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Glossary of terms

AAF – alternative aviation fuel
APR-SPK – synthetic paraffin kerosene obtained by reforming of aqueous phase
ATJ – Alcohol-to-Jet
ATJ-SPK – Alcohol to jet synthetic paraffinic kerosene
BAU – business as usual
BG – biogas
BM – biomass
CCS – carbon capture and storage
CEF – CORSIA Eligible Fuel
CH-SK (CHJ) – Catalytic hydrothermolysis synthesized kerosene
CORSIA – Carbon Offsetting and Reduction Scheme for International Aviation
DME – dimethyl ether
DSHC – Direct sugars to hydrocarbons
DSTU – State Standard of Ukraine
ETJ – Ethanol-to-Jet
JIG – Joint Inspection Group
FT – Fischer-Tropsch synthesis
FT-SPK – Fischer-Tropsch hydroprocessed synthesized paraffinic kerosene
FT-SPK/A – Fischer-Tropsch synthetic paraffinic kerosene with aromatics
FT-SPK/SKA – Fischer-Tropsch hydroprocessed synthesized paraffinic kerosene/kerosene with aromatics
GHG – greenhouse gas
G/FT or G+FT – gasification with Fischer-Tropsch synthesis
GREET – Greenhouse gas Regulated Emissions and Energy use in Transportation
GTE – gas turbine engine
HAPP – Hydro-accumulating power plant
HDCJ – Hydrotreated depolymerized cellulosic jet
HDO-SAK – Hydro-deoxygenation synthetic aromatic kerosene
HEFA – Hydroprocessed esters and fatty acids
HEFA-SPK – Synthesized paraffinic kerosene from hydroprocessed esters and fatty acids
HFO – heavy fuel oil
HFS-SIP – Synthesized isoparaffins produced from hydroprocessed fermented sugars
HTL – hydrothermal liquefaction
HPP – hydro power plant
HVO – Hydrotreated Vegetable Oil
IATA – International Air Transport Association
ICAO – International Civil Aviation Organization
IH^2 – integrated hydropyrolysis and hydroconversion process
LCA – life cycle assessment
LH_2 – liquid hydrogen
LNG – liquefied natural gas
MDO – marine diesel oil

MGO – marine gas oil
MSW – municipal solid waste
NERC – National Energy Regulation Commission
NREAP – National Renewable Energy Action Plan
PAX – passenger
PtL – Power-to-Liquid
PV – photovoltaic
RE – renewable energy
RES – renewable energy sources
RJF – renewable jet fuel
SAF – sustainable aviation fuel
SAK – synthesized kerosene with aromatics
SIP – synthesized isoparaffins
SIP-SPK – synthesized isoparaffinic kerosene
SKA – synthesized paraffinic kerosene with aromatics
SMR – steam methane reforming
SPK – synthesized paraffinic kerosene
SPP – solar power plant
TC – Technical Committee
UABIO – Bioenergy Association of Ukraine
UCG – underground coal gasification
UCO – used cooking oil
WPP – wind power plant
Ml – million liters
Mha – million hectares
Mt – million tons
Mtoe – million tons of oil equivalent
bln – billion
dm – dry matter
hp – horse power
toe – tons of oil equivalent

Introduction

The Technical Report presents detailed analysis of alternative fuels that can be used in the aviation and waterborne transport sectors and includes the following questions:

- Current state, production technologies, development forecasts, assessment of greenhouse gas emissions, logistics of supply of sustainable aviation fuels (biofuels, synthetic fuels).
- Comprehensive consideration of the aircraft electrification issue and the use of hydrogen.
- For all the considered alternative aviation fuels the following aspects are covered: forecasts of cost, volumes of production and use, analysis of the raw material and resource base for the production in Ukraine; analysis in terms of current legislation of Ukraine; generalization of the main advantages and disadvantages, assessment of the rating.
- Recommendations for choosing alternative aviation fuels for the production and use in Ukraine.
- Analysis of the current state and prospects for the use of alternative fuels for waterborne transport.
- Comprehensive consideration of the production and use of liquefied natural gas, methanol, ammonia, hydrogen, and biofuels in waterborne transport; their analysis in terms of the current legislation of Ukraine.
- Comparative analysis of all considered alternative fuels for waterborne transport with the determination of their rating.
- Recommendations for choosing alternative fuels for waterborne transport for their production and use in Ukraine.

Executive summary

Aviation

Sustainable aviation fuel (SAF) is the primary term used in the aviation sector to describe non-conventional (i.e. non-fossil) aviation fuel. According to the International Air Transport Association, SAF has three key features: its production is sustainable that is does not violate the ecological balance and does not exhaust natural resources; it is produced from raw materials that are an alternative to crude oil; it has jet fuel properties that meet the technical and certification requirements for the use in commercial aircraft.

According to ICAO, SAFs include "drop-in fuels" produced from renewable raw materials or waste that meet the sustainability criteria of CORSIA: reducing GHG emissions during the life cycle of the fuel by at least 10% as compared to petroleum jet fuel; not using biomass from lands with a high carbon stock as raw material for obtaining the fuel.

In the EU, SAFs are referred to the following types of "drop-in fuels" that meet sustainability criteria and the requirements for reducing GHG emissions according to the EU RED II Directive: synthetic aviation fuel obtained by the technology of converting electricity into liquid (PtL); advanced (II-generation) biofuel obtained from lignocellulosic raw materials and certain types of waste; advanced (III-generation) biofuel obtained from algae; biofuel produced from raw materials with "high sustainability potential" (used cooking oil, certain types of animal fats).

Currently, global use of sustainable aviation fuels is limited due to their relatively high price and limited existing production capacity. Nevertheless, since 2016, more than 370,000 flights using SAF have already taken place. Today, over 45 airlines in the world have some experience in using such alternative fuels; forward purchase contracts for about 14 billion liters of SAF have been concluded. According to expert estimates done in 2021, the cost of SAF will approach the cost of traditional jet fuel only in the period after 2030-2040.

According to existing estimates, the annual production of renewable jet fuel in the EU may increase from 1.3 Mt in 2021 to 3.4 Mt in 2030 according to BAU development scenario of the sector and up to 14 Mt according to the optimistic scenario. At that, according to the last scenario, the future is for advanced biofuels from lignocellulosic feedstock and biofuels from waste oils.

Main production pathways for biomass-based SAF are hydroprocessed esters and fatty acids (HEFA, oleochemical conversion); gasification of lignocellulose with Fischer-Tropsch synthesis (G/FT, thermochemical conversion); conversion of alcohols (ATJ, biochemical conversion); direct conversion of sugars into hydrocarbons (DSHC, biochemical conversion); hydrotreated depolymerized cellulosic jet (HDCJ, thermochemical conversion).

As of November 2021, International standard ASTM D7566 already certified 9 types of SAF with a defined maximum blending ratio with traditional jet fuel certified according to ASTM D1655 standard; three more fuels are under consideration.

Synthetic paraffinic kerosene obtained from hydrotreated esters and fatty acids (HEFA-SPK), with a maximum of 50% allowed in the mixture with traditional jet fuel was certified one of the first in 2011. The production technology of this RJF has already reached commercial level, but further expansion of the production capacity is restrained by the available resources of sustainable raw materials.

Two other technologies closest to commercialization are Fischer-Tropsch (FT) synthesis and direct conversion of sugars to hydrocarbons (DSHC). Other technologies for obtaining RJF are at various stages of development, from R&D to demonstration. It should be noted that the technologies are also characterized by different levels of availability of necessary raw material resources, from constrained (HEFA) to abundant (ATJ). This may affect their further development and expansion.

The assessment results show that the use of lignocellulosic raw materials for the production of RJF gives the best results in reducing GHG emissions, regardless of the applied conversion technology and the method of allocation of emissions between the products. The level of GHG emissions when using different technologies, among other things, depends on the efficiency of the conversion process as well as the technology's need for hydrogen and the method of obtaining it (traditional or "green" hydrogen).

The choice of raw materials for the production of HEFA-SPK fuel significantly affects the result of GHG emissions reduction assessment. The default specific GHG emissions during HEFA-based RJF production life cycle in CORSIA methodology have a wide range (g CO_{2eq}/MJ) from 13.9 for used cooking oil and 22.5 for tallow to 60 for palm oil with the treatment of process wastewater in an open pond.

The produced biojet fuel must be mixed with conventional jet fuel and delivered to airport. There are special procedures to confirm that the mixed jet fuel at various stages of supply meets ASTM standards. Most European airports operate in accordance with the international standards of the Joint Inspection Group. Blending with conventional jet fuel may takes place at the biofuel producer’s site or prior to entering the airport in a separate blending facility and cannot take place at the airport tank farm.

The current legislation of Ukraine does not use the term “sustainable aviation fuel.” The definition of the term "aviation fuel" is provided only by the Technical Regulation on requirements for aviation gasoline and jet fuel, which provides that aviation fuel is fuel for aviation engines from petroleum or other raw materials - aviation gasoline and jet fuel. Thus, aviation fuel from other raw materials (in particular, biomass) can be used in Ukraine if the aviation fuel from biomass meets the requirements of the Technical Regulation (after it enters into force). At the same time, each batch of aviation fuel must be accompanied by a copy of the declaration on the compliance of the aviation fuel with the requirements of the Technical Regulations and a quality document (quality passport).

Regarding the logistics of the supply of SAF from biomass, in our opinion, the current Instruction on ensuring refueling of aircraft with fuel and lubricants and technical fluids in civil aviation transport enterprises of Ukraine, approved by order of the State Aviation Service dated 14.06.2006 No. 416, does not take into account the possibility mixing bio reactive fuel with traditional reactive fuel and it is outdated. In the case of adopting measures to stimulate the use of SAF from biomass in Ukraine, we consider it necessary to revise the abovementioned Instruction.

Synthetic fuel for aviation needs (a type of SAF) can be obtained by electrolysis of water using electricity, in particular "green" electricity – Power-to-Liquid (**PtL**) technology. All the components of PtL production pathway, apart from the reverse water-gas shift reaction, are individually well-developed processes already applied on an industrial scale. In general, PtL technology has not yet fully reached the commercial level, but is actively developing in Iceland, Finland, Germany and Norway. Currently, there are more than 50 demonstration and pilot plants in the world that are in operation or under construction. LCA of synthetic fuel obtained by PtL technology shows that such fuel has environmental advantages (reduction of GHG emissions, mitigation of the effect of atmospheric acidification) over traditional fuel only when using renewable electricity at all stages of the implementation of this technology. Access to the required amount of "green" electricity is considered one of the key sustainability issues of PtL technology as renewable power already has many alternative applications.

Electrification of the aviation sector is currently in the initial stage of development and demonstration. At present, there are over 230 relevant projects in the world, of which only about 30 are of a commercial level. Fully electrified and hybrid aircraft designs are being developed; there are already examples of small electrified aircraft certified for flight; test flights of aircraft with modified electric motors are carried out. The start of large-scale commercial use of electrified aircraft is predicted by experts no earlier than in the middle of the 21st century. At the same time, commercial suburban and regional flights of small electric aircraft may begin as early as in 2025-2030.

The commercial introduction of electric aircraft requires further R&D of technologies in the direction of the development of batteries for long-distance flights, the creation of more powerful chargers and the corresponding charging infrastructure. Existing electric batteries have a low gravimetric energy density and a limited life cycle. This limits their use as the only source of energy in the plane to only short flights that is suburban and regional ones. World airports are just beginning to electrify their ground vehicles. The future integration of electric aircraft in the operation of airports will require significant efforts and funds, although the potential benefits and advantages from this will also be quite large.

Since synthetic fuel and electricity use in aviation transport is cutting-edge technology, there is no special regulation of their use in Ukraine.

Lately, a significantly increasing interest in using **hydrogen** in aviation has been observed in the world. The main problems of this direction are the need for a large amount of hydrogen, the need for the production of "green" hydrogen and the provision of the appropriate infrastructure for its supply. Hydrogen is a low-/carbon-free fuel that can be used in aviation in two ways: in conventional gas-turbine engines (with certain adaptation/modification) as a substitute for traditional jet fuel (including large aircraft); in fuel cells as a source of electricity. Unlike electric batteries, which require recharging, fuel cells can generate electricity as long as a supply of fuel (hydrogen) is provided. Other advantages are the possibility of arranging fuel cells in a "battery", that is, scaling, as well as the absence of moving parts in them, which ensures noiselessness and high reliability of their operation. In addition to these direct application options, hydrogen is used in the production of synthetic kerosene using the power-to-liquid (PtL) technology and in the production of many types of biomass-based SAF. Experts believe that from the mid-2030s liquid hydrogen will become cheaper and "greener" than synthetic fuel PtL (a type of SAF) that requires more electricity for its production than liquid hydrogen.

Hydrogen can be stored on the aircraft in a gaseous or liquid state. The weight of hydrogen is 3 times less than jet fuel with the same energy content, but the volume, even in the liquid (cryogenic) state, is 4 times larger. Because of this, the aircraft will need a much larger fuel tank and radical changes to the fuel system. In addition, liquid hydrogen must be stored at a very low temperature (about minus 253 °C), which requires the use of special tanks. From a technical point of view, it is easier to implement the use of gaseous hydrogen than liquid hydrogen, but gaseous hydrogen must be stored under high pressure (700 bar) in heavy tanks. This limits its use in aviation only to short-distance flights. According to the most optimistic scenario, the commercial use of liquid hydrogen in aircraft with 100-200 seats (short- and medium-distance flights) will begin no earlier than in 2035.

A significant obstacle to the use of hydrogen in Ukraine is the outdated and uncoordinated base of regulatory and legal acts and documentation on technical safety, as well as the ignorance of business entities in this area.

When determining the rating of alternative aviation fuels, the following aspects were taken into account:

- Level of the technology development and its complexity;
- Technology certification according to ASTM D7566 standard (for SAFs);
- Permissible percentage of mixing with petroleum jet fuel (for SAFs);
- Price;
- Reduction of GHG emissions during the life cycle;
- Availability / accessibility of raw material and resource base;
- Yield of jet fuel compared to the volume of other co-products (for SAFs from biomass).
- The need to change the aircraft's fuel system and airport infrastructure.

Based on results of the comprehensive comparative analysis and evaluation, the following **SAFs are considered the most promising for Ukraine's aviation**:

- Synthesized paraffinic kerosene from hydroprocessed esters and fatty acids (**HEFA-SPK**).
- Alcohol to jet synthetic paraffinic kerosene (**ATJ-SPK**) (currently, only conversion of ethanol).
- Fischer-Tropsch hydroprocessed synthesized paraffinic kerosene (**FT-SPK**).

For the production of each of these biofuels in Ukraine, there is a necessary raw material base, including straw of cereal crops and rapeseed, by-products/residues from the production of grain corn and sunflower, oilseed, woody and herbaceous energy crops, and sugar beet molasses. In order to make a final decision regarding the introduction of the production of a certain type of SAA, it is necessary to perform a complete feasibility study and life cycle assessment for various types of raw materials for the conditions of Ukraine.

Waterborne transport

With the global trend towards decarbonizing the economy, the water transport sector is preparing for a transition to new technologies and energy sources, which will have a significant impact on costs, asset values and profitability. Ship owners are already experiencing increasing pressure to reduce the greenhouse gas footprint of maritime transport. Three fundamental key drivers will push decarbonization in shipping in the coming decade: regulations and policies, access to investors and capital, and cargo owner and consumer expectations.

All alternative fuels for shipping face challenges and barriers to their uptake – although the severity of each barrier will vary between fuel types. Typical key barriers include the cost of required machinery and fuel storage on board vessels, additional storage space demand, low technical maturity, high fuel price, limited availability of fuel, and a lack of global bunkering infrastructure. Safety will also be a primary concern, with a lack of prescriptive rules and regulations complicating the use of such machinery and storage systems.

All ships running on high-sulphur fuel from 2020 must use scrubbers or other technologies to clean the exhaust gases. Scrubber technology is available on the market. Depending on engine size, investment costs for scrubbers range from 650 USD/kW (5000 kW engine) up to 150-100 USD per kilowatt (engines of 40 MW and more). Operating costs of scrubbers consist of maintenance costs and energy consumption. According to IMO MEPC 70/5/3, they represent approximately 0.7% of total fuel costs (ships with a shaft power of more than 25 MW).

Currently, ships can already operate on such **alternative fuels** as liquefied natural gas (LNG), liquefied petroleum gas (LPG), methanol and biofuel. In addition, tests of ammonia and hydrogen are ongoing. According to their chemical and physical characteristics, alternative fuels differ significantly from traditional fuels for water transport. Properties related to the risk of fires and explosions are particularly dangerous.

Availability and accessibility of fuel supply infrastructure, storage and bunkering is an important aspect for the development of the market of alternative fuels for water transport. Many ports already have operational LNG, methanol and ammonia terminals that can be upgraded for ship bunkering. In addition, new terminals are being built. In Ukraine, there is an active ammonia terminal in the port of Pivdennyi with a storage volume of 120,000 tons, which can also be used for reloading ships or barges with ammonia. There is no information on the possibility of direct bunkering of ships. Nearby in Romania, there is a methanol terminal in the port of Constanta with a storage capacity of over 50,000 tons. In Bulgaria, an LNG terminal for the bunkering of inland navigation vessels with a storage capacity of 1,000 m^3 is being built in the port of Ruse on the Danube River, which is part of the LNG master plan for the Rhine-Main-Danube highway.

In order to transfer the energy installations of ships to some alternative fuels, such as LNG, methanol and ammonia, it is necessary to carry out complex and expensive modernization of engines, their fuel system, to install additional fuel tanks, etc. Based on current technology, a distinction should be made between short-haul shipping and deep-sea long-haul shipping with respect to the applicability and barriers of different fuels. Deep-sea large and powerful vessels have fewer options for choosing fuels compared to the segment of short-distance transportation on permanent routes, where less common technologies and fuels made from local raw materials, in particular, biomass, can be used.

In recent years, among alternative types of fuel for water transport, **liquefied natural gas** has become the most popular. LNG is purified natural gas that converted into a liquid state by cooling to a temperature of 162^{0}C. LNG occupies about 1/600 of the volume of natural gas in its gaseous state (at standard conditions) and consists mainly of methane (CH_4) with some ethane (C_2H_6). LNG is used as an efficient way to comply with emission control area (ECA) restrictions on existing ships and is planned for new ships. A key environmental advantage of LNG is the reduction of SO_x, PM, NO_x and CO_2 emissions compared to traditional petroleum products. Liquefied natural gas is considered the most acceptable method in the near and medium term due to available engine and system technologies, regulations, operational experience, fuel costs, and availability of natural gas worldwide.

When using LNG, the lowest emissions of greenhouse gases are produced among fossil fuels for water transport. However, LNG systems can leak methane, which has a global warming potential 28 times greater than CO_2. Therefore, the advantages in reducing greenhouse gas emissions from the use of LNG compared to fuel oil and marine fuel in the presence of CH_4 leaks may be absent. Engine manufacturers claim that tank-to-propeller LNG CO_2 emissions of dual-fuel and clean gas engines are 10-20% lower than those of petroleum-fueled engines. It is possible to achieve a greater reduction of GHG if LNG is produced from renewable raw materials, for example, from biomass through its anaerobic fermentation in a biogas plant followed by purification of biogas to biomethane. Liquefied biomethane is called bio-LNG (LBG).

The Law of Ukraine "On the Natural Gas Market", which defines the legal basis for the functioning of the natural gas market of Ukraine, provides that LNG installation services are an economic activity that is subject to licensing and consists in the transformation of natural gas from gaseous to the liquid state (liquefaction) or conversion of liquefied natural gas from a liquid to a gaseous state (regasification) using an LNG plant. When using LNG for water transport, one should consider the requirements of this law and the by-laws adopted for its implementation.

Methanol is an excellent substitute for gasoline, is used in blended fuels, and can also provide good levels of performance in diesel engines. For use in diesel engines, it is necessary to feed a small amount of diesel fuel together with methanol or use an ignition improver. Methanol is also used to produce biodiesel, methyl tert-butyl ether (MTBE) and dimethyl ether (DME) and in fuel cells. There is no sulfur in the composition of methanol, when it is burned, NO_x emissions are produced in a small amount, and there are no emissions of solid particles (PM), so this fuel is considered promising for water transport. When converting ships to methanol, it is necessary to modify the engine, fuel tanks, pipelines and bunkering system.

The use of methanol for the production of fuels requires compliance with the current legislation, as methanol is a dangerous substance. Methanol is a highly flammable liquid, highly poisonous of a nervous and vascular nature with a pronounced cumulative effect, similar in color, smell, and taste to ethyl (wine) alcohol. In this regard, several normative legal acts defining the procedure for handling methanol are in force in Ukraine.

Ammonia is of considerable interest as a potential zero-carbon fuel for transportation. Ammonia can be used as marine fuel in both internal combustion engines and fuel cells. Due to its high-auto ignition temperature, ammonia requires a higher compression ratio (35:1 and higher) than used in typical CI engines (16-23:1). It is difficult to design such an engine, so the addition of a second fuel, with lower auto-ignition temperature, can help to combust the mixture and allows for a more stable combustion. Ammonia has a high minimum ignition energy and a low flame speed, so mixtures of ammonia with other types of fuel are also used in engines with forced ignition. Ammonia positive-ignition engines are thought to be used for smaller vessels, while modified two-stroke (dual-fuel) diesel engines may be suitable for larger ships. Combustion of ammonia or ammonia mixtures can lead to emissions of nitrogen oxides (NO_x), nitrous oxide (N_2O) and direct emissions of ammonia (NH_3). But to date, there is no experience of long-term operation of ship engines on ammonia. Therefore, there is not enough empirical data on emissions from burning this type of fuel. Commercial ammonia engines are expected to appear in 2024.

The use of ammonia requires compliance with the current legislation. Several normative legal acts defining the procedure for handling ammonia are in force in Ukraine.

Hydrogen is a colorless, odorless, non-toxic gas. For shipboard use, it can be stored as a cryogenic liquid, compressed gas, or chemically bonded. Hydrogen is very flammable, and due to its very small molecules, it is difficult to contain it in tanks, pipelines and other elements. Therefore, for the widespread introduction of hydrogen as a fuel for water transport, it is necessary to solve a number of problems, in particular with the supply, storage and distribution infrastructure, safety and regulatory framework. Now, hydrogen is in the early stages of development for use in shipping.

The most promising **biofuels** for marine shipping are biodiesel (for example, HVO – hydrotreated vegetable oil, BtL – biomass to liquid, FAME – fatty acid methyl esters) and LBG (liquid biogas, which mainly consists of methane). Biodiesel is most suitable to replace MDO/MGO, LBG to replace fossil LNG and SVO (straight vegetable oil) to replace HFO. Although other technologies are developing and, in the future, taking into account local features, they can be implemented in waterborne transport.

Biofuels can be used both in their pure form and in mixtures with traditional petroleum fuels. Currently, only biodiesel (FAME) (in concentrations up to 7% by volume) is approved for use with MGO as a marine fuel under the distillate fuel classes DFA, DFZ and DFB of the international standard ISO 8217:2017. Such biodiesel mixtures provide a significant reduction in emissions of solid particles. Reduced particulate emissions are an important environmental benefit of oxygenated fuels, and often significant reductions can be achieved at relatively low blend levels (<10%). Biodiesel cannot be directly mixed with distillate fuels, but surfactants are used to create an emulsified fuel mixture.

Direct replacement of marine gas oil (MGO) is possible provided that sufficient volumes of biofuel production are achieved. But, even in a mixed fuel, biofuel provides a reduction in emissions of solid particles and CO_2. It should be noted that for the successful implementation of the fossil fuel substitution project, the representatives of the marine engine manufacturer must confirm the compatibility of the engines with biofuels and the mandatory conditions for their reliable operation.

The Technical Regulation on requirements for automobile gasoline, diesel, marine, and boiler fuels defines marine fuel as liquid distillate petroleum fuel used in high- and medium-speed diesel engines and gas turbine installations. In our opinion, the Technical Regulation does not consider the possibility of using biofuel as a marine fuel.

Regarding the waterborne transport, among the applications of various types of fuel, short-distance and deep-sea marine shipping should be distinguished. In short-distance transportation, vessels usually operate in limited geographical areas on relatively short routes with frequent port calls. Because of their relatively low energy requirements, these vessels are often ideal candidates for testing new fuels characterized by high energy conversion or storage costs.

Deep-sea shipping includes large ocean-going vessels that operate long routes, often without a regular schedule. These vessels require the use of fuel that is available all over the world. The energy carrier that drives the ship must have a high enough energy density to maximize the available cargo space. For these vessels, LNG may be a viable option once suitable bunkering infrastructure becomes available worldwide. Environmental biofuels, methanol and liquefied gas may also be options, provided they can be made available in the required quantities and at the appropriate level of quality.

When determining the rating of alternative fuels for water transport, the following aspects are taken into account:

- Level of technology development and its complexity;
- Compatibility with existing engines, fuel system of vessels and bunkering infrastructure;
- Availability / accessibility of raw material and resource base;
- Volumetric energy content of fuel and energy carrier;
- Fuel standardization;
- Price;

- Reduction of greenhouse gas emissions during the life cycle.

According to the results of the comparative analysis and assessment, **the following fuels for water transport are considered the most promising for Ukraine:**

- Biomethane that can be used in compressed or liquefied form.
- Biodiesel (**FAME**) and hydrotreated vegetable oil (**HVO**).
- Electric power installations with accumulator batteries.
- Liquefied natural gas (**LNG**).

1. Alternative fuels in aviation

1.1. Definition of Sustainable Aviation Fuel

Sustainable aviation fuel (SAF) is the primary term used in the aviation sector to describe non-conventional (i.e. non-fossil) aviation fuel. The International Air Transport Association prefers the term SAF for this type of fuel, although the use of other terms such as sustainable alternative fuel, sustainable alternative jet fuel, renewable jet fuel or biojet fuel generally has the same meaning.

"Biofuel" usually means fuel produced from biological resources (substances of plant or animal origin). However, modern technologies make it possible to produce fuel from other alternative sources, including non-biological resources; thus, the term has been adjusted to SAF to emphasize the sustainable nature of these fuels.

Chemical and physical characteristics of SAF are almost identical to those of conventional jet fuel, so one can be safely mix SAF with the latter in different ratios, use the same supply infrastructure, and do not adapt aircraft or engines. Fuels with such properties are called "drop-in fuels", that is fuels that can be automatically included in existing airport refueling systems.

SAF must meet sustainability criteria, such as reduced carbon emissions during life cycle, limited freshwater needs, no competition with food production (for first-generation biofuels there is such competition), and no deforestation associated with fuel production.

Thus, according to IATA, **SAF has three key features** [1]:

- its production is sustainable, that is does not violate the ecological balance and does not exhaust natural resources;

- it is produced from raw materials that are an alternative to crude oil;

- it has jet fuel properties that meet the technical and certification requirements for the use in commercial aircraft.

According to ICAO, SAFs include "drop-in fuels" produced from **renewable raw materials or waste that meet the sustainability criteria of CORSIA**: reducing GHG emissions during the life cycle of the fuel by at least **10%** as compared to petroleum jet fuel as well as *not using* biomass from lands with a high carbon stock as raw material for obtaining the fuel [13]. CORSIA is a methodology for estimating GHG emissions during the life cycle of aviation fuels introduced by ICAO, which is used by ICAO member states (description is presented in **Annex 1**). In a broader sense, CORSIA is not only an assessment methodology, but also an international program for reducing carbon emissions in aviation.

In the EU, SAFs are referred to the following types of "drop-in fuels" that meet sustainability criteria and the requirements for reducing GHG emissions according to the EU **RED II** Directive [2, 3]:

synthetic aviation fuel obtained by the technology of converting electricity into liquid (PtL);

advanced (II-generation) biofuel obtained from lignocellulosic raw materials and certain types of waste (a complete list of relevant types of raw materials is given in **Annex 2**, part A);

advanced (III-generation) biofuel obtained from algae;

biofuel produced from raw materials with "high sustainability potential" (used cooking oil, certain types of animal fats, see **Annex 2**, part B).

From the list above, it can be seen that the European Commission **does not consider I-generation biofuels**, i.e. those obtained from agricultural crops intended for food and feed production, **to be SAF**. In most cases, such biofuels do not meet the requirements for reducing GHG emissions according to the EU **RED II** Directive [3]: at least **50%**, **60%** and **65%** for transport biofuel production units that started operation on or before 05.10.2015, between 06.10.2015 and 31.12.2020 and from 01.01.2021, respectively.

It should also be noted that according to EU **RED II** Directive, aviation fuel **may** contribute to the goal of achieving 14% renewable energy in the transport sector by 2030, but its **contribution is not mandatory**.

1.2. Analysis of state-of-the-art and prospects for SAF production and use

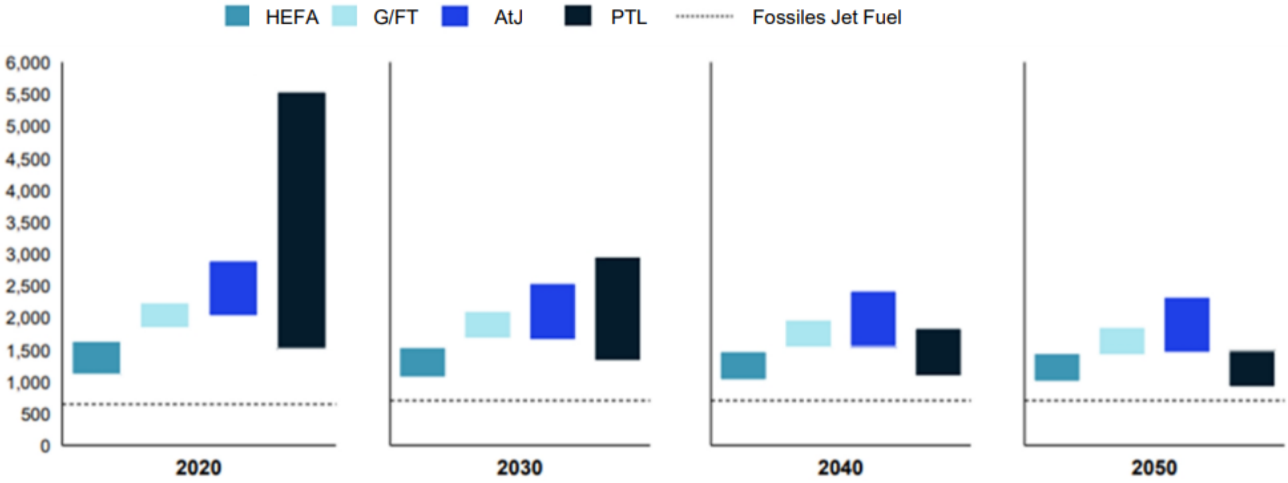
1.2.1. Current state of development

Currently, global use of sustainable aviation fuels is limited due to their relatively high price and limited existing production capacity. Nevertheless, since 2016, more than 370,000 flights using SAF have already taken place. Today, over 45 airlines in the world have some experience in using such alternative fuels; forward purchase contracts for about 14 billion liters of SAF have been concluded [38].

According to expert estimates done in 2021, the cost of SAF will approach the cost of traditional jet fuel only in the period after 2030-2040 (**Fig. 1.1, 1.2**). However, in 2022, the world price of oil increased significantly, on average to **110** USD/barrel during first half year, with a peak of almost 130 USD/barrel at the beginning of March 2022 [39]. At the same time, the average annual oil prices in previous years were (**Brent, USD/barrel**): ~**70** in 2021, ~**50** in 2020, ~**65** in 2019 r. [6]. The rise in oil prices affected the cost of traditional jet fuel, which in June 2022 was 25-30% higher than that in the same period last year, reaching about **1400** USD/t (**1120** USD/1000 l) [7]. **These price trends significantly contribute to increasing the competitiveness of sustainable aviation fuels**.

The cost of biofuel for jet engines fluctuates quite significantly on the world market depending on the type of applied technologies and raw materials for its production. Thus, according to 2018-2020 data, the selling price of biofuel (**USD/t**) obtained by HEFA technology from used cooking oil was 721...1089, from jatropha oil – 2360; by isobutanol conversion from wheat grain – 976, from wheat straw – 1564 (**Annex 3**) [8].

Until 2019, the volume of production of aviation biofuels was significantly less than 10 million l/year, and in 2019 there was a jump in production up to > **140** million l/year (**Fig. 1.3**). The development potential of this direction is high as it considerably increases the sustainability of the aviation sector and contributes to global decarbonization.



** <u>Comment by the Technical Report authors</u>: as of June 2022, cost Jet A1 is about 1400 USD/t (1120 USD/1000 l at the jet fuel density of ~800 kg/m^3) [7]*

Fig. 1.1. Forecast (2021) for the production cost of different SAF until 2050 as compared with fossil jet fuel, **USD/1000 l** [4].

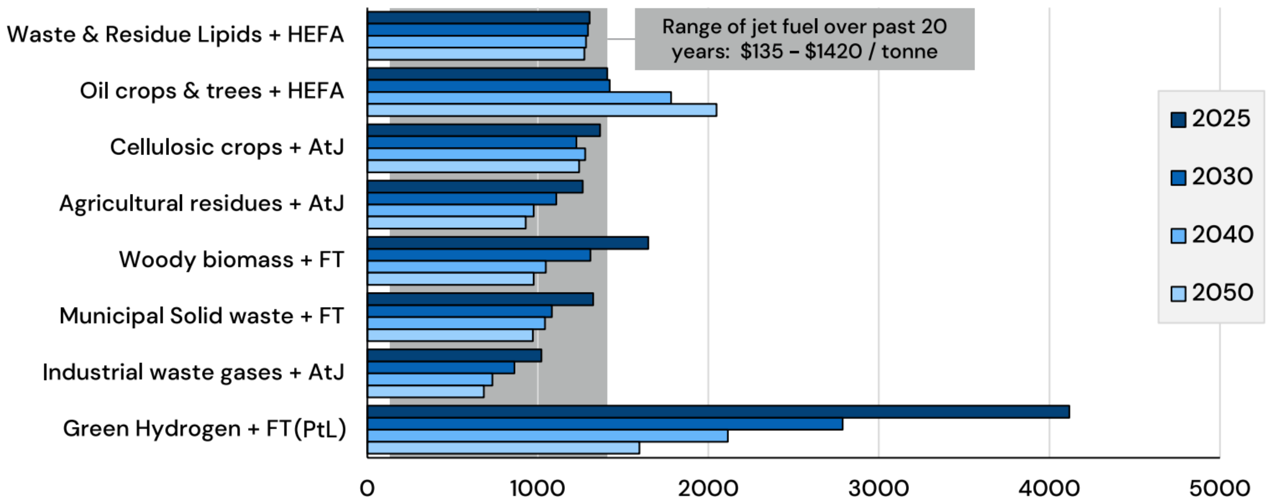


Fig. 1.2. Forecast (2021) for the production cost of different SAF until 2050 as compared with fossil jet fuel, **USD/t** [5].

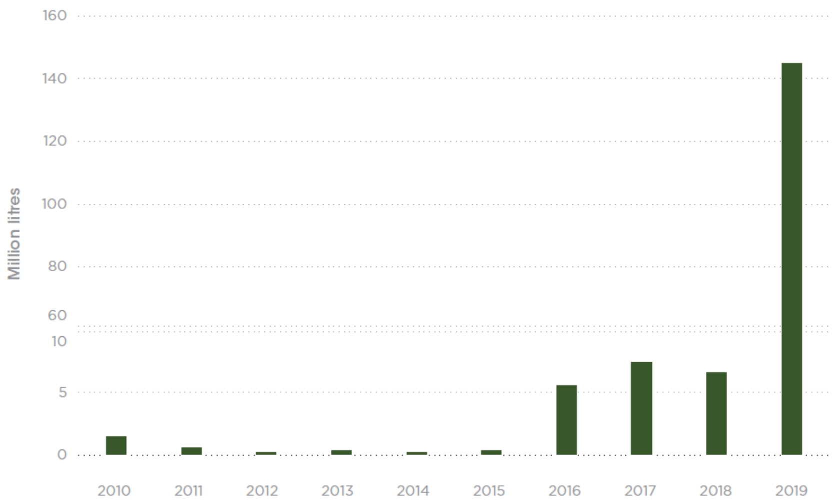


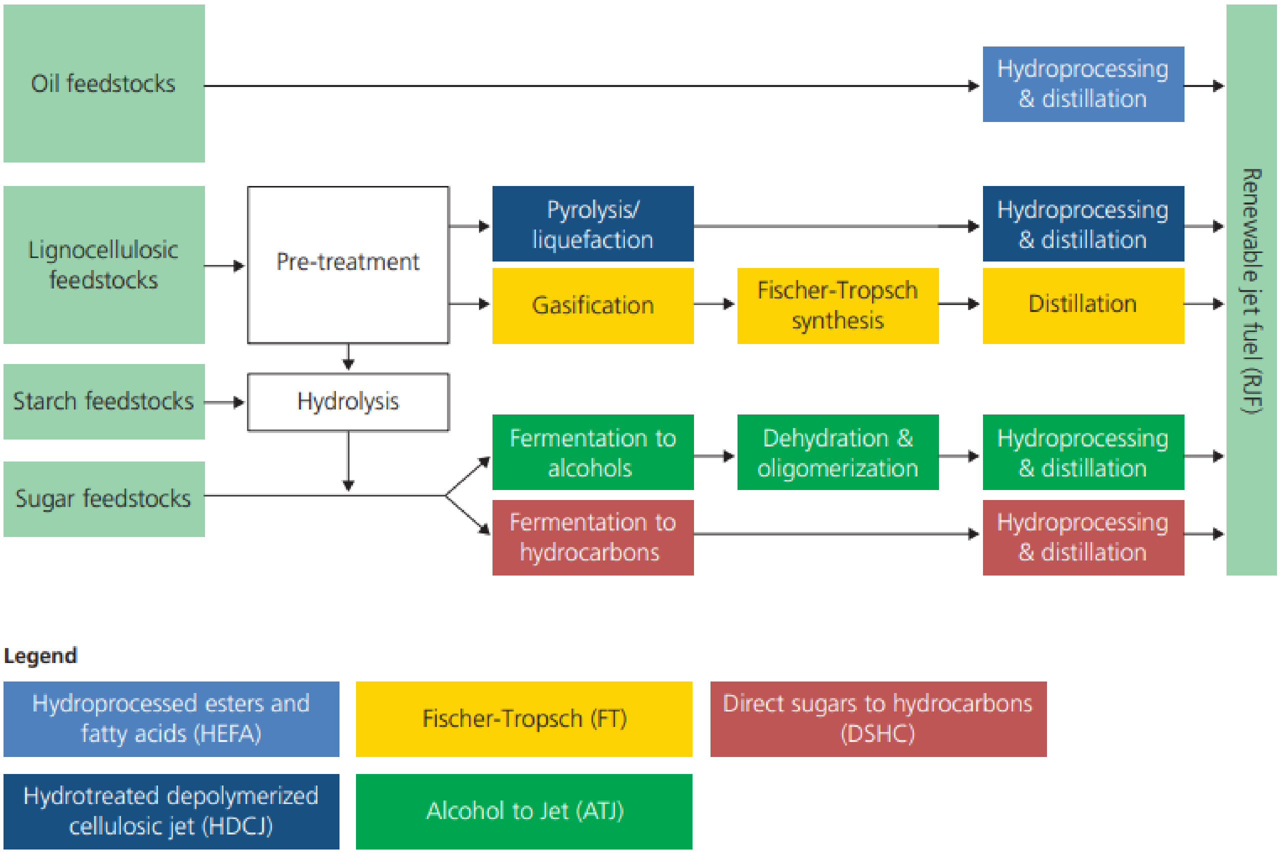
Fig. 1.3. Production of aviation biofuels in the world, **million l** [8].

1.2.2. Technologies for SAF production from biomass

Main production pathways for biomass-based SAF[1] are [9]:

- Hydroprocessed esters and fatty acids (**HEFA**, *oleochemical* conversion).
- Gasification of lignocellulose with Fischer-Tropsch synthesis (**G/FT**, *thermochemical* conversion).
- Conversion of alcohols (**ATJ**, *biochemical* conversion).
- Direct conversion of sugars into hydrocarbons (**DSHC**, *biochemical* conversion).
- Hydrotreated depolymerized cellulosic jet (**HDCJ**, *thermochemical* conversion).

The types of raw materials required for the implementation of these technologies and the main stages of conversion are presented in **Fig. 1.4**. When using lignocellulosic raw materials, the biomass fraction of household/industrial waste and other types of raw materials in accordance with part A of Annex IX of the EU RED II Directive (see **Annex 2**), ***liquid biofuels of II and III (from algae) generations*** are obtained.



Note: the currently used name of DSHC is synthesis of paraffin from hydrotreated fermented sugars

Fig. 1.4. Renewable jet fuel conversion pathways [10].

It is important that scientists and researchers are already actively working on the

[1] Production pathway for synthetic SAF PtL (power to liquid) is described in a separate chapter.

development of production technologies for **IV** generation biofuel from genetically modified organisms (**Table 1.1**). But for now, the basis of renewable jet fuels is aviation biofuels of **I** and **II** generations. At that, as already noted, **the European Commission does not classify I-generation biofuels as sustainable** [2].

Table 1.1. Feedstocks for the production of aviation biofuels of different generations [11].

First-generation (1-G)	**Second-generation (2-G)**	**Third-generation (3-G)**	**Fourth-generation (4-G)**
• Oil-seed crops: camelina, oil palm, rapeseed, soybean, sunflower, salicornia • Sugar and starchy crops: corn, wheat, sugarcane, sugar beets	• Oil-seed energy crops*: jatropha, castor bean • Grass energy crops: switchgrass, miscanthus, Napier grass • Wood energy crops: poplar, willow, eucalyptus • Agricultural and forestry residues: corn stover, sugarcane bagasse, wood harvesting/processing residues • Food and municipal waste*: used cooking oil, animal fats, biogenic fraction of municipal solid waste	• Algae: microalgae	• Genetically modified organisms • Non-biological feedstocks: CO_2, renewable electricity, water

<u>Comment by the Technical Report authors</u>: this list of raw materials types does not completely coincide with the list given in Annex IX of the EU RED II Directive (see Annex 2). Oil energy crops, used cooking oil, animal fats are not listed in Annex IX of the EU RED II Directive as those from which advanced biofuels are obtained.

As of November 2021, International standard **ASTM D7566** [12] already certified **9** types of SAF with a defined maximum blending ratio with traditional jet fuel certified according to ASTM D1655 standard [13]; three more fuels are under consideration (**Table 1.2**).

Table 1.2. SAF production pathways approved by ASTM D7566 and those in progress [14-16].

SAF	Maximum blending ratio by volume	Typical feedstock	Status
Fischer-Tropsch hydroprocessed synthesized paraffinic kerosene (**FT-SPK**)	50%	Lignocellulosic crops, residues and wastes	Approved in 2009
Synthesized paraffinic kerosene produced from hydroprocessed esters and fatty acids (**HEFA-SPK**)	50%	Vegetable oils, waste fats, oils and greases	Approved in 2011
Synthesized isoparaffins produced from hydroprocessed fermented sugars (**HFS-SIP**)	10%	Sugar crops	Approved in 2014
Fischer-Tropsch synthetic paraffinic kerosene with aromatics (**FT-SPK/A**)	50%	Lignocellulosic crops, residues and wastes	Approved in 2015
Alcohol-to-jet synthetic paraffinic kerosene (**ATJ-SPK**) (at present the alcohols are only isobutanol and ethanol)	50%	Starch and sugar crops; lignocellulosic crops, residues and wastes	Approved in 2016
Co-processing bio-oils in petroleum refinery*****	---	Vegetable oils, waste fats, oils and greases	Approved in 2018
Catalytic hydrothermolysis synthesized kerosene (**CH-SK** or **CHJ**)	50%	Vegetable oils, waste fats, oils and greases	Approved in 2020
Synthesized paraffinic kerosene from hydrocarbon-hydroprocessed esters and fatty acids (**HC-HEFA-SPK**)	10%	Microalgae	Approved in 2020
Co-processing synthetic crude oil in petroleum refinery*****	---	Lignocellulosic crops, residues and wastes	Approved in 2020
High freeze point hydroprocessed esters and fatty acids synthetic kerosene (**HFP HEFA-SPK** or **HEFA+**)	10%	Vegetable oils, waste fats, oils and greases	*In progress*
Hydro-deoxygenation synthetic aromatic kerosene (**HDO-SAK**)	10%	Starch and sugar crops; lignocellulosic crops, residues and wastes	*In progress*
Alcohol-to-jet synthetic kerosene with aromatics (**ATJ-SKA**)	not available	Starch and sugar crops; lignocellulosic crops, residues and wastes	*In progress*

** When the amount of esters, fatty acids and Fischer-Tropsch hydrocarbons used in petroleum refinery for co-processing is <5% (by volume), the obtained aviation fuel can meet the quality standards of traditional jet fuel according to ASTM D1655 [13].*

Synthetic paraffinic kerosene obtained from hydrotreated esters and fatty acids (**HEFA-SPK**), with a maximum of **50%** allowed in the mixture with traditional jet fuel was certified one of the first in 2011. The production technology of this RJF has already reached **commercial level**, but further expansion of the production capacity is restrained by the available resources of sustainable raw materials (**Fig. 1.5**).

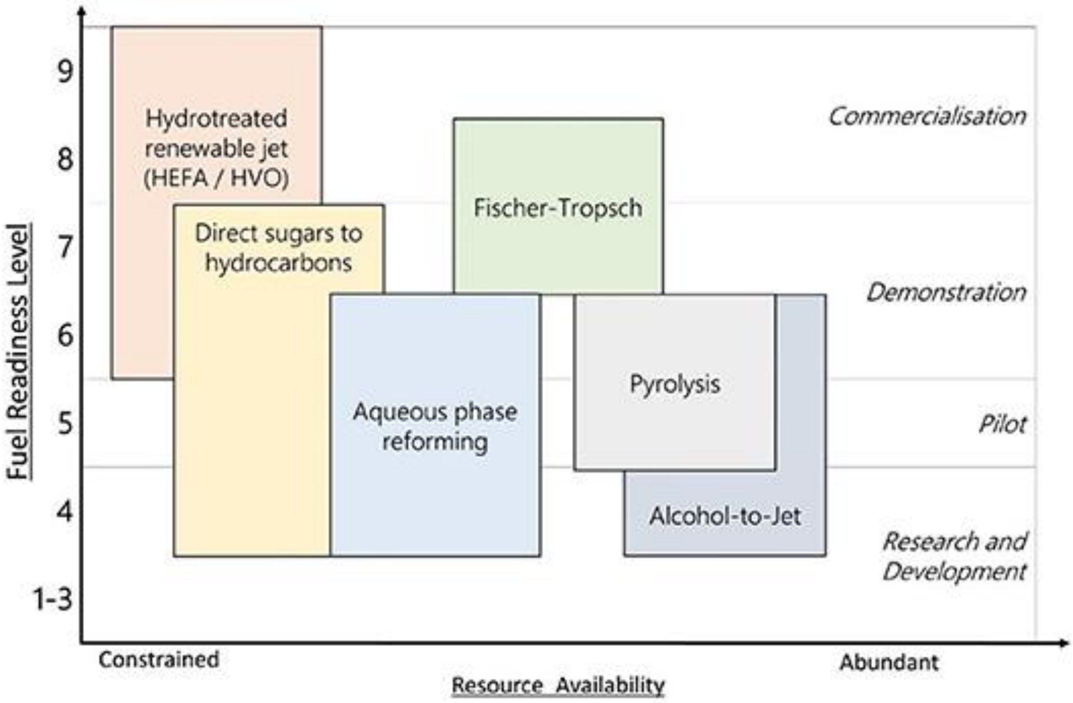
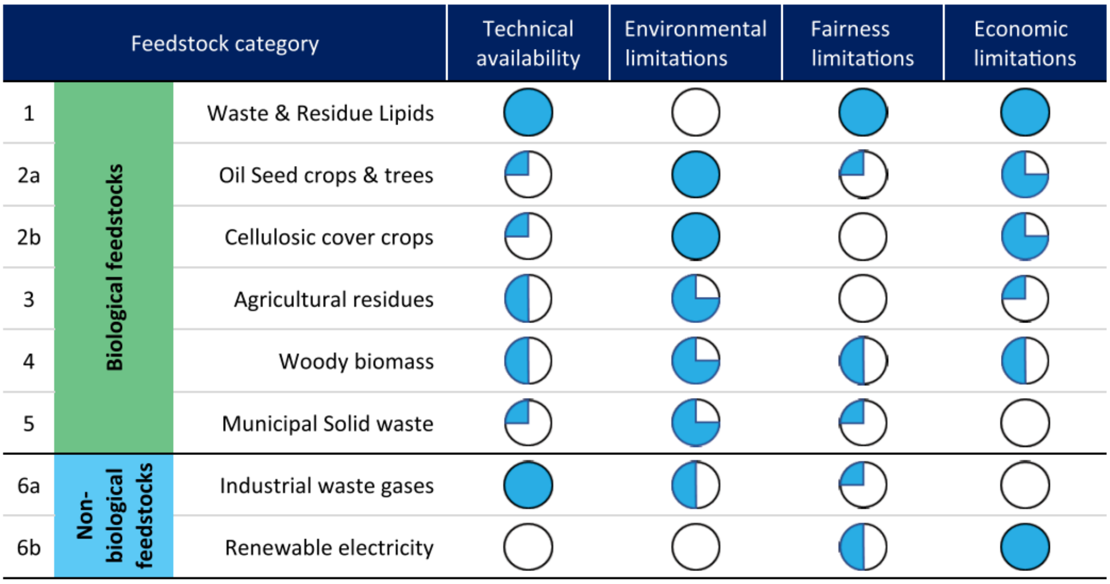


Fig. 1.5. Future scope for adapting processes to a commercial level based on resource availability and technology maturity [11].

