Global Energy Perspectives

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Global Energy Solutions e.V.

Part 1: Basic elements for avoiding greenhouse gases and generating climate-neutral energy (technical toolbox)

Chapter 2-7

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2.7 Climate-neutral fuels

2.7.1 Introduction

Oil has played a central role in the development of the transport sector over the last 100 years. In 2020, about 65% of global oil consumption was consumed in the transport sector.

Table 26: Forecast for oil consumption in 2050 according to various institutions

Institution	Oil demand in 2020	Oil demand in 2050
IEA	91 mb/d (65 % of which is consumed in transport)[329]	25 mb/d for the Net-Zero path[330]
Barclays	-	81 mb/d[331]
Total Energies	-	40 to 64 mb/d[332]

According to the IEA, global oil demand must fall to 25 mb/d by 2050,[333] to reach the net zero target. However, companies such as Barclays and Total-Energies forecast oil consumption at 81 mb/d and 40-64 mb/d respectively.

Oil demand can be partly met with biofuels if sustainable production pathways are adopted. Current first-generation biofuels can lead to conflicts with food production. The synthesis of second-generation biofuels produced from agricultural cellulosic waste can simultaneously ensure stable food production. In addition, fuels could be produced from municipal solid waste, wastewater and used vegetable oils or animal waste fats. This chapter explains the potential of such fuels to replace petroleum in the transport sector and the technologies required to synthesise such fuels. According to the Net-Zero 2050 studies by IEA[334], IRENA; BP and Shell, the contribution of bioenergy to primary energy supply could be between 10 % and 20 %.[335]

2.7.2 Organic sources

Raw materials for the synthesis of biofuels can be cellulosic waste from agriculture and agroforestry, waste oils, municipal wastewater, and municipal solid waste. The following subsections examine the global quantities of these resources. These quantities are then used to determine the primary energy potential of various bio raw materials.

[329] Cf. IEA, (2022).
[330] Cf. IEA, (2022).
[331] Cf. Barclays, (2019).
[332] Cf. Reuters, (2021).
[333] mb/d = million barrels per day = 1,590 m /day^3
[334] The contribution of bioenergy to primary energy according to the IEA: 28 PWh/a
[335] The contribution of bioenergy to primary energy according to Shell: 30 PWh/a

2.7.2.1 Biological residues from agriculture and forestry

In 2019, about 50 million km^2 of global land area was used for livestock production, animal feed production and to grow food for direct consumption. Most of the world's protein and calorie supply is still plant-based, but the remainder of protein and calorie supply comes from meat and dairy products, which require more land, as shown in Figure 118.

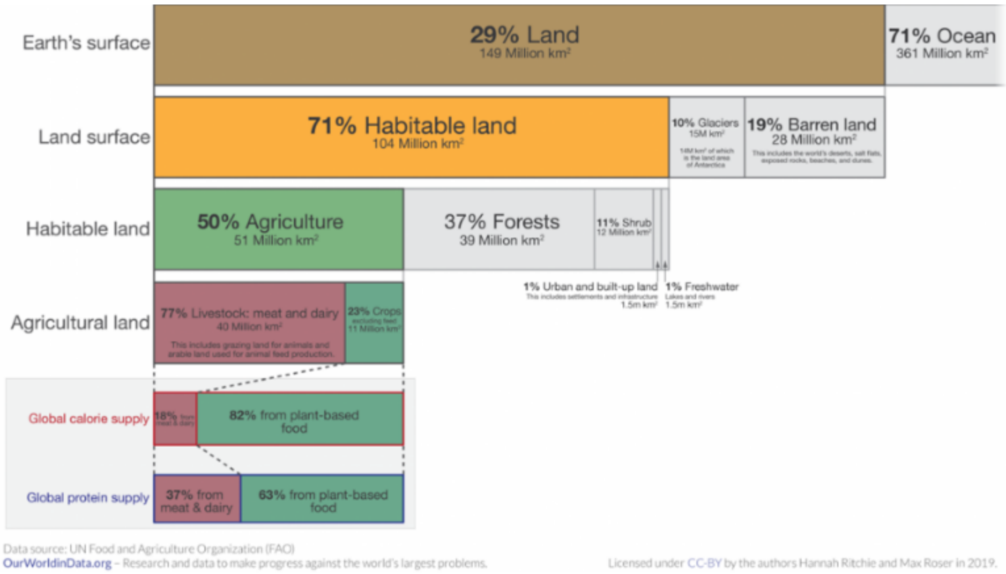

Figure 118: Global land use for food production.

Source: Our World in Data, (2019).

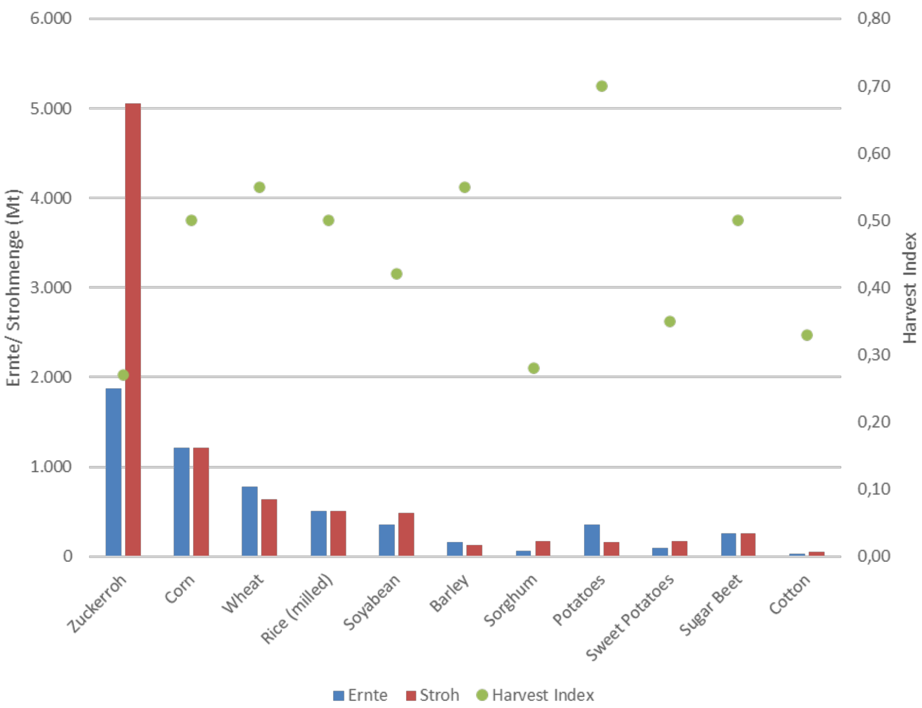

Figure 119: Harvest, straw quantity and harvest index of various food crops. Source: RESCO, (2018).

Agriculture produces large amounts of biowaste that can be used to generate fuel or electricity and heat. The ratio between the edible or usable part and the non-usable part of a food crop is defined by the harvest index. The harvest index is the ratio between the yield of a crop and the total biomass of a crop. In Figure 119 shows the harvest indices of different crops, their total global production in 2020 and their estimated straw/bio-waste production. Crops with higher harvest indices such as potatoes or barley produce little biowaste, while crops with lower harvest indices such as sugarcane produce more biowaste. It is estimated that about 8,800 Mt of waste was produced, consisting of inedible cellulosic waste, which corresponds to 35,000 TWh (126 EJ) of primary energy, assuming that the cumulative average calorific value of this biomass is about 4 kWh/kg.

