noise emission from mixing devices. The probability of bacteriological threats
Processing of substrates	Explosion of biogas, fermentation mass leaks outside the chamber with possible water contamination
Biogas treatment	Explosion of biogas, emission of hydrogen sulphide
Energy production in a cogeneration system and emergency biogas combustion in a flare	Exhaust emission, noise, gas explosion hazard
Treatment of the digestate	The prepared mass comes out with the possibility of water contamination, odours
Removal of digestate	Exhaust emissions, traffic noise, odours from transported loads, emergency spills, escape mass being transported onto the road and adjacent land with the possibility of water pollution
Recovery of digestate in arable fields	Ground contamination, water pollution with nitrogen compounds, soil over-fertilization

Stench hazards caused by the nuisance sulphur and nitrogen compounds contained in biogas are very specific threats to people and the environment of the discussed installation. Apart from the aspects related to this problem, it should be remembered that the main component of biogas - methane is explosive. The risk of explosion in the case of a mixture consisting of methane, air and inert gas (N_2 and CO_2) exists within the methane content from 4.9% (LEL - lower explosion limit) to 15.4% GGW (upper explosion limit). If an inert gas such as nitrogen or carbon dioxide is introduced into the mixture of methane and air, the explosive limits are narrowed, i.e. the LEL increases and the GGW decreases. Careless operation of a biogas plant or work in insufficiently ventilated tanks may cause poisoning or even an explosion, which results from the analysis of long-term lists of events that caused serious industrial accidents [Klemba 2015].

5.3.1. The components of biogas adversely affecting human, biogas equipment and its surroundings

Hydrogen sulphide and other sulphur compounds

In biogas, sulphur can be in the form of inorganic compounds (primarily in the form of hydrogen sulphide, but also carbon disulphide or oxysulphide) as well as organic compounds - thiophene, mercaptans, thioethers, dimethyl sulphide. With the exception of hydrogen sulphide, these compounds are usually present in trace concentrations below 1 $mg \cdot m^{-3}$ [Klemba 2015].

Ammonia

During the production of biogas, ammonia may also be formed, which is an undesirable phenomenon, as it has an inhibitory effect on the fermentation process. Ammonia emitted to the atmosphere undergoes a cycle of chemical transformations, the effect of which is a negative impact on the water environment and soil, such as eutrophication of water reservoirs and soil acidification [Klemba 2015].

Carbon oxygen compounds

Carbon dioxide is the second quantitative component of biogas that is removed to produce biomethane. In the presence of moisture, it can contribute to steel corrosion due to the formation of weak carbonic acid, which dissociates into an acidic environment. As a natural component of the air, carbon dioxide has no direct harmful effect on the natural environment, but an increase in its concentration in the atmosphere is considered to be one of the causes of global warming. Traces of carbon monoxide (CO) are usually present in biogas [Klemba 2015].

Chlorinated hydrocarbons

The average content of chlorinated hydrocarbons in biogas does not exceed 10 $mg \cdot m^{-3}$. They mainly come from pollutants contained in wastewater as well as agents used in wastewater treatment and water treatment. Examples of chlorine compounds detected in biogas are: chloroethane, dichlorofluoromethane, trichlorofluoromethane, chlorotrifluoromethane, trichloromethane, tetrachloroethane, trichloroethane, dichloromethane, dichloroethane, dichloroethene, dichloropropane, tetrachloromethane, chlorobenzethylene, and chlorachlorethylene. Halogenated hydrocarbons are characterized by high chemical activity, and when burned in the engine, they form strong acids in combination with water, which cause corrosion of the system components: hydrochloric (HCl), hydrobromic (HBr) and hydrofluoric (HF) [Szlęk 2012, Klemba 2015].

Siloxanes

Biogas from agricultural biogas plants usually does not contain them in its composition, while the average content in biogas produced from waste and sewage sludge is in the range of 3-300 $mg \cdot m^{-3}$ [Szlęk 2012]. The presence of siloxanes in the biogas hinders combustion processes and is detrimental to the installation [Klemba 2015].

5.3.2. Odour impact on biogas plant workers and local residents

The fear of odour nuisance is one of the most common causes of conflicts during the implementation of investments related to biogas production. While investment process is implemented the fear of odour nuisance is one of the most common causes of conflicts. It is declared cause of social protests (for 19.12%). Potential sources of odours are mainly substrates used for the fermentation process, as well as leakage in tanks, storage of the digestate without cover or irregularities in the operation of the installation. It is rare situation that in normally operating biogas plant there are emissions of odorous substances. Possibility of emission of those substances increase with biogas plant malfunction.