Two other technologies closest to commercialization are Fischer-Tropsch (**FT**) synthesis and direct conversion of sugars to hydrocarbons (**DSHC**). Other technologies for obtaining RJF are at various stages of development, from R&D to demonstration. It should be noted that the technologies are also characterized by different levels of availability of necessary raw material resources, from constrained (HEFA) to abundant (ATJ) (see **Fig. 1.5**). This may affect their further development and expansion. The assessment of the availability and stability of various types of raw materials is presented in **Fig. 1.6.**

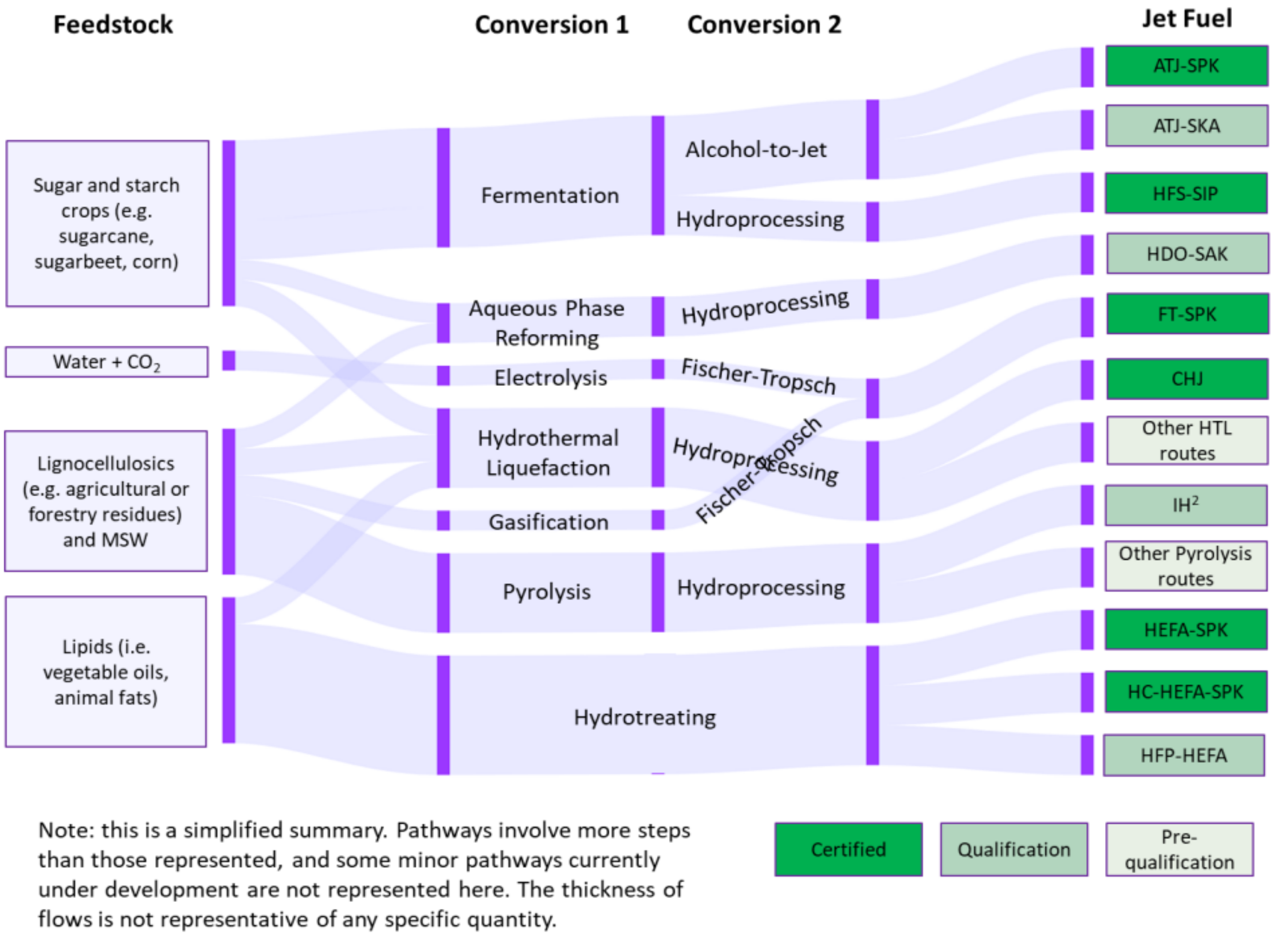
Fig. 1.7 shows a simplified production pathways for the certified and prospective SAF. When applying almost every conversion technology, aviation biofuel is only one of the fractions of the entire spectrum of the obtained products (**Fig. 1.8**). Thus, the approximate yield of aviation biofuel is [9]:

- 15-50% for HEFA;
- 70% for alcohol conversion (ATJ);
- 25-40% for gasification with Fischer-Tropsch synthesis;
- 10-30% for pyrolysis and hydrothermal liquefaction.



Note: the more complete the Harvey ball is the bigger the respective constraint is.

Fig. 1.6. Key limitations for different potential feedstock [5].



(abbreviations are available in Glossary of terms and Table 1.2)

Fig. 1.7. Certification status for SAF production pathways [16].

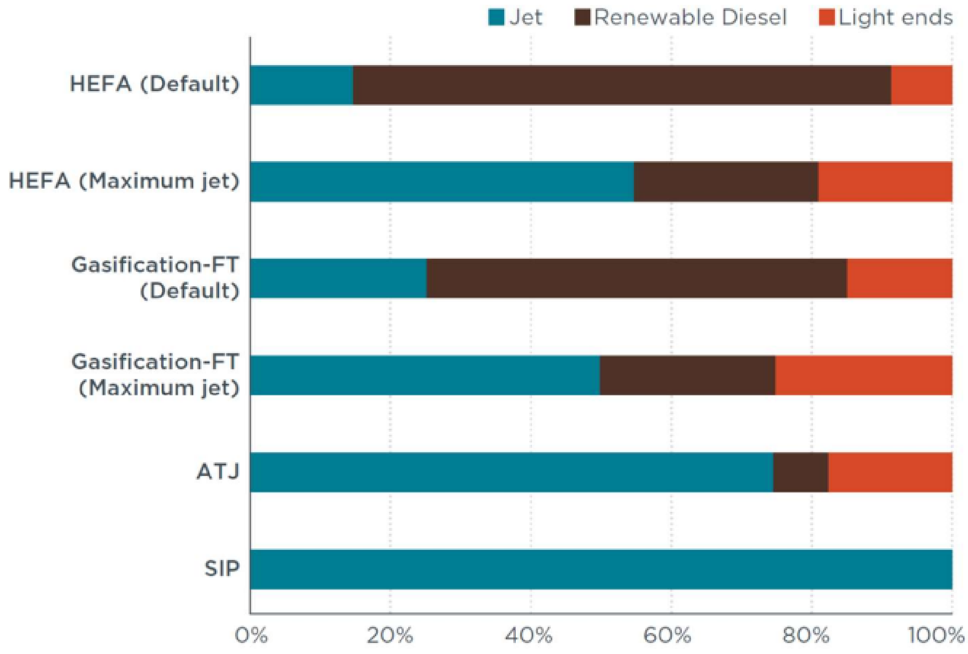


Fig. 1.8. Yield of SAF and co-products for different conversion technologies [9].

It is interesting to note that on June 20, 2022, ExxonMobil (USA) announced the development of a unique technology for the production of SAF from ***renewable methanol*** [37]. Methanol[2] obtained by gasification of biomass or produced from low-carbon hydrogen and captured CO_2 can be converted to SAF by ExxonMobil's patented technology using catalysts. According to the company's preliminary estimates, the output of jet fuel may be higher than in other technologies for obtaining SAF. ExxonMobil's technology is flexible as it allows the use of a mixture of alcohols as raw materials to produce renewable diesel, as well as other types of low-carbon chemical raw materials. The company has started testing the developed technology with the aim of further certification.

1.2.3. Forecasts for biomass-based SAF production

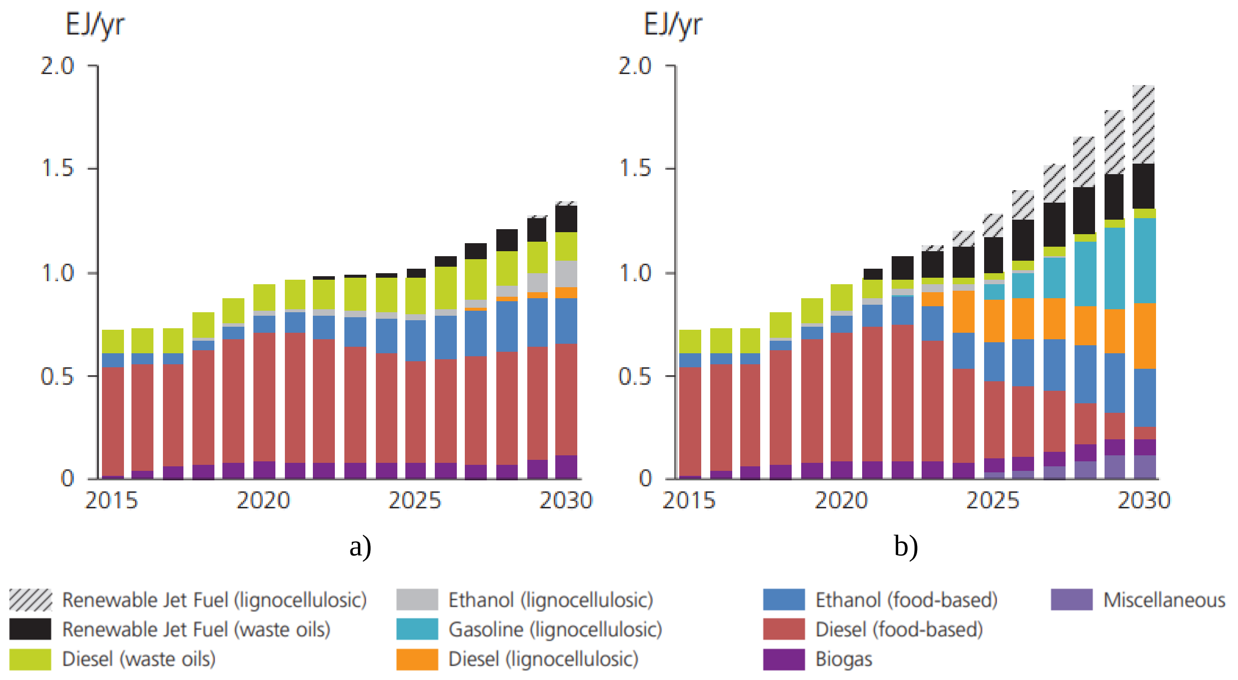
Currently, only **0.05%** of European aircraft operate on fuel obtained from renewable sources [17]. Global development of this sector is stimulated by ICAO's CORSIA program as well as the EU's emissions trading system (EU ETS). **CORSIA** (Carbon Offsetting and Reduction Scheme for International Aviation) is an international program for reducing carbon emissions in aviation. This program requires airlines to **prevent CO_2 emissions rising above 2019** level by using alternative fuels that meet CORSIA sustainability criteria or by other types of compensation such as financing emissions reduction in other sectors. The **EU ETS** system encourages aircraft to use certified biomass-based SAF which meet the sustainability criteria of the EU **RED II** Directive. It is believed that GHG emissions are zero when using such biofuels [18].

Considering the mentioned CORSIA and EU ETS schemes to be insufficiently effective, the European Commission has developed a new initiative, **RefuelEU Aviation**, aimed at stimulating the transition to sustainable aviation fuels (including synthetic ones, commonly known

[2] General information about methanol and possibility for green methanol production is presented in chapter 2.3. Methanol of the Technical Report.

as e-fuels) in the aviation sector. Within the framework of RefuelEU Aviation, there is an obligation to achieve the following minimum share of SAF supply **at each EU airport**: **2%** in 2025, **5%** in 2030, **20%** in 2035, **32%** in 2040, **38%** in 2045, and **63%** in 2050. RefuelEU Aviation is a component of the general package of proposals presented by the European Commission on 14.07.2021. The package is aimed at harmonizing the EU's climate, energy, land, transport and fiscal strategies with the aim of achieving a reduction of GHG emissions by at least **55%** by 2030 as compared to 1990 – the “fit for 55” package. Currently, the package of proposals of the European Commission is undergoing the stages of review and approval necessary for its official approval [2]. The European Parliament’s feedback to the European Commission's proposal on the mandatory share of SAF, received in July 2022, indicates that this share may even be increased, up to **85%** in 2050 [93].

According to estimates carried out as part of **RENJET** project [19], the annual production of renewable jet fuel in the EU may increase from 1.3 Mt in 2021 to 3.4 Mt in 2030 according to BAU development scenario of the sector and up to 14 Mt according to the optimistic scenario. At that, according to the last scenario, the future is for ***advanced biofuels*** from lignocellulosic feedstock and biofuels from waste oils (**Fig. 1.9**), which is in line with feedstocks listed in Annex IX of the EU Directive **RED II** (see **Annex 2**).



a) BAU scenario: carbon neutrality of aviation growth after 2020 is ensured by the international emissions trading and by the increase in RJF production; б) optimistic scenario: carbon neutrality of aviation growth after 2020 is totally ensured by the increase in RJF production

Fig. 1.9. Forecast for the production of biofuels and biogas for road transport and aviation in the EU until 2030, **EJ/yr**[3] [10].

ICAO’s experts have developed a forecast of production for various SAF in different regions of the world until 2035 [15]. Of the total **2,596** PJ (~59 **Mt**[3]) in 2035, the largest shares of

[3] Approximate ratio for RJF: **1 EJ = 23 Mt**.

SAF production will fall on the USA (29%), Brazil (19%) and the EU (17%) (**Table 1.3**). The production of SAP is expected mainly based on HEFA technologies (from oil of soybean, corn, rapeseed, palm, Carinata), Fischer-Tropsch synthesis (from miscanthus, switchgrass, poplar), alcohol conversion (from corn, sugar cane, miscanthus, switchgrass), and hydrotreatment of fermented sugars (from sugar cane and sugar beet).

Таблиця 1.3. Прогноз обсягів виробництва сталих авіаційних палив до 2035 р. за регіонами світу та технологіями [15].

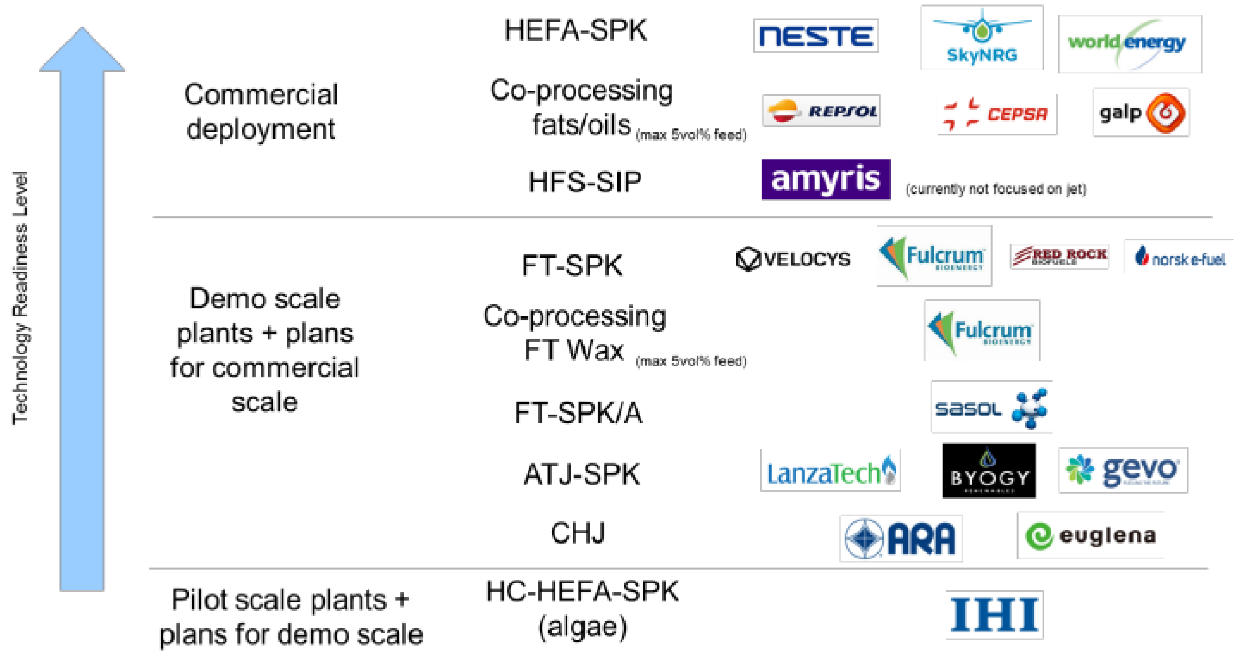
Country / region	**SAF pathway**	**SAF production**	
		PJ [3]	**Pathway share**
USA	HEFA (soy oil)	57	2.2%
	ATJ / ETJ (corn)	104	4.0%
	FT / ATJ / ETJ (miscanthus)	69	2.7%
	FT / ATJ / ETJ (switchgrass)	69	2.7%
	FT (poplar)	69	2.7%
	Other SAF including: HEFA (Carinata oil*)	373 (6.5)	14.4% (0.25%)
Brazil	HEFA (soy oil)	44	1.7%
	SIP (sugar cane)	104	4.0%
	ATJ / ETJ (sugar cane)	104	4.0%
	Other SAF including: HEFA (Carinata oil*)	243 (6,5)	9.3% (0.25%)
EU	HEFA (rapeseed oil)	65	2.5%
	FT / ATJ / ETJ (miscanthus)	52	2.0%
	SIP (цукровий буряк)	78	3.0%
	Інші САП	238	9.2%
Malaysia and Indonesia	HEFA (пальмова олія)	52	2.0%
	Інші САП	13	0.5%
Other regions		862	33.2%
Total		**2596**	**100%**

** Carinata grown as a secondary crop that avoids other crops displacement.*

The main players on the certified SAF market and their business segments are presented in **Fig. 1.10**. Among those are such well-known companies as Neste (Finland), World Energy (USA), Red Rock Biofuels (USA), Gevo (USA) and others, which already have at least one operating installation. During 2022-2025, it is planned to start operation of more than **20** installations for the production of aviation biofuels (**Table 1.4**). This will make it possible to reach the total production volumes of about **11** billion l/year (**9** Mt) by 2026 [20].

According to the estimates of the international Air Transport Action Group, which includes such organizations as Airports Council International (ACI), Civil Air Navigation Services Organization (CANSO), International Air Transport Association (IATA), International Business

Aviation Council (IAAC) and others, the need for SAF will amount to 330-445 Mt/yr by 2050 [28].



(abbreviations are available in Glossary of terms and Table 1.2)

Fig. 1.10. Summary of players across SAF certified pathways [16].

Table 1.4. Current and announced biojet fuel facilities and capacities [9, 20].

Company, start-up date	**Technolofy pathway (feedtsock)**	**Biojet fuel volume / Total capacity[4]**
World Energy (Paramount, USA), 2020	HEFA	25 / 95 Ml/yr
Neste (Porvoo, Finland), 2020	HEFA (animal fats, UCO)	34 / 128 Ml/yr
Gevo (Silsbee, USA), 2020 (demonstration)	conversion of isobutanol	0,143 kt/yr
LTU Greenfuels, 2020	G/FT (forest residues)	0,5 kt/yr
Total (La Mede, France), 2020	HEFA (oil of rapeseed, soybean, sunflower, palm, corn)	473 kt/yr
ENI, 2020	HEFA (UCO)	750 kt/yr
Velocys, 2020	G/FT (wood biomass)	57 kt/yr
Lanzatech, 2020	ATJ (MSW/residual biomass)	29 kt/yr
Lanzatech, 2021	ATJ (MSW/residual biomass)	76 kt/yr
REG, 2020	HEFA (UCO)	215 kt/yr
Fulcrum Bioenergy (Sierra, USA), 2021	G/FT (MSW)	7 / 26 Ml/yr
Red Rock Biofuels (Lakeview, USA), 2021	G/FT (forest and sawmill residues)	6 / 23 Ml/yr
Marathon, 2021	HEFA (soybean oil)	527 kt/yr
Announced facilities:		

[4] Approximate ratio for biojet fuel is **1000 l = 0.8 t** (at the density of ~800 kg/m^3).

Company, start-up date	Technolofy pathway (feedtsock)	Biojet fuel volume / Total capacity[4]
Neste (Singapore and Rotterdam), 2022	HEFA (animal fats, UCO)	480 / 1816 Ml/yr
Neste, 2023	HEFA (animal fats, UCO)	416 kt/yr
SkYNRG (Delfzijl, the Netherlands), 2022	HEFA	33 / 125 Ml/yr
Lanzajet (Freedom Pines, USA), 2022	conversion of ethanol	10 / 38 Ml/yr
Lanzatech, 2022	ATJ (MSW/residual biomass)	86 kt/yr
World Energy (Paramount, USA), 2022	HEFA (animal fats, vegetable oils)	150 / 568 Ml/yr
ECB, 2022	HEFA (soybeanoil, animal fats, UCO)	725 kt/yr
ST1 Oy, 2022	HEFA (UCO)	189 kt/yr
Diamond Green, 2022	HEFA (animal fats, UCO)	1933 kt/yr
LTU Greenfuels, 2022	G/FT (forest residues)	50 kt/yr
Gevo (Luverne, USA), 2023	conversion of isobutanol	19 / 72 Ml/yr
Go Sunshine (New Orleans, USA), 2023	HEFA	29 / 110 Ml/yr
Fulcrum #2 (Indiana, USA), 2023	G/FT	21 / 80 Ml/yr
Readifuels (USA), 2023	catalytic hydrothermolysis	24 / 91 Ml/yr
Hollyfrontier, 2023	HEFA (soybean oil)	358 kt/yr
Phillips 66 (San Francisco, USA), 2024	HEFA	290 / 1098 Ml/yr
Total (Grandpuits, Frnace), 2024	HEFA	56 / 212 Ml/yr
PREEM, 2023	G/FT (forest residues)	757 kt/yr
Preem (Gothenburg, Sweden), 2024	HEFA	70 / 265 Ml/yr
Lanzajet (USA), 2024	conversion of ethanol	90 / 340 Ml/yr
Caphenia, 2024	G/FT	0,227 kt/yr
Velocys (Altalto, UK), 2025	G/FT (MSW)	16 / 60 Ml/yr
SAF plus consortium, 2025	G/FT (forest residues)	23 kt/yr
Flexjet project, 2025	HEFA (UCO)	15 kt/yr

1.2.4. LCA of biomass-based SAF in terms of GHG emission

An assessment of GHG emissions during RJF life cycle production was performed according to GREET methodology. The assessment covered technologies that have already reached the commercial level or may reach it in the near future: HEFA, Fischer-Tropsch synthesis, hydrothermal liquefaction, pyrolysis, alcohol conversion, direct conversion of sugars into hydrocarbons. GREET methodology developed by the Argonne National Laboratory (USA) is based mainly on US data and is considered by experts to be the most popular tool for LCA of alternative aviation fuels [21, 22].

The life cycle of fuels includes all stages from the cultivation of feedstocks to the final consumption of the finished product. Three types of raw materials were considered: sugar /starch feedstock (corn grain, sugar cane), lignocellulosic feedstock (poplar, willow, forest residues, corn stover), and oil feedstock (used cooking oil, Camelina, Jatropha) (**Fig. 1.11**).

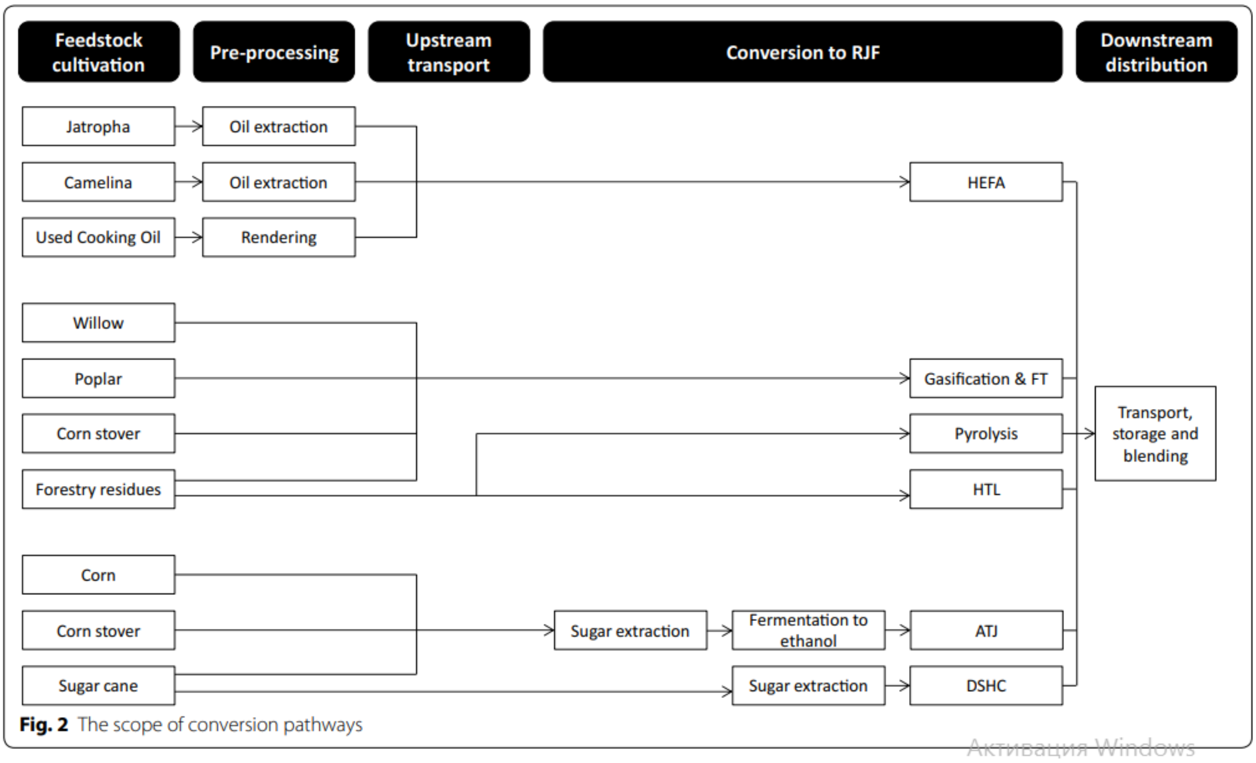


Fig. 1.11. The scope of conversion pathways for LCA [23].

The reduction of GHG emissions was determined in comparison with the traditional jet fuel with an average level of GHG emissions during the life cycle of **87.5** g CO_{2eq}/MJ. In such assessments, the method of GHG emissions allocation between the main product and co-products has a significant impact on the assessment results, especially when the volume of co-products is larger than that of the main product. A part of the GHG emission can be allocated to co-products depending on their mass, energy content and economic value. A typical example of a co-product is renewable diesel for HEFA technology. Alternatively, the displacement method (or system expansion) awards an emission credit to co-products based on the yield of the co-product and the GHG emission intensity of the displaced product (e.g., the fossil counterpart of the co-product).

The assessment results show that the use of ***lignocellulosic*** raw materials for the production of RJF gives the best results in reducing GHG emissions, regardless of the applied conversion technology and the method of allocation of emissions between the products. The level of GHG emissions when using different technologies, among other things, depends on the efficiency of the conversion process as well as the technology's need for hydrogen and the method of obtaining it (traditional or "green" hydrogen). Of the considered technologies, hydrogen is not needed only for Fischer-Tropsch synthesis; for technologies based on pyrolysis and hydrothermal liquefaction, "green" hydrogen can be obtained from gases produced in the conversion process itself. All other technologies use traditional hydrogen.

The best results regarding the reduction of GHG emissions as compared to the use of traditional jet fuels were obtained for gasification with Fischer-Tropsch synthesis (86...104%), hydrothermal liquefaction (77...80%) and alcohol conversion (60...75%) (**Table 1.5**). These emission reductions meet the requirements of the EU **RED II** Directive [3]: at least **50%**, **60%** and **65%** for transport biofuels production units that started operation on 05.10.2015 or earlier, from 06.10. 2015 till 31.12.2020 and from 01.01.2021, respectively.

Table 1.5. GHG emission reduction during the life cycle of RJF obtained via different production pathways [11, 23, 24].

Production pathway	**GHG emissions reduction as compared with fossil jet fuel**	
	Sierk de Jong et al. (2017) [23]	Doliente S.S. et al. (2020) [11]
Gasification with Fischer-Tropsch synthesis	**86…104%** Upper values: forest residues Lower values: corn stover	**92…95%** Upper values: forest residues Lower values: woody/grassy energy crops
Hydrothermal liquefaction (HTL)	77…80% (forest residues) Upper values: in situ* Lower values: ex situ**	--- (other studies [24]: 69%, in situ*)
Conversion of alcohols (ATJ)	71…75% (sugar cane) 60…75% (corn stover)	75% (corn stalks)
HEFA	~50…60% (Camelina) ~70% (used cooking oil)	~37…**98%** Upper values: algae, open pond (98%) and tallow (89%) Lower values: traditional oil crops
Pyrolysis	~50…75% (forest residues) Upper values: in situ* Lower values: ex situ**	--- (other studies [24]: 61%, in situ*)
Direct sugars to hydrocarbons (DSHC)	~50% (sugar cane, 10% of RJF in the blend)	---

** In situ – production of the necessary hydrogen "on the spot" by means of steam methane reforming of the gases produced in the conversion process. For HTL technology, hydrogen can additionally be obtained by steam methane reforming of biogas produced from the process wastewater.*
*** Ex situ – production of the necessary hydrogen by steam methane reforming of natural gas (for comparison).*

Fig. 1.12 presents the estimated reduction of GHG emissions in the production of biofuel by HEFA technology from Camelina using different methods for the allocation of GHG emissions between the main product (Camelina oil) and a non-energy co-product (animal feed with a high protein content). The best result, a reduction of GHG emissions by almost 60% when using "green" hydrogen, corresponds to the option of allocating the emission by mass of the products, which is explained by a high yield of the co-product. All other allocation methods give worse results, which are approximately the same– a reduction of GHG emissions by 50% or less.

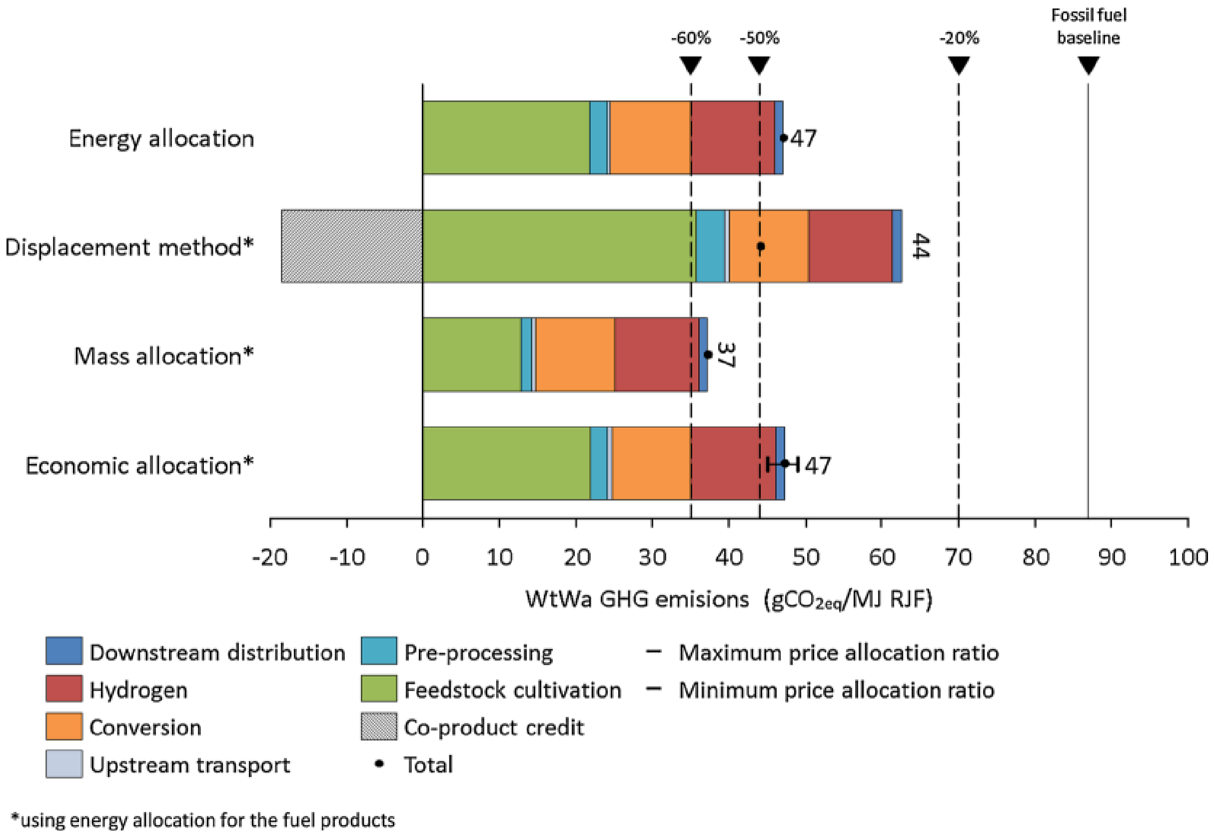


Fig. 1.12. GHG emissions (g $\mathbf{CO_{2eq}/MJ}$ RJF) for the HEFA Camelina pathway using different allocation methods for Camelina meal [23].

These results satisfy the sustainability criteria for reducing GHG emissions of CORSIA methodology for SAF (at least 10% during the life cycle), but do not meet the requirements of the EU RED II Directive. It should be noted that there are effective ways to further reduce GHG emissions in the production of biofuels using HEFA technology. Among other things, they include the use of high-yield feedstocks with a small amount of fertilizers applied, the consumption of waste and residues as raw materials, the improvement of the conversion technology efficiency, the introduction of carbon capture and storage technologies.

The choice of raw materials for the production of HEFA-SPK fuel significantly affects the result of GHG emissions reduction assessment. The default specific GHG emissions during HEFA-based RJF production life cycle in CORSIA methodology have a wide range (**g** $\mathbf{CO_{2eq}/MJ}$) from 13.9 for used cooking oil and 22.5 for tallow to 60 for palm oil with the treatment of process wastewater in an open pond (**Table A1 of Annex 1**).

The big importance of the raw material type for HEFA-SPK is also confirmed by results of LCA of several SAFs carried out in [60]. The study considered ATJ-SPK from isobutanol obtained by fermentation of corn, HEFA-SPK from tallow and SIP-SPK from sugar cane. Since the raw material for HEFA-SPK is a by-product[5] of the meat industry, the results of LCA for it are better as compared to other SAFs for all environmental indicators such as GHG emissions, use of agricultural land, consumption of fossil fuels and water, pollution of water bodies with algae – eutrophication, acidification of water and soil.

[5] According to CORSIA, tallow is a by-product; in study [60], it is considered a waste.

In particular, the estimated GHG emissions during the life cycle were about 3.2 g CO_{2eq}/MJ for HEFA-SPK, 30 g CO_{2eq}/MJ for SIP-SPK and 35.8 CO_{2eq}/MJ for ATJ-SPK (**Fig. 1.13**). At a reference value of 90 g CO_{2eq}/MJ for the traditional fuel Jet A-1, the achieved reduction is 96% for HEFA-SPK, 67% for SIP-SPK, and 60% for ATJ-SPK. To improve the results for ATJ-SPK fuel, which are the worst, there are the following options (**Fig. 1.14**): the use of renewable thermal energy in ATJ technology (GHG emissions during the life cycle are reduced to 29 g CO_{2eq}/MJ), the use of "green" heat + 50% "green" electricity (25 g CO_{2eq}/MJ), the consumption of 100% renewable heat and electricity in the conversion process (22 g CO_{2eq}/MJ). Similarly, the consumption of 100% RES can improve the indicators of the other two technologies, HEFA and SIP, if necessary.

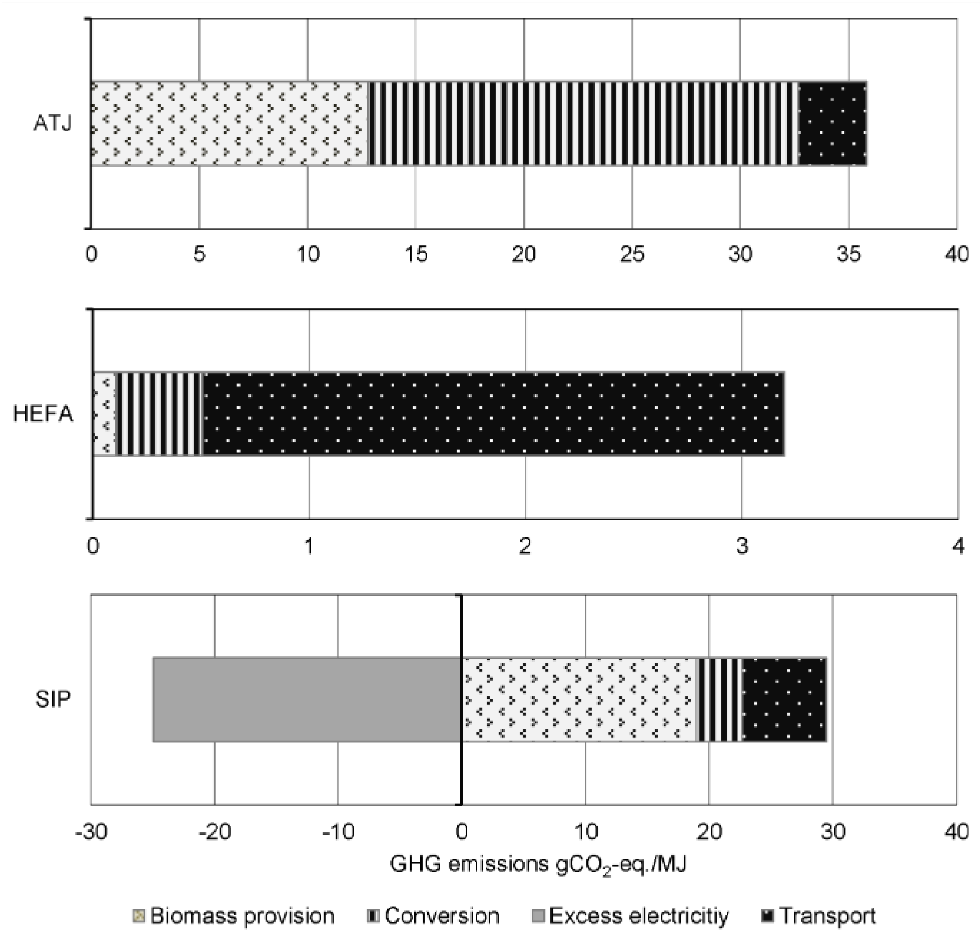


Рис. 1.13. Specific GHG emissions of different SAF [60].

Another study [11], carries out a comparison of GHG emissions reduction during the life cycle for RJF obtained by the technology of hydrotreatment of esters and fatty acids (HEFA, 4 types of raw materials) by gasification with Fischer-Tropsch synthesis (FT-jet, 2 types of raw materials) and by alcohol conversion technology (ATJ, one type of raw material). The best results, namely the reduction of GHG emissions > 90% as compared to traditional aviation fuel, were obtained for HEFA-based biofuel from algae (open pond) and Fischer-Tropsch synthesis-based biofuel from forest waste and woody/herbaceous energy crops (**Fig. 1.15**). These results do not contradict those presented above.

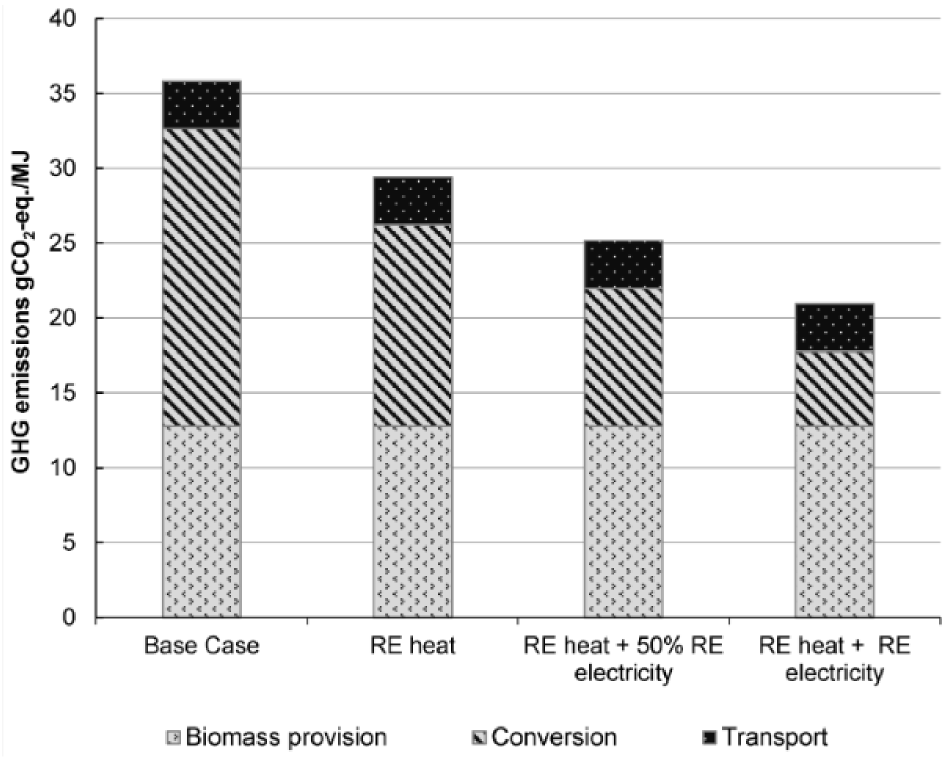


Fig. 1.14. Sensitivity analysis of GHG accounting for ATJ production [60].

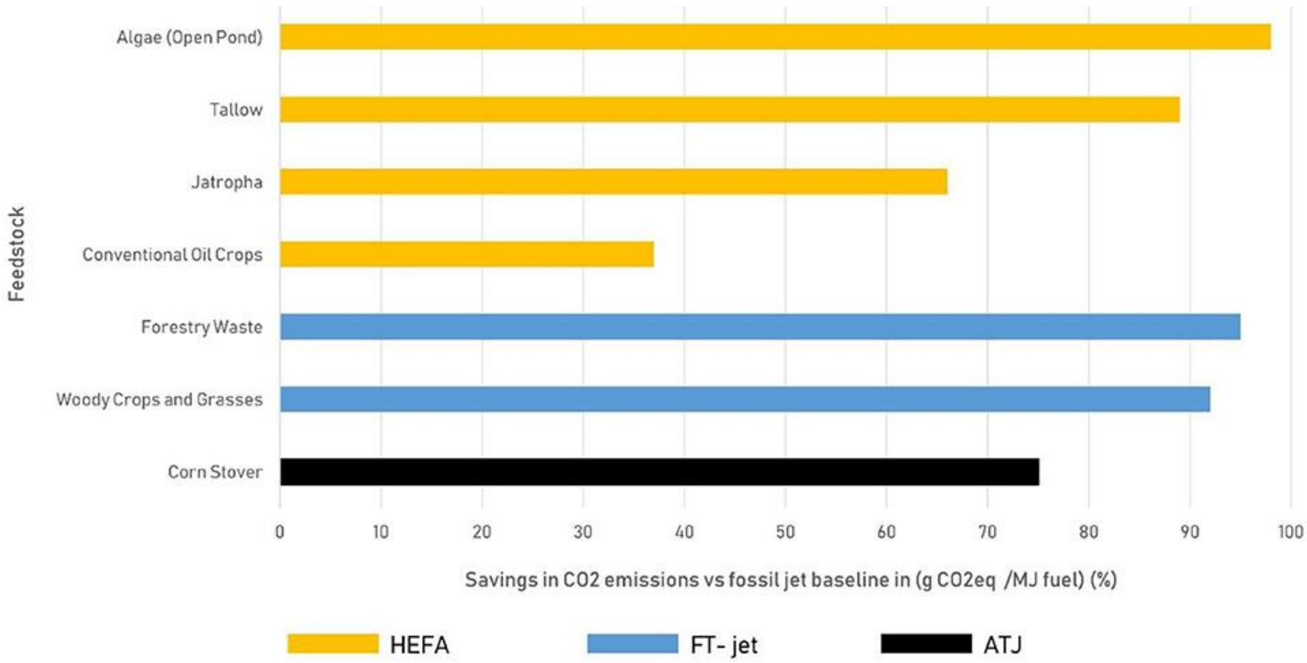


Fig. 1.15. Savings in CO_2 emissions as compared with fossil jet baseline, **%** [11].

1.2.5. Logistics of biomass-based SAF supply

The produced biojet fuel must be mixed with conventional jet fuel and delivered to airport. There are special procedures to confirm that the mixed jet fuel at various stages of supply meets ASTM standards. Most European airports operate in accordance with the international standards of the Joint Inspection Group. The main stages and options for the fuel supply/certification are as follows [9]:

1) Every batch of neat biojet fuel must be certified at the producer's site, to meet the relevant standard based on the specific Annex for that pathway in ASTM D7566.

2) If blending with conventional jet fuel takes place at the biofuel producer's site, the blend has to be certified against the standards as set out in Table 1 of the ASTM D7566 standard.

3) Once the blend has been certified under ASTM D7566, it is considered to have met all ASTM D1655 specifications. The blend is considered functionally equivalent to conventional jet fuel.

4) The blended fuel can then be transported to the specific airport where it can be inserted into the airport hydrant system or refuellers. *Changes in the airport infrastructure are not required.*

5) If the neat biojet fuel is transported to the airport, the biojet fuel has to be blended with conventional jet fuel *prior to entering the airport in a separate blending facility and cannot take place at the airport tank farm.*

6) The blended fuel must then be certified according to Table 1 of ASTM D7566.

7) The blended fuel can then be transported to the specific airport where it can be inserted into the airport hydrant system or refuellers. *Changes in the airport infrastructure are not required.*

1.2.6. Biomass-based SAF compatibility with Ukraine's current legislation

The current legislation of Ukraine does not use the term “sustainable aviation fuel.” The definition of the term "aviation fuel" is provided only by the Technical Regulation on requirements for aviation gasoline and jet fuel [94], which provides that aviation fuel is fuel for aviation engines from petroleum or other raw materials - aviation gasoline and jet fuel. Thus, aviation fuel from other raw materials (in particular, biomass) can be used in Ukraine if the aviation fuel from biomass meets the requirements of the Technical Regulation (after it enters into force). At the same time, each batch of aviation fuel must be accompanied by a copy of the declaration on the compliance of the aviation fuel with the requirements of the Technical Regulations and a quality document (quality passport).

A special law regulating relations regarding the use of biofuel is the Law of Ukraine "On Alternative Fuels" [95], but it does not use the term "aviation fuel". The question of its extension to aviation fuels will be explored in Report 3.

Sustainability issues of biofuels are not adequately reflected in the legislation of Ukraine. In particular, draft law No. 7233 dated 30.03.2022 [96] proposes introducing sustainability criteria for liquid biofuels (biocomponents) and biogas intended for use in the transport field. According to the mentioned draft law, sustainability criteria are the requirements that liquid biofuels (biocomponents) and biogas, intended for use in the field of transport, meet, in particular, indicators of the reduction of greenhouse gas emissions from the use of the specified types of biofuels and the prohibition of the use of specific land plots for obtaining raw materials necessary for the production of such types of biofuel. In the case of the adoption of the specified draft law, sustainability criteria will also apply to aviation and marine biofuels.

In addition, the Order of the State Aviation Service of Ukraine dated August 2, 2019, No. 1001 approved the Aviation Rules of Ukraine "Technical requirements and administrative procedures for monitoring emissions by aircraft operators" [97]. These Aviation Rules establish requirements for civil aviation aircraft operators and the authorized authority regarding planning, monitoring, and reporting of aircraft's annual carbon dioxide (CO_2) emissions during flights.

These Aviation Rules apply to all individuals and legal entities, regardless of the form of ownership, operating civil aircraft with a maximum certified take-off weight of more than 5700 kg. Aviation regulations apply to the operation of civil aviation aircraft performing international flights, except flights for humanitarian, medical, or firefighting purposes.

The specified Aviation Rules contain a definition of the term "CORSIA Eligible Fuel - CEF" - this is aviation fuel of sustainable production or low-carbon aviation fuel that meets the conditions of CORSIA, which the aircraft operator can use to reduce emissions.

CO_2 emissions are calculated based on fuel consumption by the aircraft. The aircraft operator monitors emissions and documents fuel consumption during international flights following the applied monitoring method, which is approved by the authorized authority through the approval of the Emissions Monitoring Plan in the form given in Appendix 1 to the specified Aviation Rules. To determine an acceptable method of monitoring fuel consumption, the aircraft operator calculates the number of emissions from international flights for the previous year.

The report on the volume of emissions is a document demonstrating the volumes of CO_2 emissions of the aircraft operator for the reporting period, which were calculated per the approved Plan. If the operator uses CEF fuel, its volume is displayed in the report. In particular, from January 1, 2021, information on applying to reduce emissions due to the use of fuels that meet CORSIA conditions is displayed. In this case, additional information on emission reduction due to the use of each type of fuel that meets the conditions of CORSIA (Appendix 2 to the Aviation Rules) is submitted to the report.

Regarding the logistics of the supply of SAF from biomass, in our opinion, the current Instruction on ensuring refueling of aircraft with fuel and lubricants and technical fluids in civil aviation transport enterprises of Ukraine, approved by order of the State Aviation Service dated 14.06.2006 No. 416 [98], does not take into account the possibility mixing bio reactive fuel with traditional reactive fuel and it is outdated. In the case of adopting measures to stimulate the use of SAF from biomass in Ukraine, we consider it necessary to revise the abovementioned Instruction.

1.3. Other alternative aviation fuels

1.3.1. Synthetic SAF (PtL)

Synthetic fuel for aviation needs (a type of SAF) can be obtained by electrolysis of water using electricity, in particular ***"green" electricity*** – Power-to-Liquid (PtL) technology (**Fig. 1.16**). The source of renewable electricity can be, for example, ***solar or wind power plants***. Access to the required amount of "green" electricity is considered one of the key sustainability issues of PtL technology as renewable power already has many alternative applications.

In addition to hydrogen formed in the process of electrolysis of water, carbon monoxide CO is also needed for synthesis of hydrocarbons. It is obtained from carbon dioxide CO_2 through the reverse water-gas shift reaction. Synthesis of hydrocarbons occurs by applying Fischer-Tropsch synthesis or synthesis with methanol as an intermediate product. It should be noted that the technology for the production of jet fuel using water electrolysis with further Fischer-Tropsch synthesis (PtL FT) is certified by ASTM D7566 standard, Annex 1 (as long as the FT synthesis is based on iron or cobalt catalysts), while that via synthesis with methanol as the intermediate product is not certified yet.