2.7.2.2 Sugar, cellulose and starch

Ethanol is a well-known biofuel based on sugar, starch and now also cellulose. The production processes are well established and practised worldwide. Bioethanol is used to partially replace or blend with fossil petrol. Global production of bioethanol in 2020 was about 110 billion litres[336][337]. The largest producing countries are the USA, Brazil and the European Union. In the USA, bioethanol is mainly produced from corn starch, while in Brazil sugar cane is the most important raw material source. In the EU, bioethanol is produced from a variety of raw materials such as wheat, corn and sugar beet.

Bioethanol is produced from sugar through fermentation. In this process, the sugar is converted into ethanol by yeast. Before fermentation, starch must first be converted into sugar (monosaccharides) by a process called "enzymatic hydrolysis". In enzymatic hydrolysis, the starchy starting material is first broken down. Then enzymes such as amylases are added to facilitate fermentation. The production of bioethanol from cellulose requires more complex processing because cellulose is a complex molecule. The cellulose must first be broken down into its components before it can be fermented. The cellulose must be broken down into simple sugars by a process known as hydrolysis, which can be done by various methods such as acid hydrolysis, enzymatic hydrolysis or steam explosion.

Overall, bioethanol from sugar and starch are an important contribution to reducing greenhouse gas emissions and dependence on fossil fuels. Nevertheless, the production of ethanol from sugar and starch competes with food production. About 60 % of the total amount of

[336] Cf. Hamburg Open Online University 2021
[337] About 60 billion litres in the US, 33 billion litres in Brazil and 5 billion litres in the EU

ethanol is produced from corn, 25 % from sugar cane, 7 % from molasses 4 % from wheat and the rest from casava, sugar beet.

2.7.2.3 Natural fats and oils

Hydrogenated vegetable oils ("HVO") are produced from natural vegetable oils by catalytic reaction with hydrogen. Examples of vegetable oils are rapeseed oil, soybean oil, palm oil and sunflower oil. This produces hydrocarbon mixtures with similar or even better properties compared to corresponding fractions from petroleum, essentially paraffin and diesel. The raw materials for HVO are vegetable oils that do not compete with food production. Used vegetable oils or fats that would otherwise be incinerated after use are used. To a lesser extent, this also includes used animal fats and waste from fish processing. HVO production in 2020 amounted to 6.2 Mt/a worldwide, with the focus on Europe (3.4 Mt/a) and the USA (2.1 Mt/a).

2.7.2.4 Waste water

A 2021 Copernicus study estimates global wastewater production at 359.4 billion m^3 per year, of which 63% (225.6 billion m^3 per year) is collected and 52% (188.1 billion m^3 per year) is treated.[338] It is estimated that approximately 172 billion m^3 per year is released untreated into the environment, which is significantly lower than previous estimates of ~80 %. An estimated 40.7 billion m^3 per year of treated wastewater is intentionally reused.

2.7.2.5 Biowaste in the MSW[339]

Every year, 2.01 billion tonnes of municipal solid waste are generated worldwide, of which at least 33 %, very conservatively estimated, are not disposed of in an environmentally friendly way (see Figure 120 right).[340] High-income countries generate relatively little food and green waste, accounting for 32 % of total waste, and generate more dry waste that could be recycled, including plastic, paper, cardboard, metal and glass, which account for 51 % of waste. According to the World Bank, middle- and low-income countries generate 53 % and 57 % food and green waste, respectively, with the share of organic waste increasing as the level of economic development decreases.

338 Cf. Jones et al., (2021).
339 MSW: Municipal Solid Waste
340 Cf. World Bank, (2020).

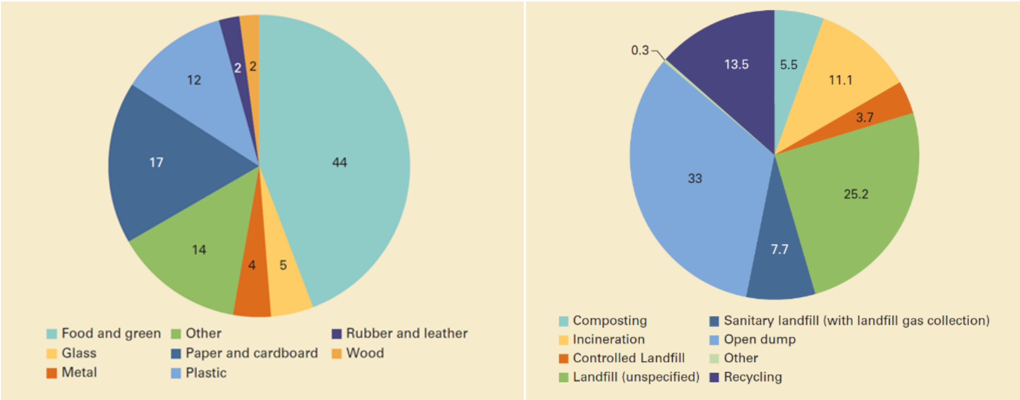

Figure 120: Composition of global MSW and type of waste disposal considered globally.

Source: World Bank, (2020).

In future, global waste generation is expected to increase to 3.40 Gt by 2050. In the regions with the fastest total waste generation, this increases as follows by 2050:

- Sub-Saharan Africa: tripling
- South Asia: doubling
- and the Middle East and North Africa: doubling

In these regions, more than half of the waste is currently "disposed of" in landfills.

2.7.2.6 Short-rotation plantations

Short-rotation plantations (SRC) are plantations of fast-growing tree species that are capable of fruiting, such as willow, alder and poplar, on agricultural land with a very short rotation period. [341][342] The biomass produced can be used as raw material, for example in the paper, pulp and wood-based materials industry, but it is mostly used as wood chips for energy production. In short-rotation plantations, so-called cuttings, i.e. sections of one-year-old, well-developed shoots, are planted in rows and, depending on the species and climate, harvested every 3 to 10 years by machine or motor (see also chapter 2.10.5). The rootstock remaining in the soil has the ability to sprout, and so after harvesting the trees sprout again without having to be replanted.

Under good conditions, short-rotation plantations can produce an average of about 5 to 10 t/ha/a dry matter, under very good conditions even double of this amount. After about 20 years, the production power of the plants decreases and the area should be replanted if it is to

[341] Cf. Bavarian State Institute for Forestry and Forestry 2021
[342] "In forestry, the rotation period is the expected period of time from the establishment of the stand to the final use by logging" Rotation period - Wikipedia

be used further. The average energy content is between 15.5 and 18.5 MJ/kg[343] . About 0.06 MJ/kg is consumed during harvesting and shredding, which makes the energy balance very good. It should be noted, however, that fast-growing plants also have a lower specific energy content, so that the volume of raw materials to be processed increases sharply. For example, one cubic metre of firewood made of oak provides approx. 1,890 kWh, while fast-growing poplar only provides 1,110 kWh.

Potential unused areas available for afforestation are in the order of 390 to 750 Mha worldwide. Assuming that these areas are used for a global short-rotation plantation programme, this results in a global primary energy potential of between 13 PWh/a and 25 PWh/a from short-rotation plantations[344] .

2.7.3 Primary energy potential of biomass for the production of fuels

In 2016, about 0.88 Gt of biodegradable waste was generated worldwide in the form of food and green waste. This corresponds to a primary energy potential of between 2,500 TWh/a and 3,600 TWh/a. This waste can be fermented to produce biogas. Waste wood, on the other hand, had a global primary energy potential of between 300 and 400 TWh/a in 2016.