It has been proven that the fermentation process in an efficiently operating biogas installation may contribute to reducing the odour nuisance of potential natural fertilizers from agricultural activities, e.g. liquid manure or manure poured onto the fields. Natural fertilizers subjected to the fermentation process become significantly less burdensome in terms of smell, and the odour is felt for a shorter period than in the case of non-fermented fertilizers. The characteristics of a few selected potentially odour nuisance substrates are presented in Table 4.

Table 4. A simplified characteristic of the aromatic effect of selected substrates from the methane fermentation process [Curkowski et al. 2014]

Substrate	Characteristic of the smell	Selected products of biomass decomposition responsible for its unpleasant smell
Corn silage (rotting)	sour smell (butyric acid), mouldy and musty	butyric acid, biogenic amines, ammonia
Post-slaughter waste	the smell of carcass	hydrogen sulphide, mercaptans, aldehydes, fatty acids, aliphatic amines
Slurry	the smell of pickled cucumbers	mercaptans, aminomercaptans, ammonia, indole, skatole, amines and fatty acids, hydrogen sulphide
Distillery stock	bread scent, fermentative, distillers	hydrogen sulphide, ammonia

The smell of biogas is not constant, but depends on the chemical composition of the substrates used for fermentation. The most odorous biogas components include mercaptans, ammonia, hydrogen sulphide, dimethyl sulphide, diethyl sulphide, methylamine, trimethylamine and butanoic acid [Curkowski et al. 2014]. Table 5 presents a simplified characteristic of the biogas components causing odours.

Table 5. Odour characteristics of the most troublesome biogas pollutants [Curkowski et al. 2014]

Substance	Summary formula	Characteristic of the smell
Thiols (mercaptans)	CH_3SH, C_2H_5SH	the smell of rotten cabbage or garlic
Hydrogen sulphide	H_2S	the smell of rotten eggs
Ammonia	NH_3	sharp, acrid ammonia smell
Dimethyl sulphide	$(CH_3)_2S$	the smell of rotting vegetables
Diethyl sulphide	$(CH_3CH_2)_2S$	the smell similar to garlic
Butanoic acid	$CH_3(CH_2)_2COOH$	the smell of rancid fat
Methylamine and trimethylamine	CH_3NH_2, $(CH_3)_3N$	putrefactive, fishy smell
Thiophenol	C_6H_5SH	putrefactive smell reminiscent of garlic
Chlorophenol	ClC_6H_5O	the smell of drugs, phenolic
Indole	$C_2H_6NH_2$	bland, faecal smell
Skatole (3-methylindole)	C_9H_9N	bland, faecal smell
Tolylthiol (thiocresol)	$CH_3C_6H_4SH$	the smell of skunk, rancid fat

The threat to the environment may be caused, among others, through [https://wios.rzeszow.pl/cms/upload/edit/file/BIOGAZOWNIA.pdf]:

- failure to maintain the environmental protection equipment and control and measurement apparatus in a proper condition,
- failure of waste hygiene equipment (e.g. post-slaughter waste),
- violation of the prohibitions:
  - application of fertilizers on soils that are flooded with water, covered with snow, frozen to a depth of 30 cm and during rainfall,
- use of natural fertilizers:
  - nitrogen fertilizers , and liquid form fertilizers - on soils without plant cover, located on slopes with a slope of more than 10%,
  - liquid form fertilizers - during the vegetation of plants intended for direct human consumption,
- predictable or unpredictable meteorological phenomena,
- other unpredictable events.

In order to avoid and minimize the above risks, it is necessary to [https://wios.rzeszow.pl/cms/upload/edit/file/BIOGAZOWNIA.pdf]:

- deployment and maintaining proper stability of the fermentation process,
- proper sealing of devices, especially fermentation chambers, e.g. through the use of concrete, sealing materials and protecting walls of tanks of the appropriate class,
- proper execution and tightness of technological pipelines,
- elimination or minimization of the use of corrosive elements in installations,
- constant monitoring - control of the technical condition of the equipment with the possibility of immediate shutdown and termination of all devices,
- adequate training of the staff in the field of operating activities, health and safety rules and fire regulations,
- strict control of people not employed in the facilities,
- application of the air composition monitoring system, especially in the buildings of biogas plants,
- installation of control systems alerting about failures and generating failure reports,
- development of a schedule for performing the required checks, inspections and checks.