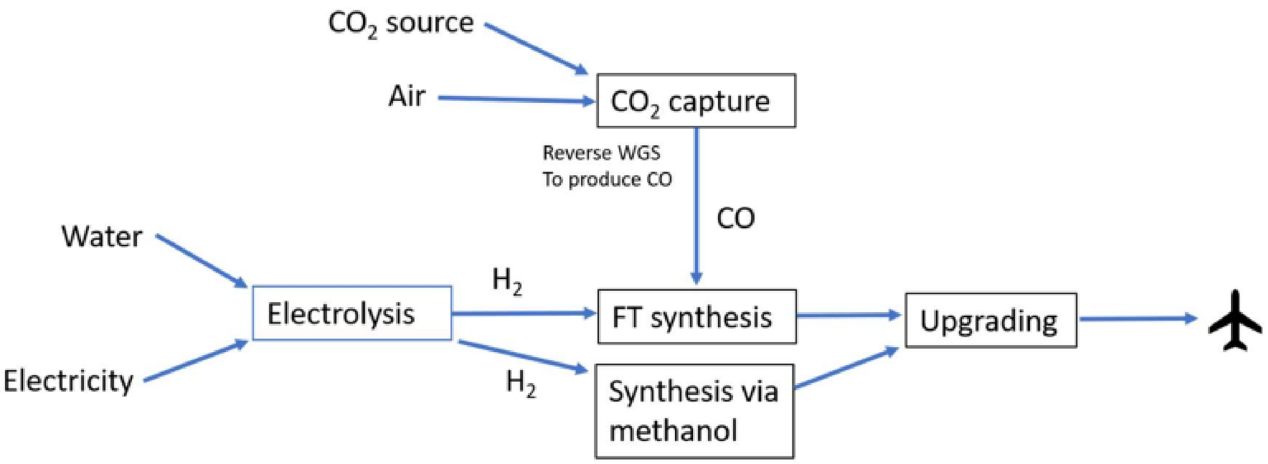


Fig. 1.16. Simplified illustration of PtL process for the production of aviation fuels [9].

There are different options for obtaining CO_2 and different electrolysis technologies for hydrogen production (alkaline electrolysis, electrolysis on a proton exchange membrane and in a solid oxide electrolyzer), which differ in cost, efficiency and flexibility. The source of CO_2 is an important aspect for PtL technology, affecting its carbon footprint and cost. Concentrated sources of CO_2 can be industrial waste gases (of fossil origin), geothermal resources, ***biogas*** as well as carbon dioxide as a by-product of ethanol production. At that, the use of CO_2 of fossil origin is not always considered a sustainable approach because it is, rather, just carbon recycling than a component of the circular economy. Alternatively, CO_2 can be captured directly from the air, which is currently a more expensive option due to high energy costs for processing large volumes of air.

All the components of PtL production pathway, apart from the reverse water-gas shift reaction, are individually well-developed processes already applied on an industrial scale. In general, PtL technology has not yet fully reached the commercial level, but is actively developing in Iceland, Finland, Germany and Norway. Currently, there are more than 50 demonstration and pilot plants in the world that are in operation or under construction.

Main components of the general chain of production and supply of synthetic fuel (PtL) in comparison with liquid hydrogen (LH_2) are shown in **Fig. 1.17**. If synthetic fuel is produced near the source of CO_2, then the chain includes the production itself, transportation and delivery to an airport, storage at the airport, refueling of aircraft. If the fuel is produced on site, i.e. at the airport, then the stages of transportation and delivery fall out of the chain. However this production option with capturing CO_2 from the air is more expensive as it requires 3 times more energy and 1.5 times more hydrogen to produce the same amount of fuel than the option of using CO_2 from a concentrated source.

LCA of synthetic fuel obtained by PtL technology shows that such fuel has environmental advantages (reduction of GHG emissions, mitigation of the effect of atmospheric acidification) over traditional fuel only when using ***renewable electricity*** at all stages of the implementation of this technology [56]. The largest consumption of electricity falls on the stage of electrolysis of water; if it is taken as 100%, then the stage of providing technology with carbon dioxide requires only 5%, and Fischer-Tropsch synthesis requires 7%. Four options for the source of electricity were considered: 1 – German power grid, 2 – Saudi Arabian power grid, 3 – WPP, 4 – solar PV plant. The source of CO_2 is flue gases from a biomass power plant.

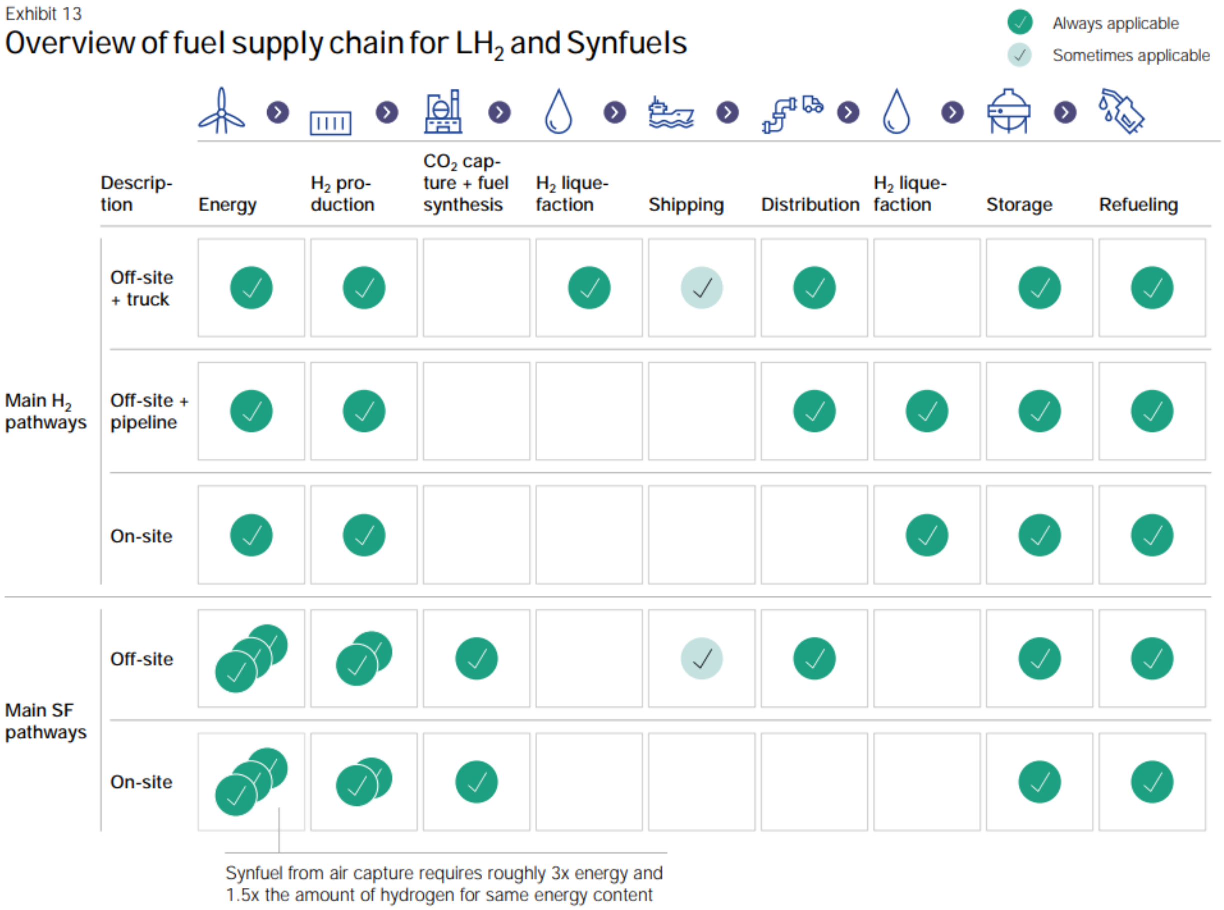


Fig. 1.17.Overview of fuel supply chain for LH_2 and synthetic fuels (SF) in aviation [31].

The best result in reducing GHG emissions (~90%) was obtained for the option of using electricity from WPP: GHG emissions during the life cycle of PtL were **8.6** g CO_{2eq}/MJ (diesel) while the reference value for jet fuel was **87.5** g CO_{2eq}/MJ. When using electricity from solar PV plant, GHG emissions during the PtL life cycle were 46 g CO_{2eq}/MJ (diesel). In study [56], all results are recalculated for diesel fuel, which is one of the final products of the technology along with kerosene and heavy gasoline. The output of kerosene in this case is 6 times higher than the output of diesel, therefore, taking into account their close heating value, it can be concluded that the results in terms of kerosene are even better.

A similar result was obtained in study [57] when considering various options for implementing PtL production pathway with Fischer-Tropsch synthesis. The biggest reduction of GHG emissions during the life cycle of synthetic fuel as compared to traditional RP, up to **87%**, is achieved when consuming renewable electricity from WPP or solar PV plant (the WPP option being slightly better) and capturing CO_2 from the air. Under the same conditions, but using a cement plant as a source of CO_2, the reduction of GHG emissions is up to **75%**.

According to estimates by [58], the reduction of global warming potential calculated per passenger*km for narrow-body aircraft (that is aircraft with a number of seats about 150) is 42%

when using electricity from WPP in PtL technology (for the United Kingdom's conditions) and 32% when using electricity from solar PV plant (for Spain's conditions) (**Fig. 1.18**).

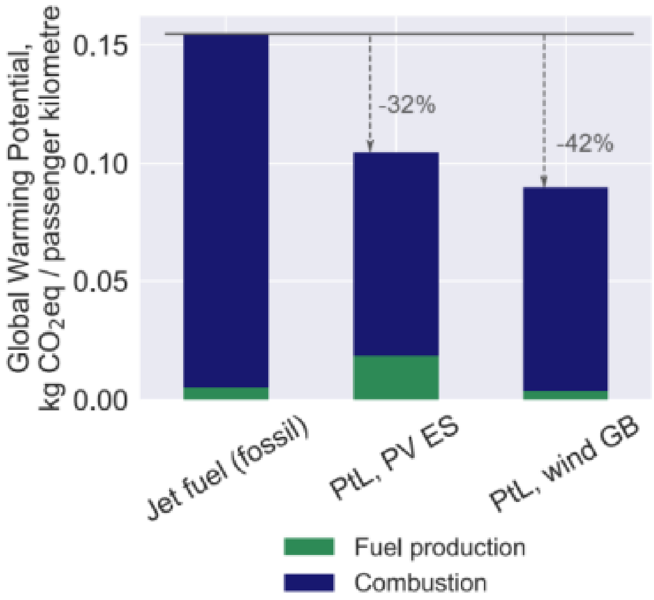


Fig. 1.18. Global Warming Potential[6] for fossil jet fuel and synthetic fuel PtL [58].

1.3.2. Electric power

Electrification of the aviation sector is currently in the initial stage of development and demonstration. As of September 2021, there were about 230 relevant projects in the world, of which only 30 were of a commercial level. Fully electrified and hybrid aircraft designs are being developed; there are already examples of small electrified aircraft certified for flight; test flights of aircraft with modified electric motors are carried out. The start of large-scale commercial use of electrified aircraft is predicted by experts no earlier than in the middle of the 21st century. At the same time, commercial suburban and regional flights of small electric aircraft may begin as early as in 2025-2030 (**Fig. 1.19**).

Manufacturers of aircraft, electrical equipment and batteries show a growing interest in the development of aviation electrification. The main driving forces of this process are considered to be the following [26]:

- Significant reduction of greenhouse gas emissions.

- Projected reduction in operational costs, aircraft maintenance costs, as well as pilot training.

- Development of the market of regional flights (up to 500 km), increasing use of regional airports with the predominant usage of hybrid ("turboelectric") aircraft (electric motor + internal combustion engine). It is estimated that about 10,000 9-seater aircraft can be replaced by electric

[6] Global warming potential (GWP 100) describes potential for the global temperature change due to greenhouse gas emissions. The time period usually used for GWPs is 100 years.
https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

and hybrid aircraft in the future, which will be 20-40% more efficient than aircraft with piston engines and gas turbine engines.

- A more economical "green" alternative for regional trips compared to using ground transport.

- Significant reduction in noise level.

	2020	2025	2030	2035	2040	2045	2050
Commuter » 9-19 seats » < 60 minute flights » <1% of industry CO_2	SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF
Regional » 50-100 seats » 30-90 minute flights » ~3% of industry CO_2	SAF	SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF
Short haul » 100-150 seats » 45-120 minute flights » ~24% of industry CO_2	SAF	SAF	SAF	SAF potentially some Hydrogen	Hydrogen and/or SAF	Hydrogen and/or SAF	Hydrogen and/or SAF
Medium haul » 100-250 seats » 60-150 minute flights » ~43% of industry CO_2	SAF	SAF	SAF	SAF	SAF potentially some Hydrogen	SAF potentially some Hydrogen	SAF potentially some Hydrogen
Long haul » 250+ seats » 150 minute + flights » ~30% of industry CO_2	SAF	SAF	SAF	SAF	SAF	SAF	SAF

Fig. 1.19. Forecast of using SAF, electricity and hydrogen in commercial aviation on flights of different distances [28].

Accumulators (batteries) needed to run electric motors can be charged from solar photovoltaic cells, hydrogen fuel cells, or traditional gasoline/diesel generators.

The prototype of the hybrid aircraft is “Electric EEL” plane of Ampaire (USA) equipped with a 160 kW electric motor and a 300 hp piston engine. Electric EEL is converted from Cessna 337 aircraft (6 passenger seats), which had two piston engines. The hybrid aircraft performed its first 20-minute demonstration flight in 2020 in Hawaii and later it performed a series of test flights in 2021 in Scotland [32, 33].

The prototype of a fully electrified aircraft is “Alice” plane of Eviation (USA). Ground tests of the aircraft were completed in May 2022, the first test flights are expected in the summer of 2022 [34].

A comparison of the cost of the required amount of fuel/electricity and the quantity of specific CO_2 emissions for a small liquid-fueled aircraft Pilatus PC-12 and an electric aircraft Alice (Eviation) was performed on the example of several flights from Denver International Airport (Colorado, USA) [26]. Pilatus PC-12 (6-9 passengers) currently operates such flights. Alice electric plane (9 passengers) with a lithium-ion battery of 820 kWh capacity and three electric motors can potentially replace Pilatus PC-12 for these flights.

The obtained results show that replacing a conventional aircraft with an electric aircraft for the flights of 65-80 minutes can significantly reduce fuel costs (from approximately 400 to 50 USD per flight) and considerably reduce CO_2 emissions – by up to 95% when using "green" electricity (**Table 1.6**).

Table 1.6. . Information for select slights from Denver (DEN) for Liquid-Fueled and Electric Aircraft [26].

Destination	Flights /day	Miles	Flight Time (mins)	Fuel Use (gals)	Fuel Costs[a]	$kgCO_2$ /PAX[b]	kWh (approx.)	Electricity Cost[c]	$kgCO_2$ /PAX Coal[c,d]	$kgCO_2$ /PAX Solar[c,d]
ALS	4	179	80	88	$440	36	334	$43	34	2
CEZ	3	277	80	88	$440	56	516	$66	53	3
MCK	2	217	65	72	$358	44	404	$52	41	2
CDR	2	222	70	77	$385	44	414	$53	42	2

[a] Assuming a $5/gallon fuel cost

[b] PAX= number of passengers carried by an airline, assuming eight passengers.

[c] Based on commercial electricity costs for Cortez, Colorado; these values provide a conservative estimate of the electricity costs. Industrial electricity cost pricing could provide a 50% reduction in these costs.

[d] kg CO2 calculated from the use of coal and utility scale solar to produce the needed amount of energy ("IPCC Working Group III – Mitigation of Climate Change, Annex II Metrics and Methodology" IPCC https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-ii.pdf#page=26).

MCK – McCook Ben Nelson Regional Airport; CDR – Chadron Municipal Airport, ALS – San Luis Valley Regional Airport; CEZ – Cortez Municipal Airport

To implement all-electric aircraft, airports must consider the dwell time available for plane recharging, as well as coincidence charging that may likely occur at higher-traffic (i.e., hub) airports.

Current route schedules for the four airports studied have turnaround times of approximately 20–30 minutes for potential refueling. To mirror current desired energy transfer rates, each aircraft would require charging stations capable of delivering an average power of around 1 MW, which exceeds the abilities of current market options. Current light-duty automobile technologies offer fast charging with power ratings of up to 250–350 kW and unit costs exceeding $100,000 per charger [29]. Each of the flights in this case study consume 300–500 kWh, and would need to fully recharge in less than 30 minutes to accommodate existing flight schedules. To fully recharge the Eviation Alice's 820- kWh battery within current dwell periods would likely require a power rating of 2 MW or more.

Thus, the commercial introduction of electric aircraft requires further R&D of technologies in the direction of the development of batteries for long-distance flights, the creation of more powerful chargers and the corresponding charging infrastructure. Existing electric batteries have a low gravimetric energy density (0.2-0.5 kWh/kg) and a limited life cycle. This limits their use as the only source of energy in the plane to only short flights that is suburban and regional ones [31].

World airports are just beginning to electrify their ground vehicles. The future integration of electric aircraft in the operation of airports will require significant efforts and funds (**Fig. 1.20**), although the potential benefits and advantages from this will also be quite large.

Study [68] is devoted to the analysis of electric-powered aircraft, including the calculation of greenhouse gas emissions using the **life cycle assessment (LCA) method**. The authors note that the topic of electric aircraft is very relevant, but a limited amount of data from real-time operations is available. The article focuses on all-electric general aviation aircrafts with one propeller. To maintain comparability, the authors consider modernized aircraft where the classic internal combustion engine is replaced by an electric engine with batteries.

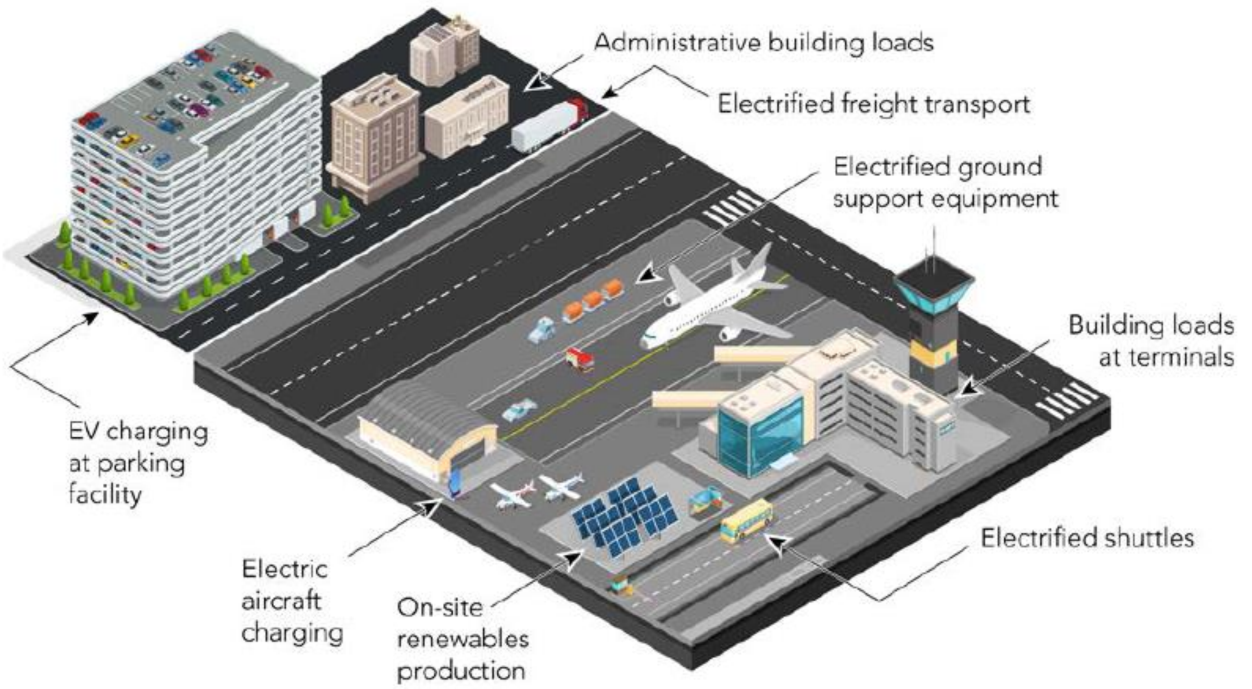


Fig. 1.20. Integrated energy requirements of future airports with electrifired aircraft [26].

For a meaningful comparison between carbon fuel and electricity, it is necessary to express their energy potential on a comparable scale. To compare small piston propelled aircrafts, the necessary energy, which has to be transferred by shaft from the engine to the propeller is considered. It is presumed that the same retrofitted aircraft, in one case, works with an AVGAS fueled piston engine, and in the second, an all-electric battery propelled aircraft. All aircraft dependent variables (such as wing aspect ratio, aircraft lift coefficient, aircraft drag coefficient, propeller efficiency, propeller diameter, etc.) are equal for both cases. The only difference is the mass of the aircraft, because of the different engine mass, and mainly because of the additional batteries` mass.

In the case of an aircraft equipped with a combustion engine, authors presume a spark-ignited piston engine with internal combustion fueled by AVGAS 100 LL fuel, used by an aircraft with maximal power less than 350 horsepower. LL stands for low lead—AVGAS 100 also exists, with about a 60% higher lead volume. In other text, AVGAS refers to the AVGAS 100LL fuel. The structure of electricity production sources, which were used to drive the electric motor, is as follows: the share of nuclear energy in the mix is 30%, renewable energy is 42%, coal is 12%, gas is 13% (corresponds to the structure of electricity production in the EU in the first quarter 2020).

The analysis results are shown in **Table 1.7**, which shows how many grams of pollutants are produced per 1 kWh of the aircraft shaft power. Greenhouse gas emissions when using kerosene fuel AVGAS 100 LL are higher than in the case of an electric engine by 68% for CO_2 and by 43% for NO. Methane emissions are 19% higher when using electricity.

The authors of the study [68] note that there is a lack of operational data to assess the environmental impact of a specific aviation fuel change from AVGAS to all-electric. Also, in order to assess the life cycle of the transition to an all-electric engine, it is necessary to know the emissions from electricity production, which largely depend on the structure of energy production in a certain country. For example, in the Czech Republic, where the energy mix is 57% coal, 37% nuclear, and 6% renewable the emissions are about 450 g of CO_2 per 1 kWh of aircraft shaft power. For such a scenario, the difference between AVGAS and electricity CO_2 emissions is only 25%. With increased percentage of renewable sources of electric energy, the difference in CO_2 production level increases. This is true even for the situation when all-electric aircraft emissions, including LCA emissions and AVGAS, do not include LCA (because of the lack of suitable data). An all-electricity aircraft always has lower carbon impact, but the significance of the difference is subject to local conditions.

Table 1.7. Emissions comparison for the use of internal combustion engine aircraft and electric aircraft, **in gram per 1 kWh shaft power** [68].

Substances	AVGAS 100 LL	AVGAS 100 LL With LCA	All-electric	All-electric with LCA
CO_2	600	1080	179	344
CH_4/CH	4.5	8.1	5.4	10
NO	1.5	2.7	0.8	1.536
SO			10	19
PM			1.25	2.4
Water wapor	360	360		
CO	300	300		
lead	0.24	0.24		

Based on [69], in 2015 there were 103,063 general aviation aircrafts registered by national aviation authorities in the EU. In the same year, there were about 6500 aircrafts used for commercial aviation in Europe. The number of aircrafts used for general aviation exceeds the commercial aviation aircrafts by, at least, a one to ten ratio. Based on annual production of Jet A1, which is more than 100 times higher than production of AVGAS, we can estimate that switching to all-electric commercial aviation would not reduce the carbon emission footprint of aviation by more than few tenths of one percent. On the other hand, AVGAS greenhouse gas emissions represent about 1,500,000 tons of CO_2 annually. The difference is more evident for emissions causing direct health issues. AVGAS is a source of CO, HC, and lead emissions. These gases mostly have local impact. The influence of these gases is most significant around the aerodrome, because of a combination of a higher volume of traffic in a small area, and a non-ideal working state of engines.

Justifying the need to perform a life cycle assessment of potential storage systems for electric aircraft, the authors [70] point out, that potential approaches to replace the fossil fuel-powered jet engines completely or at least partially include synthetic fuels, battery-electric or fuel cell-based electric propulsion systems, as well as hybrid concepts. While synthetic fuels and hybrid concepts only reduce CO_2 emissions to a certain extent, fuel cell-based propulsion systems eliminate them during flight operation. Nevertheless, none of these three approaches eliminates all of the non-CO_2-emissions, such as water vapor, sulfur dioxide, NO_x, particulate matter, and soot, completely. These emissions represent about 60% of an aircraft's total emissions by mass and have climatedamaging effects as well as other harmful effects on the environment.

A promising approach that could eliminate both types of emissions during the flight are full-electric propulsion systems. These systems are powered by electricity instead of kerosene and consist of propellers that generate the thrust for flight operation, electric motors that drive the propellers, and batteries used for energy storage. However, the specific energy of the currently available battery technologies is still limited. Therefore, the achievable flight ranges with full-electric propulsion systems are much shorter compared to their conventional counterparts.

Furthermore, the production of batteries involves energy-intensive processes with negative environmental impacts and rare and critical materials associated with various social risks, such as poor working conditions. The ongoing technological developments of battery technologies promise substantial increases in specific energy. It is still difficult to quantify an exact value, but it is conceivable that small passenger aircraft can fly fully electric in the future. In order to develop a propulsion concept that is not only technologically feasible but also sustainable from the environmental, economic, and social perspective, a preselection of potential battery systems is necessary and should be carried out in the early development stages.

For this purpose (identification of the most promising battery system), the article [70] authors use a Life Cycle Sustainability Assessment (LCSA) approach to assess eight alternative battery systems regarding their environmental, economic, and social impacts in the stages of raw materials extraction and production. The battery systems are based on different cell chemistries, including five lithium-ion batteries (LIB) based on lithium nickel manganese cobalt oxide (NMC), one LIB based on lithium iron phosphate (LFP), on LIB based on lithium nickel cobalt aluminum oxides (NCA), and one lithium-sulfur battery (LSB). The functional unit of the assessment is the production of the described battery system. For this purpose, the stages of raw material extraction, components production, battery cell production, and battery pack production are considered.

The environmental impact assessment is based on six impact categories: climate change (CC), terrestrial acidification (TA), human toxicity (HT), freshwater eutrophication (FE), photochemical oxidant formation (POF), and mineral resource depletion (MRD). The selected impact categories are chosen because they allow a comparison to the CO_2 and non-CO_2-emissions of conventional aircraft. The economic assessment is based on the life cycle cost (LC) of all unit processes involved in the life cycle of the battery system. The social impact assessment is based on the Social Hotspots Database (SHDB) impact assessment method. Selected impact categories are risk of poverty (POV), risk of corruption (COR), and risk of child labor (CHL). The results of calculations are given in **Table 1.8**.

Regarding the environmental impacts (CC, TA, HT, FE, POF, and MRD), the LIB based on LFP and the LSB tend to perform better than the LIBs based on NMC and NCA. Here, the LFP variant is advantageous in the categories terrestrial acidification, human toxicity, freshwater eutrophication, and mineral resource depletion, while the LSB is advantageous in the categories climate change and photochemical oxidant formation. On the other hand, the NMC-111, NMC-442, and NMC-532 variants are in each case worst, whereby in the category terrestrial acidification, the NMC-811 is the worst.

The Life Cycle Sustainability Assessment of the various battery systems shows a trend towards promising battery technologies. While LFP and LSB are generally advantageous in terms of environmental impacts during production, and LFP is superior to LSB in some aspects, LSB is beneficial in terms of the socio-economic effects in all impact categories.

Table 1.8. Environmental and socio-economic assessment results for a battery pack with 4.313 MWh capacity of the respective cell chemistries [70].

Impact category	Per battery pack (4.313 MWh capacity)							
	NMC-111	NMC-442	NMC-532	NMC-622	NMC-811	LPF	NCA	LSB
Environmental								
Climate change (CC), kg $CO_{2\text{-eq}}$	$3.81\cdot10^5$	$3.58\cdot10^5$	$3.63\cdot10^5$	$3.39\cdot10^5$	$3.24\cdot10^5$	$3.24\cdot10^5$	$3.78\cdot10^5$	$3.18\cdot10^5$
Terrestrial acidification (TA), kg $SO_{2\text{-eq}}$	7268.91	7268.39	8958.22	9118.99	10271.79	2004.04	5860.99	2148.3
Human toxicity (HT), kg 1,4-DCB-eq	$5.43\cdot10^5$	$5.34\cdot10^5$	$5.54\cdot10^5$	$5.38\cdot10^5$	$5.44\cdot10^5$	$2.55\cdot10^5$	$2.52\cdot10^5$	$3.76\cdot10^5$
Freshwater eutrophication (FE), kg P-eq	241.13	233.68	245.77	237.99	240.74	146.89	158.85	174.98
Photochemical oxidant formation (POF), kg NMVOC-eq	2332.0	2110.80	2324.47	2246.04	2244.50	1306.14	1840.13	1211.14
Mineral resource depletion (MRD), kg Fe-eq.	$3.54\cdot10^5$	$3.63\cdot10^5$	$3.58\cdot10^5$	$2.95\cdot10^5$	$2.66\cdot10^5$	$0.62\cdot10^5$	$1.16\cdot10^5$	$0.85\cdot10^5$
Economic								
Life Cycle Cost (LC), USD	$7.25\cdot10^5$	$6.32\cdot10^5$	$6.6\cdot10^5$	$6.17\cdot10^5$	$5.63\cdot10^5$	$7.15\cdot10^5$	$6.2\cdot10^5$	$3.78\cdot10^5$
Social (Eq. med. risk hours)								
Risk of Poverty (POV)	$5.32\cdot10^6$	$4.16\cdot10^6$	$4.82\cdot10^6$	$4.58\cdot10^6$	$4.22\cdot10^6$	$4.16\cdot10^6$	$4{,}19\cdot10^6$	$0.73\cdot10^6$
Risk of Corruption (COR)	$13.43\cdot10^6$	$11.29\cdot10^6$	$13.57\cdot10^6$	$13.17\cdot10^6$	$13.17\cdot10^6$	$6.65\cdot10^6$	$9.95\cdot10^6$	$1.22\cdot10^6$
Risk of Child labor (CHL)	$8.01\cdot10^6$	$6.48\cdot10^6$	$7.18\cdot10^6$	$6.80\cdot10^6$	$6.8\cdot10^6$	$5.12\cdot10^6$	$6.66\cdot10^6$	$1.15\cdot10^6$

Various circumstances can explain this. On the one hand, the material input for the LSB production is lower compared to the production of LIBs, and the materials used are cheaper per unit. On the other hand, different origins of the materials required for production and fewer working hours related to LSB production result in lower social risk. The LCSA also shows that, in addition to its environmental and social advantages, the LSB is an economically promising battery technology for manufacturers of future aircraft propulsion systems due to its 33-48% lower LC. The development of novel propulsion technologies for electric aircraft should, therefore, primarily focus on LSB. However, LIB variants with LFP, NCA, or NMC-811 should also be further investigated since a specific reference aircraft with a specific flight profile was used for the assessment in the context of this analysis. Under other conditions, these two battery technologies might be advantageous.

The main conclusion based on the results of the research analysis is that LSB a promising battery technology for electric aircraft. In addition to its environmental and social benefits over competing technologies, it is also advantageous from an economic perspective, which makes it interesting for manufacturers of aircraft powertrains.

Since synthetic fuel and electricity use in aviation transport is cutting-edge technology, there is **no special regulation of their use in Ukraine**. The general law regulating the use of renewable electricity in Ukraine is the Law of Ukraine "On Alternative Energy Sources" [99]. The specified law refers to renewable non-fossil energy sources, namely solar, wind, aerothermal, geothermal, hydrothermal, wave and tidal energy, hydropower, biomass energy, gas from organic waste, and gas from sewage treatment plants, and biogas. The law establishes the procedure for obtaining a "green" tariff in case of submission of renewable electricity to the unified energy system of Ukraine and does not provide for restrictions on the use of renewable electricity for other needs.

On April 15, 2022, the Law of Ukraine "On Amendments to Certain Laws of Ukraine Regarding the Development of Energy Storage Installations" was signed [100]. The law regulates a new activity in the electric energy market - energy storage. Energy storage is an activity related to the selection of electrical energy to postpone its final use to a time later than when it was produced, its transformation into another form of energy in which it can be stored, storage and further conversion of such energy into electrical energy to release it into the transmission system, the distribution system, the power plant network or the consumer network. The energy storage facility is operated by an operator who is a new participant in the electricity market. Economic activity in energy storage is carried out under obtaining a license, except in cases established by law.

1.3.3. Hydrogen

By its origin, hydrogen is conventionally divided into "black" (obtained from coal), "gray" (from natural gas), "brown" (from lignite), "black" (obtained from fossil fuels using a carbon capture and storage system), "pink" (obtained by electrolysis of water using electricity from nuclear power plants) and ***"green"*** (obtained by electrolysis of water using ***renewable*** electricity, for example from wind power plants or solar power plants)[7].

Global large-scale production of hydrogen takes place today by converting natural gas ("gray" hydrogen). SMR technology is the reforming of natural gas through reaction with steam, being the most common option. A standard installation usually has a capacity of 100,000 m^3 or 9 tons of hydrogen per hour. Another commonly accepted technology for obtaining hydrogen is water electrolysis. When replacing natural gas with biomethane in steam reforming technology and using renewable electricity for water electrolysis, ***"green" hydrogen*** is produced.

In the **draft** Roadmap for the production and use of hydrogen in Ukraine [53], the cost of "green" hydrogen obtained by electrolysis of water is estimated at 1.5-3.0 EUR/kg with electricity prices of 25-50 EUR/MWh for the period 2020-2025 with a decrease to 0.7-1.5 EUR/kg with electricity prices of 10-30 EUR/MWh by 2050 (**Table 1.9**).

Table 1.9. Forecast values of technical and economic indicators of "green" H_2 production [53].

Production of hydrogen in electrolyzers	Capital cost, EUR/kW	Yearly operating cost, %	Efficiency of the system	Electricity, EUR/MWh	Hydrogen, EUR/kg
2020-2025	300-600	1.5%	75-80%	25-50	1.5-3.0
2025-2030	250-500	1%	80-82%	15-30	1.0-2.0
Until 2050	<200	<1%	>82%	10-30	0.7-1.5

It is known that hydrogen is a gas that is difficult to store. It has the properties that must be considered and taken care of to ensure its safe use. Although there are technologies and procedures that minimize leakage and provide, if necessary, a controlled release of hydrogen, they are not well understood by the general public outside of the petrochemical industry. Indeed, in cases of safety-related hydrogen accidents, problems in the assembly of the hydrogen installation were often the cause, demonstrating the importance of using experienced professional installers and engineers. It

[7] More detailed general information about hydrogen and pathways for green hydrogen production is presented in chapter 2.5. Hydrogen of the Technical Report.

is also important that experienced technicians perform maintenance of system fuel cells, particularly those operating at high temperatures, for which the supplier recommends basic maintenance every three months.

Since 2019, a significantly increasing interest in using hydrogen in aviation has been observed in the world. The main problems of this direction are the need for a large amount of hydrogen, the need for the production of "green" hydrogen and the provision of the appropriate infrastructure for its supply. Hydrogen is a low-/carbon-free fuel that can be used in aviation in two ways [28]:

- in conventional gas-turbine engines (with certain adaptation/modification) as a substitute for traditional jet fuel (including large aircraft);

- in fuel cells as a source of electricity. Unlike electric batteries, which require recharging, fuel cells can generate electricity as long as a supply of fuel (hydrogen) is provided. Other advantages are the possibility of arranging fuel cells in a "battery", that is, scaling, as well as the absence of moving parts in them, which ensures noiselessness and high reliability of their operation.

In addition to these direct application options, hydrogen is used in the production of synthetic kerosene using the power-to-liquid (PtL) technology and in the production of many types of biomass-based SAF.

According to the most optimistic scenario, the commercial use of hydrogen in aircraft with 100-200 seats (short- and medium-distance flights) will begin no earlier than in 2035. At the same time, the share of hydrogen in the total energy consumption in the aviation sector may reach 20% in 2050 and 33% in 2060. The rest will be electricity (up to 3%), SAF and traditional jet fuel (64%) in 2060 (**Fig. 1.21**).

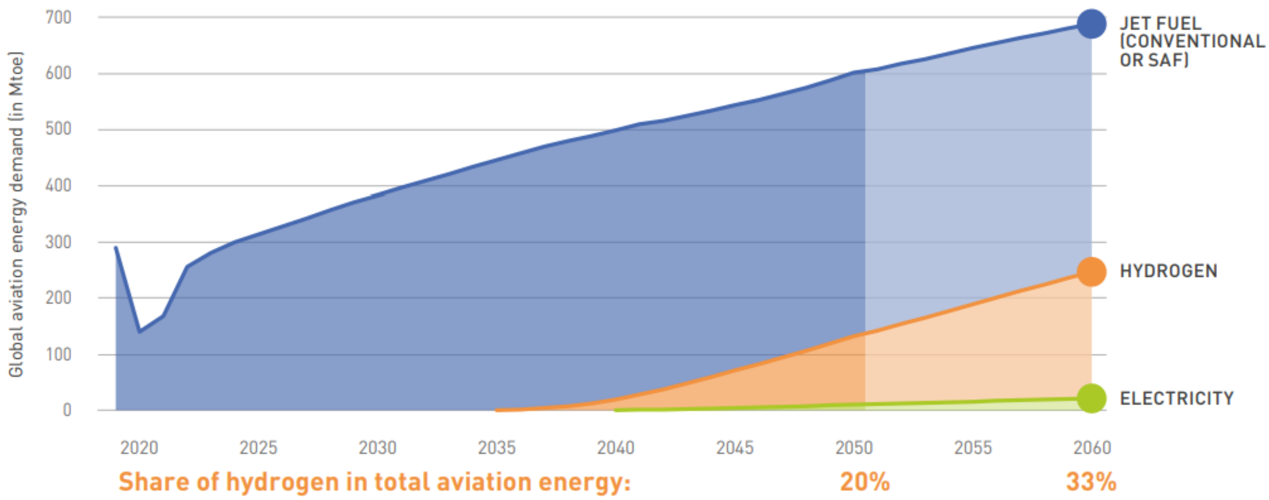
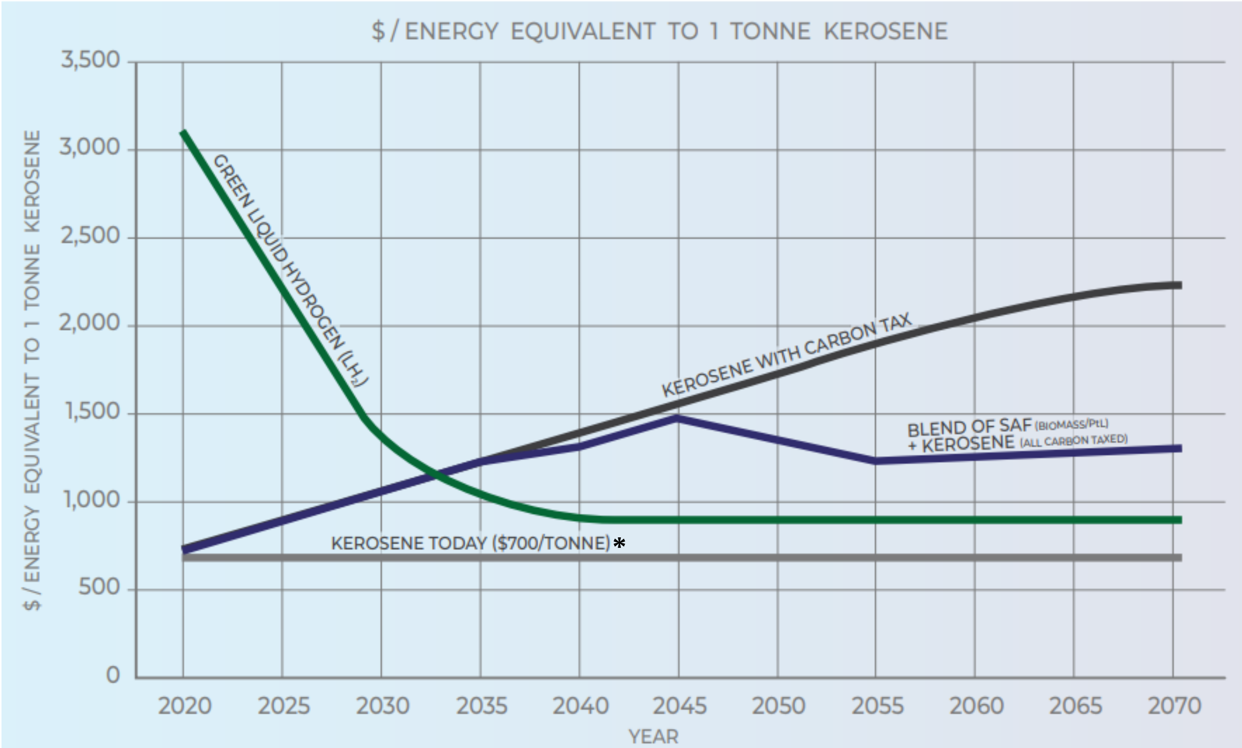


Fig. 1.21. Forecast for the total energy consumption in aviation, **Mtoe** [28].

Experts implementing FlyZero project (the United Kingdom) [25] believe that from the mid-2030s liquid hydrogen will become cheaper and "greener" than synthetic fuel PtL (a type of SAF) that requires more electricity for its production than liquid hydrogen (**Fig. 1.22**).



**** <u>Comment by the Technical Report authors</u>: as of June 2022, cost Jet A1 is about 1400 USD/t [7]***

Fig. 1.22. Forecast for aviation fuel cost, **USD/t of** kerosene energy equivalent [25].

Hydrogen can be stored on the aircraft in a gaseous or liquid state. The weight of hydrogen is *3 times less* than jet fuel with the same energy content, but the volume, even in the liquid (cryogenic) state, is *4 times larger*. Because of this, the aircraft will need a much larger fuel tank and radical changes to the fuel system. In addition, liquid hydrogen must be stored at a very low temperature (about minus 253 °C), which requires the use of special tanks. From a technical point of view, it is easier to implement the use of gaseous hydrogen than liquid hydrogen, but gaseous hydrogen must be stored under high pressure (700 bar) in heavy tanks. This limits its use in aviation only to short-distance flights.

The path to the commercial level of hydrogen implementation in aviation includes the following stages associated with solving certain technical problems [25, 30, 31]:

- Adaptation/improvement of the gas-turbine engine combustion chamber to achieve the most efficient hydrogen combustion. The goal is to achieve an efficiency of ~40-50% with a reduction in NOx emissions by 50-80% (current gas turbine efficiency is 35-40%).
- Creation of second-generation hydrogen gas-turbine engines with improved heat exchangers.
- Reducing the weight of insulation of pipelines in the aircraft body to reduce the total weight of the fuel system.
- Finding the optimal ratio between pressure and temperature of liquid hydrogen in the tank and fuel system of the aircraft. This will make it possible to find the optimal balance between weight, reliability and complexity of the fuel system design.

- Optimizing design of the cryogenic hydrogen tank on the aircraft to achieve minimum weight and maximum reliability (the goal is to achieve 12 kWh/kg / gravimetric index 35%). A promising direction may be the use of composite materials for tank walls. An example of current work in this direction is the development of an improved cryogenic hydrogen storage system for small aircraft by HEAVEN project.
- Fuel cells produce electricity with an efficiency of about 50%, so it is necessary to look for technical solutions to increase the power density. The goal is to achieve 1.7 kW/kg (including cooling) for aircraft performing suburban and regional flights, 2 kW/kg for larger aircraft (current value for fuel cells: ~0.75 kW/kg); the goal for cost is to achieve the value below 250 USD/kW in 2050). The creation of competitive hydrogen fuel cells will require research and new solutions in the fields of high-voltage electronics and powerful electric motors. An example of current work in this direction is the development of an improved system of fuel cells with proton exchange membranes by FLHYSAFE project. This system will be cheaper, lighter, easier to install and maintain, which is important for the use on board an aircraft.
- Improvements in aircraft design since liquid hydrogen will likely be stored in the fuselage rather than in the wings as it is in a conventional jet fueled aircraft. Such an approach can lead to an increase in the length of the aircraft by 10-15 m, which, in turn, may cause the need to increase the volume of boxes and other elements of the airport infrastructure to accommodate such an aircraft.

Usually, hydrogen is produced at a relatively low pressure (20-30 bar), so before transportation it must be *compressed or liquefied* (cooling to -253 °C). Delivery of hydrogen to small airports can be carried out by special trucks (**Fig. 1.23**), and to large ones through pipelines (similar to the transportation of natural gas) with subsequent liquefaction on the spot. Transportation of gaseous hydrogen through existing pipelines is the cheapest option for delivering large volumes [42]. When gaseous hydrogen is transported by a truck, it is compressed to 180 bar or more and pumped into cylinders that are stored on a trailer (see **Fig. 1.23 a**). Over long distances, it is economically more profitable to transport liquid hydrogen by cryogenic tanker trucks due to its much bigger mass for the same volume (see **Fig. 1.23 b**).

a) A tube trailer for gaseous hydrogen *b) A liquid tanker truck for liquid hydrogen*

Fig. 1.23. Special trucks for the transportation of hydrogen [40, 41].

There is also an option of transporting hydrogen in conventional oil tankers using liquid organic carriers that can absorb and release hydrogen through some chemical reactions. This technology using a dibenzyltoluene carrier is being studied and improved at the VTT research center (Finland) [31]. An alternative option, production of "green" hydrogen at the airport without the need for transportation, is currently considered unlikely due to the large need for renewable electricity on site (**Table 1.10**).

Table 1.10. Airport infrastructure options (estimate based on the UK airports examples) [25].

On-airport infrastructure option	Representation	Airport suitability	H_2 supply	Estimated capital cost (£m)
1. Storage only		Small	Tanker	Small: 20 - 55 Medium: 100 - 250 Large: 325 - 775
2. Liquefaction & storage		Medium, large	Pipeline	Small: 25 - 75 Medium: 200 - 450 Large: 625 - 1375
3. Electrolysis, liquefaction & storage		None*	N/A	Small: 100 - 165 Medium: 850 - 1350 Large: 2500 - 4050

** Scenario may be suitable if demand is very low but the airport is close to a large supply of renewable electricity*
1 GBP ≈ 1, 223 USD (https://www.x-rates.com/).

At the airport, hydrogen must be supplied to the aircraft with the help of refuellers or by an alternative method at designated locations (special refueling platforms or refueling stations). The cost of liquid hydrogen filling systems can be up to five times the cost of conventional hydrant systems due to the need to maintain high pressure and low temperature throughout the supply chain.

The issue of the optimal method of refueling with liquid hydrogen (LH_2) at the airport is still unresolved and requires further study. At small airports, in the near future, it seems appropriate to use auto-refuellers, similar to how it is currently done for refueling airplanes with kerosene. At large airports, this can lead to significant ground traffic and complicate refueling logistics. Possible options for research are the use of mobile refueling platforms, refueling stations outside passenger boarding areas, and a special hydrant system for liquid hydrogen. It is estimated that the last option (hydrant system) will become economically viable only in the long term. It is also necessary to consider the conditions for ensuring simultaneous refueling of several aircraft [31].

The technology for aircraft refueling with LH_2 requires research and optimization, since for large aircraft the refueling time may exceed the time allocated according to the schedule for their stay at the airport before the next flight. For example, if an aircraft has a 75% empty fuel tank before a long-distance flight, it will take up to 65 minutes to fill it with kerosene/SAF when using 2 hoses at a fuel supply rate of 900 l/min with one hose. At the same rate of supply, refueling with liquid hydrogen even through 4 hoses will take 140 minutes, while the time of stay of very large aircraft (such as Boeing-747) between flights at the airport is about 120 minutes today. To reduce the refueling time for LH_2, it is necessary to find technical and economic solutions to increase the fuel supply rate through one hose to more than 1000 l/min.

The use of hydrogen as an aviation fuel will require the development of new regulations and safety standards, since the behavior of cryogenic hydrogen in a tank on board an aircraft is still poorly understood. One of the key issues will also be ensuring fast and safe refueling of the aircraft before the flight. It is assumed that a safety zone with a radius of 20 m is required when connecting/disconnecting the fuel hoses, and with a radius of 8-10 m for other time periods, which requires further testing and clarification (**Fig. 1.24**). Simultaneous refueling and boarding of passengers is possible only after reliable connection of the refueling hoses to the aircraft.

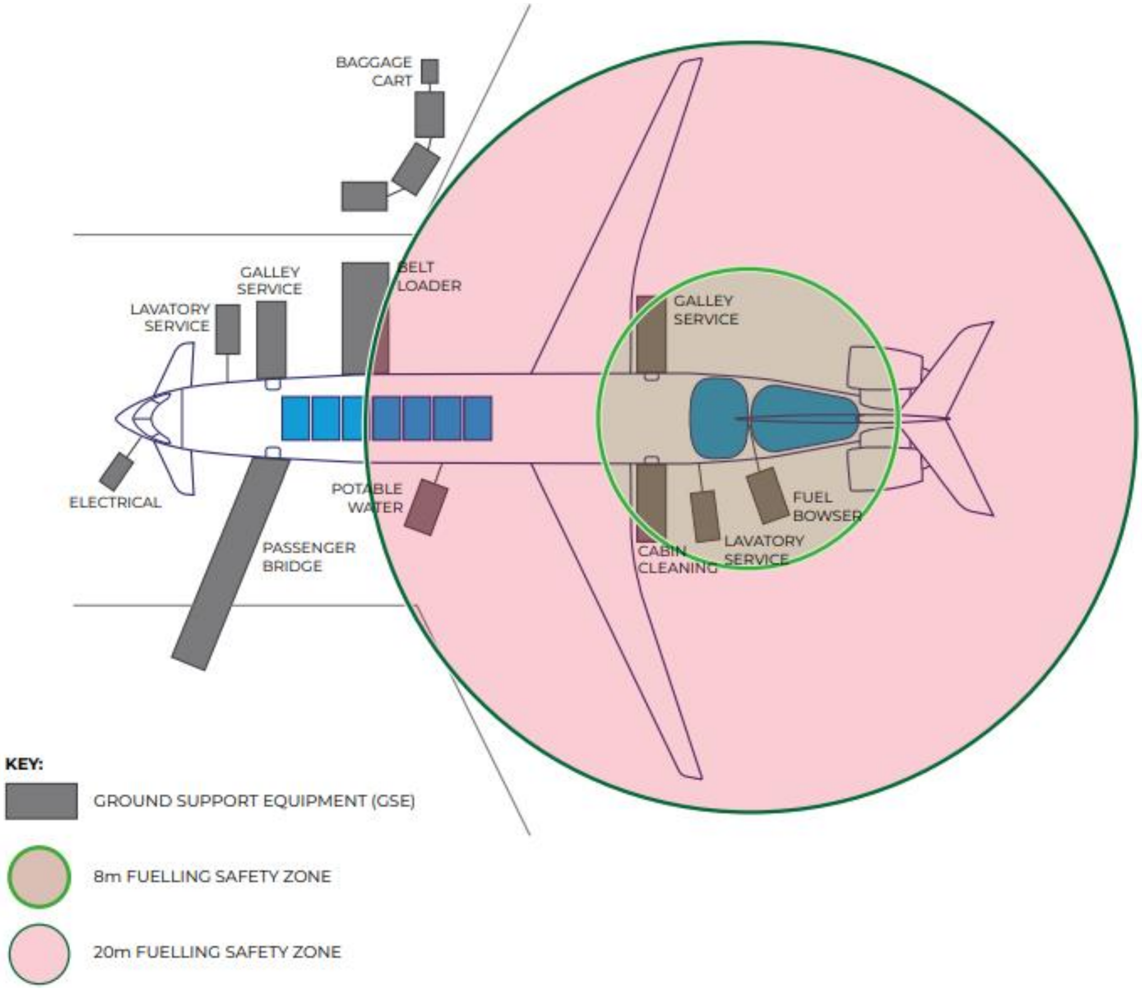


Fig. 1.24. Fuel safety zone concept for narrowbody aircraft [25].