Worldwide, about 172 billion m³ of wastewater was discharged untreated into bodies of water. This water could be used for hydrogen synthesis with the help of plasma-phase oxidisers. However, the total global potential of this resource is difficult to estimate, as the ingredients of this untreated wastewater are unknown and the technologies for hydrogen synthesis from it are still in the development phase.

By 2030, about 50 - 80 million t of HVO could be produced, corresponding to 600 TWh/a in the form of HVO. The largest bioenergy primary energy potential comes from agricultural and forestry waste with about 37 PWh/a. The potentials from different sources are shown in Table 27.

Table 27: Primary energy potential of various bio raw materials for the production of bioenergy/biofuels.

Bioresource	Quantity	Primary energy potential	Process for conversion into energy/biofuels
MSW: Food and other green waste	0.88 Gt per year (in 2016)	2.552 to 3.696 TWh/a	Fermentation
MSW: Wood	0.1 Gt per year (in 2016)	300 to 400 TWh/a	Gasification

[343] Cf. Wikipedia 2023
[344] Harvest factor of 8 t/ha/a from short rotation coppice and calorific value of the harvest of 15 MJ/kg

Untreated waste water / polluted water	172 billion m^3 per year (in 2021)	N.A.	Dark fermentation, plasma analysis, microbiological electrolysis
HVOs from used cooking oils	50-80 Mt per year (until 2030)	600 TWh	Hydrogenation of waste oils
Agricultural and forestry waste	35,456 TWh from agricultural waste (128 EJ in 2016) 1,285 - 2,116 TWh from forest waste (4.64 - 7.64 EJ in 2016)	36,741 TWh/a to 37,572 TWh/a	Fermentation, gasification, combustion

Other studies by renowned institutions such as IEA, IRENA, IPCC and WBA estimate the bioenergy potential at a minimum of 14 PWh/a and a maximum of 67 PWh/a. A summary of the estimated bioenergy potential is shown in Table 28 listed.

Table 28: Bioenergy potential according to various institutions

Source: IRENA, (2022).

Institution	Primary energy potential of bioenergy per year	Year
IEA	130 - 240 EJ (36 PWh-67 PWh)	unclear
IRENA	54 EJ (approx. 15 PWh)	2020
IRENA	153 EJ for 1.5°C scenario (approx. 42 PWh)	2050
IPCC	90 EJ (approx. 25 PWh)	unclear
IPBES	50 EJ (approx. 14 PWh)	unclear
Energy Transition Commission	40 - 120 EJ (approx. 11 PWh-33 PWh)	unclear
World Bioenergy Association[345]	30 EJ from energy crops (approx. 8 PWh) 34 EJ from agricultural residues and manure (approx. 9 PWh) 78 EJ from forestry waste (22 PWh) 8 EJ from organic waste (2 PWh)	2035

2.7.4 Process for the production of biofuels from biomass

Biomass can be used to generate electricity, to produce biofuels and as a raw material.

[345] Cf. World Bioenergy Association, (2016).

2.7.4.1 Production of 1G and 2G biofuels

Biofuels are classified according to type of production and input materials (see Figure 121) first generation (1G) biofuels are produced from biomass commonly used for food, such as corn, wheat, soy and sugarcane, through the fermentation of sugars and starches in the biomass into fuels such as ethanol.[346] Markets and technologies for first-generation biofuels are well established and widely used around the world. Rapid expansion of 1G biofuel production may negatively impact global food production. Biofuel crops used to synthesize 1G biofuels from Bio fuel crops of the first generation are in direct competition with food resources, and any displacement of food crops by biofuel cultivation could reduce food supply and increase food prices.

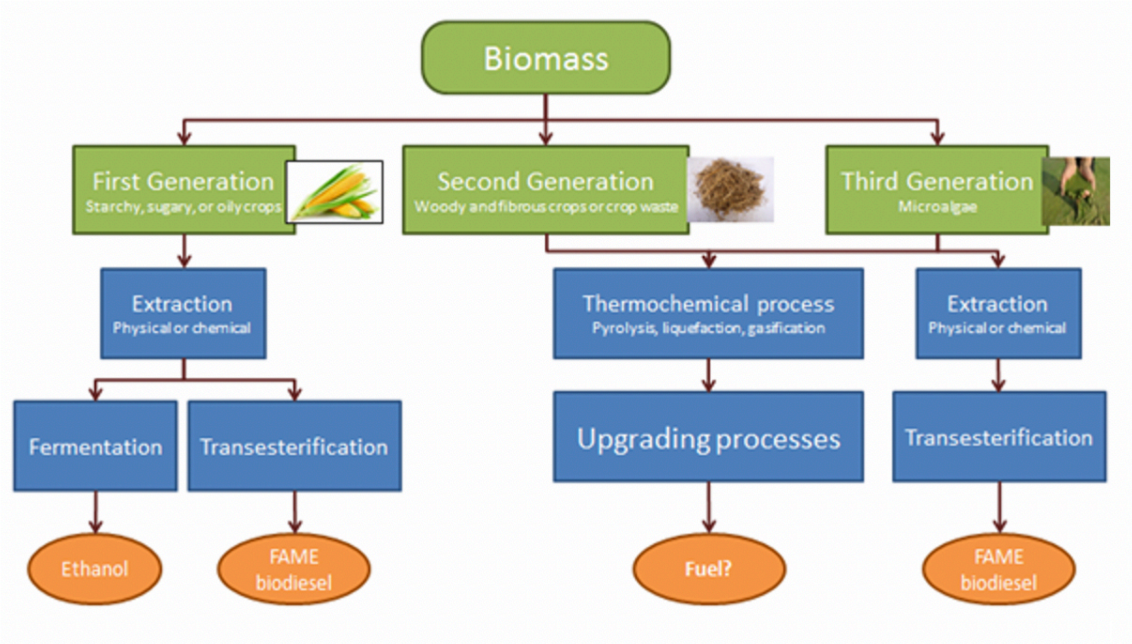

Figure 121: Classification of biofuels

Source: Fundamental Trajectory, (2015)

Second-generation (2G) biofuels are made from cellulose, such as grasses and fast-growing trees. The processes for their production are more complex and less advanced than those for first-generation biofuels and often involve the enzymatic conversion of fibrous, non-edible material called "cellulose" into corresponding sugar fractions and their fermentation into alcohols.[347]

[346] Cf. Nagler & Gerace, (2020).
[347] Cf. Nagler & Gerace, (2020).