5.3.3. Environmental conditions

In order to reduce the possible negative impacts of a biogas plant in the form of emissions: noise (>40 dB), exhaust fumes, unpleasant odours and due to the consequences of possible failures, it is required that the biogas plant was located at a distance of more than 300 m from human habitats, taking into account the prevailing directions winds, so that for as long as possible it is on the leeward side of residential buildings and protected areas. It is also advisable to eliminate the transport of raw materials and digestate through built-up areas. Biogas plants should be isolated from the adjacent inhabited areas by a system fence. It could be a metal fencing, as well as medium and high-growth belt greenery (optional).The conditions for generating waste may be the subject of decisions issued under the Act on waste.

In connection with the operation of biogas plants, the following waste may be generated:

- digested waste from anaerobic digestion of animal and vegetable waste, code 19 06 06,
- sorbents, filter materials, wiping fabrics, code 15 02 03,
- protective clothing, code 15 02 02*,
- waste oils and waste liquid fuels, code 13 02 05*.

A project consisting in the construction of an agricultural biogas plant which is well planned and designed, preceded by public consultations, analysed by independent experts, taking into account environmental, economic and technical aspects, should not pose a threat to the environment. It is provided that the installation is operated by qualified employees and the technological regimes established by public administration bodies and formal and legal requirements [https://wios.rzeszow.pl/cms/upload/edit/file/BIOGAZOWNIA.pdf].

6. Life Cycle Assessment (LCA) – technique of environmental risk assessment

The LCA life cycle assessment is one of the techniques for estimating the potential environmental impact. One of its main objectives is to seek to identify all factors related to a given project (or product), that may affect the degradation of the natural environment [Zaleska-Bartosz & Klimek 2011, Samson-Bręk 2012].

In entire life cycle of a product it is possible to identify generating factors that causes the greatest threat to the environment. This allows to minimize its negative impact by improving the technology in the most environmentally harmful phase of the product (process) life . It is possible due to the environmental analysis of the entire life cycle of a product - i.e. from the extraction / acquisition of raw materials, their transport, through manufacturing processes, to the end use of a given product and the management of the resulting by-products and waste [Zaleska-Bartosz & Klimek 2011, Samson-Bręk 2011].

6.1 Liquefied natural gas supply chain - ecological aspects - analysis of the LCA

Natural gas extraction, LNG production, transport, regasification and its use involve the use of a number of technologies, each of which has a certain environmental impact. All these stages make up the so-called "LNG supply chain" (Fig. 10).

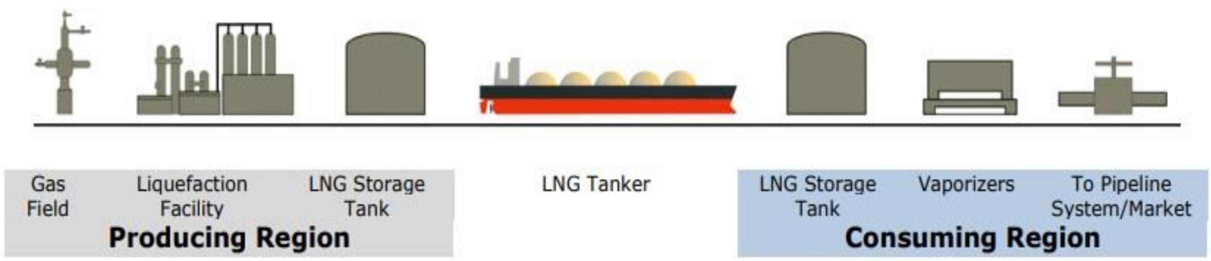

Fig. 10. LNG supply chain
[https://www.beg.utexas.edu/files/cee/legacy/LNG_Safety_and_Security_Update_2012.pdf]

The main links in the LNG supply chain are:

- exploration and appraisal works, extraction of natural gas and its transport to the LNG production plant (liquefaction of natural gas),
- liquefaction of natural gas into LNG, storage and loading onto means of transport (ships / tankers),
- sea and / or land transport to collection points (regasification stations),
- LNG regasification and assigning it to system gas parameters,
- Deliveries to end users via the gas transmission and distribution system [Zaleska-Bartosz & Klimek 2011].

Environmental impact of the first two links, i.e. exploration and appraisal works and the exploitation of natural gas deposits, depends on the scale of the project. That is the size of the area covered by exploration, the sensitivity of individual elements of the environment to changes related to the conduct of geological works (seismic and drilling), the size of the production, the type of gas produced, as well as the technological processes necessary for its purification and treatment prior to transport and delivery to the recipient. All these projects are subject to environmental impact assessments carried out at the stage of granting permits for this type of activity (concessions and building permits) [Zaleska-Bartosz & Klimek 2011].