Current documents of **legal and technical regulation** of hydrogen technologies in Ukraine are listed in **Annex 4**. A significant obstacle to the use of hydrogen in Ukraine is the outdated and uncoordinated base of regulatory and legal acts and documentation on technical safety, as well as the ignorance of business entities in this area. Besides, the technical knowledge and experience in the field of hydrogen systems is often shallow and, in many cases, non-existent. Due to the fact that training of Ukrainian professionals acquire the necessary skills to work with these technologies can take several years, Ukraine must rely on a relatively small number of qualified international experts who will be in high demand in their own markets. This can increase costs at the initial stage and delay the start of the application of hydrogen technologies in Ukraine [53].

According to the **methodology of life cycle assessment (LCA)**, in study [61] the general life cycle of an aircraft operating on different types of aviation fuel was investigated. The LCA is performed using SimaPro LCA software in combination with the Ecoinvent database. A comprehensive life cycle assessment for use in aviation was conducted for hydrogen and some other alternative fuels – ammonia, methanol, ethanol and liquefied natural gas. At the same time, it is noted that *the use of ethanol in aviation is unlikely* due to its fuel characteristics.

The life cycle phases included in the analyses are as follows: (i) production, operation and maintenance of the aircraft, (ii) construction, maintenance and disposal of the airport, (iii) production, transportation and utilization of the aviation fuel in the aircraft. The environmental impact categories taken into account in this study are human toxicity, global warming, land use, depletion of abiotic resources and stratospheric ozone depletion. All these selected fuels are considered to be combusted in the same type of aircraft. Therefore, the aircraft manufacturing and airport operational and maintenance phases are treated in an identical manner for the selected cases.

Alternative fuels are evaluated in comparison with conventional jet fuel based on kerosene; various categories of life cycle impact on the environment are considered. Options for using fossil and renewable energy carriers were compared for the production of ammonia and hydrogen fuel. It is predicted that already in the near future *ammonia will become an important carrier of hydrogen* with its high content.

For the production of hydrogen in this study, it is assumed that 95% of hydrogen is produced from the cracking of fossil fuels (underground coal gasification with carbon capture and storage), 5% of saltwater electrolysis. To compare the production of hydrogen from renewable resources, the methods of electrolysis of water from wind, hydropower, geothermal and solar energy are also evaluated. In renewable cases, the hydrogen production is conducted using electrolyzer consuming 53 kWh per kg of hydrogen.

According to the results of the life cycle assessment, land usage per entity of fuel is lowermost for the liquid hydrogen case due to its higher overall fuel heating value (**Table 1.11**). Land use intensities for jet fuel and methanol pathways are relatively similar and lower than liquid ammonia when compared with the wider collection of alternative fuel pathways. The annual land use intensities for liquid hydrogen and LNG in the study are found to be 0.0011 m^2 /t*km and 0.0014 m^2/t*km, respectively. For LNG and hydrogen, the land occupation and human toxicity potentials are significantly lower than for kerosene.

Table 1.11. Specifications of the alternative aviation fuels considered in the study [61].

Fuel	Specific energy (MJ/kg)	Density at 15 °C, t/m^3	Energy density (MJ/L)	Fuel consumption, kg/km(kg/t*km)
Kerosene (Jet A/Jet A-1)	43.2	0.808	34.9	7.99 (0.217)
Liquid hydrogen	120	0.071	8.4	2.64 (0.071)
LNG	50	0.424	21.2	9.46 (0.257)
Methanol	19.9	0.796	15.9	18.06 (0.492)
Ethanol	27.2	0.794	21.6	12.47 (0,339)
Liquid ammonia	18.6	0.73	13.6	18.82 (0.512)

Hydropower options for hydrogen and ammonia significantly lowers the environmental impacts where it corresponds to about 60% reduction and 20% reduction for ammonia and hydrogen, respectively. Liquid ammonia from geothermal energy has comparable land use values with methanol and ethanol fueled aircrafts. The low efficiency of solar photovoltaic systems (in the range of 15%-20%) causes greater land use for liquid ammonia and hydrogen routes.

The total GHG emissions from ***hydropower*** based ammonia and ***hydrogen*** are calculated to be about 0.24 kg $CO_{2\text{-eq.}}$ per traveled t*km and **0.03** kg $CO_{2\text{-eq.}}$ per traveled t*km, respectively

(**Fig. 1.25**). The global warming potential for LNG (0.84 kg $CO_{2\text{-eq.}}$ per t*km) and methanol (1.03 kg $CO_{2\text{-eq.}}$ per t*km) is lower than that of the kerosene-based jet fuels that are currently in use.

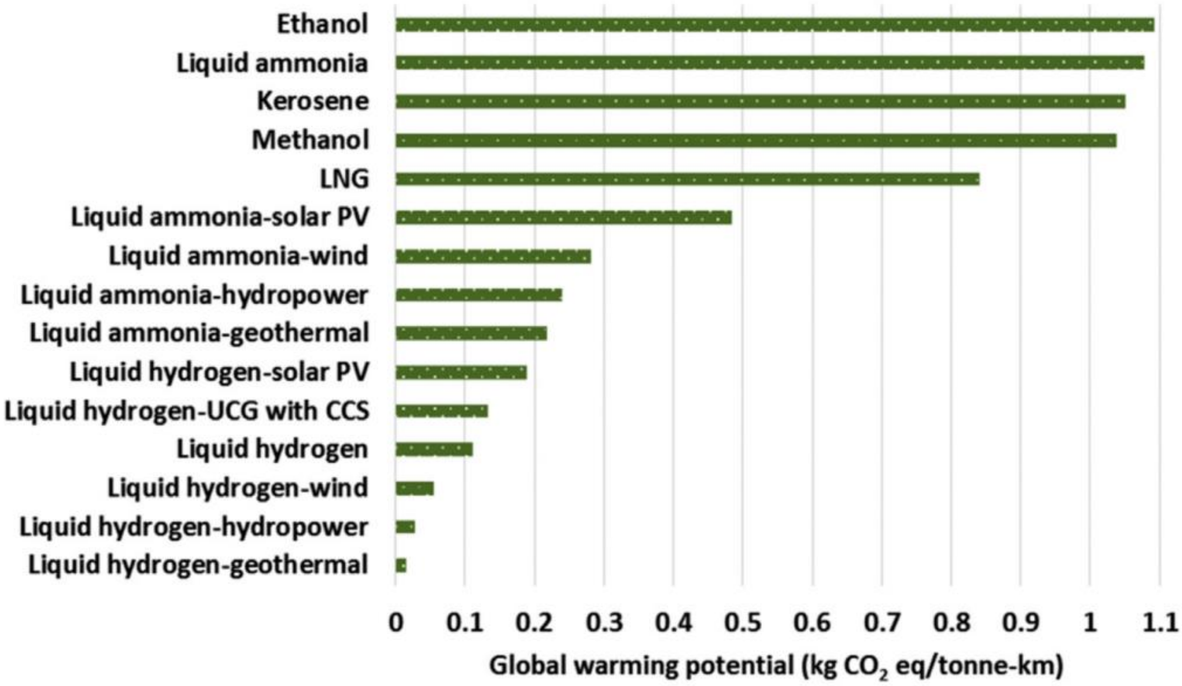


Fig. 1.25. Global warming potential of various fueled aircrafts per traveled t*km [61].

Hydrogen (produced by the use of geothermal energy) fueled aircraft route ***releases the least GHG emissions*** among the considered cases corresponding to **0.014** kg CO_2 per t*km. Although kerosene fueled aircraft releases 1.05 kg CO_2 per t*km when the complete cycle is considered.

Ammonia production is mainly dependent on natural gas causing high environmental impacts overall. However, renewable energy resources based ammonia production considerably lower the environmental impacts correspondingly to 0.23 kg CO_2 per t*km for hydropower route.

The operation of the aircraft has almost equivalent share (40.7% for hydrogen route of UCG with CCS) with operation and maintenance of the airport (44.6% for hydrogen route of UCG with CCS) in total GHG emissions. Hence, the energy supply of airport facilities are also critical when complete life cycle is evaluated.

The distribution of responsible processes for GWP of hydrogen driven aircraft is illustrated in **Fig. 1.26**. Operation of the aircraft is the second largest contributor corresponding to 34%. Operation and maintenance of the airport is the primary responsible for GWP corresponding to 48.9% in total where it is distributed into sub-processes such as natural gas burning in the furnace (22%), light fuel oil burning in the furnace (5%), lignite burning in the power plant (7%) and hard coal burning (8%) as shown in **Fig. 1.26**.

Environmental and social costs of HC, CO, NO_x, PM, and CO_2 emissions of various fueled aircrafts are evaluated in terms of USD/t*km as shown in **Fig. 1.27.** This value reflects the overall impact on the environment and human health. Since, they are associated with the amount of various type of emissions, kerosene jet fuel and fossil fuel based ammonia represent higher costs. It is noted that the total environmental and social costs for renewable based ammonia and hydrogen fueled aircrafts are considerably lower than conventional kerosene jet fuel.

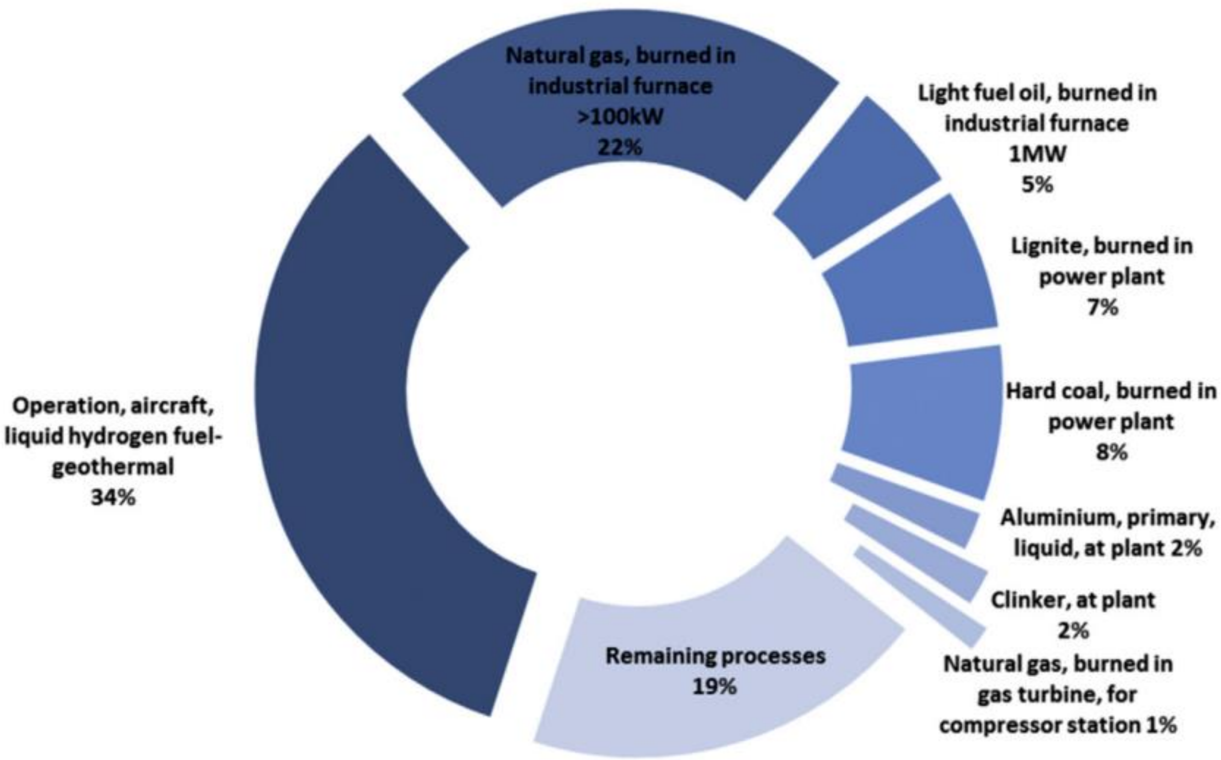


Fig. 1.26. Contribution of various processes to GWP effect of geothermal based hydrogen fueled aircraft [61].

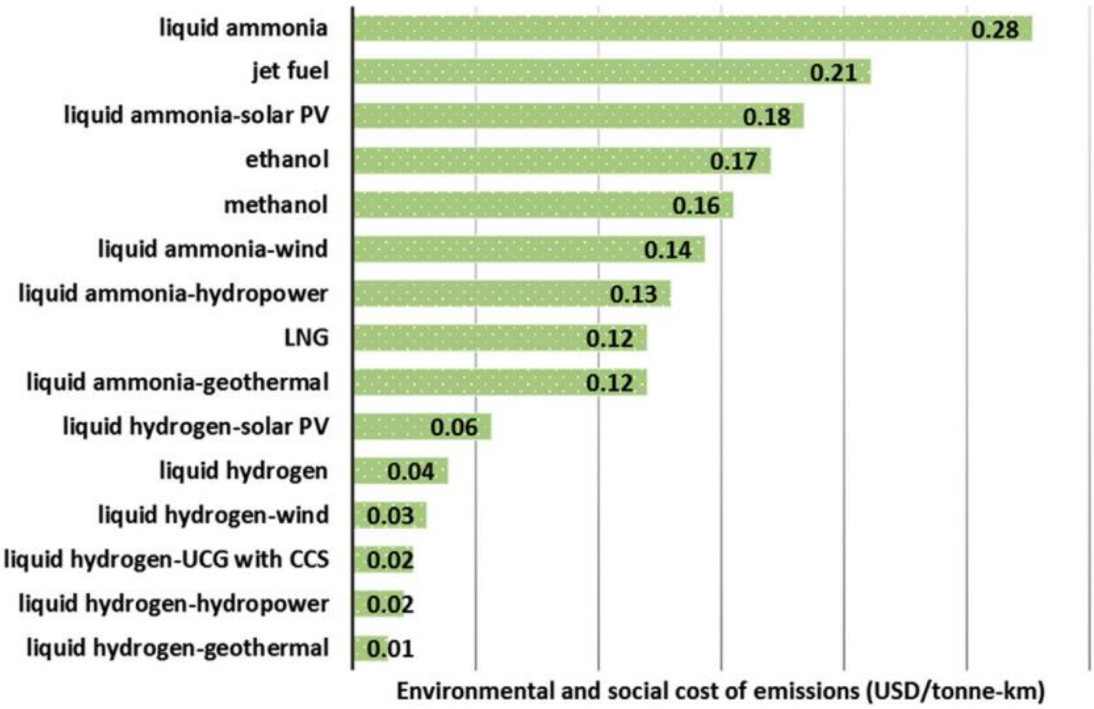


Fig. 1.27. Total environmental and social costs of emissions for various fueled aircrafts from conventional and renewable resources [61].

Among the general conclusions of the considered study, the following can be distinguished:

- Alternative aviation fuels including hydrogen, methanol, ammonia and LNG are more environmental-friendly options than kerosene.

- Although ammonia and hydrogen are carbon-free fuels, the emissions may be high when the fossil fuel are used in the production methods.

- ***Renewable sources based hydrogen*** and ammonia routes represent the most preferable option in terms of the environmental impact.

- The cost of flight is currently lower for kerosene jet fuels however by developing technologies the cost of flight for methanol, ammonia and hydrogen can compete with conventional jet fuels.

1.4. Comparative analysis of alternative aviation fuels

1.4.1. Forecast of cost, production volume and use of AAF

Among the various options for the use of alternative fuels in aviation, increasing production and use of ***sustainable aviation fuels*** (in particular, ***biofuels***) as a substitute for traditional jet fuel Jet A and A-1 is considered by experts **in the medium term to be the most realistic measure from a technical and economic point of view** to reduce greenhouse gas emissions in the sector. Thus, it is expected that only SAF as alternative fuels will provide long- and medium-distance flights until 2050, short-distance flights until 2040 (then electricity or hydrogen burning will join), regional flights until 2030 (then electricity or hydrogen fuel cells will join), and suburban flights until 2025 (then electricity will join) (**Fig. 1.28**). After 2050, use of some hydrogen is considered possible also for medium-haul flights.

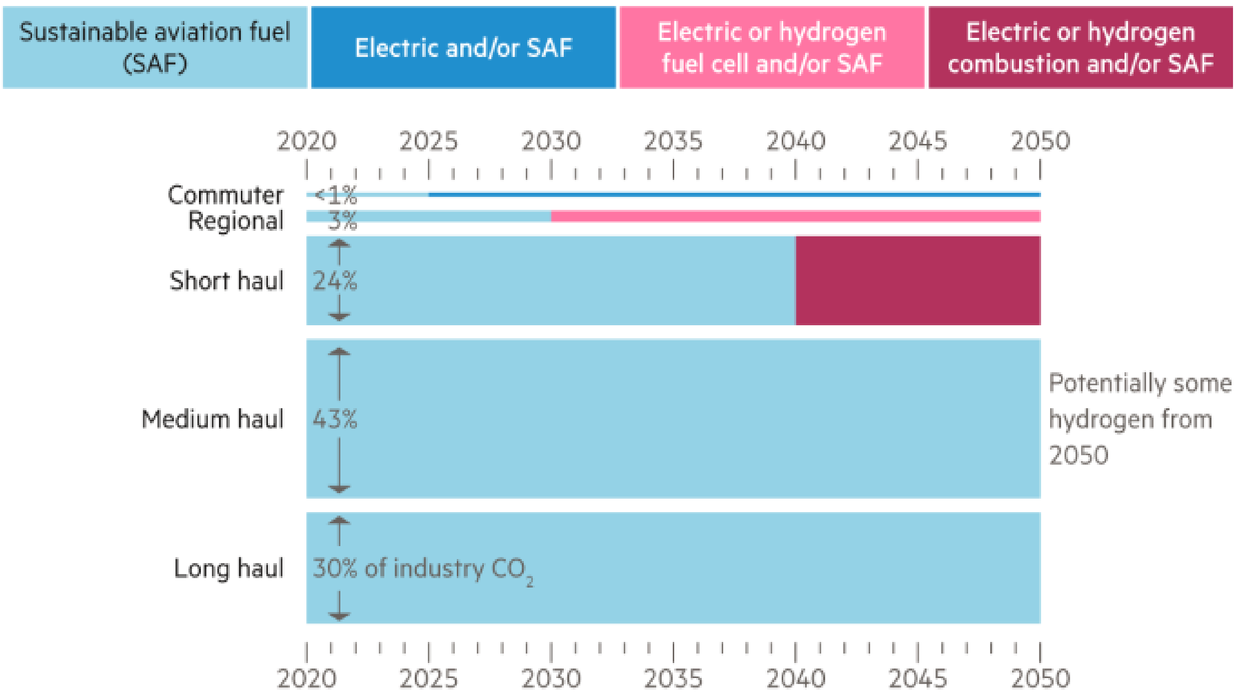


Fig. 1.28. Forecast for using SAF, hydrogen and electricity in aviation for flights of different distances [27].

Alternative low-/carbon-free energy carriers for aviation could potentially be **electricity** and **hydrogen**. However, liquid "green" hydrogen (LH_2) is currently much more expensive than aviation kerosene, and a significant reduction in its cost is predicted by experts only after 2030 (see **Fig. 1.22)** [25]. Research and demonstration of the possibilities of electrification of the aviation sector are still at an early stage, so this direction will make a significant contribution to decarbonization, rather, in the long term [26].

An alternative synthetic fuel for the aviation sector can be obtained by electrolysis of water using electricity, in particular, "green" electricity (PtL). Today, the PtL technology is much more expensive than the technologies for the production of aviation biofuels, and its significant price reduction is expected only after 2030 (**Fig. 1.29**) [4, 9, 28]. In addition, as already noted, a key sustainability issue for PtL technology is access to the required amount of renewable electricity due to possible competition from other areas of its use. As a result, in the medium-term future, biofuels appear to be a more promising type of SAF than fuels obtained by converting electricity into liquid. At the same time, there is an expert opinion that after 2040, the production of synthetic PtL fuel in the EU will prevail over biomass-based SAF due to limited raw materials for the latter (**Fig. 1.30**) [25].

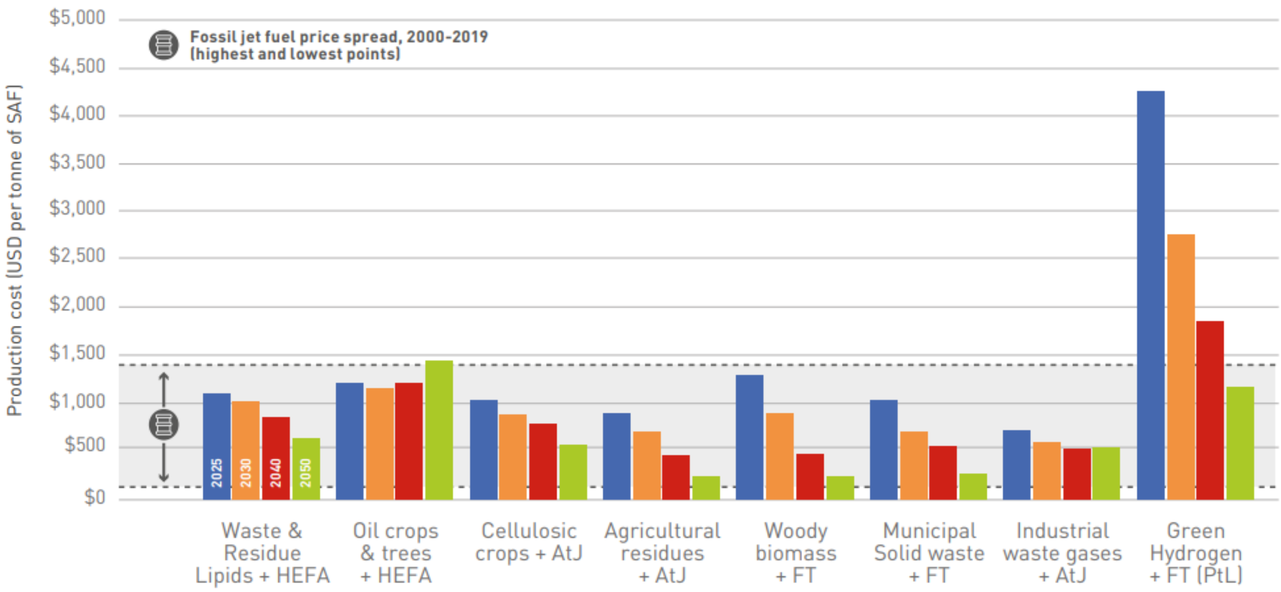


Fig. 1.29. Forecast cost for aviation biofuels (HEFA, ATJ, FT) and synthetic fuel (PtL), **USD/t** [28].

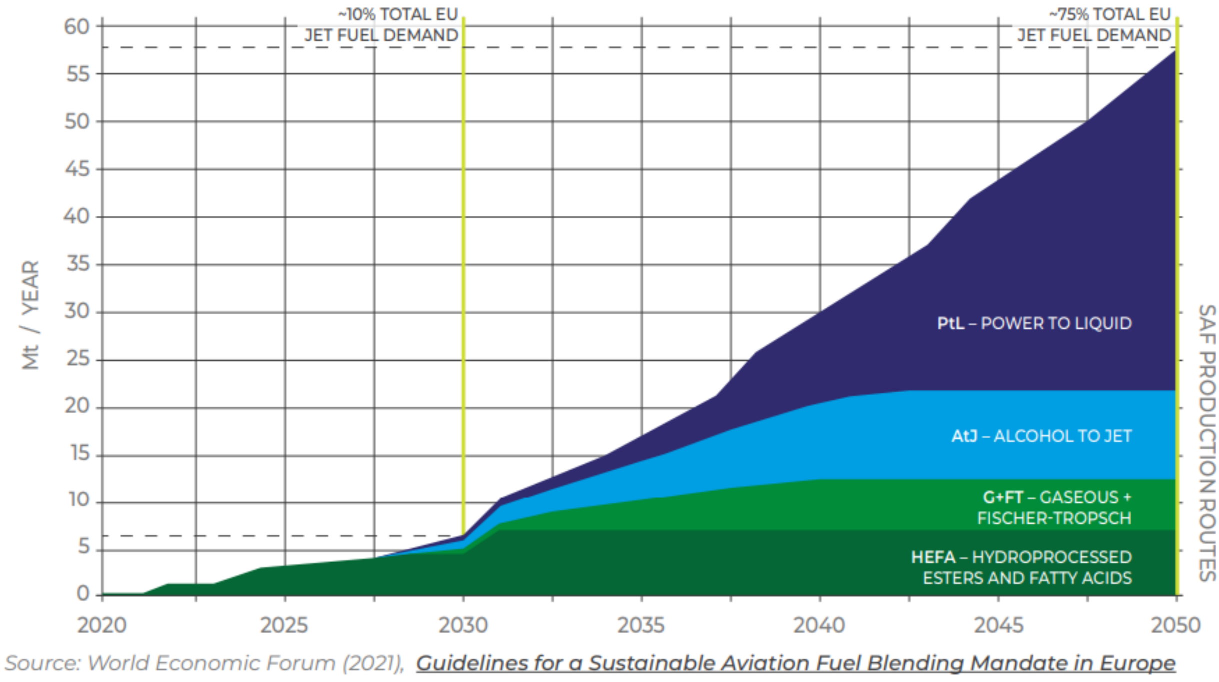


Fig. 1.30. Forecast production for aviation biofuels (HEFA, ATJ, G+FT) and synthetic fuel (PtL) in the EU, **Mt/yr** [25].

1.4.2 Analysis of feedstock base for AAF production in Ukraine

An important aspect of the comparative assessment of alternative aviation fuels from the point of view of their potential production and use in Ukraine is the analysis of the raw material and resource base available for obtaining these fuels.

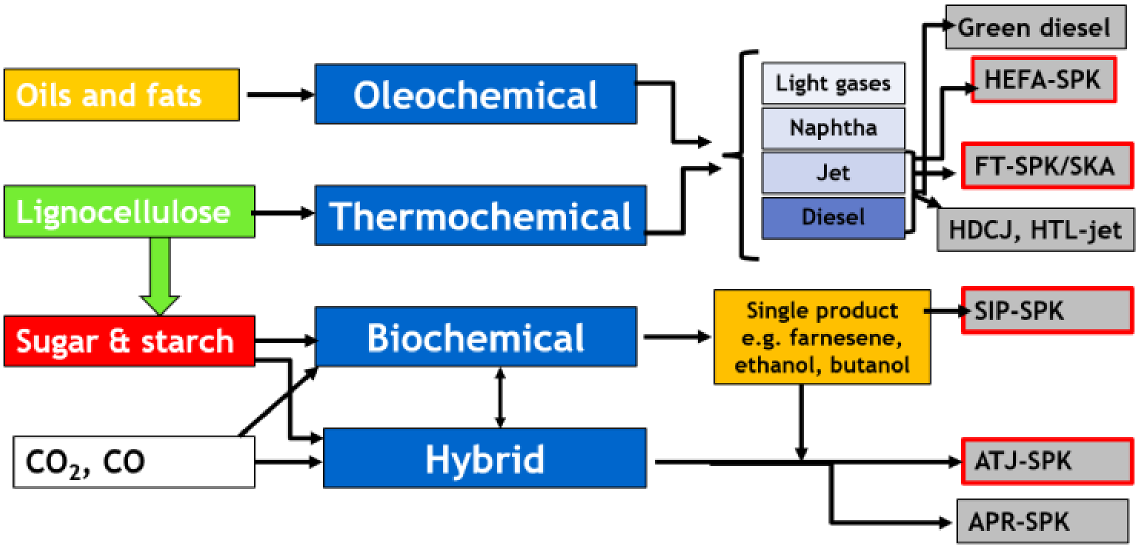
As already noted earlier, biomass-based SAF are produced from the following types of raw materials (**Fig. 1.31**):

Oil and fat feedstock – **HEFA-SPK, CH-SK (CHJ), HC-HEFA-SPK** (micro-algae)

Lignocellulosic feedstock – **FT-SPK, FT-SPK/A, ATJ-SPK**

Starch feedstock – **ATJ-SPK**

Sugar feedstock – **HFS-SIP, ATJ-SPK**



(Abbreviations are explained in Glossary of terms and Table 1.2)

Fig. 1.31. Main production pathways for SAF from biomass [46].

We will consider the amount and structure of bioenergy potential in Ukraine, forecasts of its growth until 2050, as well as the possible effects of the consequences of military actions on the territory of the country.

Ukraine has a large potential of biomass available for the production of energy and biofuels. According to 2020 data, the energy potential of biomass is almost **22** Mtoe/year, of which 43% is agricultural residues (straw, stalks of corn and sunflower, sunflower husks, etc.), 34% is energy crops (willow, poplar, miscanthus on 1 million ha for solid biofuel production and corn on 1 million ha for biogas production) (**Fig. 1.32, Table 1.12**).

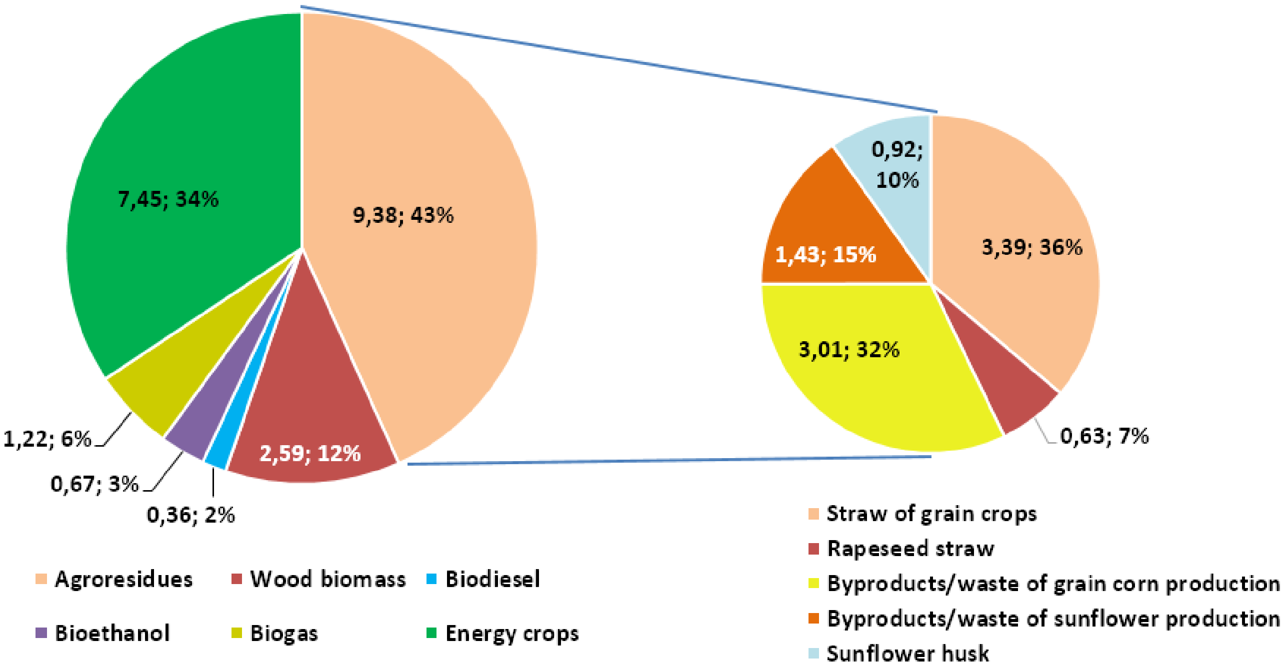


Fig. 1.32. Structure of bioenergy potential in Ukraine (2020), **Mtoe** [43].

Table 1.12. Bioenergy potential in Ukraine (2020) [43].

Biomass type	Theoretical potential, Mt	Potential available for energy (economic potential)	
		Share of the theoretical potential, %	**Mtoe**
Straw of grain crops	33.1		
Straw of rapeseed	4.6	40	0.63
By-products of grain corn production (stalks, cobs)	39.4	40	3.01
By-products of sunflower production (stalks, heads)	24.9	40	1.43
Secondary agricultural residues (sunflower husk)	2.2	100	0.92
Wood biomass (firewood, felling residues, wood processing waste)	6.7	95	1.57
Wood biomass (dead wood, wood from shelterbelt forests, pruning, uprooting)	8.8	45	1.02
Biodiesel (rapeseed)	-	-	0.36
Bioethanol (corn and sugar beet)	-	-	0.67
Biogas from waste and by-products of agricultural sector	2.8 bln m^3 CH_4	42	0.99
Landfill gas	0.6 bln m^3 CH_4	29	0.14
Sewage gas (industrial and municipal wastewater)	0.4 bln m^3 CH_4	28	0.09
Energy crops:			
- willow, poplar, miscanthus (1 Mha*)	11.5	100	4.88
- corn for biogas (1 Mha*)	3.0 bln m^3 CH_4	100	2.57
Total		-	**21.68**

* *When growing on 1 million ha of unused agricultural land.*

Despite certain fluctuations, the amount of biomass of agricultural origin in Ukraine increases almost every year due to general trend of growth in the production and yield of main agricultural crops. For example, in 2019, record over past 20 years harvests of sunflower, grain corn and some other grain crops were harvested in the country. Since 2000, the energy potential of straw of cereal grain crops, by-products and waste from the production of corn for grain and sunflower in Ukraine has increased by three times, from 2.8 Mtoe in 2000 up to 8.5 Mtoe in 2020.

The contribution of wood biomass to the energy potential is relatively small, about 2.6 Mtoe/year, or 12% of the total. This biomass can be conditionally divided into that coming from traditional sources (firewood, felling residues, woodworking waste) and that from "additional" sources (dead wood, wood from the reconstruction and restoration of field protection and other protective forest belts, waste from pruning and uprooting of orchards and vineyards).

The remaining components of bioenergy potential in Ukraine (about 10%) are biofuels (biodiesel, bioethanol) and biogas obtained from various types of raw materials (waste and by-products of the agricultural complex, industrial and municipal wastewater, municipal solid waste).

The situation with the consumption of biomass for energy and biofuels in Ukraine is actually the opposite to the structure of the available potential. Currently, wood biomass is most actively used (more than 90% of the economic potential) while the usage of residues and by-products of agricultural origin remains at a low level. Of the various types of *agrobiomass* (agricultural residues + energy crops) only sunflower husks are actively used for Ukraine's energy needs – more than 70% of its potential. Energy/biofuel production from straw is at about 3% of the available potential. There are few examples of utilizing corn for energy, while examples of energy production from sunflower stalks or baskets are currently unknown to the authors. On average, Ukraine's bioenergy potential is used by ~11%.

A number of barriers prevent the widespread development of using agricultural residues for energy. Among them, the most important ones are the lack of equipment among agricultural producers and undeveloped technologies for harvesting corn/sunflower stalks, as well as the complexity of organizing the "harvest-supply" chain, general underdevelopment of the biofuel market in the country (absence of a biofuel exchange) and some others.

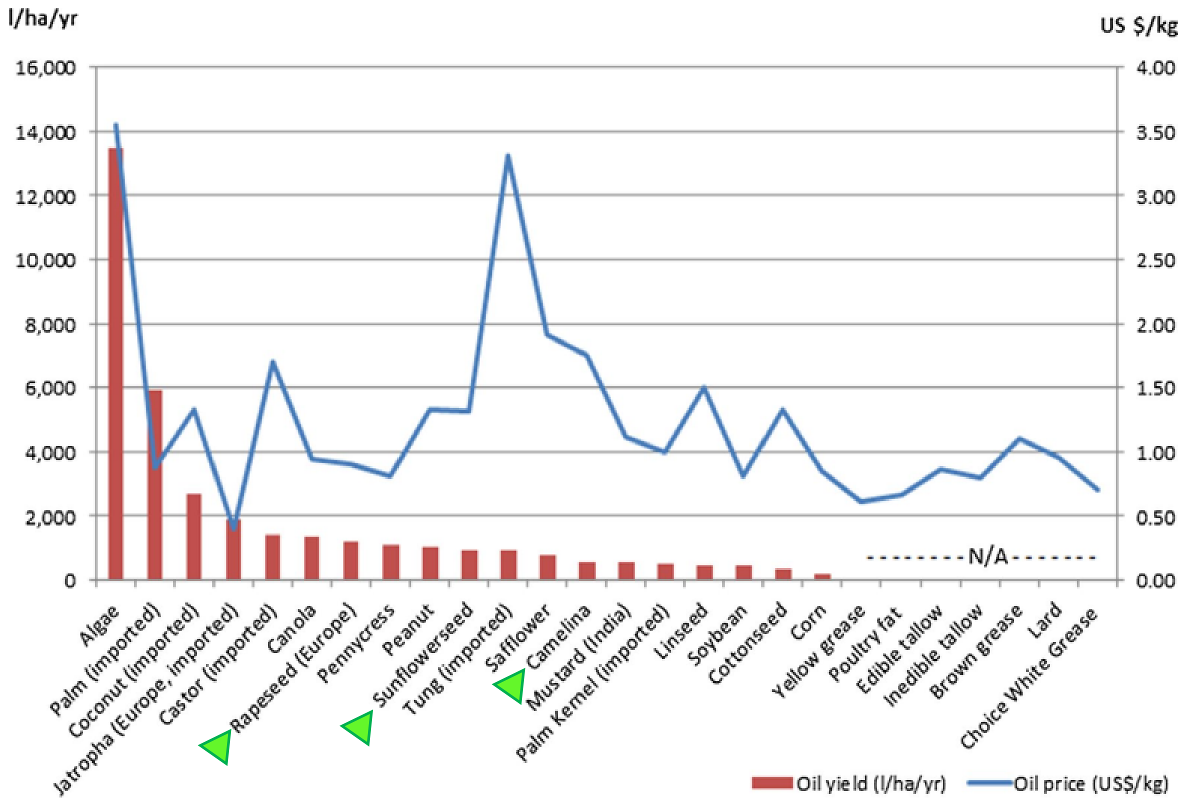
Analysis of the structure of biomass consumption for energy indicates the need for wider use of biomass of agricultural origin and energy crops. At the same time, wood biomass from so-called additional sources should be involved in this process, in particular, waste from pruning and uprooting of perennial agricultural plantations, as well as biomass from the reconstruction and restoration of field protection and other protective forest belts.

Thus, the analysis of the current potential of biomass in Ukraine indicates large volumes of **lignocellulosic raw materials** such as wood biomass of different origins, various agricultural residues, woody and herbaceous energy crops. In the considered structure of biomass potential, a certain scenario of growing energy crops on unused (low-productive) agricultural land is adopted: willow, poplar, miscanthus on 1 million ha, corn (for biogas) also on 1 million ha. If we change this scenario by allocating, say, 500,000 ha to oilseed crops, for example, *Camelina, Jatropha, pennycress*, then a certain segment of oil raw materials will appear in the structure of biomass potential (estimate for *Camelina*):

500 l/ha/year (approximate yield of Camelina oil from a hectare [47]) × 500 th. ha = 250 Ml/year, or 230 kt/year (at the density of 0.92 kg/l [48]), or ***247 ktoe/year*** *(at the heating value of 45 MJ/kg [49])*

Though Camelina can be considered a food crop (oil beneficial for health is produced from the seeds), it can be assumed that its cultivation on low-productivity lands will not create competition for food products and therefore is **sustainable**. Other food crops such as rapeseed and sunflower can be considered from the point of view of cultivation on low-productivity/marginal/contaminated land, with an appropriate LCA. Another option is the cultivation and use of oil of the non-food hybrid culture *Typhon*, created in the National Botanical Garden named after M.M. Hryshka of the National Academy of Sciences of Ukraine [59] and similar plants.

Taking into account such factors as a larger area under Camelina (if this crop is chosen), increasing its yield or growing other non-food oil crops with a higher yield of oil per hectare (for example, almost 2000 l/ha/year for jatropha, over 1000 l/ha/year for pennycress, **Fig. 1.33** [47]), it can be estimated that the potential of oil raw materials in Ukraine can reach about **0.5** Mtoe/year.



Prices are for local, US feedstock unless otherwise noted. Prices are for 2014, except linseed oil (the latest data available from the USDA are for 2010); brown grease (undisclosed time in 2011); safower and jatropha (2013/2014); mustard (2015); and camelina and algae (model-derived estimates)

Fig. 1.33. Oil yield and prices [47].

Pre-war expert assessments of the Bioenergy Association of Ukraine indicate that during the period up to 2050, Ukraine's bioenergy potential may double or even more, up to about **47** Mtoe/year (**Table 1.13**).

The main factors for the increase in bioenergy potential during this period include:

- growth in the yield of agricultural crops, primarily cereals;

- significant increase in the economic potential of biogas from various types of raw materials due to such factors as expansion of the raw material range through the inclusion of crop residues; growth in the production of basic products by various branches of industry; consolidation of livestock enterprises; transition from solid waste disposal to the use of mechanical and biological treatment technology;

- doubling the area under energy crops and increasing their yield (according to 2009-2020 data, the area of unused agricultural land is estimated at 3-5 million hectares). As mentioned above, this is a possible way to increase the volume of oil raw materials. **Table 1.13** shows only one of the possible scenarios for the cultivation of energy crops, which can be transformed towards oil crops on the area of up to 1 million hectares;

– increase in the share of felling the annual wood increment in forests;

- shift to second-generation motor biofuels and new types of raw materials for first-generation motor biofuels.

Table 1.13. Forecast for Ukraine's bioenergy potential in 2050 [43].

Biomass type	Theoretical potential, Mt	Potential available for energy (economic potential)	
		Share of the theoretical potential, %	**Mtoe**
Straw of grain crops*	49.2	30	5.04
Straw of rapeseed	4.6	40	0.63
By-products of grain corn production (stalks, cobs)*	58.1	40	4.45
By-products of sunflower production (stalks, heads)	24.9	40	1.43
Secondary agricultural residues (sunflower husk)	2.2	100	0.92
Wood biomass (firewood, felling residues, wood processing waste)*	12.3	96	2.88
Wood biomass (dead wood, wood from shelterbelt forests, pruning, uprooting)	8.8	45	1.02
Biodiesel (I and II generation)*	-	-	1.10
Bioethanol (I and II generation)*	-	-	2.33
Biogas from waste and by-products of agrisector*	8.4 bln m^3 CH_4	83	5.92
Landfill gas*	0.7 bln m^3 CH_4	70	0.42
Sewage gas (industrial and municipal wastewater)*	0.4 bln ^{3} CH_4	31	0.11
Energy crops*:			
- willow, poplar, miscanthus (2 Mha**)	34.5	100	14.65
- corn for biogas (2 Mha**)	7.5 bln m^3 CH_4	100	6.43
Total	**-**	**-**	**47.33**

** Components of the biomass potential, the growth of which is expected until 2050. Other components, according to the conservative approach, are left at their level assessed for 2020.*
*** When growing on 2 million ha of unused agricultural land.*

On the other hand, the future potential of biomass in Ukraine will be affected by the **consequences of the war** started by Russia on February 24, 2022. Currently, it is difficult to accurately assess the impact of the consequences of military actions on the size and structure of the bioenergy potential and, in general, on the features of bioenergy development in Ukraine in the post-war years; a separate study should be conducted for this. Nevertheless, based on UABIO expert assessment, the following can be assumed [44]:

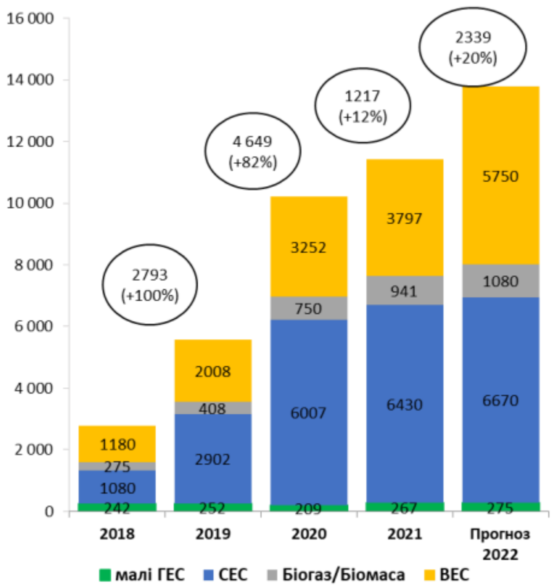
- ***Agrobiomass*** (agricultural residues and energy crops) will remain the main type of bioenergy potential in Ukraine. To expand the use of agricultural residues, it is necessary to work out technologies for baling corn and sunflower stalks.
- ***Energy crops*** for solid biofuels will continue to be grown on unused (low-yield) agricultural lands. The development of this direction from the point of view of choosing the type of energy crops (lignocellulosic, oilseed, starch- and sugar-containing) will be determined by the strategy of the post-war development of RES sector and the country's needs.
- The post-war period is likely to be characterized by high prices and shortages of mineral fertilizers, especially nitrogen fertilizers, which are produced using natural gas. Under such conditions, it is advisable to introduce fertilizing with ***digestate***, which is a residue of biomass anaerobic digestion. To obtain a sufficient amount of digestate, the appropriate amount of raw materials for fermentation, such as corn silage, is required.

- For the sake of the country's energy "survival" in the post-war period, some deviation from the sustainability criteria (or temporary change of these criteria) may be allowed. For example, ***corn for silage*** as a raw material for the production of ***biomethane*** (a substitute for natural gas) and ***digestate*** (fertilizer) will be grown on agricultural land.
- ***Biomethane*** production will be actively developing. For this, it is necessary to master and implement modern technologies for its production from lignocellulosic raw materials (up to 50% of the total mixture) using best foreign practices.
- Production and consumption of ***liquid biofuels of the first and second generation***, which is a promising direction for the development of bioenergy in Ukraine, will increase. According to the *draft* NREAP 2030 [45], the consumption of liquid biofuels in the country by 2030 will increase up to 325 ktoe/yr, including 65 ktoe/yr of second-generation biofuels.

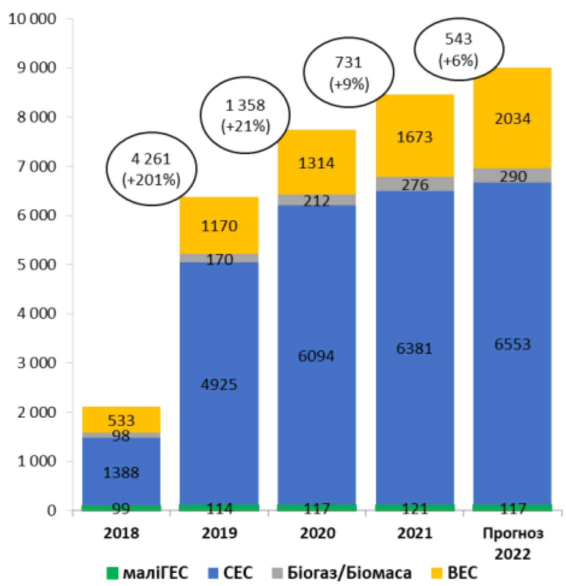
Thus, in the future, Ukraine will have a significant potential of ***lignocellulosic*** biomass, and under the condition of growing oilseed crops, it will be provided with a certain amount of ***oil*** raw materials for the potential production of respective ***biofuels***.

The production of PtL synthetic fuel, the introduction of using electricity and hydrogen in aviation requires **renewable electricity** and **"green" hydrogen**, which is also obtained with the consumption of "green" electricity.

According to NERC [50], over the past 4 years, the total installed capacity of small HPPs, SPPs (without private households), WPPs, biogas/biomass power plants has increased by 4 times from 2777 MW in 2018 to **11435** MW in 2021; growth by another 20% is forecast by 2022 (**Fig. 1.34 a**). Electricity production by these facilities also increased by 4 times, from 2,118 million kWh in 2018 to **8,451** million kWh in 2021 (**Fig. 1.33 b**).



small HPPs **SPPs** **BG/BM** **WPPs**



small HPPs **SPPs** **BG/BM** **WPPs**

a) Total installed capacity, MW (without private households)

b) Power production, GWh (without private households)

Fig. 1.34. Renewable power facilities in Ukraine in 2018-2021 and forecast for 2022 [50].

By the end of 2021, the total installed capacity of private household RE generating units was **1,200** MW, their number being 44,961 units (**Fig. 1.35**), which was 1.5 times more than in the previous year and 6 times more than in 2018.

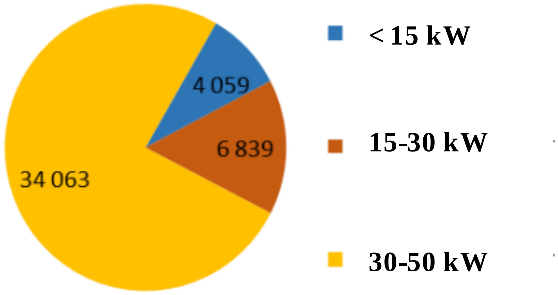


Рис. 1.35. The number of RE generating units of private households with connected capacity (2021) [50].

A significant part of renewable electricity is produced by large HPPs: about 55% in 2019, ~40% in 2020 (**Fig. 1.36**) [51]. The installed capacity of all HPPs (including hydro-accumulating power plants) was 6,335 MW in 2020 (11.5% of the total installed electric capacity), and the electricity supply was 7,415 million kWh (5.4% of the total electricity supply in the country) [52]. At the beginning of 2022, the actual RES share in the total electricity generation was **14.7%** (with HPPs and HAPPs) and **8%** (without HPPs and HAPPs) [50].