2.7.5 E-gasoline, E-diesel and E-kerosene

2.7.5.1 Production of 1G biodiesel

The production of first generation biodiesel (1G) from vegetable or animal oils takes place in several steps. First, vegetable oils are extracted from the plants by pressing or dissolving. Then the extracted oil is purified and processed to remove impurities and improve the quality of the oil. This is followed by transesterification, in which the purified and processed oil reacts with an alcohol (usually methanol) and a catalyst (usually sodium hydroxide) to convert into fatty acid methyl ester (biodiesel) and glycerol (see Figure 122). The biodiesel produced is then purified and processed again, in particular to improve its storage stability. The resulting glycerine is separated from the biodiesel to be used for other purposes. About 100 kg of oil or fat react with 10 kg of the short-chain alcohol in the presence of a catalyst to form 100 kg of biodiesel and 10 kg of glycerine.[348]

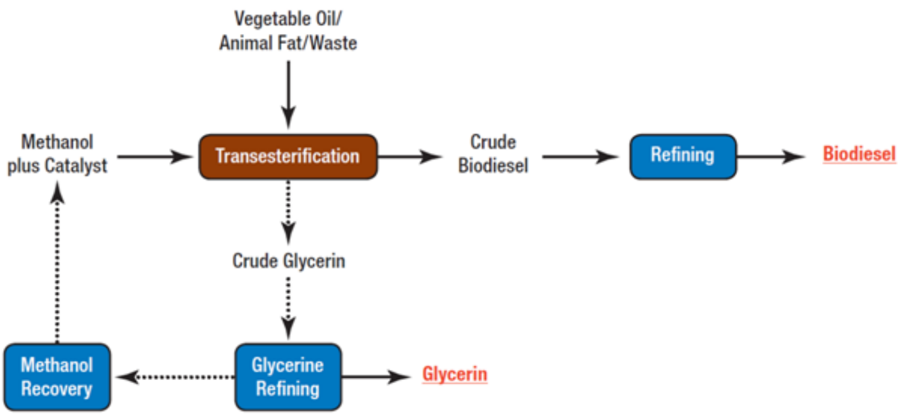

Figure 122: Synthesis of biodiesel from vegetable oils and methanol.

Source: USDOE, (2022).

2.7.5.2 Production of 2G biodiesel

Second-generation biodiesel, or HVO[349], is usually the product of the total hydrogenation of fats and oils (especially used fats/oils) to form a high-quality, petroleum-like diesel or paraffin fraction. By-products include water and propane.

The production volume of HVO is expected to more than quadruple by 2025 due to plants already under construction, especially in the USA with a forecast 12.6 Mt/a, and in Europe with 11.3 Mt/a. In Europe, two plants of Neste (in Finland and the Netherlands) with 1.5 Mt annual

[348] Cf. USDOE, (2022).
[349] HVO: Hydrotreated Vegetable Oils

capacity as well as plants of ENI, Gela and ENI, Porto Maghera in Italy (0.7 Mt/a + 0.24 Mt/a) and TOTAL, La Mède in France (0.5 Mt/a) dominate the market so far. In the period up to 2025, among others, UPM is planning a plant in Kotka, Finland (0.5 Mt/a), St1 0.1 Mt/a in Gothenburg and Preem 1.3 Mt/a in Lysekil and Gothenburg in Sweden.

Hydrogenated Vegetable Oils (HVO) are produced from natural vegetable oils by catalytic reaction with hydrogen. This generates hydrocarbon mixtures with similar or even better properties compared to corresponding fractions from petroleum, essentially paraffin and diesel.

In Germany, approx. 27 Mt of diesel were consumed in 2021, worldwide it is approx. 800 Mt. In relation to the total market, the contribution of HVO is rather small at just under 30 Mt worldwide (this is the existing capacity and the capacity under construction in 2025)[350] , but can be realised with simple measures and without changing infrastructure and engine adaptations.

HVO could become more important as a paraffin substitute for aircraft, as an alternative to the complex Fischer-Tropsch synthesis.

The raw material for HVO can be vegetable oils that do not compete with food production. Used vegetable oils or fats that would otherwise be incinerated after use are used. To a lesser extent, this also includes used animal fats and waste from fish processing.

They can be described as CO_2-neutral fuels if CO_2-neutral hydrogen is used for hydrogenation. However, hydrogenation with "grey" hydrogen also leads to a substantial reduction in CO_2 emissions.

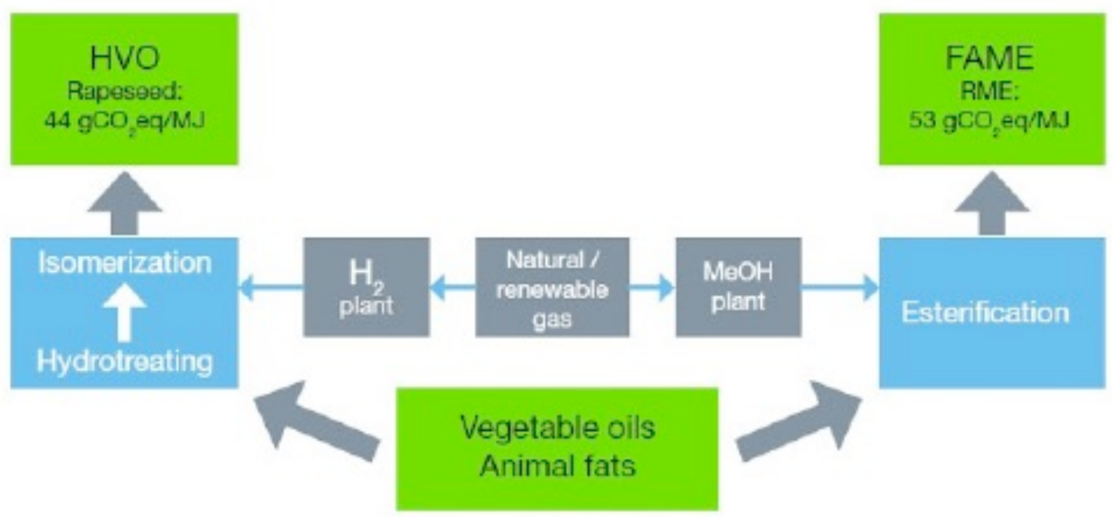

Figure 123: Comparison of CO_2 emissions of HVO and biodiesel (RME)[351]
(for hydrogenation with grey hydrogen or transesterification with grey methanol)

[350] Greenea PM, 22.7.2021
[351] Extracted from Neste Renewable Diesel Handbook.

Fossil diesel emits about 84 grams of CO_2 equivalent per MJ compared to 44 grams for HVO (produced with grey hydrogen, 48% CO_2 reduction) and 53 grams for conventional biodiesel (rapeseed methyl ester, produced with grey methanol, 35 % CO_2 reduction), see Figure 123.

When using "green" hydrogen or "green" methanol, the CO_2 reduction is 90 % and more compared to fossil diesel.

Production of HVO

The production route of HVO is shown in Figure 124[352] :