The environmental impact of the remaining links in the LNG supply chain depends on the size of the installation and its location. Generally, gas liquefaction and regasification installations are conventionally divided into installations [Zaleska-Bartosz & Klimek 2011]:

- large-scale (over 300 tons of LNG / day), for international and intercontinental deliveries by sea (so-called LNG terminals),
- medium (up to 300 tons of LNG / day), of regional importance, connected with the LNG distribution network by land transport,
- small (up to 20 tons of LNG / day) of local importance.

Large-tonnage installations for the implementation of LNG deliveries (i.e. transmitting terminals equipped with installations for liquefying natural gas), as well as LNG receiving terminals with installations for its regasification, are built on environmentally sensitive sea quays. Due to the protection of these areas, the location of the investment is very important. Both the construction stage of the terminal and its subsequent operation cannot expose to destruction valuable natural elements, important from the environmental protection requirements point of view. It is essential that gas ports must be located in places that they do not pose a threat to local residents, and are not exposed to factors such as strong winds, floods or tectonic movements. The size of the area occupied by the gas terminal depends on its storage capacity, the complexity of the infrastructure and the need to maintain safe distances between individual facilities [Zaleska-Bartosz & Klimek 2011].

Assessment of the environmental impact of the entire LNG supply cycle - i.e. all stages: from the extraction of natural gas from deposits, through its liquefaction, transport, regasification, and then distribution and use - is a very difficult task. There are no reliable data showing the environmental impact of individual links in the LNG supply chain. It cannot be unified due to the differences in the surroundings in which the same operations are carried out. The environmental assessment of the entire cycle can only be carried out when the specific locations of each step are known [Zaleska-Bartosz & Klimek 2011].

It is slightly easier to analyse the environmental issues related to the LNG supply chain by selecting one factor against which the impact of the entire chain on the global state of the environment can be assessed. This can be achieved by the environmental life cycle assessment (LCA), prepared in terms of greenhouse gas emissions (CO_2 and CH_4 converted to CO_2) occurring at all stages of the LNG supply chain (Fig. 11) [Tamura et al. 2001]. As shown by the LCA analysis by Tamura et al. (2001) in terms of the amount of greenhouse gases emitted (converted into CO_2 equivalent), the most critical link in the LNG supply chain is - due to the high consumption of fuel gas - the liquefaction stage.

On a global scale, these emissions are compensated by heat recovery, the introduction of cogeneration systems in gas liquefaction plants and the use of LNG cryogenic energy in receiving terminals.

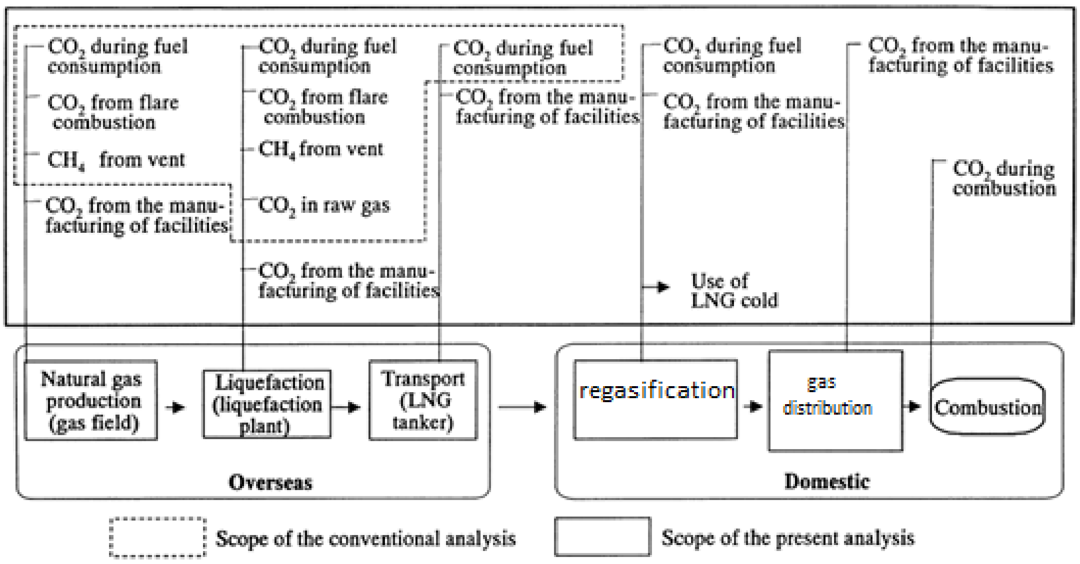

Fig. 11. CO_2 life cycle analysis from the LNG supply chain [Tamura et al. 2001]

6.2 Biogas production line and using it as a fuel for internal combustion engines - an ecological aspects and analysis of the LCA

The production and use of fossil fuels is related to high emissions of greenhouse gases and harmful substances to the environment. A chance to reduce this negative impact is the search for new, more environmentally friendly than fossil fuels, energy carriers. Agricultural biogas, used as engine fuel, becomes such a carrier [Samson-Bręk 2011].