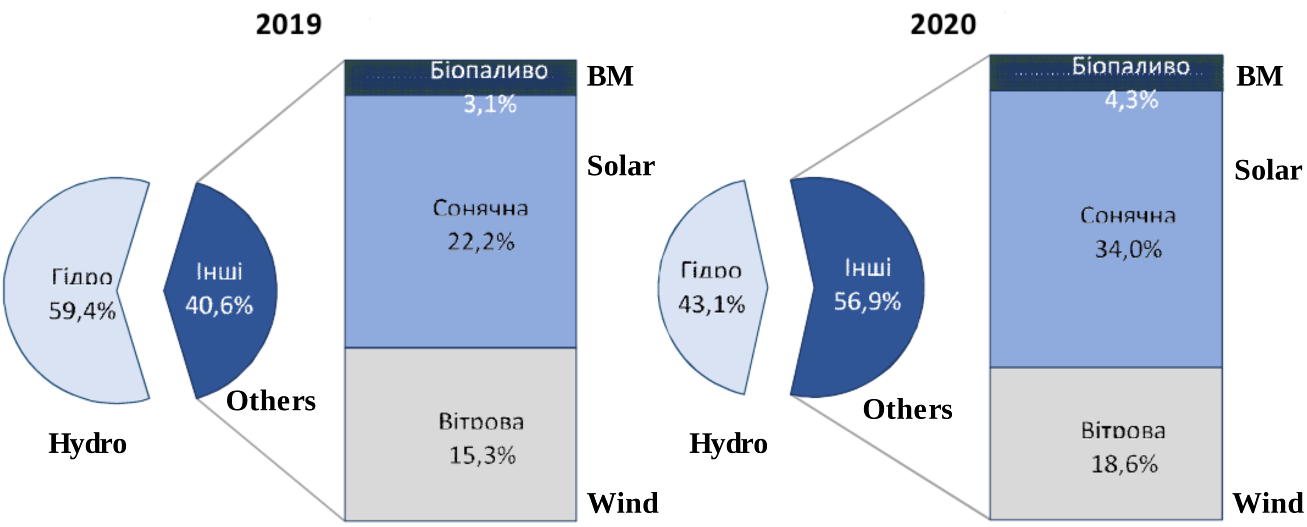


Fig. 1.36. Structure of renewable power production in Ukraine [51].

According to *draft* NREAP 2030 [45], the share of RES in the gross final electricity consumption should be **25%** in 2030. This corresponds to the installed capacity of 21,641 MW and the production volume of 40,241 GW*h in 2030. It is expected that in the period until 2030, geothermal power plants (from 2025) and offshore WPPs (from 2028) will appear in Ukraine as well as biomethane consumption at generating plants using natural gas will be introduced (from 2025).

The draft NREAP 2030 [45] also contains a section on **"green" hydrogen**. It states that the production and consumption of "green" hydrogen is a new promising direction for the development of renewable energy. The Institute of Renewable Energy of Ukraine's National Academy of Sciences has calculated the potentially possible volume of "green" hydrogen production in Ukraine using electricity from wind and photovoltaic plants. The total potential of the average annual production of "green" hydrogen is 505,132 million nm^3 (44,957 kt). The direction of hydrogen production using RES is new not only in Ukraine, but also in the world in general. Currently, the most expedient method of obtaining "green" hydrogen is the splitting of water in electrolyzers into hydrogen and oxygen with electricity produced from renewable sources. In Ukraine's conditions, first of all, we are talking about wind and solar generation facilities or their combination – hybrid power plants. A promising pathway for "green" hydrogen production is the use of biomethane as a substitute for natural gas in steam methane reforming (SMR).

In March 2021, the draft Roadmap for the production and use of hydrogen in Ukraine was presented [53]; in December 2021, the draft Hydrogen Strategy of Ukraine was laid open to the public. In the draft Strategy, three stages of hydrogen energy development in Ukraine are planned: the 1st one (2022-2025) envisages laying foundations for hydrogen energy and launching "green" hydrogen export market; the 2nd one (2026-2030) envisages diversification of primary energy sources due to the growth of hydrogen production; the 3rd stage (2031-2050) envisages rapid expansion of the market, particularly the export component. The final version of Ukraine's Hydrogen Strategy, which was being developed under the auspices of the Ministry of Energy, was preliminarily planned to be published in the spring of 2022 [54]. However, the business is already presenting some hydrogen projects that may interest domestic and foreign investors [55].

1.4.3. Main advantages and disadvantages of different AAF and their rating

The main advantages and disadvantages of using SAF, electric batteries and hydrogen in aviation for flights over different distances are given in **Table 1.14**. The main advantages of SAF are the possibility of mixing with traditional jet fuel and the absence of the need for changes in the aircraft fuel system and airport infrastructure. The main disadvantages are the limited reduction of emissions other than CO_2 (NOx, water vapor) and for biofuels, there is also a potential problem of limited raw resources in the future with a significant increase in the production capacity. As for electric batteries and hydrogen, the main advantage of their use is a significant reduction of the overall negative impact on the climate during aircraft flight (emissions of CO_2, NOx, water vapor, condensation trail), the disadvantage being the need for significant changes to the airport infrastructure.

A comparative analysis of individual SAFs and other alternative energy sources with an assessment of their rating for Ukraine's conditions is presented in **Table 1.15**. The rating is given both current and future with a focus on the *medium-term perspective* (up to 10-15 years), which makes it possible to form a **summary rating** for each type of fuel. In the long-term perspective (more than 20 years), the situation may change significantly due to the development of modern technologies, changes in economic conditions, and other factors.

Table 1.14. Comparison of SAF and new technologies [31].

Comparison vs. kerosene	Biofuels	Synfuels	Battery-electric	Hydrogen
Commuter <19 PAX	No limitation of range	No limitation of range	Maximum ranges up to 500-1,000 km due to lower battery density	No limitation of range
Regional 20-80 PAX				
Short-range 81-165 PAX				
Medium-range 166-250 PAX			Not applicable	Revolutionary aircraft designs as efficient option for ranges above 10,000 km
Long-range >250 PAX				
Main advantage ✓	Drop-in fuel – no change to aircraft or infrastructure	Drop-in fuel – no change to aircraft or infrastructure	No climate impact in flight	High reduction potential of climate impact
Main disadvantage ✕	Limited reduction of non-CO_2 effects	Limited reduction of non-CO_2 effects	Change to infrastructure due to fast charging or battery exchange systems	Change to infrastructure

When determining the rating of alternative aviation fuels, the following aspects were taken into account (**Table 1.16**):

- Level of the technology development and its complexity;
- Technology certification according to ASTM D7566 standard (for SAFs);
- Permissible percentage of mixing with petroleum jet fuel (for SAFs);
- Price;
- Reduction of GHG emissions during the life cycle;
- Availability / accessibility of raw material and resource base;
- Yield of jet fuel compared to the volume of other co-products (for SAFs from biomass).
- The need to change the aircraft's fuel system and airport infrastructure.

Based on results of the comparative analysis and evaluation, the following **SAFs are considered the most promising for Ukraine**:

- Synthesized paraffinic kerosene from hydroprocessed esters and fatty acids (**HEFA-SPK**).
- Alcohol to jet synthetic paraffinic kerosene (**ATJ-SPK**) (currently, only conversion of ethanol).
- Fischer-Tropsch hydroprocessed synthesized paraffinic kerosene (**FT-SPK**).

Table 1.15. Comparative analysis of individual sustainable aviation fuels, electricity and hydrogen for aviation [9, 25, 31].

Type of fuel/production pathway	Advantages*	Disadvantages*	Fuel rating for the introduction in Ukraine*
Synthesized paraffinic kerosene from hydroprocessed esters and fatty acids (**HEFA-SPK**)	• The only **completely** commercialized technology. • One of the first technologies certified according to ASTM D7566. • High blending ratio with fossil jet fuel – up to **50%**. • Competitive price in case of production from waste (lower values of the range): **800**-1400 USD/t. • Considerable GHG emission reduction when using certain feedstocks (for example, 98% for algae from open pond, 89% for tallow). • Certain experience and R&D preconditions are available for potential successful introduction of the technology in Ukraine (**Annex 5**). • Obtained co-products (for example, renewable diesel) can be used in other transport sectors.	• GHG emission reduction considerably depends on a feedstock type. • Comparatively limited resources of sustainable (non-food) feedstock. • I-generation biofuel (from food raw materials) is not considered sustainable by the European Commission. • Competition with renewable diesel produced in the same process	*Current*: **High** *Future*: **Above average** ***Summary (max 10):*** **9**
Alcohol (currently only isobutanol and ethanol) to jet synthetic paraffinic kerosene (**ATJ-SPK**)	• The technology is certified according to ASTM D7566. • High yield of biojet fuel (up to **70%**) as compared with co-products. • High blending ratio with fossil jet fuel – up to **50%**. • Competitive cost, especially when using waste industrial gases (lower values of the range): **700**-1400 USD/t.	• Competition with direct sale of ethanol without the production of SAF.	*Current*: **Average** *Future*: **Above average** ***Summary (max 10):*** **8**
Fischer-Tropsch hydroprocessed synthesized paraffinic kerosene (**FT-SPK**)	• The technology **almost** achieved the commercial level. • The **first** technology certified according to ASTM D7566. • High blending ratio with fossil jet fuel – up to **50%**. • Considerable reduction of GHG emission (up to **95%** and more).	• High capital costs, in particular due to the need for a complex synthesis gas cleaning before FT synthesis. • High operating costs for certain types of gasifiers (for example, for plasma ones). • In general, a complex technology with a lack of	*Current*: **Average** *Future*: **Above average** ***Summary (max 10):*** **7**

Type of fuel/production pathway	Advantages*	Disadvantages*	Fuel rating for the introduction in Ukraine*
	• Competitive price in case of production from MSW (lower values of the range): **1000-**1500 USD/t. • Non-food feedstock. • No need in hydrogen. • Fischer-Tropsch hydrocarbons in the amount of <5% (by volume) can be used in petroleum refinery for co-processing.	relevant experience in Ukraine.	
Fischer-Tropsch synthetic paraffinic kerosene with aromatics (**FT-SPK/A**)	• The technology is certified according to ASTM D7566. • High blending ratio with fossil jet fuel – up to **50%**. • Non-food feedstock. • The biofuel contains aromatic components unlike most other SAFs.	• High capital costs, in particular due to the need for a complex synthesis gas cleaning before FT synthesis. • High operating costs for certain types of gasifiers (for example, for plasma ones). • In general, a complex technology with a lack of relevant experience in Ukraine.	*Current*: **Average** *Future*: **Above average** ***Summary (max 10):*** **7**
Catalytic hydrothermolysis synthesized kerosene (**CH-SK**, or **CHJ**)	• The technology is certified according to ASTM D7566. • High blending ratio with fossil jet fuel – up to **50%**. • The technology requires 25% less hydrogen as compared with HEFA. • The biofuel contains aromatic components unlike most other SAFs.	• Comparatively limited resources of sustainable (non-food) feedstock. • I-generation biofuel (from food raw materials) is not considered sustainable by the European Commission.	*Current*: **Average** *Future*: **Average** ***Summary (max 10):*** **6**
Synthesized paraffinic kerosene from hydrocarbon-hydroprocessed esters and fatty acids (**HC-HEFA-SPK**)	• The technology is certified according to ASTM D7566 (with microalgae as feedstock). • Sustainable feedstock (micro-algae).	• Low percentage of mixing with traditional jet fuel – up to 10%.	*Current*: **Below average** *Future*: **Average** ***Summary (max 10):*** **6**
Co-processing bio-oils (esters, fatty acids) in petroleum refinery	• The technology is certified according to ASTM D7566. • Possible co-processing in existing petroleum refinery.	• A limited share of renewable substance for the co-processing (up to 5% by volume). As a result, the obtained jet fuel has a low degree of renewability.	*Current*: **Below average** *Future*: **Average** ***Summary (max 10):*** **5**
Co-processing synthetic crude oil (Fischer-Tropsch hydrocarbons) in petroleum refinery	• The technology is certified according to ASTM D7566. • Possible co-processing in existing petroleum refinery.	• A limited share of renewable substance for the co-processing (up to 5% by volume). As a result, the	*Current*: **Low** *Future*: **Average**

Type of fuel/production pathway	Advantages*	Disadvantages*	Fuel rating for the introduction in Ukraine*
	• No experience in producing Fischer-Tropsch hydrocarbons in Ukraine.	obtained jet fuel has a low degree of renewability.	**Summary (max 10): 5**
Hydrotreated depolymerized cellulosic jet (**HDCJ**) (Production pathway is based on *pyrolysis* or *hydrothermal liquefaction* of biomass)	• A large raw material base (lignocellulosic raw material) for the introduction of the technology in Ukraine. • There is experience in the implementation of biomass pyrolysis technology in Ukraine. • The possibility of obtaining biojet fuel at a competitive cost after the technology reaches commercial level. • The possibility of hydrothermal liquefaction processing of a wide range of cheap wet raw materials (for example, sewage, manure, food industry waste).	• The technology has not reached the demonstration level yet. • The technology is not certified according to ASTM D7566. According to experts, the certification is possible after 2030. • Low yield of biojet fuel (up to 30%) as compared to co-products.	*Current*: **Low** *Future*: **Average** **Summary (max 10): 4**
Synthetic fuel obtained by Power to Liquid conversion (**PtL**)	• Potential possibility to obtain very low-carbon fuel with GHG emissions reduction of up to 70% and higher when using "green" electricity. • No restriction regarding the raw material base (biomass as a raw material is not required). • Jet fuel produced by F-T synthesis is certified by ASTM D7566 standard, which means it has direct access to the market. • When using F-T synthesis, no considerable cleaning of synthesis gas is required, as it is relatively clean.	• The technology has not fully reached the demonstration level yet. • High production cost (~**4200** USD/t) as compared to other SAFs. • Possible competition with other directions of using renewable power (for example, for electric cars or for obtaining "green" hydrogen). • The option of hydrocarbons synthesis with methanol as an intermediate product is not certified yet. • In general, a complex technology with a lack of relevant experience in Ukraine.	*Current*: **Low** *Future*: **Average** **Summary (max 10): 4**
Hydrogen	• Almost 100% reduction of CO_2 emission (in case of "green" hydrogen). • Reduction of NOx emission by 50% when burning in gas-turbine engine instead of traditional jet fuel. • A significant reduction of the "cumulative" impact (all emissions and related effects)	• Currently, hydrogen production capacities are limited in the world. • High price of "green" hydrogen: ~**2700** USD/t of kerosene (for comparison with SAF). • The volume of hydrogen, even in a liquid state, is 4 times bigger than	*Current*: **Below average** *Future*: **Above average** **Summary (max 10): 4**

Type of fuel/production pathway	Advantages*	Disadvantages*	Fuel rating for the introduction in Ukraine*
	on climate – 50-75% when burning hydrogen in gas-turbine engine, 75-90% when using hydrogen fuel cells. • The weight of hydrogen is 3 times less than jet fuel with the same energy content.	that of jet fuel with the same energy content. • There still exist some unsolved technical problems (storage of liquid hydrogen in the fuel system of the aircraft; efficiency of hydrogen fuel cells etc.). • The need to reconstruct aircraft's fuel system. • The need to considerably change the airport infrastructure. • The need to solve serious safety issues (hydrogen storage, aircraft refueling, etc.).	
Synthesized isoparaffins produced from hydroprocessed fermented sugars (**HFS-SIP**)	• Technology is certified according to ASTM D7566.	• Low percentage of mixing with traditional jet fuel – up to 10%. • The biofuels is potentially more expensive than other SAFs (due to low yield of the final product).	*Current*: **Low** *Future*: **Low** ***Summary (max 10):*** **3**
Electric power	• Considerable reduction of GHG emission – up to 95% when using "green" electricity • Projected reduction in operating costs, aircraft maintenance costs, and pilot training. • Noise reduction. • Possibility of hybrid aircraft (electric motor + internal combustion engine), which increases overall efficiency and reliability.	• Early stage of R&D. • There still exist some unsolved technical problems (for example, limited capacity of charging stations and batteries), which limits the scope of application to short flights. • The need to change the airport infrastructure.	*Current*: **Low** *Future*: **Below average** ***Summary (max 10):*** **2**

**** Advantages and disadvantages for Ukraine's conditions as well as rating of individual SAF, hydrogen and electricity are evaluation by the authors of the report.***

Table 1.16. Comparative analysis and rating of SAFs, electricity and hydrogen for using in aviation (summary).

Fuel	Criteria for evaluating fuels (technologies)							Rating (max 10)
	Attaining commercial level / experience in Ukraine	Certification	Blending ratio with petroleum jet fuel / Jet fuel yield as compared with co-products	Competitiveness by cost	High enough reduction of GHG emission	Availability / accessibility of sustainable feedstock and resources	No changes in aircraft fuel system and airport infrastructure	
Synthesized paraffinic kerosene from hydroprocessed esters and fatty acids (**HEFA-SPK**)	+ / +	+	+ / ±	+	±	±	+	**9**
Alcohol (currently only isobutanol and ethanol) to jet synthetic paraffinic kerosene (**ATJ-SPK**)	- / -	+	+ / +	+	+	+	+	**8**
Fischer-Tropsch hydroprocessed synthesized paraffinic kerosene (**FT-SPK**)	± / -	+	+ / ±	+	+	+	+	**7**
Fischer-Tropsch synthetic paraffinic kerosene with aromatics (**FT-SPK/A**)	- / -	+	+ / ±	-	+	+	+	**7**
Catalytic hydrothermolysis synthesized kerosene (**CH-SK**, or **CHJ**)	- / -	+	+ / -	-	-	-	+	**6**
Synthesized paraffinic kerosene from hydrocarbon-hydroprocessed esters and fatty acids (**HC-HEFA-SPK**)	- / -	+	- / -	-	-	+	+	**6**
Co-processing bio-oils (esters, fatty acids) in petroleum refinery	- / -	+	-	-	-	±	+	**5**
Co-processing synthetic crude oil (Fischer-Tropsch hydrocarbons) in petroleum refinery	- / -	+	-	-	-	+	+	**5**
Hydrotreated depolymerized cellulosic jet (**HDCJ**)	- / ±	-	-	+	+	+	+	**4**
Synthetic fuel obtained by Power to Liquid conversion (**PtL**)	- / -	±		-	+	±	+	**4**
Hydrogen	- / -	-		-	+	±	-	**4**
Synthesized isoparaffins produced from hydroprocessed fermented sugars (**HFS-SIP**)	- / -	+	- / +	-	-	+	-	**3**
Electric power	- / -	-		±	+	±	-	**2**

2. Alternative fuels for waterborne transport

2.1. Analysis of the current state and prospects for the use of alternative fuels for waterborne transport

With the global trend towards decarbonizing the economy, the water transport sector is preparing for a transition to new technologies and energy sources, which will have a significant impact on costs, asset values and profitability. Ship owners are already experiencing increasing pressure to reduce the greenhouse gas footprint of maritime transport. Three fundamental key drivers will push decarbonization in shipping in the coming decade: regulations and policies, access to investors and capital, and cargo owner and consumer expectations [62].

The International Maritime Organization (IMO) is developing policies to reduce greenhouse gas emissions for international shipping. The first regulations, in particular, the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII) will enter into force on January 1, 2023. One of the goals of this activity is to achieve by 2030 a 40% reduction in carbon emissions compared to the 2008 level. The goal is to reduce GHG emissions by increasing the energy efficiency of ships, as well as introducing new technologies and fuels with low or zero carbon content. These documents are expected to have a significant impact on the design and operation of all vessels. Although all ships must meet the IMO's minimum requirements, commercial pressures may push ship owners to take the lead in decarbonization, as shipping companies with poor performance are expected to be less attractive in the shipping market and have problems accessing capital.

The available GHG mitigation measures range from easily achievable operational measures to capital-intensive technical solutions. New builds will have more available options than ships in operation. Available technologies to decarbonize shipping and their GHG emission reduction potential. **Figure 2.1** presents the available shipping decarbonization technologies, of which the greatest potential for reducing GHG emissions is the use of alternative fuels and renewable energy.

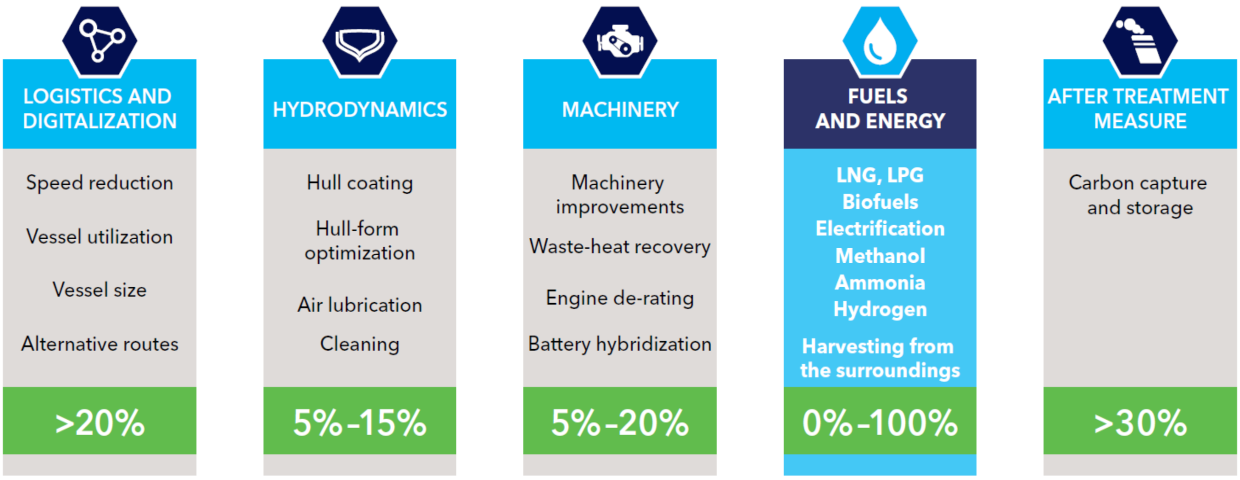


Fig. 2.1. Available technologies to decarbonize shipping and their GHG emission reduction potential [62].

All alternative fuels for shipping face challenges and barriers to their uptake – although the severity of each barrier will vary between fuel types. Typical key barriers include the cost of required machinery and fuel storage on board vessels, additional storage space demand, low technical maturity, high fuel price, limited availability of fuel, and a lack of global bunkering infrastructure. Safety will also be a primary concern, with a lack of prescriptive rules and regulations complicating the use of such machinery and storage systems. As of June 2021, only 0.5% of ships in the world used alternative fuels, but at the same time, in 2021, 11.84% of orders were for alternative fuel ships, in particular, 6.1% of LNG orders, 3.85% on batteries, 1.51% on LPG, 0.3% on methanol, 0.06% on hydrogen and 0.02% on ammonia [62].

According to the International Certification and Classification Society DNV, the most common way to reduce emissions in water transport (**Fig. 2.2**) is the use of scrubbers (4845 ships), 1835 ships can use alternative fuels, in particular, 811 ships on LNG, 229 are ready to work on LNG, 627 on electric batteries, 104 on LPG, 56 on methanol and 8 on hydrogen. The analysis of the distribution of ships by type shows that scrubbers and LNG are used for large, powerful ships (tankers, container ships, cruise ships, bulk carriers, etc.). Methanol is used on container ships and tankers for the transportation of chemicals, LPG is used as fuel only on gas tankers. Electric batteries are used for ferries and short-distance transportation.

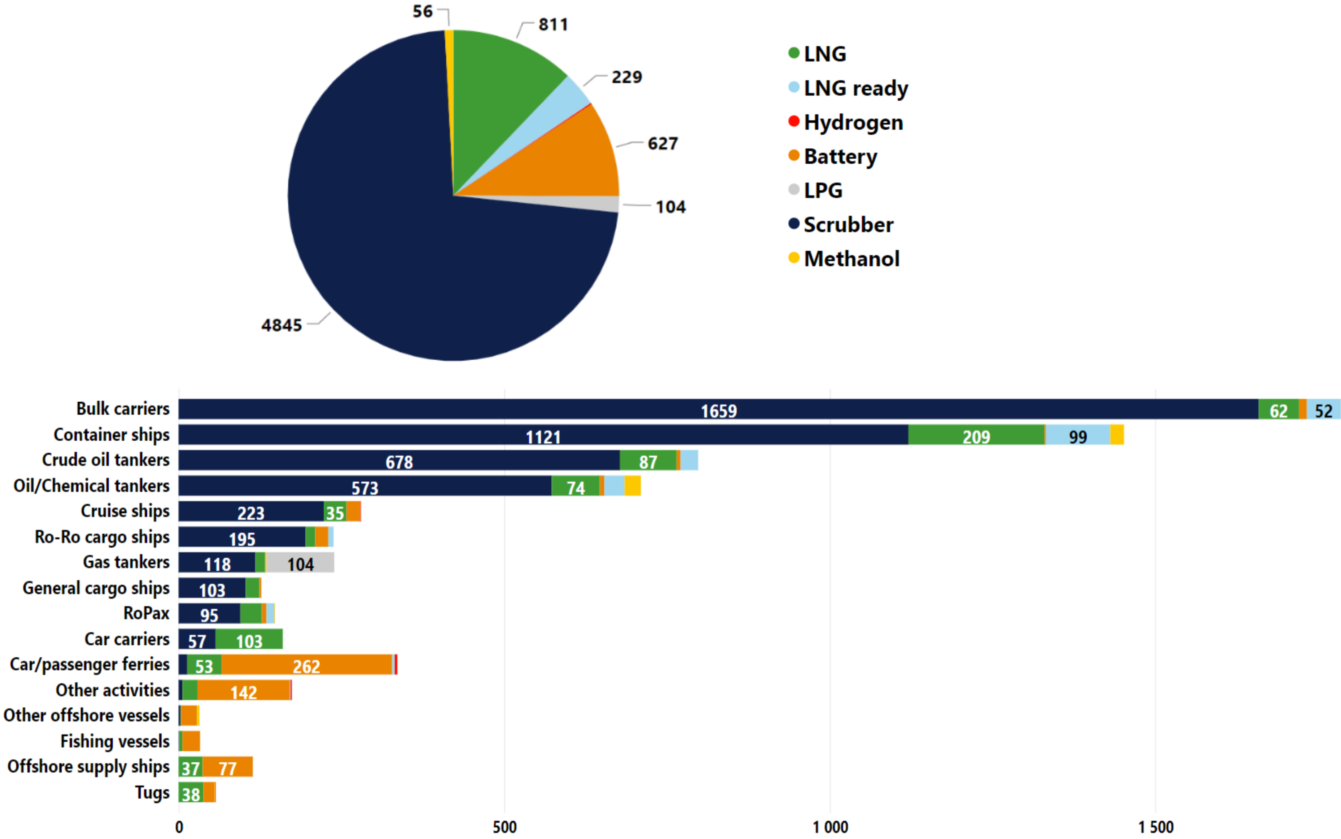


Fig. 2.2. The number of vessels in operation and on order by types of alternative fuels and the use of scrubbers and their distribution by types (https://afi.dnv.com/Statistics)

All ships running on high-sulphur fuel from 2020 must use scrubbers or other technologies to clean the exhaust gases. Scrubber technology is available on the market. Depending on engine size, **investment costs for scrubbers range from 650 USD/kW (5000 kW engine) up to 150-100 USD per kilowatt (engines of 40 MW and more). Operating costs** of scrubbers consist of maintenance costs and energy consumption. According to IMO MEPC 70/5/3, they represent approximately **0.7% of total fuel costs (ships with a shaft power of more than 25 MW)** [63].

Currently, ships can already operate on such alternative fuels as liquefied natural gas (LNG), liquefied petroleum gas (LPG), methanol and biofuel. In addition, tests of ammonia and hydrogen are ongoing. According to their chemical and physical characteristics, alternative fuels differ significantly from traditional fuels for water transport (**Table 2.1**). Properties related to the risk of fires and explosions are particularly dangerous.

Table 2.1. Properties of different marine fuels.

Properties	Diesel fuel [64]	LNG [64]	Methane [64]	Methanol [64]	LPG[d] [65]	Hydrogen [65]
Molecular formula	$C_nH_{1,8n}$; C_8-C_{20}	C_nH_m; 90-99% CH_4	CH_4	CH_3OH	C_3H_8 та C_4H_{10}	H_2
Carbon contents (wt %)	86.88	≈75	74.84	37.49		
Density at 16°C (kg/m³)	833 to 881	431 to 464[a]	422.5[a]	794.6	505	0,08
Boiling point at 101.3 kPa (°C)[b]	163 to 399	-160 (-161)	-161.5	64.5	-42	-253
Net heating value (MJ/kg)	42.5	49	50	20	47	120
Net heating value (GJ/m³)	35	22		16		
Auto-ignition temperature (°C)	257	580	537	464	457	585
Flashpoint (ºC)[c]	52 to 96	-136		11	-60	
Cetane rating	>40	0		5		
Flammability limits (vol % in air)	1.0 to 5.0	4.2 to 16.0	1.4 to 7.6	6.72 to 36.5	2.1 to 9.6	4 to 59
Water solubility	No		No	Complete		
Sulphur content (%)	Varies, <0.5 or < 0.1	< 0.06	0	0		

Notes:
[a] for methane/LNG at boiling point; [b] to convert kPa to psi, multiply by 0.145;
[c] the lowest temperature at which it can vaporize to form ignitable mixture in air;
[d] based on average content.

Modern water transport mainly uses traditional fuels. Thus, in 2020, according to IMO data, ships with a gross tonnage of 5,000 tons or more consumed 203.1 million tons of various fuels, of which 101.3 million tons were heavy fuel oil (HFO), 64.2 million tons were light fuel oil (LFO), 25.5 million tons of marine diesel fuel/gas oil (MDO/MGO), 12 million tons of LNG, 77.6 thousand tons of methanol, 16.6 thousand tons of LPG propane, 1.5 thousand tons of LPG butane and 92.8 thousand tons of other fuels [66]. It should be noted that fuel oil with a sulphur content of 3.5% is currently the cheapest fuel for water transport (**Fig. 2.3**), while the price of LPG and fuel with a very low sulphur content is about 1/3 more expensive and is about 750 USD/t of marine gas oil equivalent (MGO). The price of LNG has risen sharply since 2021 and is now around 1,500 USD/t of MGO equivalent. But, as can be seen from the graphs, fuel prices fluctuate significantly, and the existing situation may change.

Availability and accessibility of fuel supply infrastructure, storage and bunkering is an important aspect for the development of the market of alternative fuels for water transport. Many ports already have operational LNG, methanol and ammonia terminals that can be upgraded for ship bunkering. In addition, new terminals are being built. In Ukraine, there is an active ammonia terminal in the port of Pivdennyi with a storage volume of 120,000 tons (**Fig. 2.4**), which can also be used for reloading ships or barges with ammonia. There is no information on the possibility of direct bunkering of ships. Nearby in Romania, there is a methanol terminal in the port of Constanta with a storage capacity of over 50,000 tons. In Bulgaria, an LNG terminal for the bunkering of inland navigation vessels with a storage capacity of 1,000 m^3 is being built in the port of Ruse on the Danube River, which is part of the LNG master plan for the Rhine-Main-Danube highway.

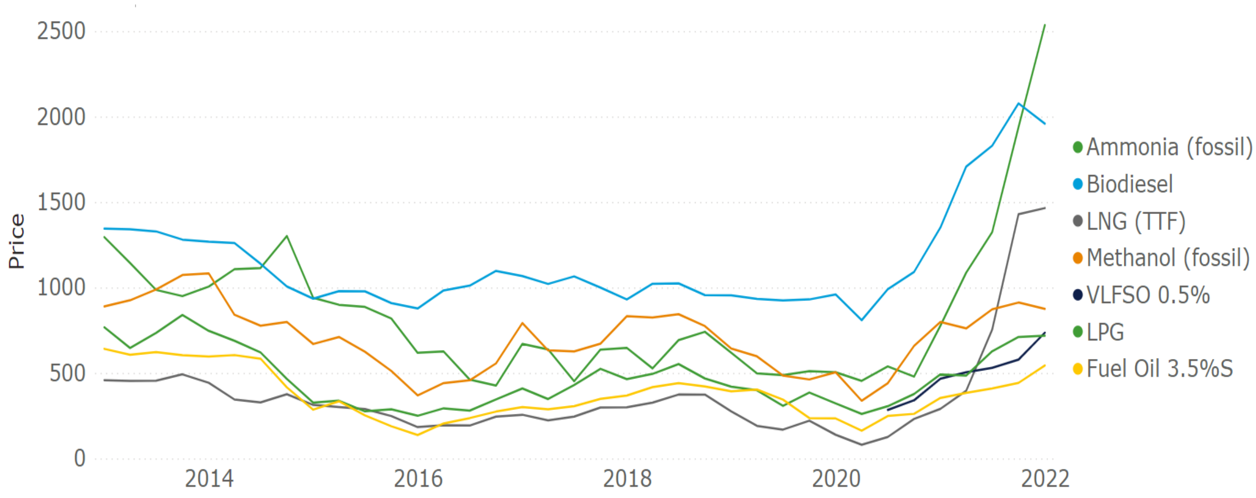


Fig. 2.3. Charts of fluctuations in fuel prices for water transport, **USD/t MGO-eq**. (https://afi.dnv.com/Statistics?repId=4)

Legend

– objects in operation

– objects, the construction of which has been decided.

LNG – liquefied natural gas; Am – ammonia; Me – methanol.

Fig. 2.4. Infrastructure of bunkering with alternative fuels in the Black Sea (https://afi.dnv.com/Map)

In order to transfer the energy installations of ships to some alternative fuels, such as LNG, methanol and ammonia, it is necessary to carry out complex and expensive modernization of engines, their fuel system, to install additional fuel tanks, etc. Based on current technology, a distinction should be made between short-haul shipping and deep-sea long-haul shipping with respect to the applicability and barriers of different fuels. Deep-sea large and powerful vessels have fewer options for choosing fuels compared to the segment of short-distance transportation on permanent routes, where less common technologies and fuels made from local raw materials, in particular, biomass, can be used.

To estimate CO_2 emissions from different types of water transport fuels, the IMO uses the carbon formation factor (C_F), which shows how many grams of CO_2 are produced when using 1 gram of the corresponding type of fuel. **Table 2.2** gives C_F values for selected fuels. Emission factors for low sulphur fuel oil are assumed to be the same as for conventional fuel oil (HFO).

Table 2.2. Types of fuels and C_F factors selectable in the IMO Ship Fuel Oil Consumption Database [66].

Type of fuel	Carbon conversion factor (C_F)
Diesel/Gas Oil	3.206
Light Fuel Oil (LFO)	3.151
Heavy Fuel Oil (HFO)	3.114
Liquefied Petroleum Gas (LPG) – Propane	3.000
Liquefied Petroleum Gas (LPG) – Butane	3.030
Liquefied Natural Gas (LNG)	2.750
Methanol	1.375
Ethanol	1.913

Let us consider in more detail the technologies of production and use of the most promising types of alternative fuels for water transport.

2.2. Liquefied Natural Gas

In recent years, among alternative types of fuel for water transport, liquefied natural gas has become the most popular. LNG is purified natural gas that converted into a liquid state by cooling to a temperature of 162^0C. LNG occupies about 1/600 of the volume of natural gas in its gaseous state (at standard conditions) and **consists mainly of methane (CH_4)** with some ethane (C_2H_6). The main physical and chemical properties of LNG are listed in **Table 2.1**.

LNG is used as an efficient way to comply with emission control area (ECA) restrictions on existing ships and is planned for new ships (**Table 2.3**). A key environmental advantage of LNG is the reduction of SO_x, PM, NO_x and CO_2 emissions compared to traditional petroleum products. Application of LNG is considered the most acceptable method in the near and medium term due to available engine and system technologies, regulations, operational experience, fuel costs, and availability of natural gas worldwide [67].

The LNG supply chain consists of three main stages (**Fig. 2.5**):

1. **Upstream** includes production of natural gas, its primary transportation, liquefaction and transportation to the LNG terminal;

2. **Midstream** covers LNG bunkering infrastructure that can use tank depots, pipeline system, LNG bunkering vessel (feeder), bunkering barge and LNG tank truck;
3. **Downstream** envisages the use of LNG on vessels on sea and inland waterways.

Table 2.3. Comparison of three methods to reduce emissions of pollutants into the atmosphere from the ship engines operation under ECA restrictions [67].

Method	Advantages	Disadvantages	Problems/Questions
Diesel fuel with low sulfur content	– Simple, technically mature way, low CAPEX – Reduction of SOx and PM – Global availability – Capability is confirmed	– Expensive fuel – Problems with fuel switching – Selective Catalytic Reduction (SCR) or Exhaust Gas Recirculation (EGR) must be used for NOx	– Global availability – Fuel quality – High prices in the future?
Fuel oil + scrubber	– Low cost of fuel oil (HFO) – Lower CAPEX than for LNG – Easier conversion – Maturity of technology – Global availability	– Space required for installation – Waste disposal, consumables (closed/hybrid) – Complexity of maintenance – Selective Catalytic Reduction (SCR) or Exhaust Gas Recirculation (EGR) must be used for NOx	– Approval of the flag – Reliability / corrosion stability – Load dependence – Compatible with SCR redundancy
LNG	– Low natural gas cost – Technology Maturity – Reduction of SO_x, PM, NO_x, CO_2 – Lower CAPEX for a smaller vessel than for a scrubber – Ecological profile	– The cost of the engine, fuel system and tanks – Space for LNG tank – Gas mileage may be limited – Lack of LNG bunkering infrastructure – Security risks and issues – Some regulations are still being developed	– Approval of the flag – LNG prices – Global availability of bunkering - LNG fuel quality standards – GHG emissions (methane leaks/emissions)

At the upstream stage, natural gas is produced or imported natural gas is received, which is then transported by pipeline to the LNG liquefaction plant. Before liquefaction, natural gas is pretreated to remove dust and slag (water and condensate), which are removed along with hydrogen sulfide (H_2S) and mercury (Hg). These pollutants can cause corrosion and freezing problems, especially in aluminum heat exchangers. Then acid gas, in particular CO_2, is removed, and dehydration takes place so that no ice is formed during liquefaction. Next, heavy hydrocarbons (C5+) are separated and liquefied. After pre-cooling, natural gas moves through a tube circuit in the main cryogenic heat exchanger (MCHE) where it is liquefied and sub-cooled to between -150°C to -162°C and supplied for the tank. Each tank is insulated to maintain LNG at approximately -160°C and has sophisticated automatic protection systems to monitor the tank level, pressure, temperature and any potential leakage. LNG is transported in special double-hull ships. Each type of cargo tank uses cryogenic materials for containment that are insulated to reduce the cargo boil-off to less than 0.15 percent per day. The LNG is off-loaded from the jetty to terminal storage tanks, which takes approximately 14-16 hours. The LNG remains at -160°C for the duration of the process [72].

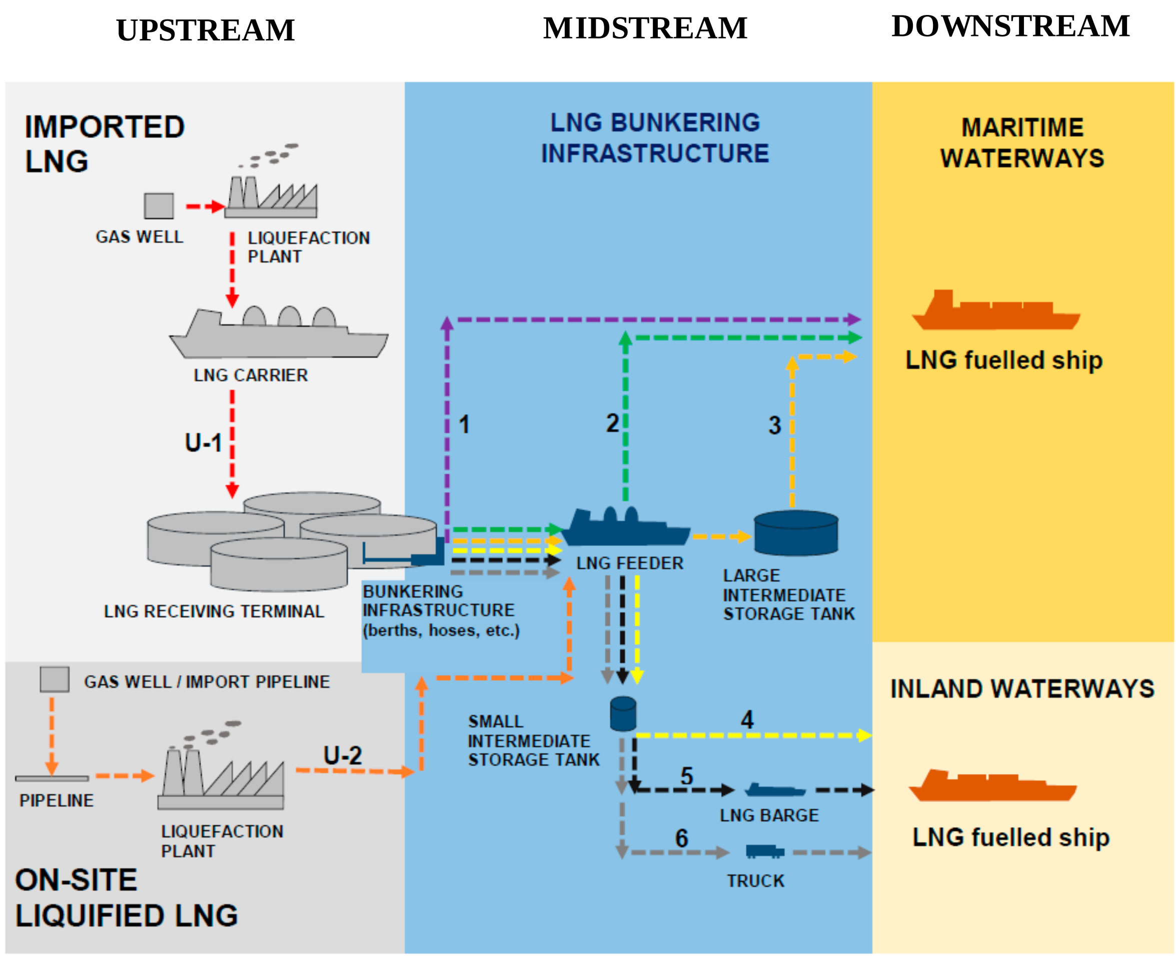


Fig. 2.5. The most likely LNG bunkering routes for sea and inland waterways [68].

In order to use LNG, it is necessary to build midstream infrastructure - specialized terminals that provide reception, storage and bunkering. LNG terminals require significant investment. When the terminals are built, they will serve a large number of customers in industry and infrastructure, as well as shipping. **Investments in the LNG terminal**, for example, built in Nineshamn, Sweden, **with a storage capacity of 20,000 m^3, amount to about 50 million EUR** [64].

There are three main options for bunkering a ship running on LNG [67]:

1. Delivery from a tank truck - Truck to Ship transfer – TTS;
2. Delivery from bunker vessel - Ships to Ship STS;
3. Supply by shore tank and pipeline –Shore Tank to Ship – TPS.

In addition to these bunkering options, standardized containers can also be used for LNG delivery. These containers can be delivered directly to the ship. The "Containers of Ukraine" company offers in Ukraine a 20-foot cryogenic tank container T75 for LNG with a volume of up to 26 m^3, priced from UAH 3,105,000 (**Fig. 2.6**).

Fig. 2.6. 20-foot cryogenic tank container T75 for LNG
(https://containers.ua/products/tank-konteyner-t50-dlya-szhizhennyih-gazov/)

A tanker truck can carry up to approximately 22 t of LNG depending on the capacity of the tank, national transport regulations, road infrastructure and the standard of roads to be used. If the bunkering vessels need a large quantity (>50 t of LNG), then it is more appropriate to use other bunkering options. **The cost of an LNG filling station is 650,000 USD** [67]. **Investments in the bunkering vessel amount to about 30 million EUR** [64].

LNG ships have been in operation since 2000. On January 1, 2017, the IMO IGF Code for LNG and Compressed Natural Gas entered into force, establishing an international regulatory framework for the design and construction of LNG ships. Currently, the technology of using LNG as ship fuel is mature. Reciprocating engines and gas turbines, several types of LNG storage tanks, and other process equipment are commercially available. LNG ships use pure gas reciprocating engines and dual-fuel reciprocating engines that can run on gas or marine fuel or some combination of gas and marine fuel. In a gas engine, the working mixture of natural gas is ignited by a spark plug, and in dual-fuel engines - by using an auxiliary portion of marine fuel. It should be noted that LNG requires larger fuel tanks than traditional marine fuels, and their location is a very important aspect from a safety point of view. Also taking into account the specific requirements associated with cryogenic temperatures, LNG tanks require significant capital costs to equip ships. IMO Resolution MSC 285(86) requires a fully redundant fuel supply system. For single-fuel installations (gas only), the fuel storage space must be divided between two or more tanks of approximately the same size. Dual-fuel engines can use one gas tank and use liquid fuel as a reserve. **Modernization of a ship with conversion to LNG fuel costs about 1,000 EUR/kW** [64].

For the introduction of LNG in waterborne transport, economic feasibility is a key factor, especially in regions with less environmental constraints outside the ECA area. Converting natural gas to LNG requires capital and energy, but transporting liquefied gas by ship with gas carriers offers more flexibility than using pipelines. Prices for LNG in the regions of the world are different and fluctuate significantly (see **Fig. 2.3**). For consumption, it is also necessary to invest in the infrastructure of reception, storage, bunkering and equipment of vessels, which is listed in **Table 2.4**. Operating expenses for such an infrastructure amount to 26.82 USD/t LNG.

The main safety aspects of using LNG as a fuel are as follows [67]:

– fire and explosion hazard:

- limits of flammability in air from 5% to 15%;
- natural gas is odorless and colorless;

– low temperature of liquefied gas / cold streams from compressed natural gas – LPG -163°C:

- LNG or cold gas can cause serious injury from cooling;
- ordinary ship steel will be very brittle and may break under LNG exposure.

– the gas tank has a significant energy content:

- protection from the side and the bottom (collision and grounding);
- protection against external fire and BLE VE (boiling expanding liquid explosion);
- protection against mechanical impact.

Table 2.4. Cost estimation of LNG bunkering infrastructure components [71].

Component name	Unit cost, million USD	Operational cost, USD/t	Annual capacity, million t/year
Pipeline (1 km)	0.6	0.1	0.90
Mining fee	–	2.48	–
LNG tank (50 th. m^3)	120	18.7	0.91
LNG tank (700 $м^3$)	9	0.2	0.01
LNG feeder vessel (10 th. m^3)	60.7	2.7	1.84
LNG bunkering vessel	41.9	2.2	0.60
Truck 50 m^3	0.22	0.04	0.04
Other (mooring, hoses, services, administration)	40.8	0.4	0.90

The international certification and classification society DNV has developed classification rules and standards for various aspects of the production, transportation, bunkering and use of LNG, some of which also apply to LPG. The society of gas as a marine fuel (SGMF) has developed a number of safety instructions for the use of LNG and other gases as marine fuel, in particular, the manual "LNG as Marine Fuel. Safety and operating instructions. Bunkering (Version 3.0)".

When using LNG, the lowest emissions of greenhouse gases are produced among fossil fuels for water transport (**Fig. 2.7**). However, LNG systems can leak methane, which has a global warming potential 28 times greater than CO_2. Therefore, the advantages in reducing greenhouse gas emissions from the use of LNG compared to fuel oil and marine fuel in the presence of CH_4 leaks may be absent. Engine manufacturers claim that **tank-to-propeller LNG CO_2 emissions** of dual-fuel and clean gas engines are **10-20% lower than those of petroleum-fueled engines** [73]. It is possible to achieve a greater reduction of GHG if LNG is produced from renewable raw materials, for example, from biomass through its anaerobic fermentation in a biogas plant followed by purification of biogas to biomethane. Liquefied biomethane is called bio-LNG (LBG).

In addition to CO_2 emissions reduction, the use of LNG makes it possible to reduce the emission of other pollutants into the atmosphere. Due to the absence of sulfur in LNG, there are no SO_x emissions in gas engines, and in dual-fuel engines it depends on the sulfur content of the auxiliary fuel. NO_x emissions are produced during fuel combustion and their amount mainly depends on the temperature in the combustion zone. Diesel engines produce more NO_x emissions than Otto cycle gas engines. Therefore, in dual-fuel engines, there may be a need to use gas cleaning equipment for ECA zones. Particulate matter emissions are associated with incomplete fuel combustion. According to research, emissions of solid particles are reduced by about 85% when using natural gas. [67].

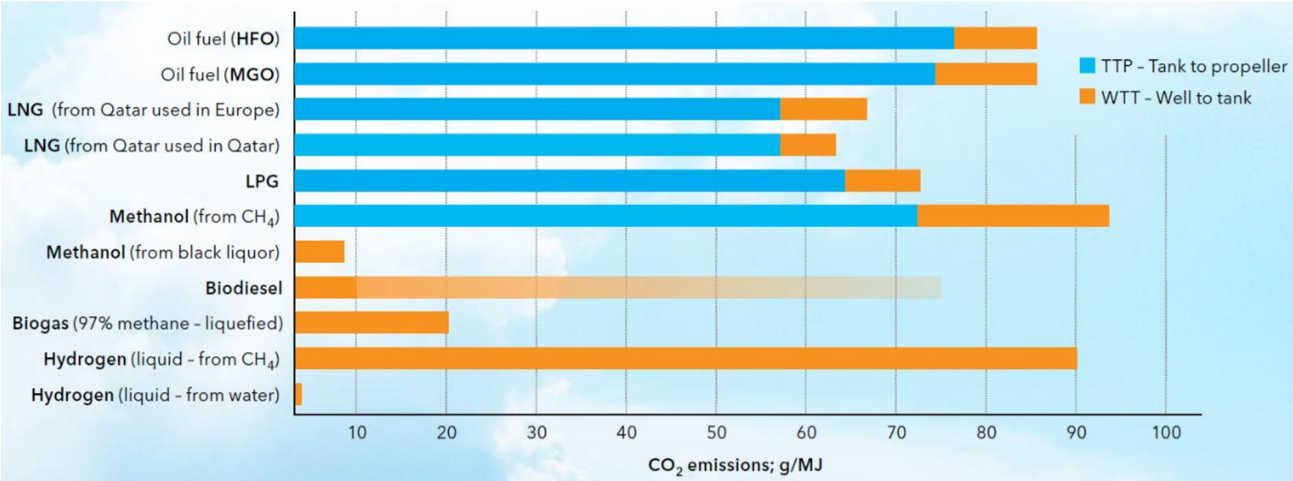


Fig. 2.7. CO_2 emissions from alternative fuels in water transport [73].

Despite the fact that the technology is quite mature, there is still no LNG infrastructure in Ukraine. Although about ten years ago, a project for the construction of an LNG terminal near Odesa was discussed, and in 2012 an agreement was even signed with the Spanish company Gas Natural Fenosa. However, the implementation of this project was not started.

Given the need for significant investments in the construction of a new infrastructure for the supply, storage and bunkering of LNG from fossil natural gas with a slight greenhouse gas emissions reduction (see **Fig. 2.7**), we believe that the introduction of LNG for water transport in Ukraine is impractical, especially given the insufficient supply and high prices of natural gas in Europe. Perhaps with the introduction of large-scale production of biomethane in Ukraine and the development of technologies for its liquefaction in the medium term, prerequisites will be created for the use of bio-LNG, in particular, produced from waste, which will contribute to the decarbonization of water transport. In the near future, compressed biomethane and liquefied propane/butane, which can also be produced from biomass, can be used as fuel. However, this requires systematic work on the justification of technical solutions, which are based on the equipment and components available on the market.