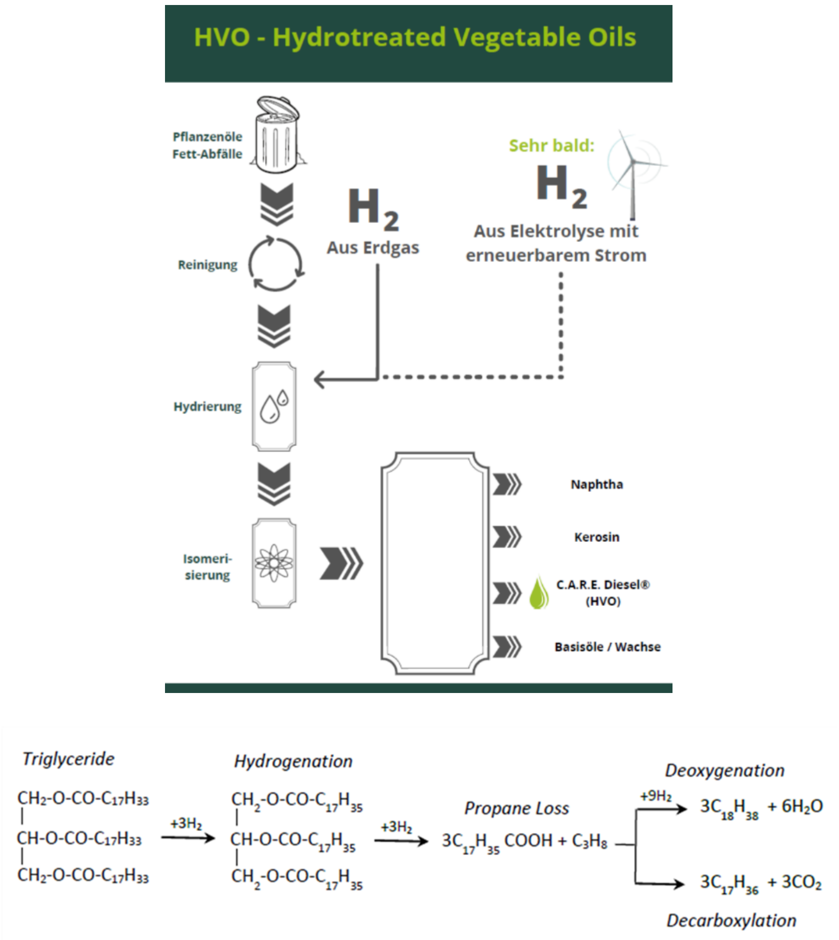

Figure 124: Production of HVO

The chemical reaction of the oil (triglyceride) with hydrogen leads to aliphatic hydrocarbons as well as to the by-products propane, water and, through decarboxylation as a side reaction, also to small amounts of CO_2.

Conventional biodiesel is different: here, the triglyceride is transesterified with methanol. The fatty acid methyl ester (FAME, in the case of rapeseed: RME) and glycerol

352 Flyer CARE Diesel (Tool Fuel Services GmbH, Hamburg)

are produced as a by-product. Attempts to produce (green) hydrogen by glycerol reforming have not found any technical application.

HVO processes are established in a large scale and are licensed, among others, by

- Haldor Topsoe (DK): HydroFlexTM process
- UOP / ENI (US/I): Ecofining process
- Axens (F): Vegan process
- NextChem/Technimont Saola Energy process

Neste, Shell, ConocoPhillips and PetroBras, among others, have their own processes.

Engine properties of HVO

These are generally better than of the corresponding fossil fuels, and adjustments to the engines or turbines are not necessary. The exhaust gas quality is also significantly better, as shown in a comparison in Table 29 and in Figure 125.[353] EN 590 is conventional summer diesel, GTL a Fischer-Tropsch-based diesel fraction and FAME a rapeseed oil-based one.

Table 29: Properties of HVO compared to fossil desulphurised diesel (EN 590), Fischer-Tropsch diesel (GTL) and rapeseed oil-based biodiesel (RME),

Source: Aatola, H. et al (2008)

	HVO	EN 590 (summer grade)	GTL	FAME (from rape seed oil)
Density at 15 °C (kg/m^3)	775 ... 785	≈ 835	770 ... 785	≈ 885
Viscosity at 40 °C (mm^2/s)	2.5 ... 3.5	≈ 3.5	3.2 ... 4.5	≈ 4.5
Cetane number	≈ 80 ... 99	≈ 53	≈ 73 ... 81	≈ 51
Distillation range (°C)	≈ 180 ... 320	≈ 180 ... 360	≈ 190 ... 330	≈ 350 ... 370
Cloud point (°C)	−5 ... −25	≈ −5	−0 ... −25	≈ −5
Heating value, lower (MJ/kg)	≈ 44.0	≈ 42.7	≈ 43.0	≈ 37.5
Heating value, lower (MJ/l)	≈ 34.4	≈ 35.7	≈ 34.0	≈ 33.2
Total aromatics (wt-%)	0	≈ 30	0	0
Polyaromatics (wt-%)$^{(1)}$	0	≈ 4	0	0
Oxygen content (wt-%)	0	0	0	≈ 11
Sulfur content (mg/kg)	< 10	< 10	< 10	< 10
Lubricity HFRR at 60 °C (µm)	< 460$^{(2)}$	< 460$^{(2)}$	< 460$^{(2)}$	< 460
Storage stability	Good	Good	Good	Very challenging

$^{(1)}$ European definition including di- and tri+ -aromatics
$^{(2)}$ With lubricity additive

[353] Cf. Aatola, H. et al, (2008)

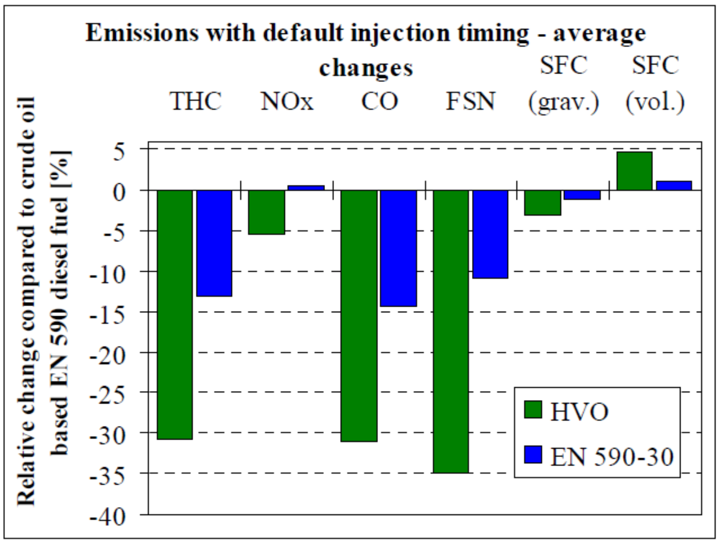

Figure 125: Exhaust gas quality of HVO and of an HVO/diesel 30/70 mixture compared to 100% diesel

Source: Aatola, H. et al (2008)

The favourable properties of HVO - as with diesel from low-temperature Fischer-Tropsch plants - are based on the high content of long-chain paraffinic hydrocarbons, a low proportion of naphthenic hydrocarbons and the absence of aromatic compounds.

Indicative of the high quality of HVO (and GTL diesel) is the high cetane number as an indicator of the fuel's ignition readiness.

All other parameters are comparable. (Except for the low storage stability of biodiesel (RME), which tends to form resinous flocculation, especially when exposed to oxygen).

Availability and production volumes

Worldwide and in Europe:

HVO production in 2020 amounted to 6.2 Mt globally, with a focus on Europe (3.4 Mt) and the USA (2.1 Mt).

The capacity in 2020 amounted to 7 Mt, see Figure 126.[354]

This is expected to more than quadruple by 2025 due to plants already under construction, especially in the USA with a forecast 12.6 Mt/year and 11.3 Mt/year in Europe [355][356] . The largest project is the conversion of a Phillips 66 oil refinery into an HVO refinery in California with a capacity of 2.5 Mt/year from 2023[357] .

In Europe, the market has so far been dominated by two Neste plants (in Finland and the Netherlands) with an annual capacity of 1.5 Mt, as well as plants operated by ENI, Gela and ENI, Porto Maghera in Italy (0.7 million + 0.24 Mt) and TOTAL, La Mède in France (0.5 Mt).