Growing social awareness and stricter legal requirements in the field of environmental protection result in increased interest in methods that may reduce the negative impact on the environment. LCA life cycle assessment is helpful in the selection and modification of the method. Due to its comprehensive nature, LCA assessment allows for a full assessment of the environmental impact of the entire production process, from the acquisition of raw materials to the final management of waste resulting from the use of the product. In the case of the production of agricultural biogas used as engine fuel, the LCA assessment was conducted on the production of biogas, its purification and use as engine fuel. It was also assumed that the post-fermentation sludge constituting post-production waste can be used as a fertilizer for agricultural purposes [Samson-Bręk 2011].

The use of the LCA method brings a number of benefits, both environmental and economic. This method may prove to be useful in making investment decisions to minimize the environmental impact of the installation's operation. Based on the results of the assessment, it is possible to develop technologies that will meet all environmental protection requirements.

Table 6 shows input and output data in the process of biomethane formation with 98% methane content.

Table 6. Input and output data in the process of biomethane formation [Samson-Bręk 2011]

Input from "nature"	
Water	
Inputs from the "technosphere" (materials, fuels, electricity and heat)	
Main substrate	Slurry
Fuel consumption	Fuel consumption during raw material transport
Electric Energy usage	Electricity consumption in the installation (biogas production and purification process)
Thermal Energy consumption	Consumption of thermal energy to maintain an appropriate temperature in the fermentation chamber
The output	
Main product	Biogas with 98% methane content
Waste and emissions	
Solid waste	Post-fermentation sludge - used as a fertilizer (avoided products - i.e. avoided production of ammonium nitrate and nitrogen fertilizers)
Emissions to air	CH_4
	CO_2
	NO_2
Emissions to water	Waste water from the biogas purification process

According to Samson-Bręk (2011), in the case of the life cycle assessment of biogas production and use as an engine fuel (Fig. 12), the most important category in the LCA analysis will be the impact on climate change category (Table 7).

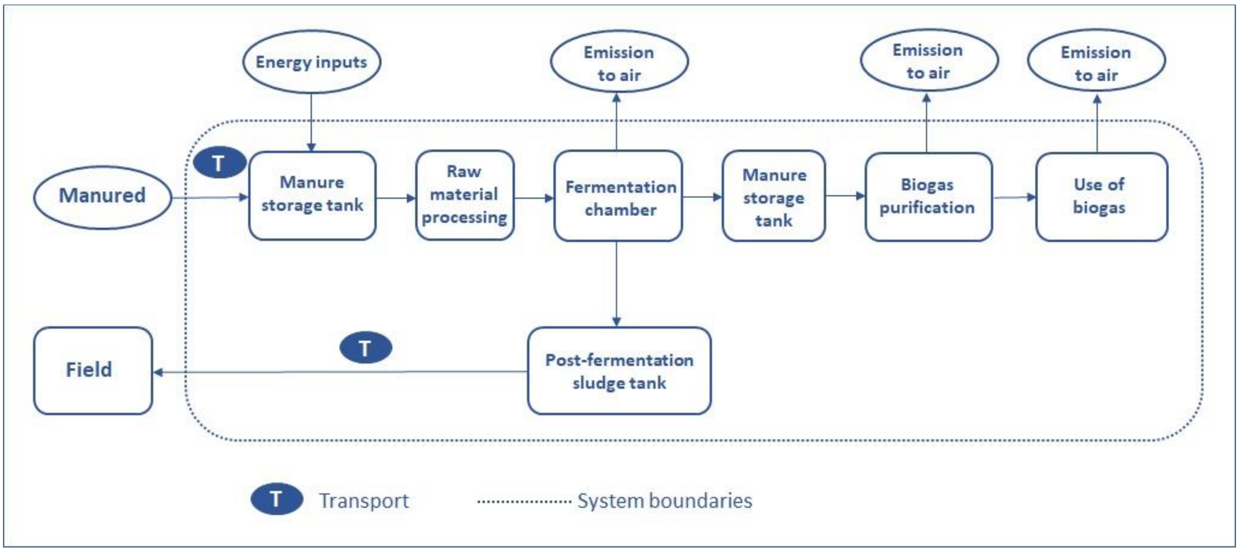

Fig. 12. General diagram of the model of the tested biogas production line, including all stages taken into account in the LCA analysis [Samson-Bręk 2011]