The Law of Ukraine "On the Natural Gas Market" [101], which defines the legal basis for the functioning of the natural gas market of Ukraine, provides that LNG installation services are an economic activity that is subject to licensing and consists in the transformation of natural gas from gaseous to the liquid state (liquefaction) or conversion of liquefied natural gas from a liquid to a gaseous state (regasification) using an LNG plant. When using LNG for water transport, one should consider the requirements of this law and the by-laws adopted for its implementation.

The International Maritime Organization is an international intergovernmental organization, a specialized agency of the United Nations. The activities of the IMO are aimed at the abolition of discriminatory actions affecting international merchant shipping, as well as the adoption of norms (standards) to ensure safety at sea and prevent environmental, primarily marine, pollution from ships. Ukraine is a member of the IMO under the resolution of the Verkhovna Rada of Ukraine dated February 4, 1994, No. 3938-XI "On the adoption of the Convention on the International Maritime Organization of 1948 in the version of 1982". Acts of the IMO may have a mandatory or advisory nature and are subject to implementation in the legislation of Ukraine.

The Law of Ukraine "On Amendments to Certain Laws of Ukraine Regarding the Development of Biomethane Production" [102] defines the legal basis for biomethane production in Ukraine. According to the mentioned law, biomethane is biogas, which according to its physical and chemical characteristics, meets the requirements of legal acts for natural gas for supply to the gas transportation or gas distribution system or use as motor fuel. The law does not define the specifics of the use of biomethane in water transport, but it opens up opportunities for its production and use in Ukraine.

2.3. Methanol

Methanol (methyl alcohol) is the simplest monoatomic alcohol with the chemical formula **CH_3OH**. Under normal conditions, it is a transparent, colorless, flammable and volatile liquid with a characteristic alcohol smell. Methanol is an excellent substitute for gasoline, is used in blended fuels, and can also provide good levels of performance in diesel engines. For use in diesel engines, it is necessary to feed a small amount of diesel fuel together with methanol or use an ignition improver. Methanol is also used to produce biodiesel, methyl tert-butyl ether (MTBE) and dimethyl ether (DME) and in fuel cells. There is no sulfur in the composition of methanol, when it is burned, NO_x emissions are produced in a small amount, and there are no emissions of solid particles (PM), so this fuel is considered promising for water transport.

The existing fuel storage infrastructure, their distribution and bunkering, after minor and inexpensive modification, can also be used for methanol, which is characterized by a low flash point of 11^0C (see **Table 2.1**). The toxicity of methyl alcohol should be noted. Its toxic effects can occur through inhalation, skin and eye contact, and ingestion. Ingestion of more than 20 ml can be fatal, and smaller amounts cause irreversible blindness. The technology for handling flammable chemicals is well developed and there is extensive experience in the safe handling of methanol. In all tests conducted, methyl alcohol demonstrated good combustion properties and energy efficiency, as well as low emissions during combustion [64]. The disadvantage of methanol, like other alcohol fuels, is its lower energy content compared to traditional fuels (see **Table 2.1**). Given the equivalent energy density, the volume required to store methanol in a tank would be approximately double that of traditional diesel fuels.

Methanol is a globally available commercial product with extensive distribution and storage capabilities. Worldwide annual production of methanol nearly doubled over the past decade to reach about 98 Mt in 2019. Methanol demand is expected to continue increasing to reach more than 120 Mt by 2025 and 500 Mt by 2050. Currently, methanol is produced almost exclusively from fossil fuels. About 65% of methanol production is based on natural gas reforming (gray methanol) (**Fig. 2.8**), while the rest (35%) is mainly based on coal gasification (brown methanol). However, methanol can also be made from other feedstocks that contain carbon, including biomass, biogas, waste streams and CO_2 (for example, captured from flue gases or through direct air capture). Currently only about 0.2% comes from renewable sources (green methanol) [74].

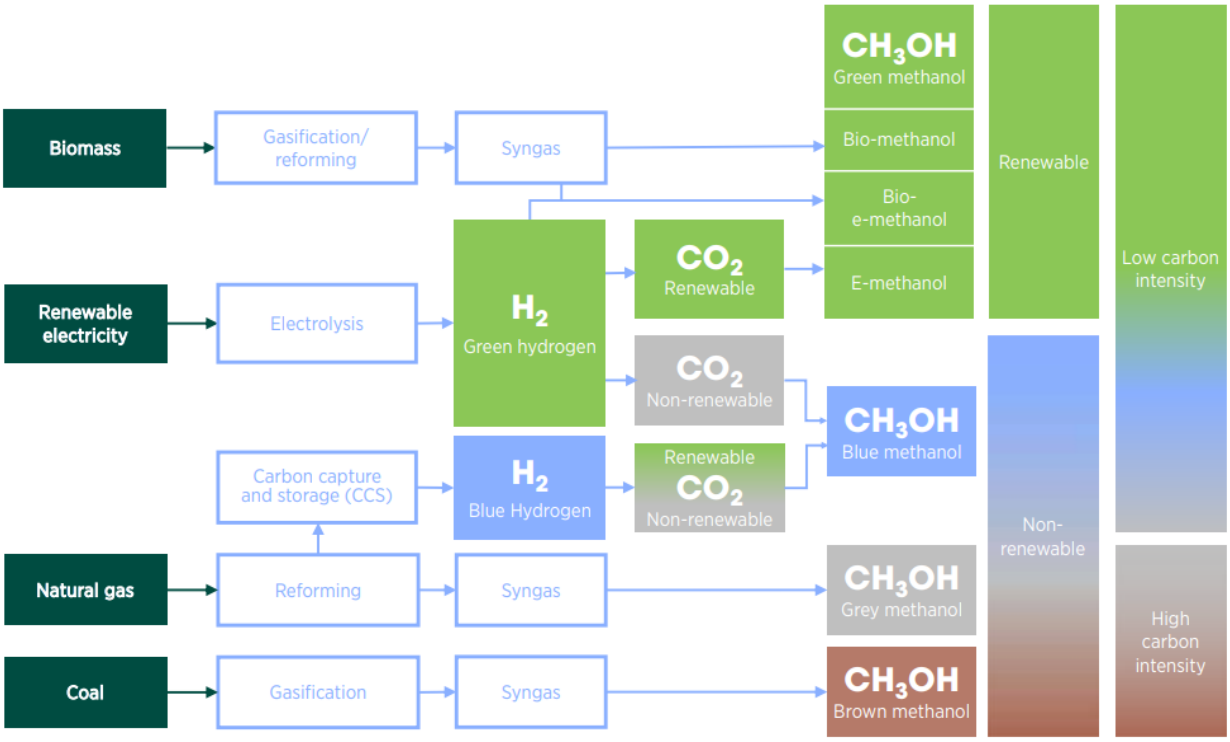


Fig. 2.8. Principal methanol production routes [74].

Note: *Renewable CO_2: from bio-origin and through direct air capture (DAC).*

Non-renewable CO_2: from fossil origin, industry.

Methanol can also be classified as renewable and non-renewable. To qualify as renewable, all feedstock used to produce methanol must be of renewable origin (biomass, solar, wind, hydro, geothermal, etc.). Renewable methanol can be produced using renewable energy and renewable feedstocks via two routes:

• Bio-methanol is produced from biomass. Key potential sustainable biomass feedstocks include: forestry and agricultural waste and by-products, biogas from landfill, sewage, MSW and black liquor from the pulp and paper industry.

• Green e-methanol is obtained from CO_2 captured from renewable sources (e.g. via BECCS or DAC) and green hydrogen, i.e. hydrogen produced with renewable electricity [74].

Less than 0.2 Mt of renewable methanol is produced annually. Those renewable methanol commercial facilities and demonstration projects focus mainly on using waste and by-product streams from other industrial processes, which offer the best economics at present.

To produce methanol, natural gas and coal first have to be converted to synthesis gas (syngas), a mixture of carbon monoxide (CO), hydrogen (H_2) and carbon dioxide (CO_2). In the case of coal, syngas is obtained by gasification (**Fig. 2.9**) that combines partial oxidation and steam treatment at high temperature (800-1 800°C depending on the process and feedstock). To produce syngas from natural gas a number of processes are available including steam reforming, partial oxidation dry reforming, autothermal reforming or a combination thereof. These are high-temperature processes (> 800°C). The syngas obtained by coal gasification requires much more pretreatment, conditioning and adjustment to remove impurities and contaminants (tars, dust, inorganic substances) to optimise its composition for methanol synthesis. Due to its higher H/C ratio, the CO_2 emissions associated with the production of methanol from natural gas are also substantially lower than from coal (about 0.5 kg of carbon dioxide equivalent [$CO_{2\text{-eq}}$] per kg methanol for natural gas compared to 2.6-3.8 kg $CO_{2\text{-eq}}$/kg methanol for coal). The overall energy conversion efficiency for a large, modern natural gasbased plant is around 70%. For coal to methanol the energy conversion efficiency is in the order of 50-60% depending on technology selection. A typical world-scale methanol plant using natural gas as a feedstock has a production capacity of about 3000-5000 t/day or 1-1.7 million t/year [74].

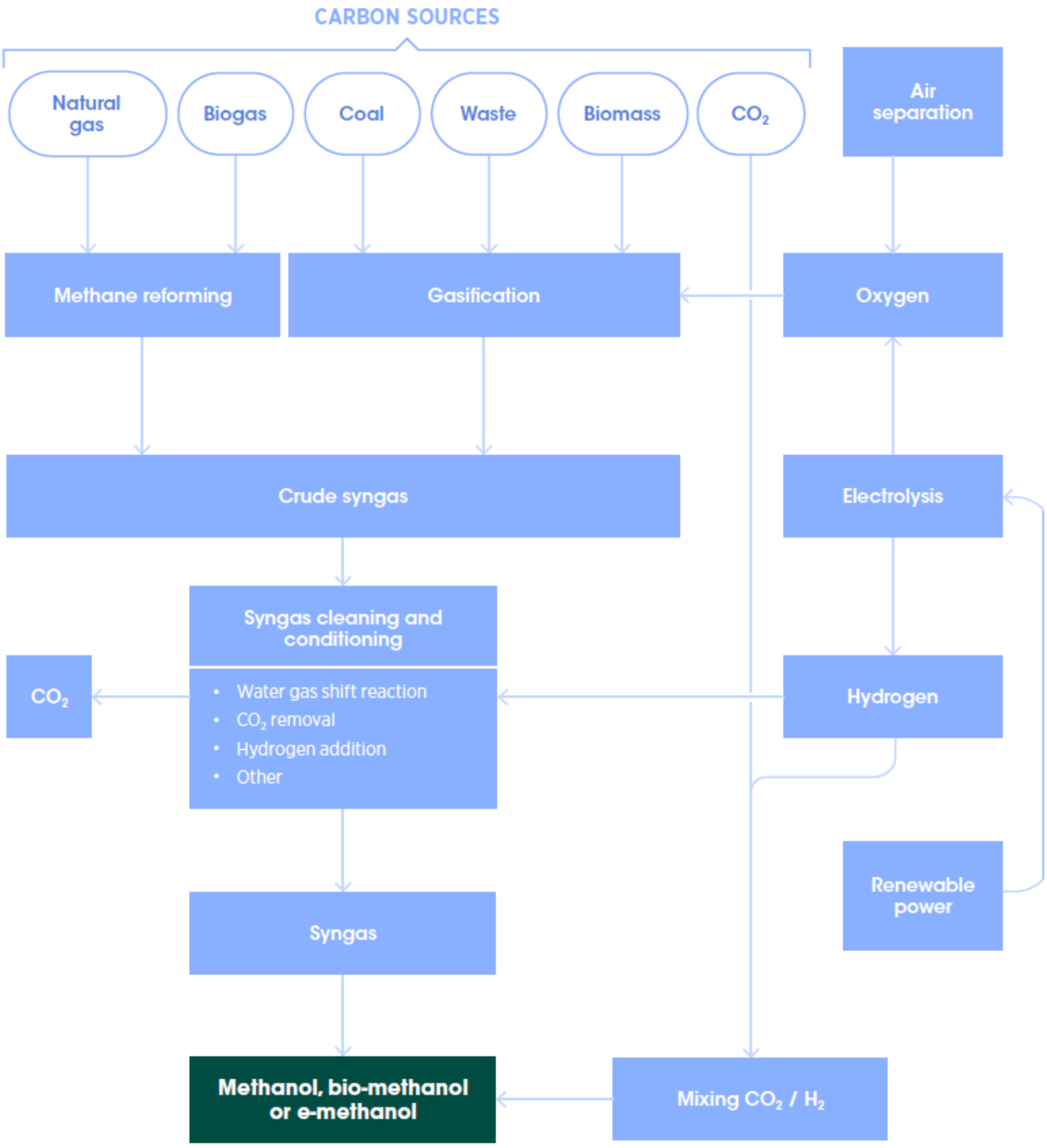


Fig. 2.9. Overview of the main processes of methanol production from various carbon sources [74].

In the production of bio-methanol, reforming for biogas and gasification for biomass and waste are also used. However, these processes and preparation of raw materials are somewhat different. In particular, it is necessary to ensure the homogenization of biomass and waste, and biogas needs pretreatment to achieve the quality of fossil natural gas. For methanol synthesis, the optimal H_2/CO ratio is close to 2. Because the production of methanol from biomass generates a lot of CO_2, the apparent conversion rate of biomass into methanol is reduced. The overall carbon efficiency in this type of scheme is around 50%, meaning that only about 50% of the carbon in the feedstock ends up in methanol; the rest is in the emitted CO_2.

E-methanol is a liquid product easily obtainable from CO_2 and green hydrogen through a one-step catalytic process. Produced through a Power-to-X technology, e-methanol is considered an electrofuel (e-fuel) and electrochemical. To produce one tonne of methanol, about 1.38 t of CO_2 and 0.19 t of hydrogen (~1.7 t of water) are needed. About 10-11 MWh of electricity are required to produce one tonne of e-methanol; most of it for the electrolysis of water (assuming CO_2 is provided). With a 100 MW electrolyser, about 225 t/d of e-methanol could be produced.

The production costs of renewable methanol are significantly higher than the current production of methanol based on natural gas and coal (the production costs of which are in the range of 100-250 USD/t). With the lowest cost of raw materials and improved production processes, the cost of renewable methanol production from biomass gasification or MSW, or using CO_2 and renewable hydrogen, can approach the current cost and price of methanol from fossil fuels, as shown in **Fig. 2.10**.

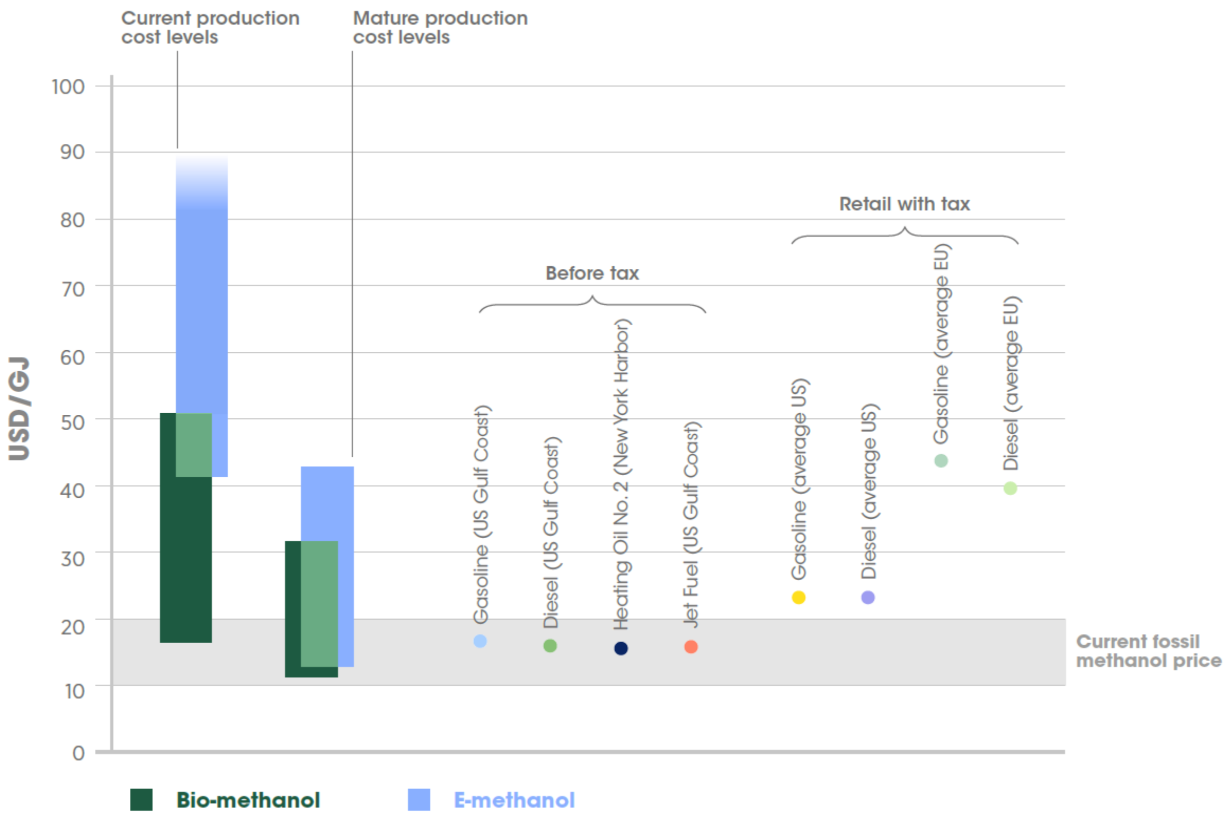


Fig. 2.10. Current and future production costs of bio- and e-methanol [74].

The current supply chain infrastructure for methyl alcohol is based on its widespread use in the chemical industry worldwide. This ensures wide availability, although there may be a need for additional terminals for methanol to be used as marine fuel. Methanol can be easily bunkered by trucks. The installation cost of a small bunkering unit for methanol has been estimated at around € 400,000. An existing barge can be converted into a bunker vessel for methanol at a cost of approximately € 1.5 million. For a 20,000 m^3 methanol tank and the installations for loading the tank from a tank vessel and unloading it to a bunker vessel, the cost is approximately €5 million [64].

When converting ships to methanol, it is necessary to modify the engine, fuel tanks, pipelines and bunkering system. The low cetane number (**see Table 2.1**) is a property that methanol shares with LNG, and the engine needs an ignition booster. In the dual-fuel system, a small amount of diesel fuel is used as an auxiliary fuel. Gas-diesel technology is used to convert existing engines. The difference with a gas dual-fuel engine is that the gas compressor used for natural gas is replaced by high-pressure methanol pumps to increase the fuel pressure. In a converted vessel, the conventional fuel system can work as a spare. Pipelines for methanol are made double-walled. The high-pressure piping system can be purged with nitrogen gas to allow maintenance without operator contact with methanol [64].

The cost of upgrading a vessel from diesel fuel to a methanol/diesel dual-fuel system is estimated at 250-350 EUR/kW for large engines (10-25 MW) [64]. The cost of additional costs for a new vessel to use methanol can be less than upgrading an existing one. For example, the additional costs for a new roller-type ship with a methanol fuel system with a 24 MW main engine and a 3-day fuel tank is 5.6 million USD, while the cost of converting an existing similar vessel to methanol is 10.5 million USD [75].

The additional cost of a methanol engine for a new ship is about half that for a retrofit, mainly because the fuel tank is included in the design of the new ship from the outset and its placement will not be an additional cost to the ship owner. For the modernization option, it is taken into account that the separate tank is not integrated into the existing vessel, and this will require additional costs. If the new vessel spends 100% of its time in ECA and the price of methanol is 75% of marine gas oil (MGO) (on an energy equivalent basis), the payback period is 6.8 years. This is a relatively long payback period for most of the ship owners. For the option of a modernized vessel, the payback period under similar conditions will be even higher, and therefore even less economically attractive. As of June 2022, the cost of methanol in Europe is 593 USD/t [76], while the cost of marine gas oil (MGO) in the port of Rotterdam is 1,337 USD/t [77]. Taking into account the energy content of these fuels, the current ratio of methanol to MGO prices is 94%. Thus, the indicated fuel prices in Europe do not create prerequisites for the economic feasibility of switching ships to methanol.

Given the properties of methanol, in particular, its flammability and toxicity, safety measures must be observed when working with it. Additional monitoring and control systems such as overflow alarms, automatic shut-off, ventilation monitoring and gas detection must be used in the supply chain and on methanol-powered vessels [75]. Detailed measures to reduce the risk of working with methanol are specified in DNV GL rules, Chapter 6 «Low flashpoint liquid fueled engines» [78]. Vessels constructed in accordance with the requirements of this section may be assigned the LFL (low flash point liquid) class designation. The use of low flash point liquid fuels is covered by the IGF Code /SOLAS II-1/G/56 and 57. However, alcohols are covered by guidance developed as a supplement to this code.

Methanol is soluble in water and easily biodegradable. Methyl alcohol, when it gets into water, quickly dissolves to low concentrations, allowing microorganisms that occur in nature to decompose it in a relatively short time. When using methanol as marine fuel, compared to fuel oil, SO_x emissions are reduced by more than 99%, PM by 95%, and NO_x by 60-80% [74]. It should be noted that the reduction of greenhouse gas emissions is an important advantage of methanol from biomass and CO_2. Comparing different sources of biomass for methanol production, it was determined that the equivalent CO_2 emissions "from well to wheel" for black liquor were 3-12 g CO_{2-eq}/MJ, wood waste – 5.3-22.6 g CO_{2-eq}/MJ, agricultural wood (obtained from tree plantations) – 4.6-16.5 g CO_{2-eq}/MJ. Methanol from crude glycerol and biogas had slightly higher emissions, 30.6 g CO_{2-eq}/MJ and 30-34.4 g CO_{2-eq}/MJ, respectively. Well-to-wheel CO_2 emissions for methanol from the processing of CO_2 and H_2 from renewable sources have been estimated at 1.74-33.1 g CO_{2-eq}/MJ, depending on different assumptions. For comparison, GHG emissions of methanol obtained from natural gas were 91-101.6 g CO_{2-eq}/MJ, methanol from lignite 170.8 g CO_{2-eq}/MJ, and methanol from hard coal – 219-262 g CO_{2-eq}/MJ. Thus, bio-methanol and e-methanol are promising alternative fuels, the use of which allows reducing emissions of pollutants and greenhouse gases.

The use of methanol for the production of fuels requires **compliance with the current legislation**, as methanol is a dangerous substance. Methanol is a highly flammable liquid, highly poisonous of a nervous and vascular nature with a pronounced cumulative effect, similar in color, smell, and taste to ethyl (wine) alcohol. In this regard, several normative legal acts defining the procedure for handling methanol are in force in Ukraine. In particular, they are:

1. Rules of labor protection at facilities for the production of basic organic products and polymers [103].
2. Exemplary instructions on labor protection when working with methanol [104].
3. DSTU 3057-95 Technical Methanol. Technical conditions (GOST 2222-95) [105].

4. Decree of the Cabinet of Ministers of Ukraine dated July 11, 2002 No. 956 "On identification and declaration of safety of objects of increased danger" [106]. The Regulation provides that methanol belongs to individual hazardous substances. The threshold mass for methanol is 1 class – 5000 t, 2 class – 500 t. If the business entity owns or uses facilities where hazardous substances (including methanol) are manufactured, processed, stored, or transported, in that case, such facilities must be identified and assigned to the appropriate hazard class.

2.4. Ammonia

Ammonia is of considerable interest as a potential zero-carbon fuel for transportation. Ammonia is an inorganic compound **NH_3**. Under normal conditions it is a colorless gas with a sharp suffocating smell, lighter than air and well soluble in water. The boiling point of ammonia is -33.3°C. At a pressure of more than 8.6 bar and a temperature of 20°C, ammonia is a liquid with a density of 0.61 t/m^3. At the boiling point, the density is 0.68 t/m^3. Calorific value of ammonia is 18.6 MJ/kg. Compared to MGO marine fuel, the energy content of liquid ammonia is less than half by mass and about 30% by volume. Exposure to very high concentrations of ammonia gas in the air can cause lung damage and even death. Therefore, it is important to ensure the implementation of safety measures for working with ammonia. In addition, ammonia is corrosive to some materials, such as copper, copper alloys, and zinc, so care must be taken when selecting materials.

Ammonia is known to cause stress corrosion in carbon-manganese and nickel steels. The use of steels with a nickel content of more than 5% for parts in contact with ammonia is prohibited. Although it should be noted that ammonia has been used for the production of fertilizers for many decades. Therefore, in many countries, in particular, in Ukraine, there is an infrastructure for the transportation and storage of ammonia, and there are regulatory and legal documents regarding its handling. In 2018, the world production of ammonia amounted to 170 million tons. According to the Center for European Political Studies, about 80% of the world production of ammonia is used for the production of fertilizers [79]. Of which the most common is urea, which is formed as a result of the reaction between ammonia and carbon dioxide.

Ammonia is mainly produced by the Haber-Bosch process, which combines nitrogen gas and hydrogen under high pressure and elevated temperatures to form ammonia. The ammonia production scheme is shown in **Fig. 2.11**. The conversion efficiency of natural gas to ammonia using the best available technology is about 66% based on the lower calorific value. However, it was reported [79] that in 2012 the weighted average European natural gas energy consumption was 10.8 MWh per ton of ammonia, which corresponds to only 48% efficiency, and one of the largest ammonia producers sets an efficient plant value of 53%. Instead of natural gas, biogas can be used as a source of methane for ammonia production after treatment, in particular, from landfills or wastewater management systems. In the Haber-Bosch process, biomass, which is first subjected to gasification, is also processed into ammonia. There are also promising methods of ammonia production using RES for hydrogen production. Green ammonia is distinguished, which is produced from renewable electricity, and therefore it is considered CO_2 neutral. Blue ammonia is made from fossil fuels with carbon capture and storage. Brown ammonia is obtained from fossil sources such as natural gas and coal.

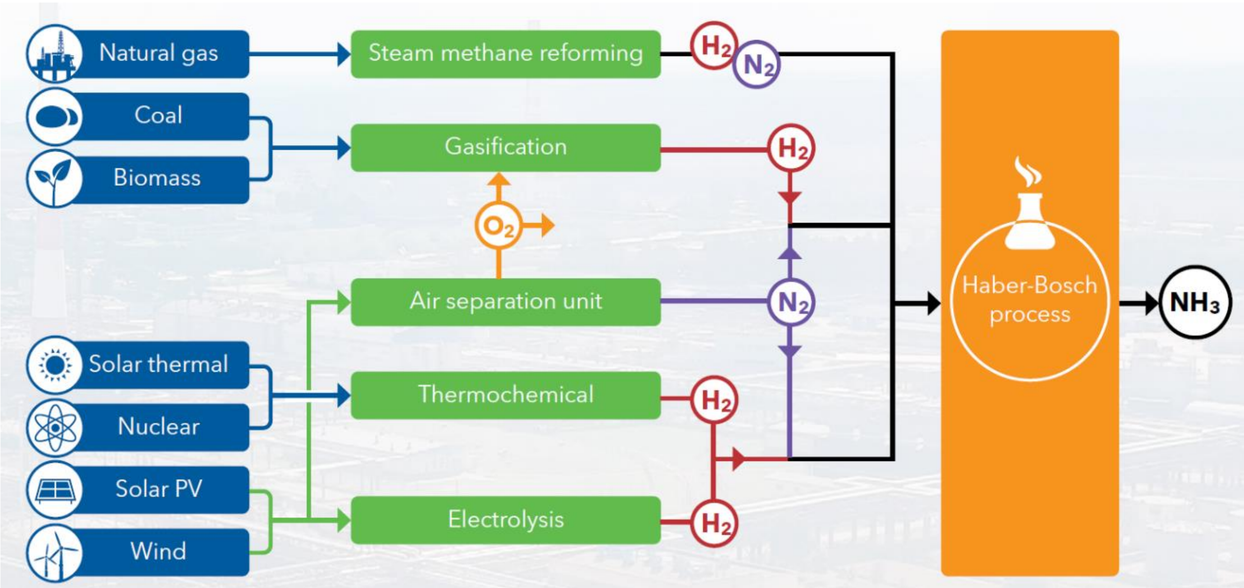


Fig. 2.11. Ammonia production methods [79].

Natural gas as a feedstock has both higher efficiency and lower capital and operating costs compared to coal. Capital costs for ammonia production from natural gas, oil, and coal are 860, 1,203, and 2,063 USD respectively per ton of annual production capacity, while annual operating costs are 2.5%, 2.5% and 5% of capital costs, respectively. Other ways of ammonia production on a large scale are not yet commercially available.

Anhydrous ammonia is transported in gas carriers designed for the transportation of ammonia. In this case, three methods can be used:

1. with cooling at a temperature of -50℃ and at a pressure close to the ambient;

2. with semi-cooling, usually at -10ºC and a pressure of 4-8 bar;

3. under pressure, usually 17 bar, which corresponds to the vapor pressure of ammonia at about 45ºC.

Smaller volumes of ammonia are transported by the last two ways. Large quantities of ammonia are usually stored on land in refrigerated tanks. Capital costs for refrigerated storage are about 700 USD per ton of ammonia.

Ammonia can be bunkered in many different ways: from terminals or trucks on land or from bunkering vessels. Loading and unloading from terminals to ships carrying ammonia is currently carried out safely thanks to proper specialized training. The bunkering vessel and the vessel to be bunkered must have the necessary equipment and facilities for safe ammonia bunkering, given that this substance can be stored under pressure or under refrigeration. Also, strict safety measures must be followed when using gas stations.

Ammonia can be used as marine fuel in both internal combustion engines and fuel cells. Due to its high-auto ignition temperature, ammonia requires a higher compression ratio (35:1 and higher) than used in typical CI engines (16-23:1). It is difficult to design such an engine, so the addition of a second fuel, with lower auto-ignition temperature, can help to combust the mixture and allows for a more stable combustion. Ammonia has a high minimum ignition energy and a low flame speed, so mixtures of ammonia with other types of fuel are also used in engines with forced ignition. Ammonia positive-ignition engines are thought to be used for smaller vessels, while modified two-stroke (dual-fuel) diesel engines may be suitable for larger ships. Combustion of ammonia or ammonia mixtures can lead to emissions of nitrogen oxides (NO_x), nitrous oxide (N_2O) and direct emissions of ammonia (NH_3). But to date, there is no experience of long-term operation of ship engines on ammonia. Therefore, there is not enough empirical data on emissions from burning this type of fuel [80]. Commercial ammonia engines are expected to appear in 2024.

CO_2 emissions are generated from the production and supply of ammonia, while its use results in carbon dioxide emissions from dual-fuel engines where ammonia is combusted with additional hydrocarbon fuels. CO_2 emissions from ammonia production are 85 kg CO_2/GJ for natural gas and 215 kg CO_2/GJ for coal. Thus, ammonia produced from natural gas produces the same emissions as low-sulfur MGO marine fuel (88 kg CO_2/GJ). Therefore, a significant reduction in greenhouse gas emissions can be achieved if ammonia is produced using renewable energy sources [79].

Strict safety guidelines must be implemented for the safe handling of ammonia on board ships. Even in small concentrations in the air, ammonia can be extremely irritating to the eyes, throat, and respiratory tract. Therefore, due to possible risks of use, this fuel may not be applicable in all segments of water transport, for example, on passenger ships.

The production cost of green ammonia is estimated to range between 100-150 €/MWh in the near future, mainly depending on the electricity prices, compared to a fossil-based ammonia of around 55 €/MWh [80]. Currently, there are no tested commercial engines on ammonia, and now its price is much higher than the prices of fuel oil, marine fuel, LPG, LNG, methanol, and biodiesel (see **Fig. 2.3**), so there are still no economic prerequisites for the introduction of the use of ammonia as a fuel for water transport in Ukraine. In addition, the use of commercially available brown ammonia does not provide significant environmental benefits. Although in the long term, when commercial technologies for the blue and green ammonia production will be created, this fuel can become an important direction for the decarbonization of waterborne transport.

The use of ammonia requires **compliance with the current legislation**. Several normative legal acts defining the procedure for handling ammonia are in force in Ukraine. In particular, they are:

1. Rules for the safe operation of synthetic liquid ammonia ground warehouses [107].
2. Labor protection rules during pipelines' operations for transporting liquid ammonia (ammonia pipelines) [108].

2.5. Hydrogen

Hydrogen (**H_2**) is a colorless, odorless, non-toxic gas. For shipboard use, it can be stored as a cryogenic liquid, compressed gas, or chemically bonded. The boiling point of hydrogen is -253°C at a pressure of 1 bar. Hydrogen can be liquefied at temperatures up to -240°C by increasing the pressure to the "critical pressure" for hydrogen, which is 13 bar. The energy density per mass of hydrogen, taking into account the calorific value of 120 MJ/kg, is approximately three times higher than the energy density of fuel oil. At the same time, the volume density of liquefied H_2 (LH_2) (71 kg/m^3) is only 7 percent of fuel oil. This results in about a fivefold increase in volume compared to the same energy stored in fuel oil. When storing hydrogen as a compressed gas, its volume is approximately 10–15 times (depending on the pressure [700–300 bar]) greater than the volume of the same amount of energy in fuel oil [73]. More detailed characteristics of hydrogen are given in **Table. 2.1.**

Hydrogen is an energy carrier and widely used chemical product. World production of hydrogen is more than 50 million tons per year. It can be produced from various energy sources, for example, by electrolysis of water using renewable energy sources or by natural gas reforming (**Fig. 2.12**). Currently, 95% of hydrogen is produced from fossil fuels, mainly natural gas (68%), as well as oil (16%) and coal (11%). 5% of hydrogen is produced by electrolysis. Natural gas reforming is currently the most common method. If at the same time the generated carbon dioxide is captured, it will be possible to achieve zero CO_2 emissions. Thus, four types of hydrogen are distinguished according to the emissions that are released during its production:

– brown hydrogen obtained during coal processing;

– gray hydrogen obtained as a result of other fossil fuels or natural gas processing;

– blue hydrogen produced by processing fossil fuels accompanied by emission control technologies including carbon capture, utilization and storage (CCUS) techniques.

– green hydrogen produced from renewable energy sources, usually by electrolysis using water. Sources of electricity generation can be renewable energy sources to ensure hydrogen production with carbon neutral emissions.

Hydrogen is very flammable, and due to its very small molecules, it is difficult to contain it in tanks, pipelines and other elements. Therefore, for the widespread introduction of hydrogen as a fuel for water transport, it is necessary to solve a number of problems, in particular with the supply, storage and distribution infrastructure, safety and regulatory framework. It is assumed that pipeline infrastructure will be used to transport large volumes of compressed hydrogen. Ukraine is considering the possibility of using the existing GTS to initially transport a mixture of green hydrogen with natural gas in affordable proportions, and in the future pure hydrogen will be transported [81]. Another way is to transport liquefied hydrogen at a cryogenic temperature of -253^{0}C. Liquefied hydrogen occupies a smaller volume than compressed hydrogen, but the liquefaction process requires about 30% of the energy content of the gas, and energy is also needed to maintain the low temperature in the tanks. Due to the problems associated with gaseous hydrogen, it is considered appropriate to transform it into a less dangerous and more convenient energy carrier. In particular, the conversion of hydrogen into ammonia, synthetic methane, or a liquid organic hydrogen carrier (LOHC), such as cycloalkanes or formic acid, is being studied [82].

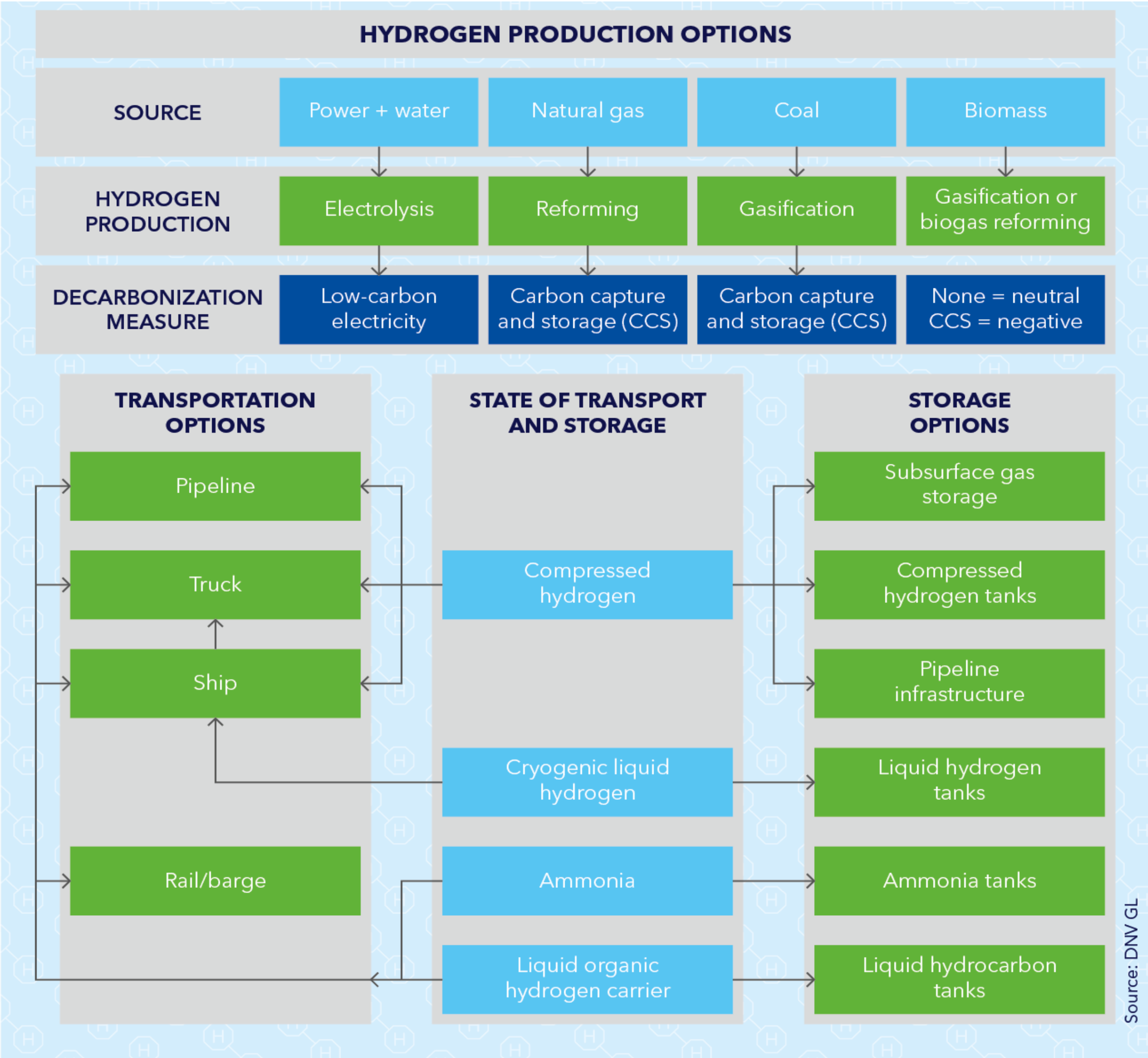


Fig. 2.12. The main methods of hydrogen production, transportation and storage [82].

The cost of H_2 production varies significantly depending on the price of electricity (when using electrolysis) or natural gas (when using reforming), as well as the scale of the production enterprise. The need for transportation and compression or liquefaction also affects the purchase price for the consumer. The cost of hydrogen obtained by electrolysis ranges from approximately 3.5 to 8.3 USD/kg (from 1,170 to 2,770 USD per ton of crude oil equivalent). The cost of producing hydrogen by reforming natural gas or biogas ranges from approximately 1.51 to 6.50 USD/kg (from 800 to 2,170 USD per ton of fuel oil equivalent), on average about 4.1 USD per kg (1,370 USD per ton of crude oil equivalent) [73].

The infrastructure for the distribution and bunkering of hydrogen for waterborne transport is still missing. For compressed hydrogen, it is assumed that the main fuel supply lines on the ship board from the bunker will be a pipe within a pipe. Hydrogen transfer can be achieved by pressure balancing or direct compression of the hydrogen before transfer to the vessel. For ship bunkering with liquefied hydrogen, the bunkering station must consist of three main components: fuel outlet tank, inert gas source and flexible bunker hose. Two hose connections are required: one for the inert gas/liquefied hydrogen and the other for the chilled hydrogen return. Inert gas is used to remove moisture and air to ensure a clean fuel supply for bunkering. Due to its low boiling point, liquid helium can be used as an inert gas and for pre-cooling the bunkering line [83].

While fuel cells are considered a key technology for hydrogen use, other options are also being considered, including gas turbines or internal combustion engines in stand-alone operation or in systems that include fuel cells. The additional capital costs of conventional energy converters such as reciprocating engines are expected to be similar to those of LNG engines. Liquefied hydrogen storage tanks on ships will be more expensive than LNG tanks due to the lower storage temperature, higher insulation quality, and lack of experience using hydrogen for water transport. Costs for other equipment (pipes, ventilation, heat exchangers, and pumps) will be comparable to LNG systems. However, since the physical properties of hydrogen differ from those of natural gas, the components of the LNG system will require changes [73].

Fuel cells produce electricity as a result of an electrochemical process, which converts the chemical energy of the fuel into electricity by reacting hydrogen with oxygen through a catalyst, and water is formed as a byproduct [83]. The maximum output power of demonstration projects using hydrogen fuel cells in waterborne transport is only a few hundred kW, which does not meet the requirements of ocean shipping. Durability testing of practical scenarios for the use of this technology on board ships is negligible. More convincing results depend on the accumulation of more real data. At the moment, the short life of installations, high initial investment and operating costs are the main obstacles to the widespread use of fuel cells in water transport. However, it is expected that their large-scale application in the future will significantly reduce costs and they will reach an acceptable level. In addition, strict regulatory requirements, investments in infrastructure for fuel bunkering, and the development of design and operation rules must simultaneously accompany the development of this technology [84].

Thus, various challenges related to the use of hydrogen as a fuel for waterborne transportation must be resolved before it becomes commercially available for large-scale applications. Hydrogen is in the early stages of development for use in shipping. **Table 2.5** provides an analysis of the advantages and disadvantages of using hydrogen as a fuel for waterborne transport.

The production of gray and brown hydrogen produces significant carbon dioxide emissions ranging from 71 kg CO_2/MJ H_2 for natural gas to 166 kg CO_2/MJ H_2 for coal, but these emissions can be reduced or eliminated by CCUS technology [85]. When using electricity from renewable energy sources or from nuclear plants, the production of green hydrogen is considered carbon neutral. During the transportation of hydrogen and its compression or liquefaction, GHG emissions are formed. Hydrogen used in fuel cells produces no CO_2 emissions and can eliminate NO_X, SO_X and particulate matter (PM) emissions from ships. Internal combustion engines running on hydrogen fuel in water transport can also minimize greenhouse gas emissions, although it is impossible to avoid NO_X emissions [73]. Thus, for the decarbonization of water transport, it is necessary to use green and blue hydrogen.

Table 2.5. Advantages and disadvantages of hydrogen usage as fuel for waterborne transport [85].

Advantages	Disadvantages
– Does not contain carbon and sulfur – Can be produced using electricity from RES and bio-renewable processes – Can be stored and transported in liquid or gas form – Defined commercial product on the ground – Without emissions of gases, solid particles and greenhouse gases from fuel cells – High ability to stay on the surface and dissipates in case of leakage, even at liquid hydrogen temperature	– Lack of experience in sea transportation – High cost of fuel is possible – Low availability of renewable hydrogen – Fuel infrastructure and bunkering require investment – New power generation systems will require more technological innovation and cost reduction – High risk of explosion in closed space – Low cryogenic temperatures (storage, management, leaks, etc.) – Problems with materials (permeability, hydrogen embrittlement, etc.) – NOx emissions during hydrogen combustion in internal combustion engines.

2.6. Biofuels

Biofuel is obtained from primary biomass or biomass residues, which are converted into liquid or gaseous fuel. There is a wide variety of processes for the production of traditional (first generation) and advanced (second and third generation) biofuels, involving different types of raw materials (oils, sugar/starch-containing biomass, lignocellulosic biomass, wood pulp and algae) and different conversion technologies (esterification, hydrotreatment, fermentation, solvolysis, thermochemical and catalytic transformations) (**Fig. 2.13**). Assessment of the existing bioenergy potential in Ukraine and its forecast for 2050 are presented in chapter 1.4.2 of the Technical Report. **Table 2.6** lists the main properties of biofuels for waterborne transport.

Currently, three main types of biofuels are produced from oil raw materials: **straight vegetable oil (SVO), biodiesel (FAME) and renewable diesel fuel (HVO)**, which are used as a substitute for diesel fuel or as a component of blended fuel. Technologies for the production of SVO, FAME and HVO are developed and commercially available. **Straight vegetable oil is oil extracted from the seeds of oil crops and used as fuel without processing**. Studies have shown that SVO can be used to replace fuel oil in low-speed engines. It should be noted that long-term use of SVO leads to excessive wear of engine parts. In addition, this biofuel loses its stability during long-term storage, but the addition of antioxidants can improve the efficiency of long-term storage.

Processing of oils in the process of esterification into fatty acid methyl esters (FAME), also called biodiesel, is more widely used. In addition to SVO, FAME can also be produced from used cooking oil and animal fats. Biodiesel has a lower viscosity than oil and is characterized by good lubricating properties. FAME is more suitable for use in marine engines and can be used to replace MDO or MGO. Due to rapid biodegradation, biodiesel spills do not cause problems for the environment. Theoretically, it is possible to use marine diesel engines on 100% biodiesel fuel, this requires certain engine settings and its certification, so more often FAME is used in mixed fuels [87]. Although biodiesel represents a technically feasible substitute for MDO and MGO, the availability of oil feedstock and the issue of its sustainability create difficulties to meet the needs of water transport with such a fuel.

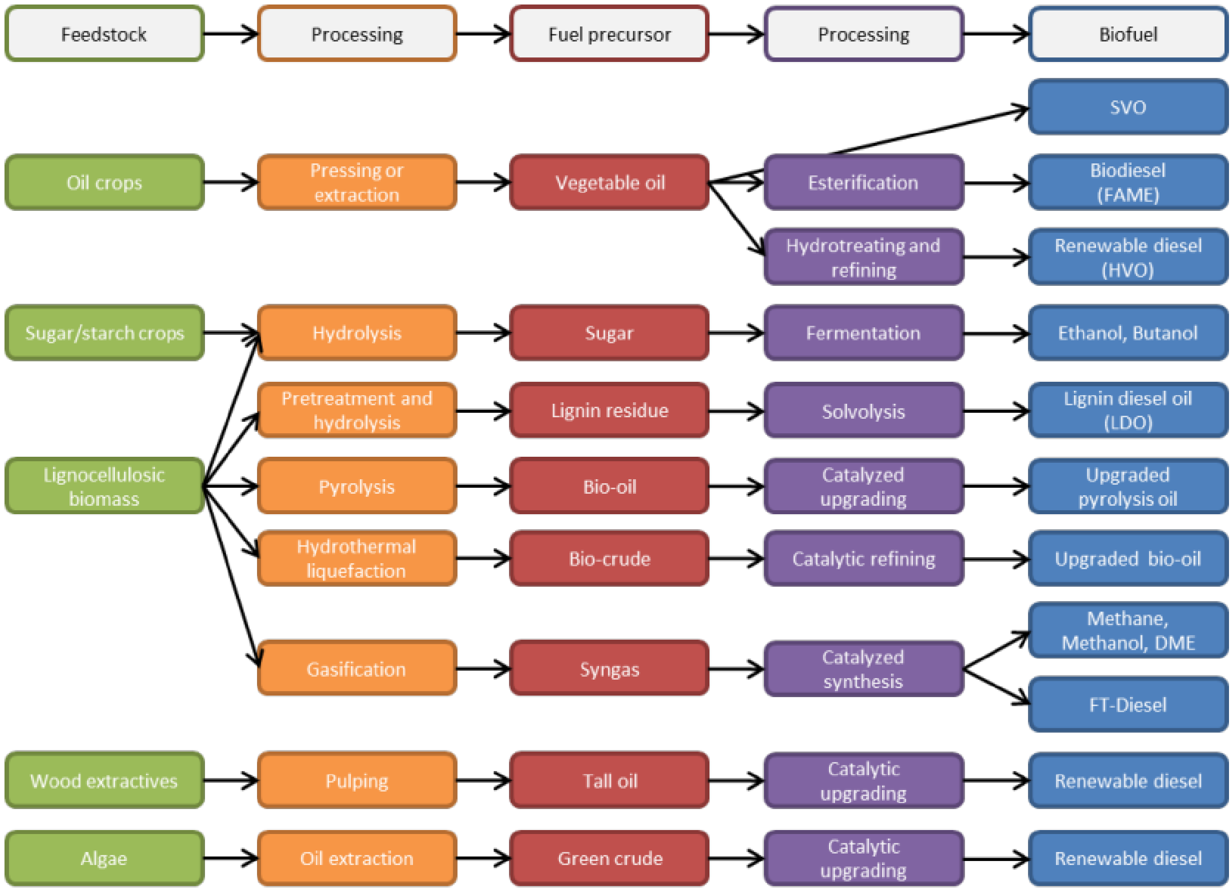


Fig. 2.13. Overview of different feedstock conversion routes to marine biofuels including both conventional and advanced biofuels [86].

Table 2.6. Key fuel properties of selected biofuels for marine use [88].

Property	Biodiesel	Renewable diesel	F-T diesel	FP bio-oil (woody feeds)	Upgraded bio-oil	HTL Biocrude (woody feeds)
Specific gravity	0.88	0.78	0.765	1.1–1.3	0.84	1.1
Kinematic viscosity (40°C), cSt	4–6	2–4	2	40–100		
Cetane number	47–65	>70	>70			
Lubricity, μm		650	371			
Lower heating value, MJ/kg	37.2	44.1	43	16		≈32
Cloud point, °C	-3–15	-5 to -34	-18			
Pour point, °C	-5–10			-9 to -36		
Water content, mass %	0	0	0	20–35	0.1	8
Oxygen content, mass %	11	0	0	34-45	0.5	10–13
Sulfur content, mass %	<0.0015	<0.0005	<0.1	0–0.05	<0.005	0

The high oxygen content of FAME also results in lower oxidation resistance. Antioxidants are used to prevent premature decomposition of biodiesel. Also, the use of biodiesel is associated with the problem of its ability to accumulate moisture, which leads to a decrease in the efficiency of fuel use, an increase in microbiological contamination and accelerated gelation of the fuel at low temperatures. Thus, the use of pure biodiesel requires the addition of a biocide to inhibit the growth of microorganisms.

Modernization of marine engines to consume new types of fuel requires significant resources and funds. On the other hand, ship owners will be willing to switch to new fuels only if the fuel supply is guaranteed throughout the lifetime of their ship's engine. Thus, if new fuels could be functionally equivalent to existing ones, they would be fully compatible with existing fuel infrastructure without the need for significant investment in infrastructure modification. For compatibility with the existing petroleum infrastructure, animal fats and vegetable oils must undergo a hydroprocessing stage to be converted into oxygen-free hydrocarbon biofuels.