[354] Cf. Statista 2022, "HVO Global HVO biodiesel capacity worldwide in 2020 with forecast 2025,
[355] Cf. Quantum Commodity Intelligence, 22.7.2021
[356] Cf. Global HVO biodiesel capacity 2020-2025, by region, Statista
[357] Cf. PM, Phillips 66 Corporate Communications, 11.8.2020

In the period up to 2025, among others, UPM is planning a plant in Kotka, Finland (0.5 Mt per year), St1 0.1 Mt per year in Gothenburg and Preem 1.3 Mt per year in Lysekil and Gothenburg in Sweden.

Further plants are to be built at PKN, Plock/Poland and in Litvinov, Czech Republic.[358]

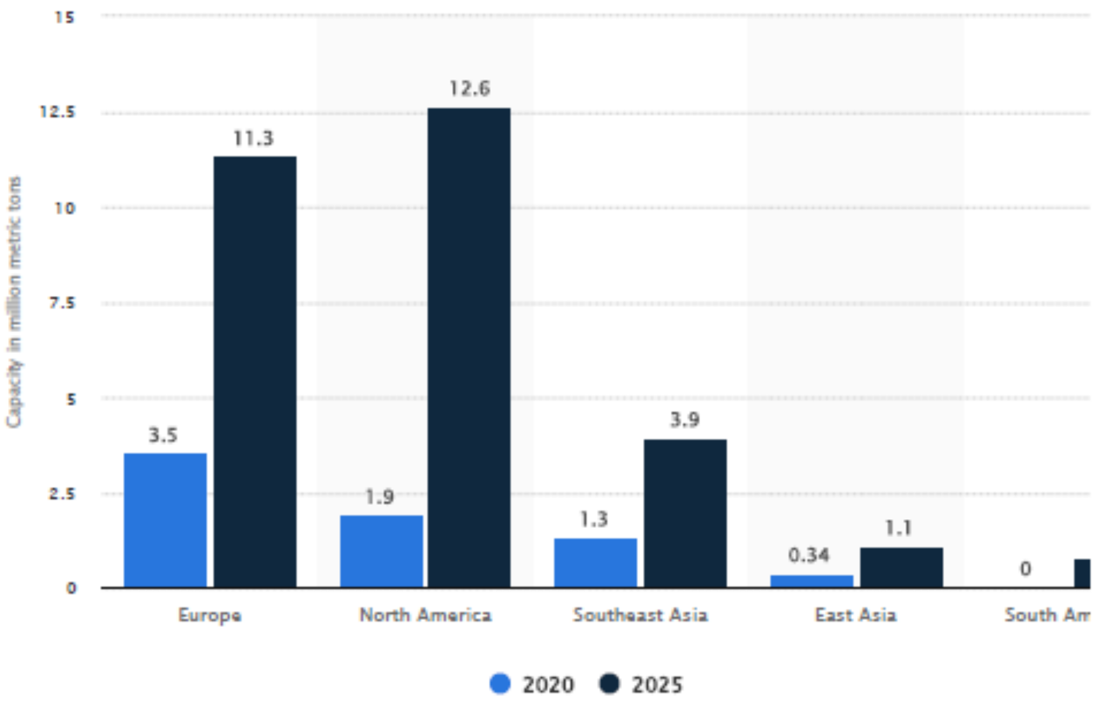

Figure 126: Worldwide HVO production capacity 2020, forecast for 2025

Source: statista 2022, HVO Global HVO biodiesel capacity worldwide in 2020 with forecast 2025,

The majority of HVO is sold in the form of blends with conventional diesel in the range of 10-50 %. HVO 100 is mainly sold in the production countries (Netherlands, Scandinavia).

Germany:

No HVO is produced in Germany, nor is there currently a project. Small quantities are imported mainly from the Netherlands and distributed through a single-digit number of petrol stations. The estimated total volume of biodiesel (sum of FAME and HVO) for 2022 is about 2.5 Mt[359], which corresponds to about 9% of total consumption (7 % is the blending rate with conventional diesel fuel).

Infrastructure (petrol station network):

[358] Cf. S. Wright, "Rise of HVO to be the downfall of traditional biodiesel in Europe", ICIS Insights, 28.11.2019.
[359] Cf. PM, UFOP-Union for the Promotion of Oil and Protein Plants eV, Berlin, 9.9.2022

HVO or HVO blends are currently offered by approx. 9400 petrol stations worldwide, with a focus on the USA (California) and Europe. In Europe at approx. 8,000 petrol stations.[360]

Figure 127 shows a map of filling stations for Europe with a subdivision of HVO 100, HVO blends and (from 2023) seven filling stations for "e-fuel diesel" as an ad-on mixture.[360] The latter are likely to use hydrogen generated from renewable electricity to produce the HVO.

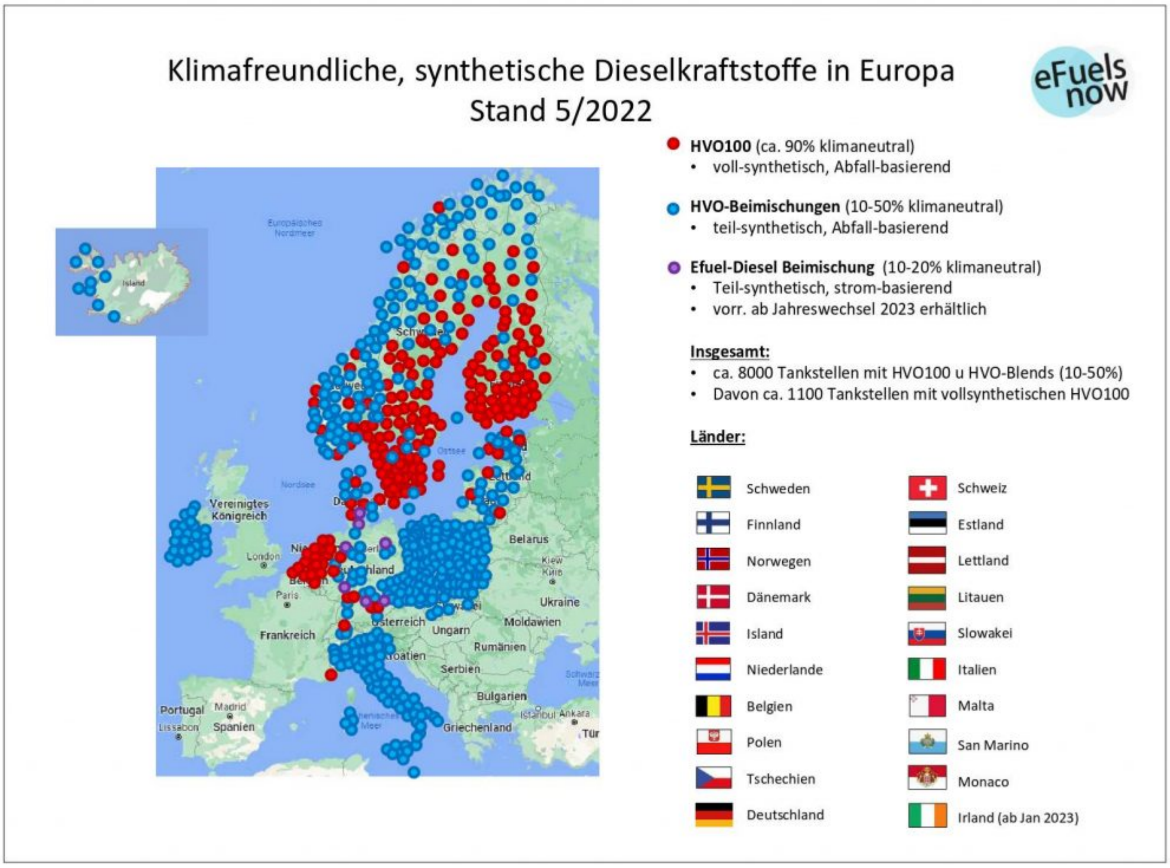

Figure 127: "Filling station map" for HVO-containing diesel fuels in Europe

Source: www.efuelsnow.de (17.9.2022)

Estimated total potential:

Worldwide, 213 Mt of vegetable oils were produced in 2021. The largest share was either thermally recycled after use, processed into (conventional) biodiesel and, to a lesser extent, also used in oleochemistry (for detergents), and for animal feed production.