Table 7. Impact categories in the LCA assessment of biogas production and its use in internal combustion engines [Samson-Bręk 2011]

Impact category	Data relating to inputs and outputs to / from the environment	Indicator
Climate change	- carbon dioxide (CO_2) - nitrogen dioxide (NO_2) - methane (CH_4)	Re-counting the data to carbon dioxide equivalent (CO_2)
Acidification	- sulphur oxides (SO_x) - nitrogen oxides (NO_x) - hydrochloric acid (HCl) - ammonia (NH_4)	Re-counting the data to ion hydrogen equivalent H^+
Eutrophication	- phosphates (PO_4) - nitrogen oxides (NO_x) - nitrogen oxide (NO_2) - nitrates - ammonia (NH_4)	Re-counting the data to phosphate equivalent (PO_4)

The importance of the above categories is mainly related to the emission of greenhouse gases and other harmful substances both during biogas production and during its combustion in the engine. The factors that have the greatest impact on the climate change category are methane losses during the transport of the raw material to the installation and the production of biogas (about 3%) as well as carbon dioxide generated during the combustion of biomethane. Methane belongs to the group of Greenhouse gases that affect climate change known as the greenhouse effect. According to various assessments, the impact of methane on the deepening of the greenhouse effect is 21 times higher than that of carbon dioxide.

For other impact categories, such as acidification or eutrophication, the environmental impact of biogas is largely compensated by the use of digestate as a fertilizer, thus avoiding the production of ammonium nitrate and nitrogen fertilizers. The production of mineral fertilizers requires large amounts of energy from fossil fuels, and their use causes significant emissions of nitrogen compounds, thus affecting the eutrophication process, acidification and damage to the ozone layer [Samson-Bręk 2011]. We are dealing here with the so-called secondary ecological effect.

Based on the information contained in the final LCA analysis, decisions are made to minimize the negative impact of the activity, as well as decisions regarding technological solutions aimed at improving the environmental quality of the product.

According to Samson-Bręk (2011), the production and use of fuels is associated with high emissions of greenhouse gases and harmful substances to the environment. A chance to reduce this negative impact is the search for new, more environmentally friendly than fossil fuels, energy carriers. Agricultural biogas, used as engine fuel, becomes such a carrier.

6.3 Growing biomass for energy purposes - an ecological aspects and analysis of the LCA

The use of the LCA method to estimate the environmental impact of biomass grown for energy purposes allows for the awareness and indicates the interdependence between human activity and its consequences for the natural environment [Samson-Bręk 2012].

Figure 13 shows a general scheme of the model of the tested biomass production line intended for energy purposes, taking into account all stages in the LCA analysis [Chłopek and Samson-Bręk 2017]. It presents unit processes typical for the cultivation of energy crops.

Table 8 presents the impact categories in the LCA assessment of biomass production intended for energy purposes [Chłopek and Samson-Bręk 2017].

The results show that the two unit processes related to the cultivation of e.g. maize for silage have the greatest impact on the environment. This result is related to the need of allocation land for maize cultivation and the use of mineral fertilizers and plant protection products, the production and use of which requires energy input. This results in significant particulate and gas emissions into the air. Moreover, fuel combustion (diesel oil) during field works and raw material transport to the biogas plant is also the main component. It is also worth emphasizing that the process of generating electricity from biogas has a positive impact on the environment [Chłopek and Samson-Bręk 2017].