One such alternative to diesel fuel made from oil crops is **hydrotreated vegetable oil (HVO), in which vegetable oils or animal fats are thermochemically treated with hydrogen**. This fuel is often referred to as renewable diesel and hydrotreated esters and fatty acids (HEFA). HVO can be used as a direct replacement for diesel fuel because it is more stable than FAME due to its low oxygen content. For the production of HVO, it is possible to use the technology of hydrotreatment of existing oil refineries. HVO has been tested on marine diesel engines and is compatible with existing fuel infrastructure.

Since 2019, the HEINEKEN Company has been refueling ships with biofuel. In particular, on the Alferium-Rotterdam/Antwerp route, container ship MS FOR-EVER with two Scania DI-16 engines with a capacity of 386 kW each and MS ALPHENAAR containership with two 400 kW Veth L-drive VL-400 engines operate on HVO called Bio-fuel Oil MR1-100 of the Dutch biofuel supplier GoodFuels. MS ALPHENAAR containership also has a 2.4 MWh battery and two 600 kW and 200 kW generators allowing up to 5 h of electric propulsion [117]. GoodFuels is active in the distribution of biofuels for water transport and provides test flights on a variety of vessels. In particular, on July 21, 2022, during a visit to the port of Rotterdam, the Hyperion-class cruise ship AIDAprima [118] with a displacement of 124,500 tons and a passenger capacity of 3,400 passengers was refueled with biofuel. GoodFuels biofuel is characterized as "drop-in fuel" that do not require modifications to the engine or fuel tanks. This biofuel is obtained from raw materials that are certified as 100% waste or residues, without land use or deforestation problems and without competing with food production. This allows to reduce CO_2 emissions by 80-90% compared to fossil fuels.

Sugar and starch-containing raw materials are processed into alcoholic biofuels (bioethanol, biomethanol and biobutanol) during the fermentation process. Of these types, **bioethanol** is produced in the largest volumes and is already added to automobile gasoline in the USA, the EU, and Brazil in mixtures of up to 85% (mass). Ethanol can be burned in most gasoline engines in a mixture of up to 20% with gasoline, and pure ethyl alcohol can be used as a fuel with minimal tuning and engine upgrades. In Ukraine, molasses is currently the main sugar-containing raw material for the production of alcohol, and sugar sorghum can also be grown for this purpose; the main starch-containing raw material is grain, in particular, corn. Such raw materials are considered food, and therefore they are used to produce bioethanol of the first generation, the use of which is restricted in the EU. According to the RED II Directive, the contribution of first-generation biofuels (that is, produced from food crops) to the share of final energy consumption in the transport sector for a specific country cannot exceed the percentage achieved by it in 2020 plus 1%, but not more than 7%.

Second-generation bioethanol can be produced from lignocellulosic feedstock, which has significant biomass potential and is considered a more sustainable feedstock. There are still no second-generation bioethanol production enterprises in Ukraine, although such biofuel is already commercially produced in many countries. Given the available biomass resources, the main raw material for the domestic production of second-generation bioethanol can be considered post-harvest residues: straw, by-products of corn and sunflower. In the future, energy crops can also be involved.

Butanol can also be produced from lignocellulosic or sugarbased feedstocks via a fermentation process, however the high toxicity of butanol (1.5-2 g/L) to fermenting organisms makes its application and industrial scale-up economically challenging. An important advantage of ethanol is that distribution and storage systems already exist and are present in many ports where they can be easily connected to bunkering infrastructure. Upgrading the fuel storage bunkers is also easy and therefore this fuel will fit well into the existing infrastructure. Ethanol is characterized by a flash point of 14^0C, which determines its fire hazard and the need to implement appropriate safety measures when handling it [87]. Although alcohol blends can be added to modern gasoline engines with minimal engine modifications, ethanol is not suitable for use in compression ignition (diesel) engines due to its physical properties. However, there are options for installing multi-fuel engines or engines designed to work exclusively on alcohol fuels on ships.

Thermochemical processes for biofuel production use high temperature and/or pressure and possibly homogeneous and/or heterogeneous catalysts to convert biomass into liquid fuels and chemicals, as well as heat and electricity [86]. In contrast to the lipid feedstock which is used to produce biodiesel and HVO, the feedstock converted by thermochemical processes is mainly lignocellulosic. Thermal conversion starts with the conversion of biomass (wet or dry) into liquid intermediates (gas or oil) and then catalytically processed or hydrotreated to hydrocarbon fuels.

Pyrolytic processing involves biomass impacting by high temperatures, short residence times in the absence of oxygen, and often in the presence of an inert gas. The biomass is treated at 500°C for a few seconds, after which some of it goes into the gas phase and the other fraction is converted into **pyrolysis bio-oil**, biochar and syngas (methane, hydrogen, carbon monoxide and carbon dioxide). Biomass must be crushed and dried (moisture content less than 10%) before entering the pyro-reactor. Combustion of pyrolysis bio-oil results in lower emissions of SO_x and NO_x, although the content of solid particles remains quite high. The yield of pyrolysis bio-oil during pyrolysis varies depending on the feedstock, the type of process and conditions, as well as the efficiency of product collection, and can reach 70-80%, although low yields of 20% are also found.

Syngas produced by pyrolysis can also be used to produce methanol, albeit at a very low yield. To remove oxygen from pyrolysis bio-oil and increase its storage stability to meet fuel specifications, a catalytic enrichment step is necessary. Hydrogenation converts pyrolysis bio-oil into hydrogenated pyrolysis bio-oil (HPO), which can then be suitable for use in diesel engines. Also, pyrolysis bio-oil can be used as a component of emulsion biofuel for water transport to increase its thermal efficiency and reduce emissions of solid particles when used in diesel engines.

Pyrolysis bio-oil emulsions not only increase fuel stability, the addition of emulsifiers (surfactants) acts as a viscosity modifier to create more optimal fuel properties.

Hydrothermal liquefaction is a thermochemical process that heats wet biomass to elevated temperatures and pressures (250-550 ^{0}C, 5-25 MPa) in the presence of catalysts, forming **crude bio-oil**. This bio-oil has an energy content of 32-36 MJ/kg, which is significantly higher than that of pyrolysis bio-oil of 17-20 MJ/kg, and has an oxygen content of between 5-20% (typically 12-14%). Depending on the processing conditions, the obtained bio-oil can be used for marine engines, or after enrichment it can be made into diesel fuel, gasoline or jet fuel. Hydrothermal liquefaction technology is particularly interesting for waste processing, which often creates problems for manufacturers. There is a number of commercial bio-oil productions based on this technology in the world, but it is not used on a large scale yet.

Solvolysis is a thermal process in which biomass is liquefied in a closed chamber with a supercritical organic solvent under pressure. This is similar to hydrothermal liquefaction, but instead of water, an organic solvent with a low boiling point is used. The raw material can be any biomass or residues of hydrolyzed lignin obtained from 2nd generation bioethanol production facilities. The tested organic solvents are methanol, ethanol, 1-propanol and 1-butanol. The product of the reaction is **bio-oil**, which can be further processed into fuel with a low oxygen content. Depending on the feedstock material, the final product is sulfur-free and suitable for blending or use as a fuel. The entire process is catalyst-free and does not require hydrotreating before mixing with diesel fuel. The process has been tested on a laboratory scale, and the transition to pilot production is planned.

Gasification technology involves converting biomass at high temperature (900°C) and pressure in the presence of a small amount of oxygen and/or steam into gas, where the intermediate product is called synthesis gas. Chemically, gasification breaks down the feedstock into its primary components (CO, H_2, and CO_2), which can be used directly as fuel for gas engines and turbines, heat production, and power generation. To produce liquid transportation fuels, syngas can be processed in a Fischer-Tropsch catalytic process and hydrotreating into a wide range of hydrocarbon liquids such as methanol, diesel, or other synthetic fuels. This is a very energy-intensive process, but it has some advantages over direct combustion of the raw material. The end product has a higher stability compared to using pyrolysis.

Feedstock can range from woody biomass to agricultural residues (lignocellulosic waste streams). Commercial biofuels produced by gasification are known as **BtL (biomass-to-liquids)** or **synthetic Fischer-Tropsch (F-T) fuels**. Biofuels produced by gasification have greater potential in the jet fuel market compared to marine fuel because the added value of jet fuel outweighs the energy and processing costs to produce a higher quality clean fuel. For the water transport sector, synthesis gas can be catalytically converted into methanol with a yield of up to 75%. In addition, synthesis gas obtained during gasification can also be converted into **dimethyl ether (DME)**. DME can be used as a fuel in diesel engines, gasoline engines and gas turbines. During the combustion of DME, very low levels of particulate matter, NO_x and CO are emitted, but there are also problems with lubrication.

Tallow oil is a dark, viscous liquid produced during the manufacture of kraft pulp as a by-product after the treatment of spent cooking liquor. The volume of formation of this raw material is limited by the pulp and paper industry. The output of tall oil is within 30-50 kg per ton of pulp. **Hydrogenation of tallow oil creates an HVO-like fuel** that can be used as diesel fuel or blended with conventional fuel. The production setup is similar to the production of HVO that occurs in traditional refineries using chemical catalysis.

Photosynthetic algae and/or cyanobacteria can be grown using saline and wastewater with a higher yield of lipids per unit area than plants. **Fuels made from algal lipids** can have a high flash point, are biodegradable and compatible with conventional biodiesel. The main disadvantage of producing biofuel from algae is the cost of processing, in particular, the cost of obtaining oil due to the high moisture content in algae can be higher than the cost of the oil itself. The processing of algae into biofuel has not yet received commercial distribution.

Biogas made from anaerobic fermentation is potentially a feedstock for producing **liquefied biogas (LBG)**. The only technical requirement for processing biogas into LBG is purification of biogas into biomethane by removal of CO_2. This purification process is already common at biogas plants connected to a gas grid. This process is used commercially in biomethane plants that are connected to gas networks. In the future, biogas can be liquefied using LNG liquefaction technology. In 2023, it is planned to launch the first demonstration plant for the production of liquefied biomethane for maritime sector in the frame of FirstBio2Shipping project in the Netherlands (**Fig. 2.14**). The demonstration plant aims to produce 6 million Nm^3/year of biogas, 2,400 tons/year of biomethane and 5,000 tons/year of bio-CO_2. The project will reduce GHG by 92% compared to a reference scenario [89].

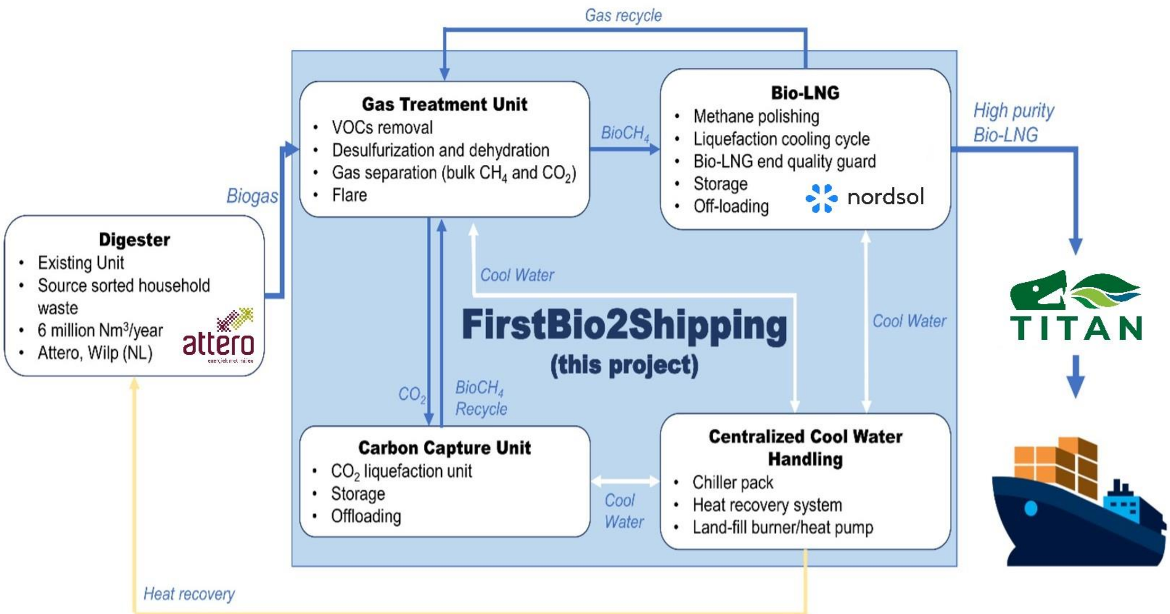


Fig. 2.14. Scheme of FirstBio2Shipping project with the use of liquefied biogas vessel bunkering [89].

In the EU, biofuels for diesel engines are subject to the Fatty Acid Methyl Esters (FAME) EN 14214 and Synthesis or Hydrotreated Paraffin Diesels EN 15940 standards, which include hydrotreated vegetable oil (HVO) and biomass to liquid (BtL). Biofuels can be used both, in their pure form and in mixtures with traditional petroleum fuels. Currently, only biodiesel (FAME) (in concentrations up to 7% by volume) is approved for use with MGO as a marine fuel under the distillate fuel classes DFA, DFZ and DFB of the international standard ISO 8217:2017. Such biodiesel mixtures provide a significant reduction in emissions of solid particles. Reduced particulate emissions are an important environmental benefit of oxygenated fuels, and often significant reductions can be achieved at relatively low blend levels (<10%). Biodiesel cannot be directly mixed with distillate fuels, but surfactants are used to create an emulsified fuel mixture [88].

Direct replacement of marine gas oil (MGO) is possible provided that sufficient volumes of biofuel production are achieved. But, even in a mixed fuel, biofuel provides a reduction in emissions of solid particles and CO_2. It should be noted that for the successful implementation of the fossil fuel substitution project, the representatives of the marine engine manufacturer must confirm the compatibility of the engines with biofuels and the mandatory conditions for their reliable operation. A comparison of the production cost of biofuels with the approximate price of MGO marine fuel in 2020 is given in **Table. 2.7**.

Table 2.7. Selected production cost ranges for alternative fuels, relative to MGO price [90].

Biofuel type	Feedstock	Production cost		Fossil fuel price		Price multiple
		USD/L	USD/MJ	USD/L	USD/MJ	
FAME Biodiesel	Vegetable oil, waste FOGs	0.75–1.25	0.02–0.035	0.57	0.016	1.3–2.2
HVO	Vegetable oil, waste FOGs	0.84–1.38	0.024–0.039			1.5–2.4
FT diesel	Lignocellulosic biomass	0.85–2.36	0.024–0.066			1.5–4.1
Biomethanol	Lignocellulosic biomass	0.33–0.59	0.021–0.037			1.3–2.3
Methanol	Natural gas, coal	0.22–0.41	0.014–0.026			0.9–1.6
DME	Natural gas, coal	0.27–0.40	0.014–0.021			0.9–1.3

Therefore, the most promising biofuels for marine shipping are diesel biofuel (for example, HVO – hydrotreated vegetable oil, BtL – biomass to liquid, FAME – fatty acid methyl esters) and LBG (liquid biogas, which mainly consists of methane). Biodiesel, HVO and BtL are most suitable to replace MDO/MGO, LBG to replace fossil LNG and SVO (straight vegetable oil) to replace HFO [73]. Although other technologies are developing and, in the future, taking into account local features, they can be implemented in waterborne transport. The list of the main aspects of the commercialization of biofuel production is shown in **Fig. 2.15**. These aspects must be taken into account when introducing biofuels for the water transport sector of Ukraine.

Greenhouse gas emissions of biofuels and alternative fuels for water transport determined by the life cycle assessment (LCA) method are shown in **Fig. 2.16**. The total greenhouse gas emissions of each stage of the fuel life cycle are marked with purple diamonds and are compared to the baseline MGO emissions (90 gCO_{2eq}/MJ, green line).

Feedstock

- Availability
- Security of supply
- Cost and its variation
- Quality and its variation
- Collection
- Storage and transport logistics
- Sustainability criteria

Conversion technology

- Technological maturity
- Production capacity and scalability
- Widespread applicability
- Price per ton fuel
- Energy efficiency

Local and global regulations and markets

- Sustainability criteria
- Renewable fuel mandate
- Carbon tax
- GHG emission targets
- Sulphur gap
- R&D support

Fuel utilization

- Bunker infrastructure
- Fuel system and engine compatibility
- Fuel tank volume
- Freight price

Society and environment

- Sustainability certification
- Food vs. fuel
- Public opinion

Fig. 2.15. Central aspects of marine biofuel commercialization [87].

Second-generation biofuels made from wastes and lignocellulosic biomass offer the deepest GHG reductions: 70% to almost 100% well-to-wake GHG emission savings compared with MGO. That is due to their small impact on land use, large biogenic carbon uptake, and modest use of fossil fuel energy for feedstock conversion. DME and FT diesel made from cellulosic feedstocks have particularly low GHG emissions – close to zero. ILUC modelling generally suggests that energy crops like Miscanthus have low or negative ILUC emissions. First-generation biofuels produced from soy oil and palm oil generate high enough ILUC emissions that they are comparable to MGO in terms of life-cycle GHG emissions. In particular, oil crops for biofuel production can compete for land suitable for growing food crops, causing food prices to rise. From a climate perspective, the worst alternative fuels are made from natural gas. These emit more GHGs than MGO due to the need for extra upstream energy for fuel synthesis [90].

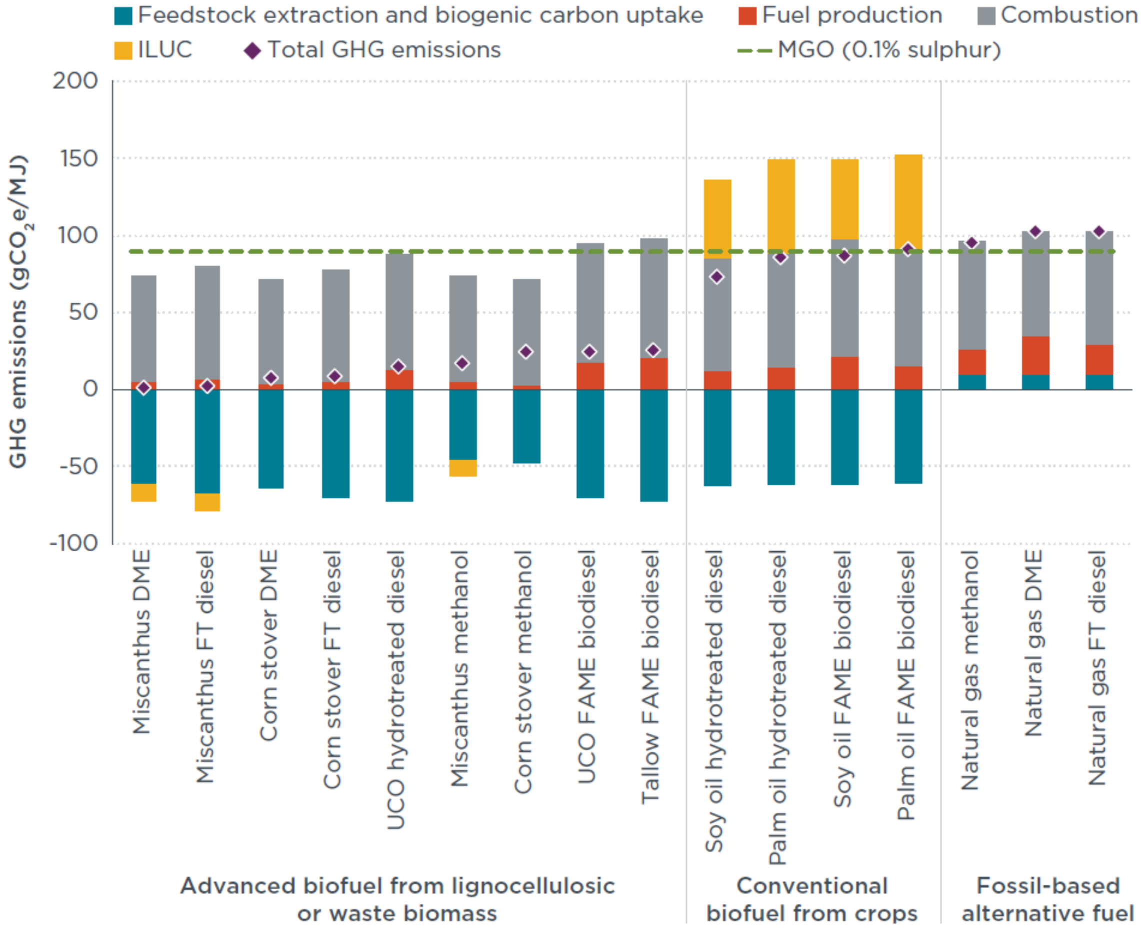


Fig. 2.16. Life-cycle GHG emissions (100-year GWP) of the alternative liquid marine fuels and feedstocks analyzed, by the life-cycle stage [90].

It should be noted that there are various commercial technologies for the production of biofuels for marine shipping that can be implemented in Ukraine, and the main aspect for the implementation of projects in this direction is the availability of the necessary volumes of raw materials with guaranteed stable supplies. Given the presence of significant areas of marginal land in Ukraine, it is advisable to grow energy crops for further processing into biofuel. For waterborne transport, in view of further processing into biofuels to replace existing marine fuels, the cultivation of energy oil crops and the production of biodiesel and HVO are of primary interest, which will allow to reduce the existing GHG emissions. Also, in case of the appearance of ships with gas engines, it is possible to quickly establish the production of biomethane for use as fuel for marine shipping.

The **Technical Regulation** on requirements for automobile gasoline, diesel, marine, and boiler fuels [109] defines marine fuel as liquid distillate petroleum fuel used in high- and medium-speed diesel engines and gas turbine installations. In our opinion, the Technical Regulation does not consider the possibility of using biofuel as a marine fuel.

2.7. Comparative analysis of alternative fuels for waterborne transportation

Among the applications of various types of fuel, short-distance and deep-sea marine shipping can be distinguished. In short-distance transportation, vessels usually operate in limited geographical areas on relatively short routes with frequent port calls. Because of their relatively low energy requirements, these vessels are often ideal candidates for testing new fuels characterized by high energy conversion or storage costs. For example, the Norwegian ferry sector is in the process of electrification, about 50 electric ferries will be put into operation in the coming years [73].

It should be noted that the use of electric ships with batteries in ports requires a special powerful charging infrastructure. For example, charging 1000 kWh (roughly equivalent to 100 liters of petroleum fuel) within 30 minutes requires 2000 kW of electrical power; charging the same amount of energy within 10 minutes requires 6000 kW of electric power. This often places a significant strain on the local power grid and may require additional resources [119].

The use of hydrogen is also technically possible, and in 2021 the Norwegian operator Norled launched the world's first liquefied hydrogen steamer powered by fuel cells [91]. At the same time, ship owners consider the introduction of new fuels due to economic feasibility and therefore invest in commercially mature technologies.

Deep-sea shipping includes large ocean-going vessels that operate long routes, often without a regular schedule. These vessels require the use of fuel that is available all over the world. The energy carrier that drives the ship must have a high enough energy density to maximize the available cargo space. For these vessels, LNG may be a viable option once suitable bunkering infrastructure becomes available worldwide. Environmental biofuels, methanol and liquefied gas may also be options, provided they can be made available in the required quantities and at the appropriate level of quality.

The international certification and classification society DNV [73] identified LNG, LPG, methanol, biofuel and hydrogen as the most promising alternative fuels for shipping. In addition, battery systems, fuel cell systems and wind propulsion systems have good potential for use on ships among new technologies. Fuel cell systems for ships are in development, but it will take time for them to reach a degree of maturity sufficient to replace main engines. Battery systems are already in use, but on most marine vessels their role is limited by the level of efficiency and flexibility. Batteries cannot store the vast amounts of energy needed to power a large ship (**Fig. 2.17**). Wind propulsion, while not a new technology, will require some development to make a significant difference to modern vessels. Key factors in the adoption of alternative fuels for water transport are related to environmental benefits, compatibility with other fuels, availability of sufficient volumes of fuel for shipping needs, bunkering costs and international regulations.

The optimal mix of different types of alternative fuels for the decarbonization of marine shipping has not yet been determined according to the conclusions of the report [92] prepared by the Joint Research Center of the European Commission (JRC). There are potential sustainability, infrastructure and distribution gaps associated with, in particular, biofuels, biomethane, ammonia, hydrogen and methanol. Investigating the advantages and disadvantages of different alternative fuels for different types of marine shipping would be useful to support increased production as well as their use in marine engines.

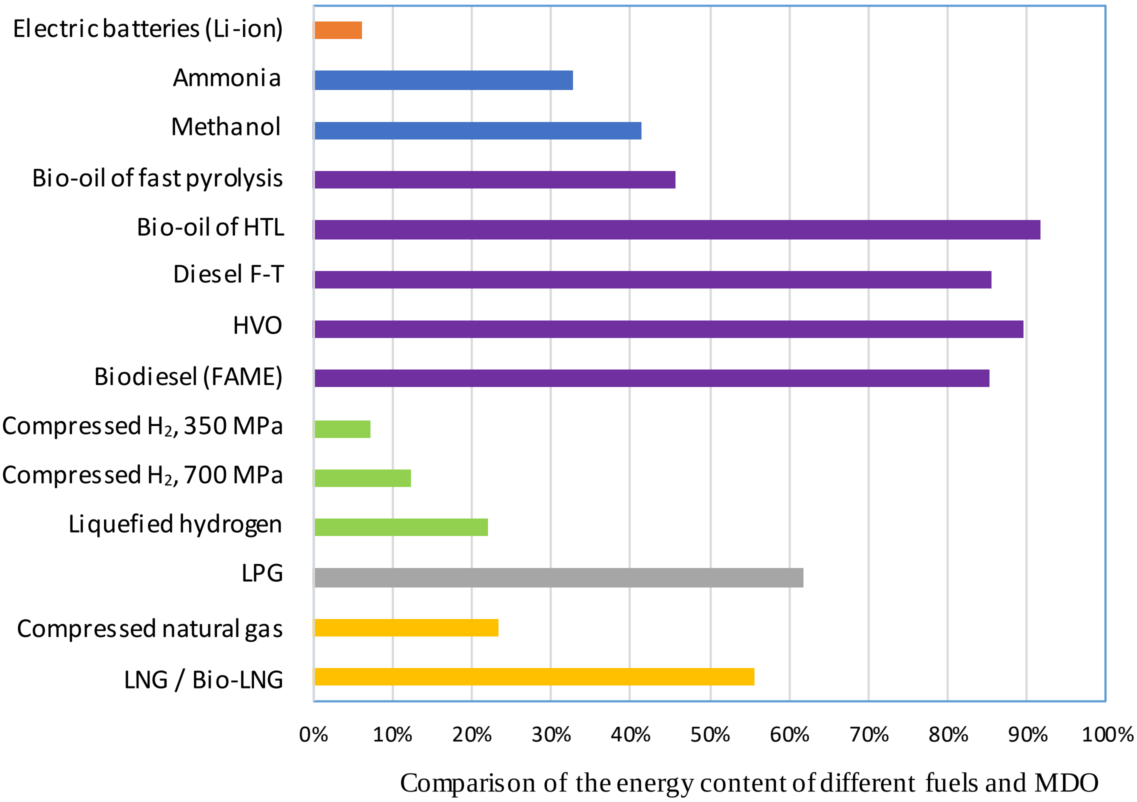


Fig. 2.17. Comparison of the energy content of a volume unit of different fuel (energy carriers) types for water transport with the energy content of MDO (100%).

In the short term, alternative low-carbon fossil fuels such as LNG, LPG and compressed natural gas are proposed to achieve rapid reductions in shipping pollution, but their contribution to decarbonization is limited depending on engine type and methane emissions. A further consideration is needed on how the transition from such fuels should be managed to pave the way for low-carbon fossil fuels such as bio-LNG, biodiesel, ammonia, methanol or hydrogen, and whether such transition fuels may divert attention from the development of long-term ones low- or zero-carbon fuels, which creates risks for investments in the latest infrastructure. The use of battery technology for water transport is considered promising for short-distance transportation. In the future, with the development of this technology, in particular, an increase in charging speed, energy density and a decrease in cost, it will be possible to use battery systems for other directions of shipping. Achieving the EU's climate goals by 2050, as well as the necessary emission reductions by 2030 in accordance with the European Green Deal, will require radical changes regarding the introduction of alternative fuels and renewable energy sources and improving the efficiency of the marine shipping sector.

To promote the transition to clean water transport, the project **"Structuring on the way to zero-emission water transport" (STEERER)** is being implemented under the coordination of the EU Water Transport Technology Platform. The project received funding from the EU Research and Innovation Program Horizon 2020. Based on the research results of this project [121], prospects for the use of alternative fuels for 6 profiles of the operational activity of vessels are considered:

– **Long-distance shipping** involves large ocean-going vessels in which a very large proportion of energy consumption is related to the movement of the vessel at a constant speed over long distances. Today, these vessels are powered by two-stroke internal combustion engines with mechanical direct drive or gear drive. Engines are highly energy efficient for this purpose. Such vessels require globally available fuel, and the energy density of the fuel is important to maximize the space available for transporting cargo over long distances.

– **Vessels in the short voyage segment** are generally smaller than vessels of the previous profile, with more varied operating parameters, and a greater proportion of their time and energy is spent on purposes other than sustainable propulsion. For these vessels, shorter distances and highly variable power requirements can make electric or hybrid electric power and propulsion systems (including diesel/gas electric ones) more efficient than traditional mechanical drives. The presence of a power distribution system provides more efficient energy distribution over a wide range of engine load profiles. It also increases the flexibility of using energy from batteries, fuel cells and waste heat, as well as renewable energy sources. For short-sea ships, the potential share of energy consumption to be optimized with batteries and fuel cells is higher than that for deep-sea vessels.

– **The inland water transport sector** is quite diverse and consists of vessels for inland navigation, tugs and floating equipment. Inland vessels are generally smaller compared to offshore vessels and have less capacity installed on board. The vast majority of the European inland fleet uses high-speed (>1250 rpm) standard diesel engines (according to EN590). The type of vessel and its operational activity are two key elements that determine the suitability of a particular environmental technology/fuel. For example, vessels plying short distances on canals may use all-electric powertrains, while clean liquid fuels may be more suitable for large vessels plying long distances on rivers (e.g. Rotterdam-Basel).

– **Cruise liners** are high-tech vessels with high added value that require large amounts of energy, including that to provide various services for passengers. In the short term, the logical choice for these vessels is upgrading to be able to use a number of potentially environmentally friendly fuels, as well as shore power. In the next generation of cruise ships, different combinations of energy carriers and technologies may be combined, for example, fuel cells with storage batteries, internal combustion engines and other types of RES.

– **Ferries** run between fixed points and are most suitable for conversion to fully electric with a total zero emission level. For ferries with a range of up to 200 nautical miles, electric batteries, fuel cells and alternative fuel combustion engines are possible, with regional conditions and political priorities influencing the choice. The requirements for zero emissions during docking and parking in the harbor will push the use of hybrid solutions with batteries. For long-distance ferries, the most competitive solution will be internal combustion engines on alternative fuels complemented by energy efficiency measures and a smart power source in ports.

– **Offshore vessels** are a broad category of vessels that provide installation, operation and maintenance of marine equipment. These types of vessels usually have high energy consumption at peak times. The variety of work operations, as well as the size of vessels, make offshore vessels ideal candidates for innovative solutions. Their activities near the shore allow for more frequent refueling and, therefore, low-density energy carriers can be used. Working close to shore also means that SOx and PM (particulate matter) emissions must be reduced as much as possible.

At that, an analysis of the electrification of ships and three directions of using energy carriers were carried out covering the available options of alternative fuels for the development of the water transport sector until 2030 and beyond:

– 1) **Light gases: LNG → Bio/e-methane → Hydrogen**. In general, a light low-molecular weight fuel with a high energy content, but more demanding on supply and storage systems, mainly due to cryogenic conditions. In this direction, if methane release is not taken into account, LNG can reduce GHG emissions by approximately 20%; biomethane can be carbon-neutral, while hydrogen can become a zero-carbon fuel in the future.

– 2) **Heavy gases and alcohols: LPG/methanol → Bio/e-fuel → Ammonia**. Typically heavier, more complex molecules, but with less fuel supply and storage requirements than for the light gas direction. Methanol can reduce CO_2 emissions by around 10%, while biomethanol can be carbon neutral and ammonia can be considered as a zero carbon fuel in the future.

– 3) **Bio/synthetic fuels: Bio/renewable diesel → Gas to liquid fuels → 2nd and 3rd generation biofuels.** These fuels have properties similar to diesel and are, therefore, much less demanding in terms of new infrastructure and on-board technology, and can be used with minimal changes to current ship designs. The availability of these low-carbon liquid fuels is still very limited, but to decarbonize the EU's aviation, waterborne and road transport, it is assumed that every liter of liquid transport fuel can become climate neutral by 2050.

As a result of the analysis, the following conclusions were obtained:

1) For light gases:

o LNG provides the lowest fossil fuel emissions (minus potential gas emissions), is technically mixable with hydrogen (adding up to 10% pure H2) and is suitable for almost all types of vessels. Some ships already use LNG, including ships with dual-fuel engines. However, LNG requires 2-3 times more tank volume than fuel oil with the same energy content and; so far, there are few infrastructure facilities for LNG bunkering in the world. In addition, the use of LNG is losing public and political support. There are a limited number of projects to improve this technology.

o Hydrogen (internal combustion engines and fuel cells). Very little operational use (small ships), but many ongoing projects with rapid technological improvements for larger ships and longer distances. Currently, the technology still faces a number of challenges: high production prices, low energy density and energy efficiency; insufficiently developed accompanying infrastructure (for example, for bunkering); high CAPEX; incomplete legal/policy framework.

2) For heavy gases and alcohols:

o Liquefied petroleum gas (LPG). A fossil fuel with very low but slightly increasing market penetration. Limited supply and no legal framework.

o Methanol. A promising alternative fuel, clean, available in many regions, with infrastructure similar to traditional fuels and dual-fuel engines. Slow market penetration. Some projects continue to develop dual-fuel engines. Methanol has low energy density and requires high costs to modernize ships and fuel infrastructure, but can be used as a method of carbon capture, use and storage. Incomplete legal framework regarding methanol as an energy carrier or fuel.

o Ammonia. A hydrogen carrier, but easier to store (including compared to LNG or batteries), can be CO_2-free under appropriate circumstances. However, there is no actual or planned market advancement at this time, although some of the newer engines can run on ammonia. Some ammonia projects are being developed, including those outside the EU. Weaknesses: low volumetric energy density and high fuel cost; high toxicity; no legal framework (IGC code for toxic cargoes that cannot be used as fuel).

3) For bio/synthetic fuels:

o Biofuels. Depending on the source of biomass, the processing and type of energy used to convert the biomass into fuel, the carbon reduction or sustainability potential of each biofuel will also vary. The advantage is that biofuels can be mixed in large proportions with traditional fuels as "drop-in fuels", which avoids the need for new fuel tanks and fuel systems. Engines do not need changes. However, biofuels are more expensive than most other fuels, so market penetration is extremely low, with no clear prospects for improvement.

o Synthetic fuels (PtL). In order for these fuels to be considered "low carbon", it is important to use hydrogen produced using zero-carbon energy (such as electrolysis with RES or nuclear energy) and CO_2 extracted from the atmosphere. Synthetic fuels can be used in existing infrastructure.

It should be noted that to ensure a larger reduction of GHG, certain types of alternative fuels for water transport can be produced from renewable raw materials and/or energy, such as bio-LNG and bio-hydrogen from biomass.

Electrification. A significant number of vessels, mostly hybrid ones, are already in operation; more ships are ordered, there is an increase in all-electric ones. Mostly ferries and other types of medium and small vessels. Main problems are: this is impractical for some vessels, particularly large ships, due to the size and weight of the batteries required, and the increased frequency of bunkering.

The World Bank report on the course for decarbonization of maritime transport [123] states that in order to achieve the necessary reduction in GHG emissions (**Fig. 2.19**), **shipping will require a transition from fossil fuels to bunker fuels with zero carbon content, which include, for example, biofuels, hydrogen and ammonia or synthetic carbon-based fuels**. In this context, zero-carbon bunker fuel includes fuels that from the point of view of GHG emissions are "effectively" zero (that is the fuel is produced from non-biogenic renewable electricity) or carbon-neutral (that is when the fuel is produced, a certain amount of carbon dioxide is removed from the atmosphere, which is equivalent to that released during combustion). From 2030, zero-carbon bunker fuels are expected to enter global shipping, accounting for at least 5% of total bunker fuels, and will spread rapidly to meet the IMO's 2050 climate target.

For this, within the framework of the current decade, it is necessary to establish the production of new ships and the modernization of existing ones, which will allow the consumption of bunker fuels with zero carbon content. The assessment identified ammonia and hydrogen as the most promising zero-carbon bunker fuels to date, as biofuels are at risk of being constrained by sustainable biomass supply and inter-industry competition; carbon-based synthetic fuels are likely to be less competitive with cost perspective.

The analysis of LNG’s role of did not reveal the prerequisites for the large-scale use of LNG as a bunker fuel for engines. Therefore, from the perspective of the sector as a whole, LNG's role as a bunker fuel is likely to be concentrated in niche applications. Examples may include its use on existing routes that already benefit from existing LNG terminals in ports; specific vessel types such as LNG tankers where the cargo can be used as fuel; ferries, cruise ships or coastal vessels where air quality is an important benefit; special circumstances where there may be strong domestic interests favoring LNG.

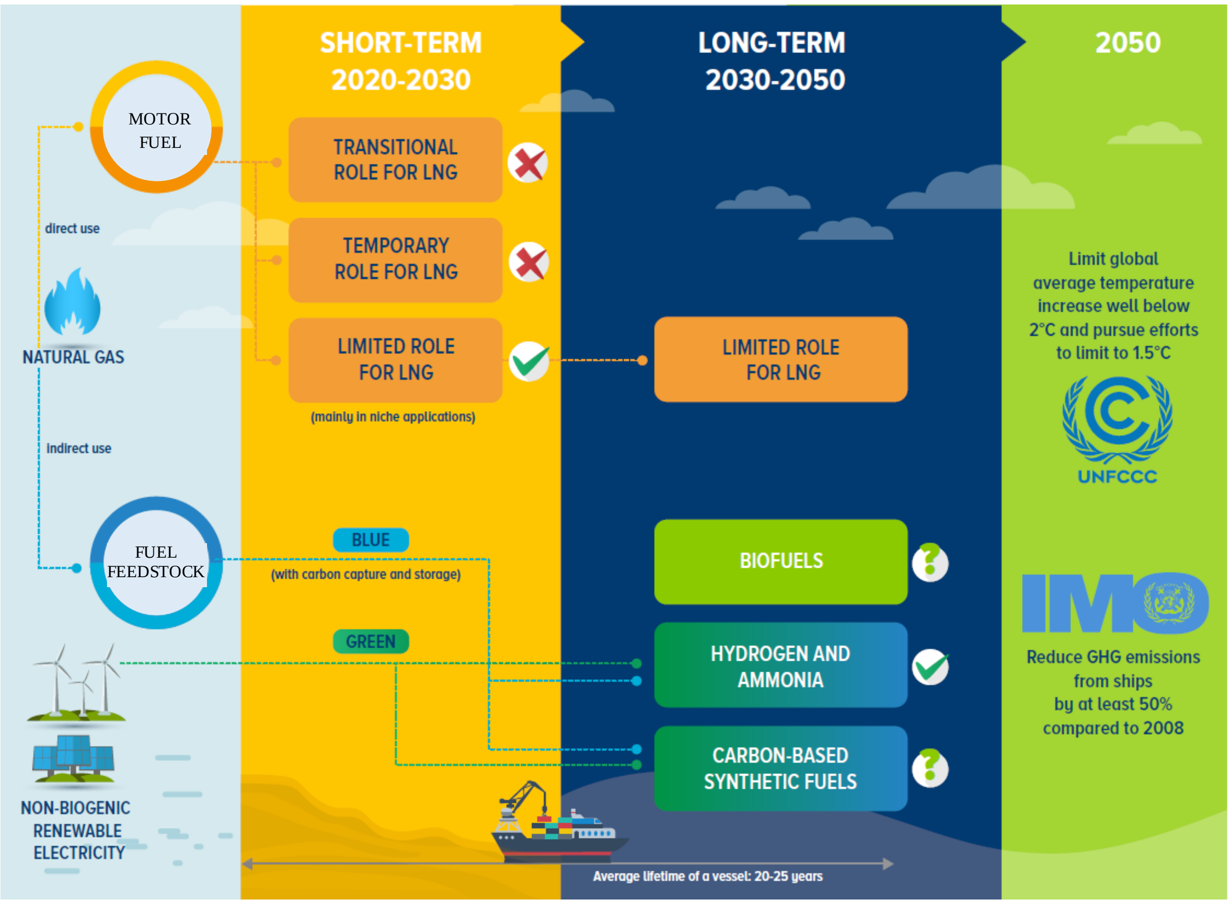


Fig. 2.18. The proposed role of natural gas as a bunker fuel and as a fuel raw material for the decarbonization of shipping [123].

The specificity of the water transport sector of Ukraine is related to the existing practice of river and sea navigation. There are 4 operators working on inland waterways, of which 3 are private companies (Ukrrichflot, Nibulon and Kyiv River Port) and the state enterprise Ukrainian Danube Shipping, which have a river fleet, a river-sea fleet, a towing and service-auxiliary fleet. These companies could potentially introduce the use of alternative fuels that are suitable for existing ship engines, in particular oilseed biofuels such as biodiesel or HVO. In addition, NIBULON LLC has significant resources for the production of such biofuels, in particular, the company cultivates 77 thousand hectares of agricultural land and has a modern grain logistics infrastructure with a storage capacity of 2.25 million tons of grain. The Nibulon Shipping Company was established in 2009, and it uses relatively new vessels, while 81.9% of Ukraine's river fleet is technically and morally outdated vessels with an average age of operation from 25 to 30 years.

Also, biofuels that replace traditional fuel oil and diesel fuel can be introduced for use in sea transportation, which allows the use of existing infrastructure, and therefore does not require significant investments. But there are many different companies and ship owners operating in the shipping market, including those with foreign registrations, and therefore stakeholders are focused on global bunkering trends in terms of fuel and emissions requirements. Companies offering bunkering services in Ukraine need to adapt to global trends, in particular, the development of LNG, ammonia, methanol and hydrogen. On small vessels with gasoline engines, it is possible to use mixed fuels based on gasoline with the addition of ethanol and methanol and LPG. The introduction of alternative fuels for water transport: LNG, ammonia, methanol, hydrogen and batteries requires significant investments in supply, storage and bunkering infrastructure, charging stations as well as in new vessels or modernization of existing vessels.

Table 2.8 provides a comparative analysis of promising alternative fuels and energy carriers with an assessment of their rating for Ukraine's conditions. When determining the rating, the approach similar to rating alternative aviation fuels (chapter 1.4.3 of the Technical Report) was used. Both, current and future rating with focus on the *medium-term perspective* (up to 10-15 years) was determined, which makes it possible to form a **total rating** for each type of the fuel. In the long term (more than 20 years), the situation may change significantly due to the development of the latest technologies, changes in economic conditions, and other factors.

Table 2.8. Comparative analysis of individual alternative fuels, electricity and hydrogen intended for waterborne transport [63, 73, 86, 87, 90, 120, 121, 122].

Type of fuel/production pathway	**Advantages***	**Disadvantages***	**Fuel rating for the introduction in Ukraine***
Biomethane	• Proven production technology and the ability to transport in existing gas networks. • The possibility of processing various biomass into the same final product - biomethane. • Due to the use of biomass, a significant reduction in greenhouse gas emissions is achieved. • To increase the energy capacity of fuel tanks, the possibility of liquefaction as LNG or compression.	• The volume of production is limited by the available local reserves of feedstocks. • Significant capital expenditures in biogas plants and equipment for cleaning biogas into biomethane. The CAPEX of a biomethane plant of 10 million m^3/year is about 10 million EUR. • For use as a fuel for transport, biomethane must be liquefied at a cryogenic temperature of -162^{0}C into bio-LNG (LBG) or compressed to a pressure of 200-250 bar.	*Current*: **Low** *Future*: **High** ***Summary (max 10):*** **9**
Electricity	• Flexibility and convenience of using electricity. High efficiency of electric drives. • If the electricity comes from RES, it can be assumed that an all-electric ship does not emit CO_2, NOx, PM and SOx. • Depending on the power unit, it is also possible to significantly reduce engine noise.	• Due to the significant size and cost of batteries, it is impractical to convert large ships and long-distance vessels to electricity. • Loss of cargo space due to the relatively small energy content of batteries (fig. 2.17). • Increasing the frequency of bunkering.	*Current*: **Average** *Future*: **High** ***Summary (max 10):*** **8**
Fatty acid methyl esters (**FAME**)	• Possibility of use as "drop-in fuels" in existing fuel	• Limited resources of raw materials, especially waste.	*Current*: **Average**

Type of fuel/production pathway	Advantages*	Disadvantages*	Fuel rating for the introduction in Ukraine*
	systems, using existing tanks and bunkering infrastructure. • The current international standard ISO 8217 allows adding up to 7% FAME to distillate fuels. • Significant reduction of greenhouse gas emissions during production from used cooking oil and waste fats. • Many projects using FAME mixtures up to 20% have been implemented in waterborne transport.	• When producing from oil crops, greenhouse gas emissions may be lower than the requirements of the EU Directive RED II. • High cost in production from oil crops. • The necessity of using methanol in the production of FAME. • When using pure FAME, a slight modernization of engines is necessary, in particular, the replacement of hoses, filters and gaskets with those adapted to biodiesel. • Various additives must be used in pure FAME (to inhibit bacterial growth, reduce cold filter plugging point, improve stability, etc.).	*Future*: **Above average** ***Summary (max 10):*** **8**
Hydrotreated vegetable oil (**HVO**)	• High-quality fuel from biomass, the chemical composition of which corresponds to traditional fuel. In the EU, HVO is standardized by EN 15940. • The energy content is close to traditional marine fuel. • Can be used in existing infrastructure and fuel systems in its pure form and as an additive to traditional fuels. • Commercial product.	• Significant reduction of greenhouse gases (80-90%) when produced from waste, while HVO from oilseeds can have lower GHG emissions than the requirements of the EU Directive RED II. • Limited resources of sustainable feedstocks. • Complex technology determines the high cost of biofuel.	*Current*: **Average** *Future*: **High** ***Summary (max 10):*** **8**
Liquefied natural gas (**LNG**)	• Cooling and liquefaction reduce the volume of gas by 600 times, making this fuel more energy-intensive. • Maturity of the technology, many ships have already been converted to LNG, and a significant number of LNG-fueled ships are on order. • Reduction of emissions of SOx, PM, NOx, CO_2. • The use of LNG in dual-fuel engines and its increasing availability worldwide make	• Considerable energy consumption for liquefaction and the need to maintain cryogenic temperature (-162^{0}C). • Lower GHG emissions by 10-20% compared to fuel oil, but significantly more than alternative low-carbon fuels. • Possible methane leakage. • Uses non-renewable resources. • Lack of LNG infrastructure in Ukraine.	*Current*: **Low** *Future*: **Above average** ***Summary (max 10):*** **7**

Type of fuel/production pathway	Advantages*	Disadvantages*	Fuel rating for the introduction in Ukraine*
	LNG a reliable and viable intermediate fuel. • It is technically possible to mix LNG with 5-10% pure hydrogen without changing the properties of liquefied natural gas.	• High CAPEX for conversion and building a new vessel. The cost of ship modernization with conversion to LNG is about 1,000 EUR/kW	
Methanol	• Methanol is a promising alternative fuel for reducing emissions and improving the environmental performance of shipping. • Globally available commercial product with large distribution and storage capabilities. • The ability to produce biomethanol and green e-methanol (PtL) allows to significantly reduce greenhouse gas emissions.	• Compared to fuel oil, the required tank volume is larger (233%). • The additional capital cost of installing methanol-capable systems on ships is about 1/3 of the costs associated with LNG systems. • Special methanol tanks and special bunkering infrastructure are required. • Flammability and toxicity.	*Current*: **Low** *Future*: **Average** ***Summary (max 10):*** **6**
Ammonia	• Carbon-free fuel. • The boiling point is minus 33.3°C, so by applying moderate pressure, ammonia can be liquefied. • Presence of an ammonia port terminal in Ukraine. • The possibility of producing blue and green ammonia.	• Lack of commercial engines, the appearance of the first one is expected in 2024. • Low energy content, approximately 30% by volume compared to MGO marine fuel. • Specialized bunkering infrastructure is required. • Toxicity and corrosiveness to some metals.	*Current*: **Low** *Future*: **Average** ***Summary (max 10):*** **6**
Hydrogen	• Carbon and sulphur-free, using green and blue H_2 will result in almost zero carbon emissions. • A large number of research programs in various sectors can accelerate the spread of hydrogen as a fuel. • Possibility of use as an energy carrier in fuel cells.	• The technology is still being developed in pilot projects. • Undeveloped bunkering infrastructure. • Production and storage of H_2 are energy intensive and expensive and require significant investment. • Liquefied hydrogen must be cooled to cryogenic temperatures (-253^{0}C) and for this, it is necessary to spend about 30% of its energy content.	*Current*: **Low** *Future*: **Average** ***Summary (max 10):*** **6**

Type of fuel/production pathway	Advantages*	Disadvantages*	Fuel rating for the introduction in Ukraine*
		• Compressed hydrogen is obtained at a pressure of 700-300 bar. • Low energy density, especially if the hydrogen is compressed rather than liquefied. • Cryogenic and explosion danger.	
FT diesel	• Prospective fuel is suitable for use as "drop-in fuels" in existing fuel systems and existing bunkering infrastructure. The EN 15940 standard applies in the EU • It is possible to use significant resources of sustainable feedstocks, in particular, lignocellulosic, which will ensure a significant reduction in greenhouse gas emissions.	• Fuel with high added value, the production technology of which is focused on the expensive segment of transport, in particular, aviation. • The Fischer-Tropsch process has been developed and is commercially used for the processing of coal and natural gas. However, the use of biomass, this technology is still developing and has not reached a commercial scale of production.	*Current*: **Low** *Future*: **Average** ***Summary (max 10)*: 6**
DME	• Synthesis gas can be processed in DME as an alternative to the F-T process. • High cetane number of 55-60. • DME is stored in a liquid state at a relatively low pressure of 0.5 MPa. • Used in modernized or special engines.	• The low energy density (19 MJ/l of liquefied DME), low viscosity and poor lubricating properties. • Not distributed as a commercial fuel. It was used as fuel for small vessels in demonstration projects. • Toxic in high concentrations.	*Current*: **Low** *Future*: **Average** ***Summary (max 10)*: 5**
HTL bio-oil	• The high energy content of 32-36 MJ/kg. • Can be used for marine engines. • It is possible to process waste, which provides a significant reduction in greenhouse gas emissions.	• The technology has not yet reached the commercial level. • Chemically different from petroleum fuels and may not meet the current requirements of the ISO 8217-2017 standard	*Current*: **Low** *Future*: **Average** ***Summary (max 10)*: 5**
Bioethanol	• Bioethanol is the most widespread biofuel in the world. • Bioethanol of the 2nd generation is produced from lignocellulosic raw materials, not from food and feed, and	• Bioethanol is used in gasoline engines. • The development of new multi-fuel diesel engine technologies could potentially open up the marine fuel market for bioethanol, but it will be	*Current*: **Average** *Future*: **Average** ***Summary (max 10)*: 5**

Type of fuel/production pathway	Advantages*	Disadvantages*	Fuel rating for the introduction in Ukraine*
	provides a significant reduction in greenhouse gases. • Simple modernization of the existing bunkering infrastructure for bioethanol introduction.	decades before these technologies can be found in more vessels. • High cost of bioethanol from lignocellulosic feedstocks. • Flammability.	
LPG	• Liquefaction takes place under moderate pressure. (Propane is in a liquid state at a pressure of more than 8.4 bar and a temperature of 20°C). • Despite the low use of LPG as an alternative fuel, the number of vessels with dual fuel LPG engines on order is increasing, indicating that the technology is maturing. • Experience in using CNG in road transport. • Safe to use. • The possibility of producing LPG from renewable resources, in particular, biomass.	• LPG from fossil resources is mainly offered on the market, which reduces CO_2 emissions by up to 18% compared to fuel oil. • Undeveloped bunkering infrastructure, although the country has a large network of LPG import and export terminals. • LPG supply is limited: the technology is currently of interest to vessels carrying LPG as cargo. • The need for investment in a dual-fuel engine.	*Current*: **Low** *Future*: **Average** ***Summary (max 10):*** **5**
Straight vegetable oil (**SVO**)	• Simple production technology can be used to replace fuel oil in low-speed engines. • Limited use as a commercial fuel.	• Prolonged use leads to the wear of engine parts. • Loses stability during storage and therefore requires the use of antioxidant additives. • Limited volumes of sustainable raw materials. In the case of production from oil crops, reductions in greenhouse gas emissions may be lower than the requirements of the EU Directive RED II.	*Current*: **Low** *Future*: **Below average** ***Summary (max 10):*** **4**
Pyrolysis bio-oil	• Reduction of SOx and NOx emissions. • Can be used as a raw material for methanol production. • Can be used as a component of emulsion biofuel for marine diesel engines to increase thermal efficiency and reduce PM emissions.	• The technology has not yet reached the commercial level. • High emissions of particulate matter (PM). • Low energy content (17-20 MJ/kg). • High oxygen content to consider as a hydrocarbon fuel. The pyrolysis bio-oil has a high oxidation ability.	*Current*: **Low** *Future*: **Low** ***Summary (max 10):*** **3**

**** Advantages and disadvantages for Ukraine's conditions as well as rating of individual alternative fuels, hydrogen and electricity for waterborne transport are evaluation by the authors of the report.***

When determining the rating of alternative fuels for water transport, the following aspects are taken into account (**Table 2.9**):

- Level of technology development and its complexity;
- Compatibility with existing engines, fuel system of vessels and bunkering infrastructure;
- Availability / accessibility of raw material and resource base;
- Volumetric energy content of fuel and energy carrier;
- Fuel standardization;
- Price;
- Reduction of greenhouse gas emissions during the life cycle.