360 Cf. www.efuelsnow.de (17.9.2022)

One driver for the increased use of HVO based on waste oils and fats instead of FAME is the use of imported palm oil from Southeast Asia for the production of biodiesel, which has come under criticism and is therefore decreasing.

The global market for used vegetable oils and fats is not very transparent, so that a very rough estimate of the available potential for HVO could be 50 - 80 Mt per year. This would correspond to 6 -10 % of current diesel or 15 - 25 % of current paraffin consumption worldwide.

Regarding synthetic aviation fuel (SAF), this estimate is consistent with a demand estimate for 2022 of approx. 70 Mt of SAF, whereby this is only partly derived from HVO and otherwise from other biogenic sources due to insufficient available production capacity.

2.7.5.3 Production of biosynthesis gas and biomethane

Gasification of biomass to synthesis gas is one of the processes for converting biomass into gaseous biofuels. In this process, biomass is gasified at approx. 700 - 900°C with a limited supply of oxygen. By using air or oxygen, the biomass is partially oxidised, and syngas is produced, which consists of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2) and pollutants. The syngas is then purified and could be burnt in a gas engine to generate electricity; the exhaust gas can be used to generate steam and is then used in a steam turbine (see Figure 120).

The waste heat from the exhaust gases can also be recovered and fed into a district heating system.[361] The overall efficiency of a co-generation system can be up to 85 %.[362]

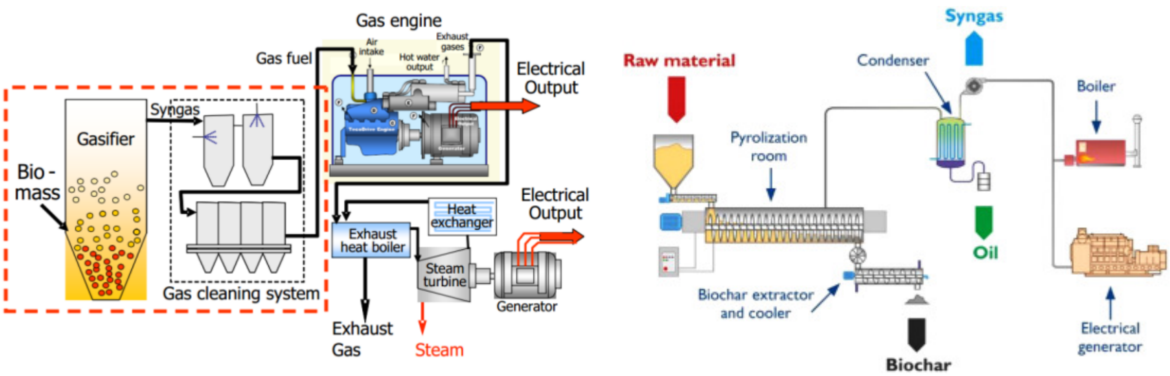

Figure 128: Gasification (left) and pyrolysis (right) of biomass for power generation.

Source: Access Biomass Power Ltd, 2018; Shen et al., (2016).

[361] Cf. European Regional Development Fund & Interreg, (2021).
[362] ibid

In pyrolysis, biomass is thermally decomposed at high temperatures of 400 to 900°C in the absence of oxygen. This produces syngas (from carbon monoxide and hydrogen), bio-oil and bio-char.[363]

Biogas is a mix of methane, CO_2 and small amounts of other gases produced by anaerobic fermentation of organic matter in an oxygen-deficient environment. The methane content of biogas is typically between 45 vol% and 75 vol%, with most of the remainder being CO_2. This variation means that the energy content of biogas can vary; the lower heating value is between 16 MJ/Nm^3 and 28 MJ/Nm^3.[364]

Biogas can be used directly to generate electricity and heat or as an energy source for cooking. The exact composition of biogas depends on the type of feedstock and the production route; this includes the following main technologies:[365]

- Bio-digestion systems: These are airtight systems (e.g. containers or tanks) in which organic material diluted in water is broken down by naturally occurring microorganisms. Impurities and moisture are usually removed before the biogas is used.
- Systems for the utilisation of landfill gas: The decomposition of municipal solid waste under anaerobic conditions at landfills produces biogas. This can be collected via pipes and extraction wells together with compressors to be piped to a central collection point.
- Sewage treatment plants: These plants can be equipped to recover organic matter, solids and nutrients such as nitrogen and phosphorus from the sewage sludge. After further treatment, the sewage sludge can be used to produce biogas in an anaerobic digester.

2.7.5.4 Production of biofuels from algae

Algae are organisms that grow in aquatic environments and use light and carbon dioxide to produce biomass. There are two classifications of algae: Macroalgae and Microalgae. Macroalgae, are the large multicellular algae that often grow in ponds. Microalgae, on the other hand, are measured in micrometres in size. They are tiny, single-celled algae that usually grow in suspension in a body of water. Microalgae have long been considered potentially good sources for biofuel production because they have a relatively high oil content and produce biomass quickly.[366]

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[363] Cf. Zhou et al., (2020).
[364] Cf. IEA, (2020).
[365] ibid
[366] Cf. Farm Energy, 2019; Chisti, 2007.

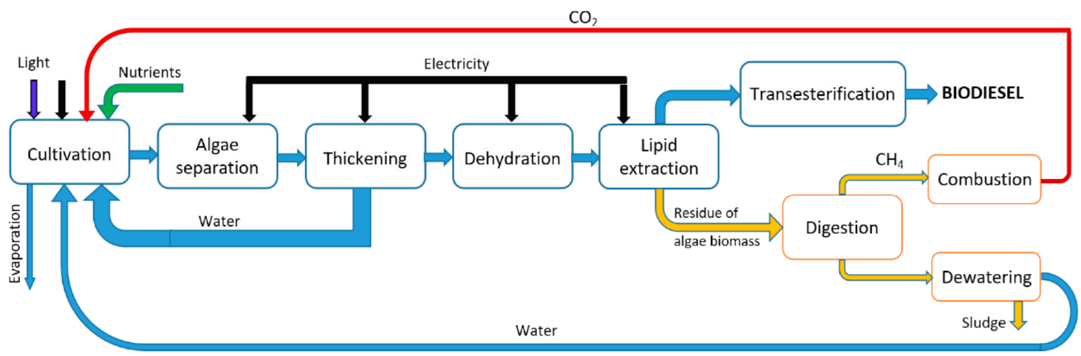

Figure 129: Production of biofuels from algae

Source: Clarens et al., 2011.