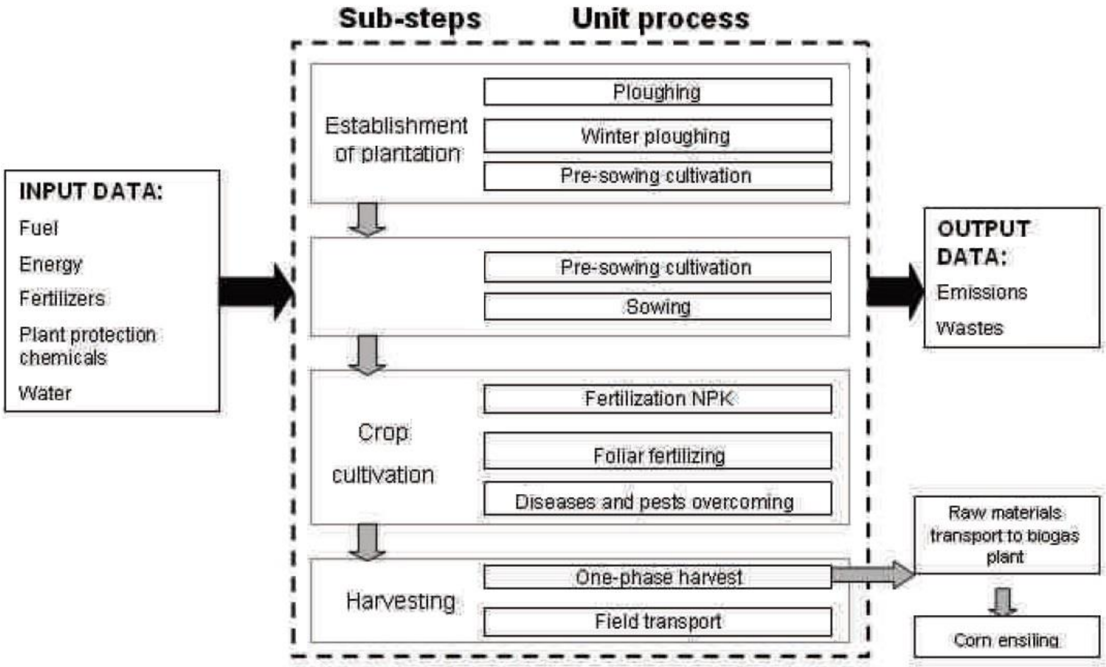

Fig. 13. General scheme of the model of the tested biomass production line intended for energy purposes, taking into account all stages in the LCA analysis [Chłopek and Samson-Bręk 2017, Samson-Bręk 2012]

Table 8. Impact categories in the LCA assessment of production intended for energy purposes [Chłopek and Samson-Bręk 2017, Samson-Bręk 2012]

Impact category	Inputs and outputs (LCI)	Indicator
Climate change	carbon dioxide (CO_2), nitrogen dioxide (NO_2), methane (CH_4), chlorofluorocarbon (CFC), hydrochlorofluorocarbon (HCFC)	Re-counting the data to carbon dioxide equivalent (CO_2)
Ozone layer depletion	chlorofluorocarbon (CFC), hydrochlorofluorocarbon (HCFC), halons	
Acidification	Sulphur oxides (SO_x), nitrogen oxides (NO_x), ammonia (NH_4)	ecosystem quality (in categories: acidification, eutrophication and land use) – the value of the damage is given in PDF unit (Potentially Disappeared Fraction); for ecotoxicity damage is expressed in PAF × m^2 × year unit, showing the percentage of species living in the environment under the toxic stress)
Eutrophication	nitrogen oxides (NO_x), ammonia (NH_4), phosphate (PO_4), nitrates	
Land use	area of the land used for crops as well as its transformation and degree of transformation	
Fossil fuel depletion	the amount of fossil fuels and minerals used	depletion of natural resources MJ/t

7. Environmental pros and cons. The New Gas Boom

The Global Energy Monitoring Report of June 2020 provides alarming information. The authors of the report see some incorrections in this rapidly developing industry. The future of gas infrastructure may be risky in the long term, they inform. The performed analysis uses a common basis, called CO_2 equivalent or CO_2, where 1 tonne of methane emissions corresponds to 21 tonnes of CO_2. Two comparisons were made in the report - in the period of 20 years and the second in the period of 100 years. The 20-year horizon is important for understanding how much methane emissions will affect the climate in the short term. The 100-years horizon give information about methane emission impact in the long term.

Significant development in construction threatens to lock in huge amounts of greenhouse gas (GHG) emissions. Intergovernmental Panel on Climate Change (IPCC) identified tipping point of global warming to the 1.5°C. Expressive development in construction may thwart the chances of it.

Public acceptance of LNG is questionable as research has disproved the image of fossil gas as an environmentally friendly "bridge fuel" to low-carbon prospects.

In 2016 the authors of the IPCC's 2014 assessment concluded that methane's impact on global warming is about 25% higher than previously estimated. Unstable emissions from the gas supply chain elements (e.g. gas fields) invalidate the arguments in favor of gas [Plant et al. 2019].

Lifecycle emissions for power from LNG are from 29% lower to 16% higher than coal-fired power. This includes estimations of methane leakage throughout the system.

Due to the consequences of further locking in fossil combustion, replacement coal to gas gives no opportunity to achieve carbon neutrality and reduction in greenhouse gas emissions [Plant et al. 2019].