According to the results of the comparative analysis and assessment, **the following fuels for water transport are considered the most promising for Ukraine:**

• Biomethane that can be used in compressed or liquefied form.
• Biodiesel (**FAME**) and hydrotreated vegetable oil (HVO).
• Electric power installations with accumulator batteries.
• Liquefied natural gas (**LNG**).

Table 2.9. Comparative analysis and rating of alternative fuels for using in waterborne transport (summary).

Fuel to be replaced	Alternative fuel	Technology	Feedstock	Criteria for evaluating fuels (technologies)							Rating (max 10)
				Attaining commercial level / experience in Ukraine	Compatibility with existing engines/ infrastructure	Availability/ accessibility of feedstock	Volumetric energy content of fuel and energy carrier	Standar-dization	Price	Reduction of GHG emission	
Distillate fuel (MGO)	FAME	Esterification	Vegetable oils and UCO	+ / +	± / +	+ / ±	+	+	±	± / +	**8**
	HVO	Hydrotreatment	Vegetable oils	+ / -	+ / +	+	+	+	±	±	**8**
			UCO and fats	+ / -	+ / +	±	+	+	+	+	**8**
	FT diesel	Gasification and FT Synthesis	Biomass	- / -	+ / +	+	+	+	±	+	**6**
	Methanol	Reforming	Natural gas	+ / -	- / -	+	±	+	+	-	**3**
		Gasification/ reforming	Biomass	+ / -	- / -	+	±	+	+	+	**6**
	Bioethanol	Fermentation	Sugar-/ starch-based	+ / +	- / +	+	±	+	+	±	**5**
		Hydrolysis/ fermentation	Lignocellulose	+ / +	- / +	+	±	+	±	+	**5**
	DME	Gasification	Biomass	- / -	- / -	+	±	-	±	+	**5**
Residual fuel. Heavy fuel oil (HFO)	SVO	Extraction	Vegetable oils	+ / -	± / ±	+	+	-	±	±	**4**
	Pyrolysis bio-oil	Pyrolysis	Biomass	- / -	± / ±	+	±	-	±	+	**3**
	HTL bio-oil	Hydrothermal liquefaction	Biomass	- / -	+ / +	+	+	-	±	+	**5**
Modernization of engines with transfer to alternative fuel	LNG	Liquefaction	Natural gas	+ / -	-	+	+	+	±	-	**7**
		Fermentation/ liquefaction	Biomass	+ / -	-	+	+	+	±	+	**9**
	LPG	Liquefaction	Propane/butane	+ / +	± / -	±	±	±	+	-	**5**
	Hydrogen	Reforming	Natural gas	+ / -	-	+	-	-	-	-	**3**
		Gasification	Biomass	+ / -	-	+	-	-	-	+	**6**
		Electrolysis	Water	+ / -	-	+	-	-	-	+	**6**
	Ammonia	Reforming	Natural gas	+ / -	-	+	±	-	-	-	**3**
		Gasification	Biomass	+ / -	-	+	±	-	-	+	**6**
		Electrolysis	Water	+ / -	-	+	±	-	-	+	**6**
	Electricity	RES		+ / -	-	±	-	+	±	+	**8**

3. Feasibility assessment of the production and supply chains for alternative aviation and waterborne fuels

3.1. Assessment of the feedstock cost for the alternative fuels production

Based on the existing domestic practice of agriculture, forestry and processing, four types of oil crops were selected for further conversion into biofuel: sunflower, rapeseed, rye and soybean; one type of grain crop: maize for grain; lignocellulosic biomass: straw, corn stalks, miscanthus, energy willow and wood chips from logging waste; corn silage; beet molasses and used cooking oil. **Table 3.1** provides the main assumptions and characteristics for estimating the approximate value of the considered types of raw materials, taking into account the costs of growing and harvesting in accordance with technological maps for agricultural crops [110] and energy crops; expenses for straw harvesting, stacks and wood chips; the cost of selling beet molasses and used cooking oil; transport costs for transportation of these types of biomass for a conditional distance of 50 km and profitability of 20%.

Table 3.1. Characteristics of domestic raw materials for the production of biofuels.

Feedstock	Yield, t/ha			Basic humidity, %	Calorific value, MJ/kg	Specific costs per ton (Aver. option), EUR/t	Specific transportation costs, EUR/(t·km)
	Min	Avar.	Max				
Sunflower	2.0	3.0	4	8	20.0	305	0.071
Rapeseed	2.0	3.0	3.8	8	20.0	260	0.063
Rye	1.5	2.0	3.2	12	20.0	240	0.063
Soybean	1.8	2.5	3.5	12	17,0	354	0.063
Maize	4,3	7,7	10,3	14	16.0	159	0.063
Silage	20.0	32	50	65	4.3	19	0.063
Baled straw	2.5	3.3	4	15	14.0	15	0.098
Baled corn stalks	3.3	4.7	6.7	25	12.5	15	0.072
Chipped miscanthus	10.0	14.0	20.0	15	14.7	15	0.231
Energy willow	10.0	14.6	20.0	50	8.0	19	0.120
Molasses				25	12.5	100	0.063
Wood chips				40	10.2	45	0.063
Used cooking oil				2	37.0	200	0.075

The diagram with the estimation results of the expected raw materials cost is presented in **Fig. 3.1**. Therefore, lignocellulosic biomass has the lowest specific energy cost: straw in bales at 1.7 EUR/GJ, corn in bales at 1.8 EUR/GJ. The specific energy cost of miscanthus is 2.2 EUR/GJ, and energy willow is 3.8 EUR/GJ, assuming that the miscanthus plantation will produce marketable biomass for 21 years and willows for 24 years.

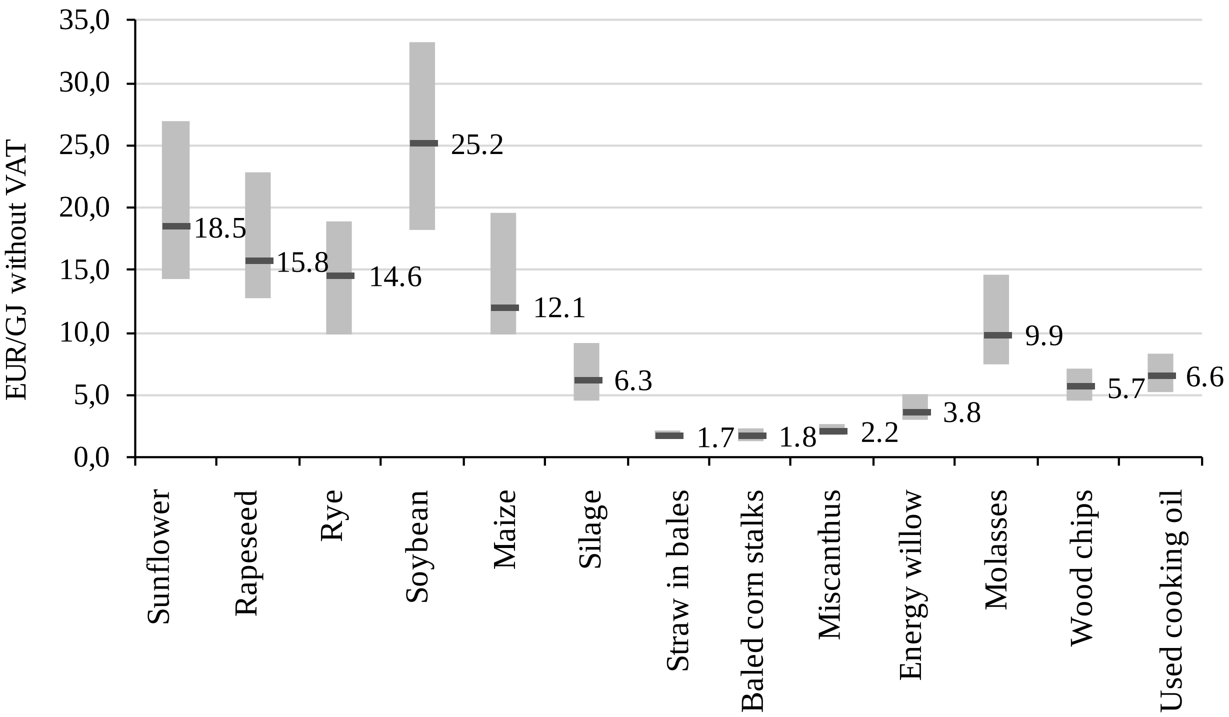


Fig. 3.1. Expected biomass specific value for processing in 2022

Among the oil raw materials, used cooking oil has the lowest specific value of 6.6 EUR/GJ. Corn silage, which can be used for anaerobic fermentation and obtaining biogas, has an expected specific cost the level of 6.3 EUR/GJ. Corn, which can be processed into bioethanol, has a specific biomass value of 12.1 EUR/GJ. Oilseeds that can be processed into straight vegetable oil, fatty acid methyl esters or hydro-refined oil have a specific value of 18.5 EUR/GJ for sunflower, 15.8 EUR/GJ for rapeseed, 14.6 EUR/GJ for rye and 25.2 EUR/GJ for soybeans. The specific value of wood chips from logging waste is 5.7 EUR/GJ.

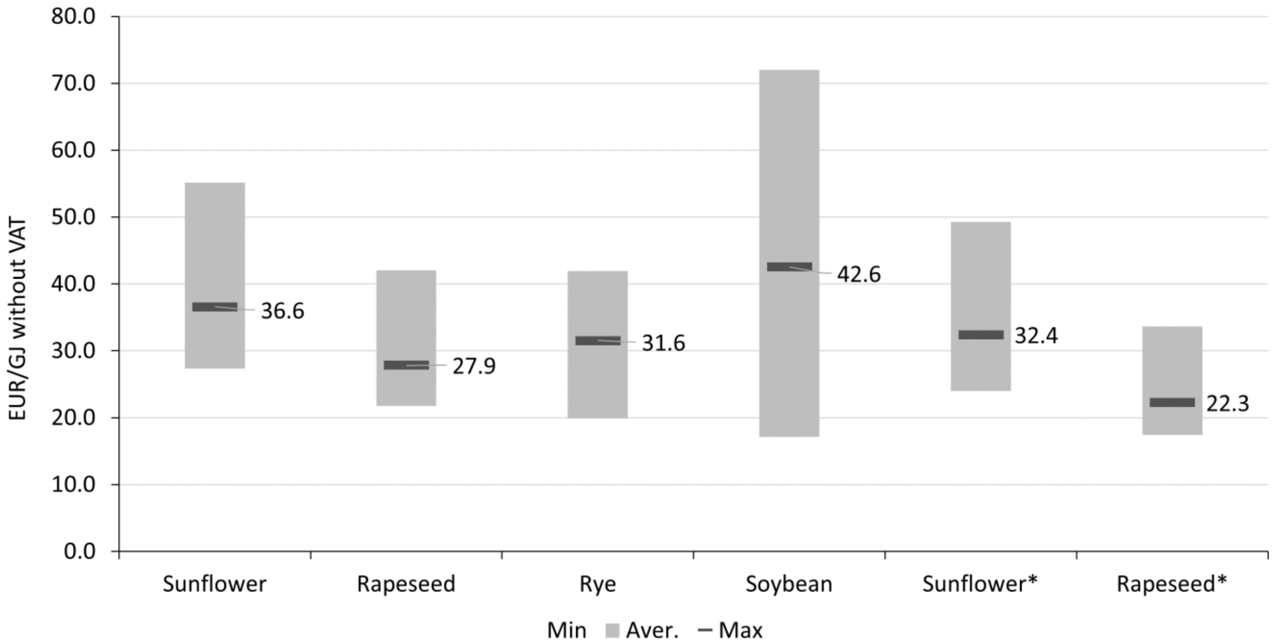
3.2. Assessment of the straight vegetable oil` cost

Sunflower, rapeseed, rye and soybean seeds can be processed into vegetable oil, which is suitable for use as a fuel oil substitute. For small volumes of production, the technology of squeezing out oils using the press method is used. Let's determine the production cost of straight vegetable oil (SVO) by a two-stage pressing method with annual seed productivity of 2500 t/year and purification by filtration. The main assumptions accepted in the calculations are given in the **Table 3.2**.

To obtain oil on an industrial scale, the extraction method is used, which allows for an increase in the yield of oil from seeds. The calculation of oil production at an oil extraction plant with a capacity of 3,000 tons of oil per day was carried out. Data on input materials, byproducts, and energy consumption were taken from the life cycle assessment of sunflower and rapeseed oils [111]. The results of estimating the expected specific value of direct vegetable oil from sunflower, rapeseed, sorghum and soybean at profitability of 20% are shown in **Fig. 3.2**. The cost of extracted rapeseed oil is **22.3** EUR/GJ, which is lower than the cost of pressed rapeseed oil of **27.9** EUR/GJ.

Table 3.2. Processing of oilseeds into vegetable oil by pressing

Indicators	Sunflower	Rapeseed	Rye	Soybean
SVO yield, kg/t of seeds	**300**	**320**	**270**	**150**
By-products:				
Sunflower husk, kg/t of seeds	175			
Oilcake, kg/t of seeds	427	554	566	686
By-product cost	**64**	**66**	**57**	**262**
Expenses on 1 t of seeds, EUR/t				
Energy and materials	9,5	9,7	8,9	11,8
Maintenance and repair	2,80	2,80	2,80	2,8
Salary	12,5	12,5	12,50	12,5
Amortization	2,8	2,80	2,80	2,8
Total	**28**	**28**	**27**	**30**



***Note:** * oil obtained using the extraction method.*

Fig. 3.2. Expected specific cost of SVO obtained from the oil crops seeds in 2022.

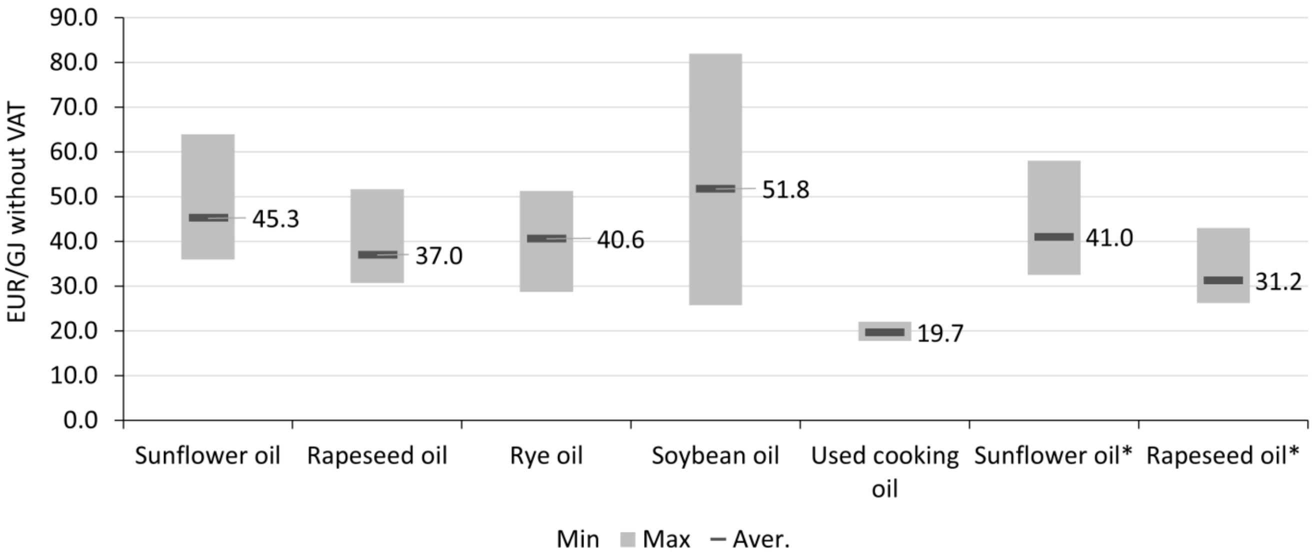
3.3. Biodiesel cost assessment

Considering the occurrence of malfunctions in engines during long-term use of straight vegetable oil to replace fuel oil, it is more appropriate to process oils into other types of biofuels, in particular, biodiesel. The production of methyl esters of fatty acids from vegetable oils using the classical technology of methanolysis with an alkaline catalyst in batch reactors was considered [112]. It is assumed that the crude glycerol obtained as a result of the reaction will be sold to a specialized enterprise. The assumptions used in the calculations for SVO and used cooking oil are listed in the **Table 3.3.**

Table 3.3. Processing of oils into methyl esters of fatty acids.

Indicators	SVO	Used cooking oil
FAME yield, kg/t of oil	950	809
By-product's cost, EUR/t of oil	58.5	52
Additional raw material costs (without oil), EUR/t of oil	235	239
Energy expenditure, EUR/t of oil	12.3	12.3
Labour expenditure, EUR/t of oil	2.89	2.89
Maintenance and repair expenditure, EUR/t of oil	28	28
Amortization, EUR/t of oil	28	28
Total, EUR/t of oil	**249**	**259**

The results of estimating the expected specific value of methyl esters from straight vegetable oil and used cooking oil at profitability of 20% are shown in **Fig. 3.3**.



Note: ** oil obtained using the extraction method.*

Fig. 3.3. Expected specific cost of biodiesel in 2022.

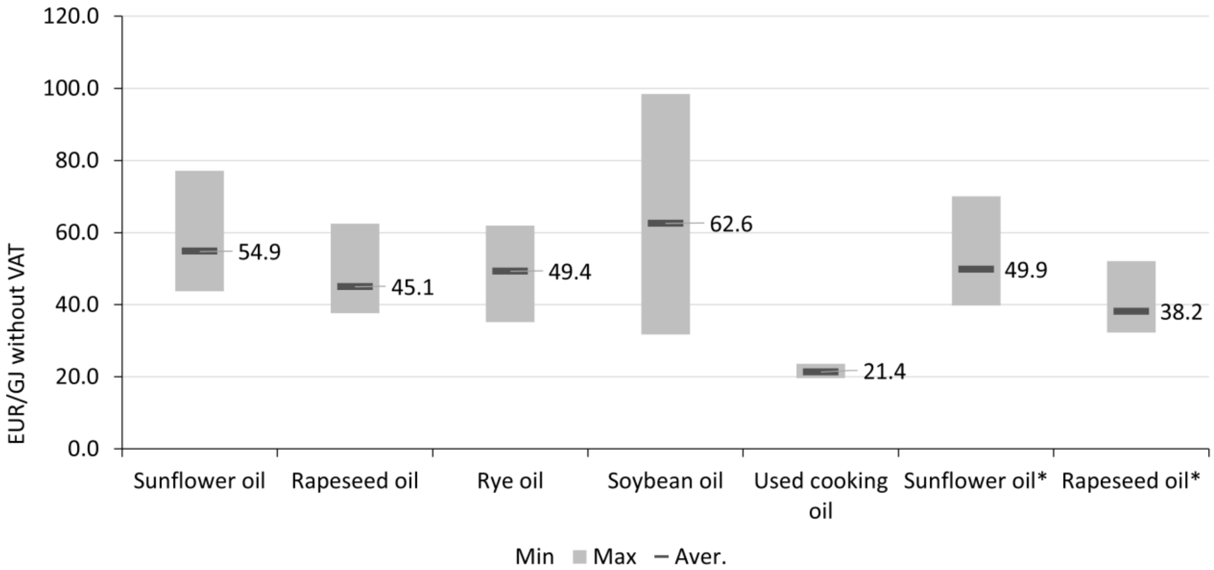
The expected specific cost of biodiesel from used oil is the lowest and is **19.7** EUR/GJ, and the specific cost of methyl esters of fatty acids (FAME) produced from extracted rapeseed oil is **31.2** EUR/GJ.

3.4. Assessment of the hydrotreated vegetable oil cost

To obtain oxygen-free hydrocarbon biofuel, hydrotreated vegetable oil (HVO) or hydrotreated esters and fatty acids (HEFA) vegetable oils are treated with hydrogen. Similarly to the production of biodiesel, we will consider the processing of sunflower, rapeseed, rye, soybean oils and used cooking oil. The assumptions used in the calculations are given in the **Table 3.4**. The results of the assessment of the specific value of HVO are shown in **Fig. 3.4**.

Table 3.4. Processing of oils into hydrotreated vegetable oil.

Indicators	Straight vegetable oil	Used cooking oil
HVO yield, kg/t of oil	830	762
By-product's cost, EUR/t of oil	77	59
Additional raw material costs (without oil), EUR/t of oil	98.3	98.3
Energy expenditure, EUR/t of oil	200	200
Labor expenditure, EUR/t of oil	1.5	1.5
Maintenance and repair expenditure, EUR/t of oil	56	56
Amortization, EUR/t of oil	56	56
Total, EUR/t of oil	**334**	**352**



Note: ** oil obtained using the extraction method.*

Fig. 3.4. Expected specific cost of HVO in 2022.

The lowest specific cost of HVO can be obtained from used cooking oil: **21.4** EUR/GJ, but in order to collect large volumes of such raw materials in Ukraine, it is necessary to carry out systematic work in order to encourage catering establishments to collect, store and hand over oil. Rapeseed extractive oil allows obtaining a specific value of HVO at the level of **38.2** EUR/GJ.

3.5. Assessment of the first-generation bioethanol cost

Maize for grain and beet molasses can mainly be used for the production of first-generation bioethanol in Ukraine. In calculations for bioethanol production, technical and economic assessments of the Ukrainian technological company UTC were used [113]. The assumptions used in the calculations are given in the **Table. 3.5**. The estimation results for the specific bioethanol value are shown in **Fig. 3.5**. The expected specific cost of bioethanol from molasses is **32** EUR/GJ, from maize for grain – **32.5** EUR/GJ.

Table 3.5. Processing of maize and molasses into bioethanol.

Indicators	Maize for grain	Molasses
Bioethanol yield, kg/t of feedstock	270	226
By-product cost, EUR/t of feedstock	88.1	28.6
Costs of chemical additives, EUR/ t of feedstock	20.3	5.2
Energy cost, EUR/t of feedstock	66.3	42.6
Labor cost, EUR/t of feedstock	9.0	4.9
Maintenance and repair cost, EUR/t of feedstock	19.1	7.4
Amortization, EUR/t of feedstock	15.9	6.9
Total cost, EUR/t of feedstock	**130.6**	**67.1**

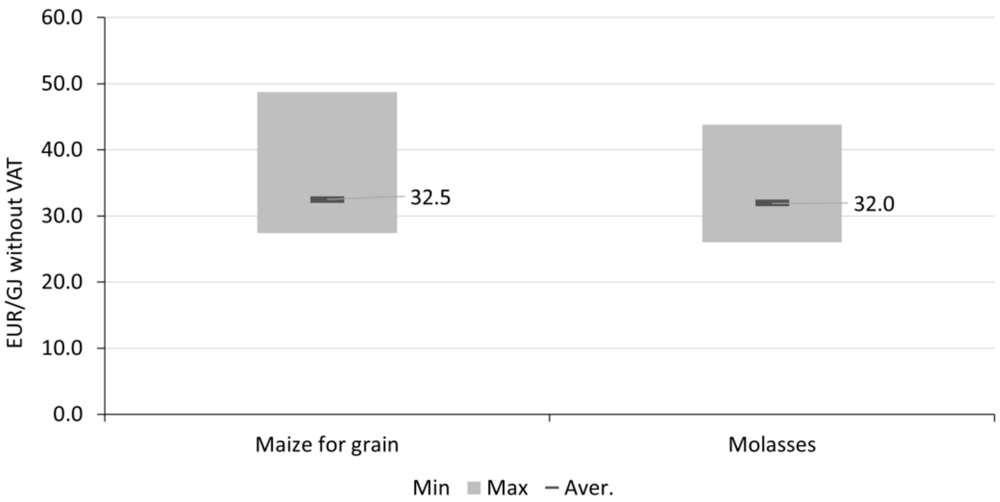


Fig. 3.5. The expected specific cost of the first-generation bioethanol in 2022.

3.6. Assessment of the advanced bioethanol cost

For the production of second-generation bioethanol in Ukraine, post-harvest residues, in particular, straw and corn stalks, and miscanthus can be used. In the calculations of bioethanol production from lignocellulosic raw materials, data of studies [114, 115] were used. The assumptions used in the calculations are given in the **Table 3.6**. The results of the bioethanol` specific cost estimation are shown in **Fig. 3.6**. The expected specific cost of second-generation bioethanol from the considered raw materials is **46-46.5** EUR/GJ.

Table 3.6. Processing of lignocellulosic raw materials into bioethanol of the second generation.

Indicators	Value
Bioethanol yield from straw (humidity 15%), kg/t of feedstock	229
Bioethanol yield from corn stalk (humidity 25%), kg/t of feedstock	199
Bioethanol yield from miscanthus (humidity 15%), kg/t of feedstock	272
Costs of chemical additives, EUR/t of bioethanol	436.6
Energy cost, EUR/ t of bioethanol	170.7
Labor cost, EUR/ t of bioethanol	10.2
Maintenance and repair cost, EUR/ t of bioethanol	154.4
Amortization, EUR/ t of bioethanol	154.4
Total cost, EUR/t of bioethanol from lignocellulosic raw materials	**926.3**

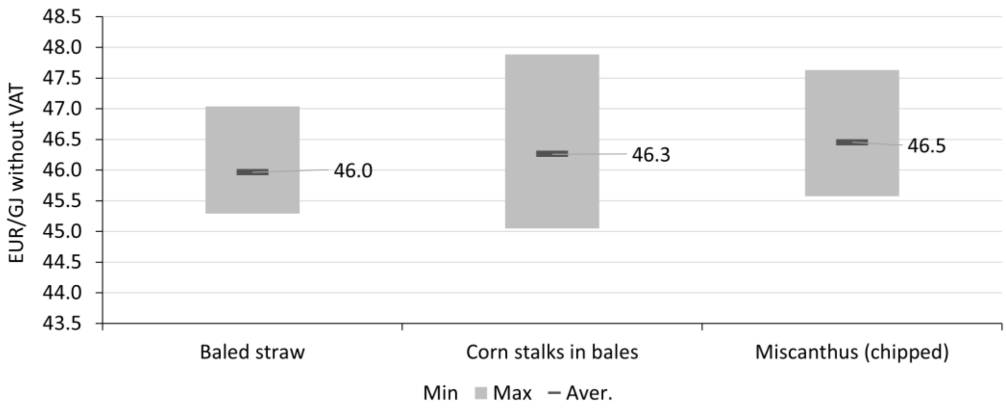


Fig. 3.6. The expected specific cost of second-generation bioethanol in 2022.

3.7. Assessment of the biomethane cost from silage and corn

Considering the reduction of livestock in agricultural enterprises and the reduction of the amount of livestock waste for the production of biomethane in Ukraine, the use of silage and corn is considered. Data from the report of the Scientific Research Center "Biomass" [116] were used for the calculations of biomethane production. The assumptions used in the calculations are given in the **Table 3.7**. The results of the biomethane` specific cost estimation are shown in **Fig. 3.7**. The expected specific cost of biomethane is **10.7-12.3** EUR/GJ.

Table 3.7. Processing of silage and corn stalks into biomethane.

Indicators	Silage	Corn stalks
Biomethane yield, nm³/ t of feedstock organic dry mass	338	296
Annual biomethane yield, million nm³/year	5.9	5.1
Annual volumes of feedstock processing, kt dm/year	18.7	21.1
Income from the sale of thermal energy, EUR/year	54450	
Income from the sale of fermented fertilizers, EUR/year	130149	
Capital cost, th. EUR	8.715	
Operating costs without basic raw materials, EUR/year	463330	
Additional costs for preparation of raw materials for fermentation, EUR/year	-	296544
Total cost, EUR/t of feedstock	**130.6**	**67.1**

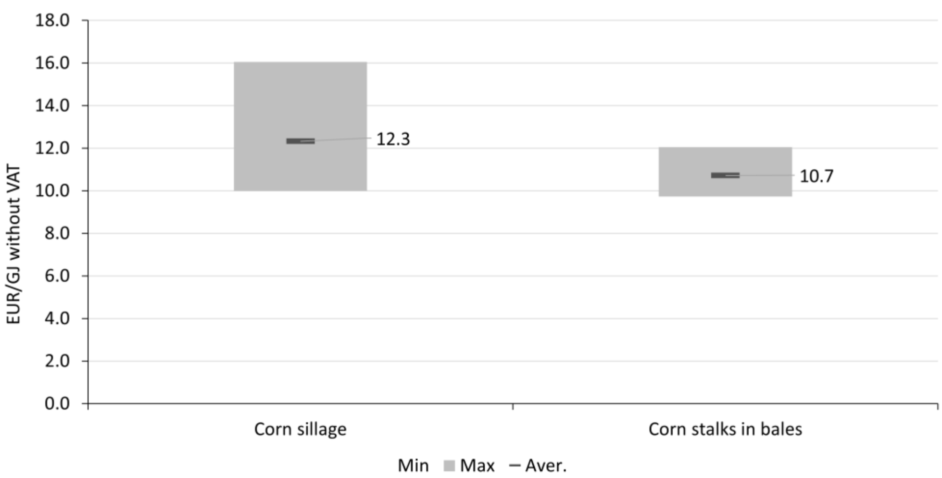


Fig. 3.7. Expected biomethane specific cost in 2022.

Conclusions

The use of alternative fuels in the aviation and waterborne transport sectors is a promising direction of general decarbonization and improvement of ecological compatibility of Ukraine's transport sector.

Based on results of the comparative analysis and evaluation, the following **SAFs are considered the most promising for Ukraine's aviation**:

- Synthesized paraffinic kerosene from hydroprocessed esters and fatty acids (**HEFA-SPK**).
- Alcohol to jet synthetic paraffinic kerosene (**ATJ-SPK**) (currently, only conversion of ethanol).
- Fischer-Tropsch hydroprocessed synthesized paraffinic kerosene (**FT-SPK**).

For the production of each of these biofuels in Ukraine, there is a necessary raw material base, including straw of cereal crops and rapeseed, by-products/residues from the production of grain corn and sunflower, oilseed, woody and herbaceous energy crops, and sugar beet molasses. In order to make the final decision regarding the introduction of the production of a certain type of SAF, it is necessary to perform a complete feasibility study and life cycle assessment for various types of raw materials for the conditions of Ukraine.

Regarding the **waterborne transport**, among the applications of various types of fuel, short-distance and deep-sea marine shipping should be distinguished. In short-distance transportation, vessels usually operate in limited geographical areas on relatively short routes with frequent port calls. Because of their relatively low energy requirements, these vessels are often ideal candidates for testing new fuels characterized by high energy conversion or storage costs.

Deep-sea shipping includes large ocean-going vessels that operate long routes, often without a regular schedule. These vessels require the use of fuel that is available all over the world. The energy carrier that drives the ship must have a high enough energy density to maximize the available cargo space. For these vessels, LNG may be a viable option once suitable bunkering infrastructure becomes available worldwide. Environmental biofuels, methanol and liquefied gas may also be options, provided they can be made available in the required quantities and at the appropriate level of quality.

According to the results of the comparative analysis and assessment, **the following fuels for water transport are considered the most promising for Ukraine:**

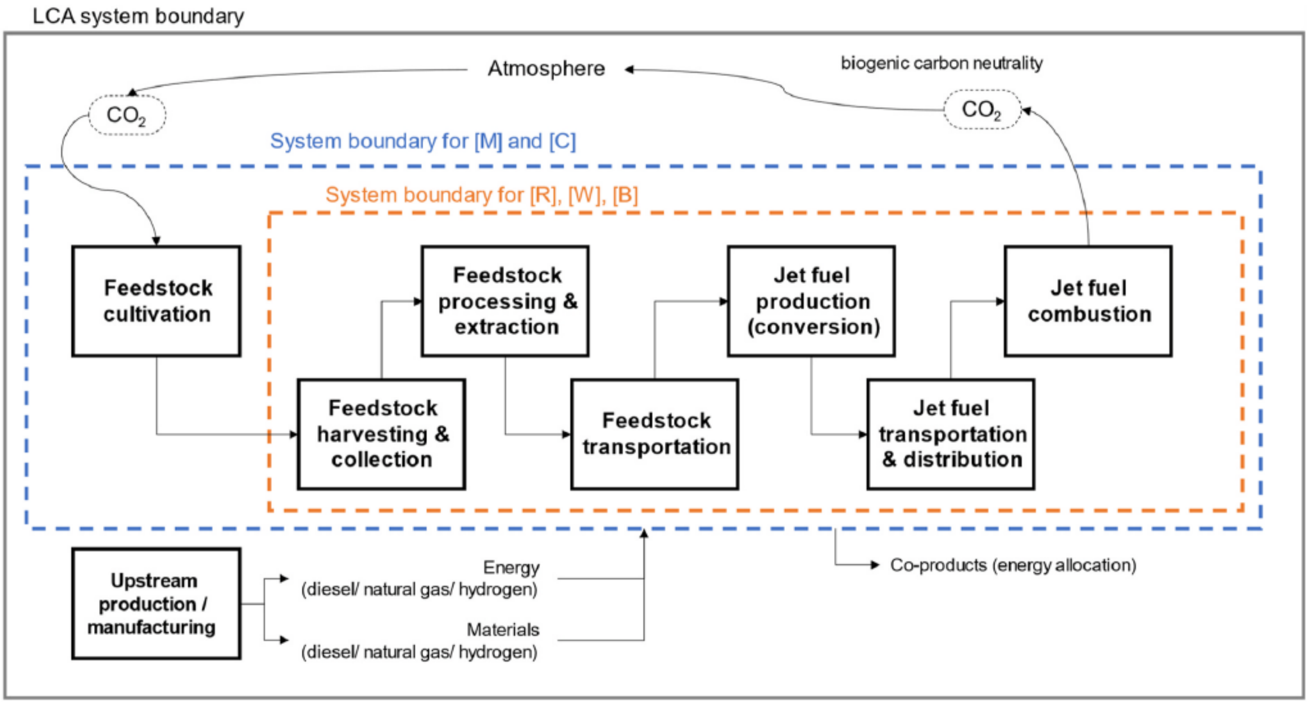
- Biomethane that can be used in compressed or liquefied form.
- Biodiesel (**FAME**) and hydrotreated vegetable oil (**HVO**).
- Electric power installations with accumulator batteries.
- Liquefied natural gas (**LNG**).

Annex 1. CORSIA methodology for the assessment of GHG emission reduction during SAF life cycle

CORSIA methodology makes it possible to calculate the amount of GHG emission reductions obtained due to the production and use of various types of ***sustainable aviation fuels*** and ***low-carbon aviation fuels***[8].

The main approaches used in the CORSIA methodology [15]:

- SAFs obtained by HEFA, Fischer-Tropsch synthesis, hydrotreatment of fermented sugars (SIP), isobutanol and ethanol conversion (ATJ), HEFA as a compatible process in traditional oil refining are considered.
- The fuel life cycle includes all stages from growing raw materials to combustion. For raw materials in the form of waste, residues and by-products of other processes, the life cycle stages begin with harvesting, that is, they do not include the growing stage (**Fig. A1**).
- The emission of GHG between the main and secondary products of SAF production technologies is distributed according to their energy content.
- The baseline values for determining GHG emissions reduction are 89 gCO_{2e}/MJ for jet fuel and 95 gCO_{2e}/MJ for AvGas.
- SAF sustainability criteria: minimum GHG emissions reduction – 10%; biofuels cannot be produced from biomass grown on high-carbon land.
- The values of GHG emissions during the SAF life cycle (by default), presented in **Table A1**, are used.



Feedstock category: M – main product, C – co-product, R – residues, W – waste, B – by-product

Fig. A1. LCA system boundary in CORSIA [13].

[8] As of November 2021, CAEP (Committee on Aviation Environmental Protection) calculated life cycle GHG emission values (by default) only for SAFs.

Table A1. Technologies/fuels considered by CORSIA, relevant feedstocks and life cycle GHG emission values (default) [15].

Conversion process	**Feedstock**	**Type of feedstock***	**GHG emission during the life cycle, default value, gCO_{2e}/MJ**
Fischer-Tropsch (FT)	Agricultural residues	R	7.7
	Forestry residues	R	8.3
	MSW, 0% NBC	W	5.2
	MSW, NBC as % of total C	W	NBC ×170.5 + 5.2
	Short-rotation woody crops	M	12.2
	Herbaceous energy crops	M	10.4
Hydro-processed esters and fatty acids (HEFA)	Tallow	B	22.5
	Used cooking oil	W	13.9
	Palm fatty acid distillate	B	20.7
	Corn oil	B	17.2
	Soybean oil	M	40.4
	Rapeseed oil	M	47.4
	Camelina oil	M	42
	Palm oil (treatment of industrial wastewater in a closed pond)	M	37.4
	Palm oil (treatment of industrial wastewater in an open pond)	M	60
	Brassica Carinata	M	34.4
Synthesized IsoParaffins (SIP)	Sugarcane	M	32.8
	Sugar beet	M	32.4
Iso-butanol Alcohol-to-jet (ATJ)	Sugarcane	M	24.0
	Agricultural residues	R	29.3
	Forestry residues	R	23.8
	Corn grain	M	55.8
	Herbaceous energy crops	M	43.4
	Molasses	C	27.0
Ethanol Alcohol-to-jet (ATJ)	Sugarcane	M	24.1
	Corn grain	M	65.7
	Agricultural residues (standalone)	R	39.7
	Agricultural residues (integrated)	R	24.6
	Forestry residues (standalone)	R	40.0
	Forestry residues (integrated)	R	24.9
	Miscanthus (standalone)	M	43.3
	Miscanthus (integrated)	M	28.3
	Switchgrass (standalone)	M	43.9
	Switchgrass (integrated)	M	28.9

** M – main product, C – co-product, R – residues, W – waste, B – by-product.*

Annex 2. Feedstocks for the production of biogas for transport and biofuels, the contribution of which towards the minimum shares may be considered to be twice their energy content (Directive RED II, Annex IX)

Part A. Feedstocks for the production of ***biogas*** for transport and ***advanced biofuels***, the contribution of which towards the minimum shares referred to in the first and fourth subparagraphs of Article 25(1) may be considered to be **twice their energy content**:

(a) Algae if cultivated on land in ponds or photobioreactors;
(b) Biomass fraction of mixed municipal waste, but not separated household waste subject to recycling targets under point (a) of Article 11(2) of Directive 2008/98/EC;
(c) Biowaste as defined in point (4) of Article 3 of Directive 2008/98/EC from private households subject to separate collection as defined in point (11) of Article 3 of that Directive;
(d) Biomass fraction of industrial waste not fit for use in the food or feed chain, including material from retail and wholesale and the agro-food and fish and aquaculture industry, and excluding feedstocks listed in part B of this Annex;
(e) Straw;
(f) Animal manure and sewage sludge;
(g) Palm oil mill effluent and empty palm fruit bunches;
(h) Tall oil pitch;
(i) Crude glycerine;
(j) Bagasse;
(k) Grape marcs and wine lees;
(l) Nut shells;
(m) Husks;
(n) Cobs cleaned of kernels of corn;
(o) Biomass fraction of wastes and residues from forestry and forest-based industries, namely, bark, branches, precommercial thinnings, leaves, needles, tree tops, saw dust, cutter shavings, black liquor, brown liquor, fibre sludge, lignin and tall oil;
(p) Other non-food cellulosic material;
(q) Other ligno-cellulosic material except saw logs and veneer logs.

Part B. Feedstocks for the production of ***biofuels*** and ***biogas*** for transport, the contribution of which towards the minimum share established in the first subparagraph of Article 25(1) shall be limited and may be considered to be **twice their energy content**:

(a) Used cooking oil;
(b) Animal fats classified as categories 1 and 2 in accordance with Regulation (EC) No 1069/2009.

Source: Directive **RED II** [3].

Annex 3. Summary of minimum fuel selling prices of biojet fuel for different technology pathways

Technology	Feedstock	Minimum fuel selling price, USD/t	Publication year
HEFA/HVO	UCO	721-1089	2020
	Yellow grease	825-1550	2017
	Tallow	988-1775	2017
	Soybean oil	1086-2000	2017
	Jatropha oil	2360	2018
	Palm oil	1050	2018
	Vegetable oil	2220	2016
Gasification/FT	Forest residues/wheat straw	2124-3127	2015
	Biomass	898-1724	2020
	All wastes	635-1245	2020
	MSW	1188-1738	2017
	Lignocellulose	2440	2016
Pyrolysis, bio-oil and upgrading	Forest residues/wheat straw	1534-2183	2015
	Forest residues/wheat straw (bio-oil co-processing)	946-1664	2020
	Forest residues/wheat straw (bio-oil stand-alone)	982-1520	2020
	Forest residues/wheat straw (FP bio-oil)	1120	2013
	Woody biomass (FPH)	1275-2625	2017
ATJ	Forest residues (mixed alcohols)	2832-4130	2015
	Ethanol	938	2018
	Isobutanol	736-1113	2018
	Wheat straw/isobutanol	1564	2018
	Wheat grain/isobutanol	976	2018
	Corn stover	1773	2017
	Sugarcane	1200	2017
	Corn grain	1263	2017
	Switch grass	1725	2017
	Sugarcane fermentation	2540	2016
Advanced Fermentation	Sugarcane (advanced)	1375-2450	2017
	Corn grain (advanced)	1625-2673	2017
	Herbaceous biomass (advanced)	2700-3650	2017
	Lignocellulose (syngas)	3430	2016
Catalytic hydrothermolysis	Brown grease	829	2018
	Yellow grease	1162	2018
	Carinata oil	1767	2018

Source: [8].

Annex 4. Ukrainian normative documents and regulations regarding hydrogen technologies

Hydrogen is classified as a dangerous fuel gas, therefore, activities related to the design, construction, production, operation of technological facilities, systems and equipment, production and use of hydrogen are regulated in Ukraine by a number of regulations and legal acts (norms, rules, technical regulations) and relevant standards of different levels. The main regulatory requirements include:

1. Technical Regulation:

– equipment and protective systems intended for use in a potentially explosive atmosphere (aligned with Directive 2014/34/EU of 26 February 2014);
– pressure equipment (aligned with Directive 2014/68 / EU of 15 May 2014);
– simple high-pressure vessels (aligned with Directive 2014/29/ EU of 26 February 2014);
– water heating boilers operating on liquid or gaseous fuel;
– devices for gaseous fuel (aligned with EU Regulation 2016/426 of 09 March 2016);
– mobile pressure equipment (aligned with the Directive: 1999/36/ EU of 29 April 1999);
– requirements for automobile gasoline, diesel fuel, marine and boiler fuel (aligned with Directives 98/76/EU of 13.10.1998 and 2005/33/EU of 06.07.2005).

2. Safety rules, labor protection rules, safety rules during operation:

– rules of fire safety in Ukraine (NAPB A.01.001-2014);
– safety rules for the production of hydrogen by electrolysis of water (NPAOP 24.11-1.03-78);
– safe operation of piston compressors operating on explosive and toxic gases (NPAOP 0.00-1.14-76);
– safety of gas supply systems (NPAOP 0.00-1.76-15)
– occupational health and safety during the operation of pressure equipment (NPAOP 0.00-1.81-18)
– safety during the operation of means and systems of automation and control in the gas plant industry (NPAOP 11.1-1.07-90);
– electrical installations (NPAOP 40.1-1.32-01);
– safe operation and maintenance of automobile gas filling compressor stations (NPAOP 63.2-1.06-02).

Normative technical safety requirements regarding the used equipment, devices, systems and their components are established, as a rule, by standards. Since the state of the national regulatory technological base in relation to hydrogen does not correspond to the existing world level, the introduction of national standards harmonized with international ones will eliminate the existing administrative and technical barriers caused by outdated Ukrainian regulatory documents that do not comply with a number of EU directives and current legislation of Ukraine in the field of standardization (Law No. 114-IX of September 19, 2019).

The development of standards at the state level is carried out by technical standards committees, which include producers and consumers of products, research and public organizations, regulatory bodies, etc. In Ukraine, in 2020, the Technical Committee for Standardization TC 197 "Hydrogen Technologies" was established (Order of the State Enterprise "UkrNDNC" No. 130 of 22.06.2020), which works in hydrogen technologies in accordance with the accepted 99 international classification of standardization. Due to the fact that hydrogen technologies cover various fields, TC 197 also coordinates the activities of national technical committees whose activities are related to the design, construction, production, operation of technological facilities, systems and equipment, production and use of hydrogen:

TC 8 “Pipes and steel cylinders”
TC 21 “Dynamic and volumetric pumps”
TC 25 “Fire safety”
TC 26 “Operation of aircraft”
TC 28 “Compressors”
TC 38 “Refined and petrochemical products”
TC 55 “Methanol, synthesis products”
TC 80 “Motor transport”
TC 108 “Pipeline fittings”
TC 133 “Natural gas”
TC 146 “Materials, equipment, technologies and equipment for the oil and gas industry”
TC 187 “Explosion-proof equipment”
TC 318 “Construction of oil and gas production, transport and storage facilities”

Source: Draft Roadmap for the production and use of hydrogen in Ukraine [53].

Annex 5. Examples of studies on alternative aviation fuels in Ukraine

Scientists of the National Aviation University (Kyiv) conducted bench tests of gas turbine operation parameters using traditional and alternative aviation fuel [35]. For bench tests, traditional jet fuel Jet A-1 and new alternative types of fuel with ***bio-additives*** (in the amount of 10% and 20%) were used, which are ***ethyl esters of fatty acids*** of rapeseed oil, which were produced at the Institute of Bioorganic Chemistry and Petrochemistry of the National Academy of Sciences of Ukraine and specially modified by vacuum distillation. The results showed that, compared to the traditional JF Jet A-1, the use of alternative fuel for gas turbines, modified with bio-additives based on ethyl esters of fatty acids:

- Contributes to the improvement of traction characteristics of GTE.
- Causes a decrease in fuel consumption, which is achieved due to the higher density of alternative fuel.
- Leads to a decrease in the gas temperature behind the turbine, which will have a positive effect on increasing the durability of the materials and structure of the exhaust system of the GTE, as well as on reducing the total NO_x emissions.
- Leads to a decrease in the relative frequency of rotation of the GTE rotor, and therefore ensures more efficient operation of the GTE.

As a result of the bench tests, it was concluded that the operating parameters of the gas turbine using new alternative fuels fully satisfy the operating standards established for the tested gas turbine.

At the Lviv State University of Life Safety, promising types of renewable plant materials, which are the most appropriate for the production of alternative aviation biofuels in Ukraine, were analyzed [36]. ***Bio-additives*** were obtained for their use as components of aviation biofuels. Bio-additives for aviation fuels were obtained by ***esterification*** of rape and rye oil with methyl, ethyl and iso-butyl alcohols. In order to increase the purity of fatty acid esters (FAEs) and remove hard-boiling compounds, FAEs were subjected to vacuum distillation. The research of the obtained bio-additives was carried out according to the parameters of physic-chemical properties that are typical for aviation fuel, in particular fuel for air-jet engine: density, viscosity, solidification temperature, lower heat of combustion and flash point. It was established that the introduction of bio-additives to Jet fuel in the amount of up to 20% fully satisfies the requirements of the standards.

It was concluded that the most promising direction of development is the creation of combined mixtures from components of vegetable and petroleum origin. That is, a fuel component is produced from various vegetable raw materials, which has good, but insufficient characteristics for use in aviation. Such a component is added to the oil fraction, and a complex of additives is also introduced. Due to the efficient combustion process, such a mixture can be successfully used as an alternative to traditional petroleum aviation fuel.

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