Algae use light as a source of energy to produce biomass from water and CO_2 by means of photosynthesis (see Figure 129). Algae also need nitrogen and phosphorus as important nutrients. Various factors influence the optimal growth of algae and their lipid accumulation. These include the availability of micro- and macronutrients, light intensity, CO_2, water temperature and pH.[367] Microalgae can provide more oil per hectare of occupied land compared to conventional biodiesel crops. For example, the yield of algae with 30% oil in dry biomass is up to 58,700 litres/ha/a, which is much higher compared to rapeseed (1,190 litres/ha/a) or soybean (446 litres/ha/a).[368] The following three systems are relevant in the production of biofuels from algae:

- *Open Pond*: This involves growing algae in open ponds or basins that are exposed to the sun. This method is simple and inexpensive, but it is prone to contamination and can have difficulty controlling the conditions in which the algae grow.
- *Closed Pond:* This involves growing algae in closed ponds that are protected from environmental conditions. This method allows better control of growing conditions, but it is also more expensive than the Open Pond method.
- *Photobioreactor*: This involves cultivating algae in controlled systems using light and nutrients. This process allows very good control of growth conditions and can achieve higher algae productions, but it is also the most expensive process.

The Department of Energy (DOE) put considerable effort into advancing the commercial production of algae biofuel in the 1980s to 1990s. After 16 years of research, the DOE concluded that algae biofuel production is still too expensive to be commercialised in the near future. There are four main factors limiting commercial algae production: the difficulty of obtaining desirable species in the culture system, the low yield of algae oil, land requirements, and the

[367] Cf. Bošnjaković & Sinaga, (2020).
[368] Cf. Bošnjaković & Sinaga, (2020).

high cost of harvesting algae biomass. DOE concluded that there is need for a significant amount of land, water and CO_2 to support algal biofuel technology.[369]

2.7.5.5 Production of hydrogen from sewage sludge and wastewater

Various biomass-based technologies for the production of green hydrogen are being developed. Wastewater from various sources such as sewage treatment plants and distilleries can be recycled and used to produce green hydrogen. This can then be sold as fuel for various applications in different sectors. Another technology currently being tested is the "Graforce Wastewater Plasmalyzer".[370] (see also chapter 3.4.3.3) It uses solar or wind energy to generate a high-frequency voltage field above the wastewater. It splits the carbon and nitrogen-containing compounds such as urea, nitrates and ammonium into the individual atoms C, N, H and O. The gases are then separated with the Graforce. The gases are separated and transported further using Graforce membrane technology. This plant for the production of green hydrogen from wastewater (3,000 l/h) is in operation at Berliner Wasserbetriebe Waßmannsdorf wastewater treatment plant. It produces up to 50 kg of hydrogen per day, which requires 20 kWh of energy per kg of hydrogen produced.[371] However, this technology is still in the early demonstration phase.

2.7.5.6 Water balance for the production of bio-ethanol and bio-diesel

The water consumption for the production of biodiesel is higher than that for the production of ethanol.[372] The production of biodiesel from Atropa (spurge family) is the most water-intensive. The water balance of various plants for the synthesis of bioethanol and biodiesel is shown in Figure 130.

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[369] Cf. Farm Energy, (2019).
[370] Future Bridge, (2022).
[371] Cf. Future Bridge, (2022).
[372] Cf. Winnie et al., (2009).

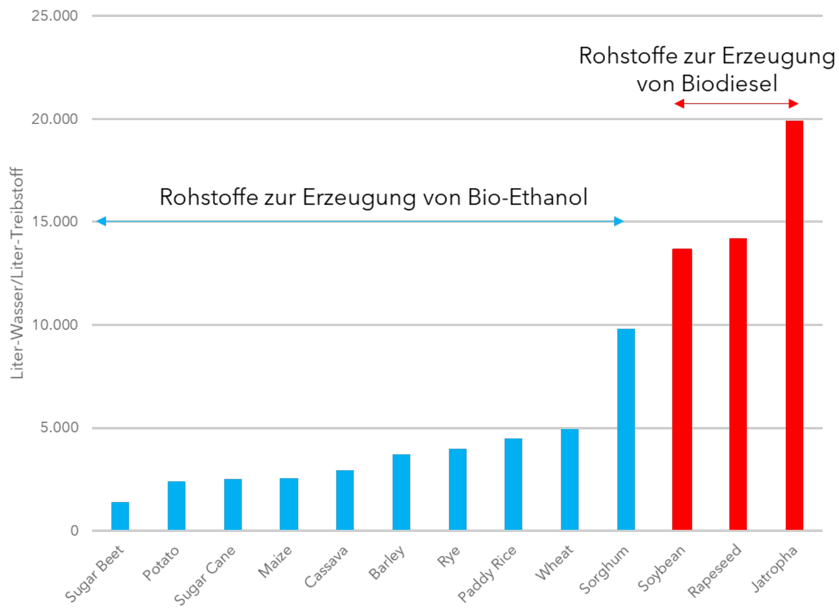

Figure 130: Water balances (green + blue) of various energy crops for the synthesis of bioethanol and biodiesel.

Source: Winnie et al., (2009).

The water balance consists of three components: the green water balance, the blue water balance and the grey water balance. The green water balance refers to rainwater that evaporates during production, mainly during plant growth. The blue water balance refers to surface and groundwater for irrigation that evaporates during plant growth. The grey water balance is the amount of water polluted during production, defined as the amount of water needed to dilute the pollutants discharged into the natural water system to the extent that the quality of the surrounding water remains above the agreed water quality standards.

2.7.6 Developmental relevance

The production of 1G bioethanol is an established process and is used worldwide to replace petrol or blend with petrol. In the USA and China, biodiesel is mainly produced from corn, while in India and Brazil it is produced from sugar cane molasses and sugar cane.[373] In addition to the above-mentioned feedstocks, cassava, sweet potato, sorghum and wheat are also used in Southeast Asia, China and the EU. Countries in sub-Saharan Africa and Latin America also promote the production of first-generation bioethanol from sugar cane. Biodiesel production in the USA, Brazil and Argentina predominantly uses soybeans as feedstock.[374] The most important raw material for the production of first-generation biodiesel in the EU, on the other hand, is rapeseed. Southeast Asian countries such as Indonesia and Malaysia export palm oil

[373] Cf. Gasparatos et al., (2013).
[374] Cf. Gasparatos et al., (2013).

for biodiesel production, and Atropa is also promoted in India, China, Latin America and sub-Saharan Africa for the production of first-generation biodiesel.

Nevertheless, the production of 1G biofuels can have negative impacts on the environment, biodiversity, soil and food security. For example, the conversion of natural habitats into agricultural land can lead to a loss of biodiversity and ecosystem services. The use of pesticides and fertilisers in bioenergy production can pollute water and reduce soil fertility.

Competition for limited land and resources can lead to higher food prices and reduced food security. Although bioenergy is considered renewable and carbon neutral, its production and processing can still contribute to significant greenhouse gas emissions and contribute to climate change. In India, sugarcane-based ethanol production has led to water scarcity and reduced access to clean drinking water.[375] In the US, corn-based ethanol production has been criticised for its high use of fertilisers and pesticides and its contributions to rising food prices and food security problems.[376] In Brazil, soy-based biofuel production is linked to the clearing of the Amazon rainforest, loss of wildlife habitat, and soil degradation. Palm oil biofuel production in Southeast Asia has been linked to deforestation, habitat loss for endangered species such as orange tomatoes, and greenhouse gas emissions from land use change.[377]

[375] Cf. Supriya, (2022).
[376] Cf. USDA, (2009).
[377] Cf. WWF, (2021).