Due to reduced carbon dioxide production compared with coal-fired power plants (about half as much carbon dioxide) fossil gas has been advertised as a "clean bridge fuel" that could allow to shut down coal-fired power plants. It has been consider as a temporary solution until renewable energy becomes more affordable. Hence there has been a pressure to expand natural gas systems with LNG as a relevant part of it [IEA 2019].

The major problem of fossil gas system is leakages. Fossil gas consists mainly of methane which is a greenhouse gas that is more significant than CO_2. Methane leaks may occur from extraction wells, compressors, and pipelines. It is worldwide issue, appearing in many gas-producing countries as a major source of methane emissions. [ESA 2020] Methane leak studies are based mainly on U.S. data. Recent studies have found that US Environmental Production Agency underestimated methane leakage data [Alvarez et al. 2018].

The overall leakage of the U.S. fossil gas system is estimated to be 2.3% . U.S. research data shows [Alvarez et al. 2018]. Due to methane leaks, the emission of this gas is similar to the natural gas burning in power plants or heating. A period of 20 years was evaluated. Of these causes methane leaks could double warming [Alvarez et al. 2018].

Using fossil gas for electricity can achieve only slight reductions in warming compared with using coal. It is caused by the leakage in the U.S. fossil gas system. Fossil gas system locks in long-term fossil infrastructure. In those circumstances the transition to combinations of renewables and battery storage is delayed.

Due to differences of the nature of methane and carbon dioxide, there are difficulties in comparisons of the global warming profiles of those gases.

The influence on global warming by building a new gas plant (supplied by LNG) instead of a new coal plant, can range from 29% lower to 16% higher. It is estimated by taking into consideration methane leakage rates, relative efficiencies of the coal-fired plants , relative efficiencies of the gas-fired power plants, and the period of time over which warming is being measured.

Exchange from coal to gas does not seem to be an efficient solution for reducing greenhouse gas emissions, and achieve carbon neutrality. It is due to the aftermath of further locking in fossil combustion instead of switching to renewable power.

The water transport of fossil gas (LNG) substantially increases greenhouse gas emissions. Turning LNG into a liquid requires massive energy input . It is to run compressors to cool the gas to very low temperatures. Usually 10–20% of the incoming gas is burned to power the liquefaction process. [Lowell et al. 2013]. LNG tankers traveling long distances add more emissions from the fuel they burn. For instance transect from Texas to Japan. The use of fossil gas as LNG cause increase CO_2 emissions even to 25% more those from burning the gas for electricity or heat [Pavlenko et al. 2020].

Fossil gas is continuously more used for land and marine transportation (in cars, trucks, and ships). It is an exchange from liquid fossil fuel like gasoline, diesel, heavy fuel, and marine gas oil fuels used in transportation. Taking into consideration the methane leakage rates in the U.S. fossil gas system, replacement liquid fuels to gas surprisingly increases the emissions from these vehicles [Alvarez R. et al. 2012, Pavlenko et al. 2020].

The measurement of gas leakage becomes more accurate throughout the natural gas supply system. There is also more research on methane's potential as a greenhouse gas. Hence approach to gas in a climate-constrained energy system has changed over the time. From positive to negative in the last decade.

Even though carbon dioxide plays a big role as a greenhouse gas. Many recent findings point out that the role of methane in global warming is bigger than it was thought before. The table below shows seven key methane numbers illustrate the shift in understanding.

Seven Key Methane Numbers [Nace et al. 2019]

700	gas level in the pre-industrial era in ppb (parts per billion) (NASA 2016)
1,850	atmospheric methane had risen from 1,775 ppb in 2006 to 1,850 ppb in 2017 (climate scientists reported in 2018) and it was growing at an accelerating rate. The rapid growth, which had not been expected, “is sufficient to challenge the Paris Agreement” (Nisbet 2017)
25%	the percentage of global warming to date caused by methane (Myhre et al. 2014).
2.3%	leakage rate for the U.S. gas system. 60% higher than the figure previously used by the U.S. government in major assessments of natural gas (Alvarez et al. 2018).
86	methane’s global warming impact is 86 times that of carbon dioxide, according to the most recent IPCC assessment (over a 20-year horizon). In comparison with CO_2, CH_4 is a relatively short-lived but with high potential greenhouse gas. It remains in the atmosphere for a decade and in that time has a hundred times greater impact on global warming than carbon dioxide (Myhre et al. 2014).
34	methane’s global warming impact is 34 times that of carbon dioxide (over a 100-year horizon), according to the most recent IPCC assessment (Myhre et al. 2014).
25%	methane’s impact on global warming is about 25% higher than previously estimated (conclusion in 2016 by IPCC’s 2014 assessment), further raising concerns (Etminan et al. 2016).

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