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 2-6

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2.6 Production and use of hydrogen derivatives

2.6.1 Production of e-ammonia

Traditionally, ammonia production is based on natural gas or coal. Thanks to optimised technologies, economies of scale make plants with a capacity of 3,000 tons of ammonia/day and more relatively cost-effective. However, these plants have high greenhouse gas emissions of about 1.68 t CO_2 /t ammonia - so for a plant with a capacity of 3,000 t ammonia/day about 1.75 Mt CO_2 /year! Accordingly, technologies for the production of ammonia with a "low carbon footprint" have been developed (e-ammonia or "green" ammonia), which are considerably more climate-friendly by dispensing with fossil fuels. Other reasons for developing these e-ammonia production technologies were to move towards decentralised production and thus avoid high transport costs and import or CO_2 taxes.

Today, one of the world's most produced chemicals can be produced in an environmentally friendly way and can serve as a low carbon footprint feedstock for various industries and products. Ammonia could thus be transformed from a CO_2 -heavy pollutant into a climate-neutral solution with the potential for an environmentally friendly future.

Climate-friendly ammonia technologies are based on the generation of low carbon H_2 from water electrolysis powered by renewable energy (see. Figure 107), in contrast to conventional ammonia plants where hydrogen is usually produced by steam reforming of natural gas.

The nitrogen required for ammonia synthesis is produced here by an air separation unit (ASU) or a nitrogen generation unit (NGU).

Plants for the production of e-ammonia are usually small plants with capacities of e.g. 50 - 500 t ammonia/day. However, studies have already been carried out for plants with capacities of e.g. 5,000 t ammonia/day. For these small plants to be economically viable, they should ideally be able to compete with conventional plants. Major cost drivers are the capital expenditure, the availability and cost of renewable energy, possible restrictions and costs of ammonia transport, CO_2 emission restrictions and CO_2 taxes. Here, it is not surprising that the aforementioned economies of scale of conventional large-scale plants result in more favourable

[317] Cf. International Renewable Energy Agency, (2022).

production costs. Nevertheless, e-ammonia is becoming increasingly interesting as a suitable energy storage and carrier medium for renewable energy producers.

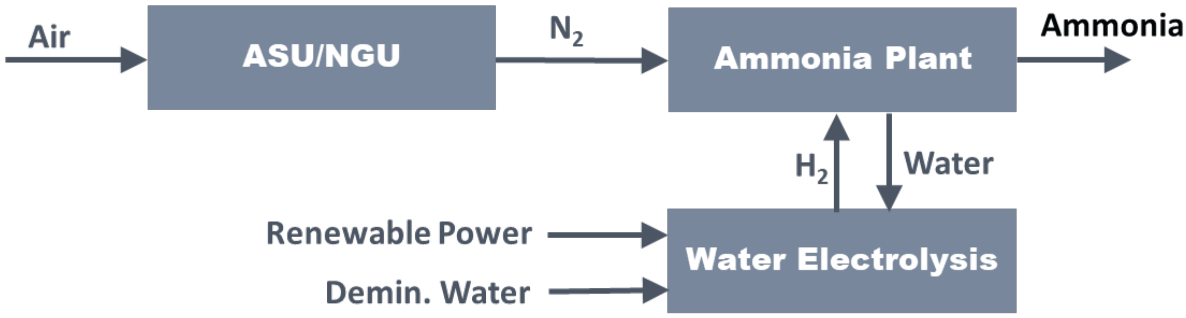

Figure 107: Simplified concept of an e-ammonia plant.

Source: Author

2.6.1.1 Case study Northern Europe

The investment costs for a plant with a capacity of 500 t e-ammonia/day in Northern Europe amount to € 450 million on the basis of a "class 5" investment cost estimate (± 50 %) according to the rules of the AACE (American Association of Cost Engineers). With an estimated owner's cost of 30 %, the TIC[318] amounts to € 585 million.

For the production of e-ammonia from renewable hydrogen, 2,000 Nm³ of hydrogen and 660 Nm³ of N_2 are required per tonne of e-ammonia. If, in the best case, 4.5 MWh are required per 1,000 Nm³ of hydrogen, 9.0 MWh are needed to produce 1 t of e-ammonia. Based on this, 4,500 MWh are theoretically required to produce 500 t e-ammonia/day (corresponds to an installed water electrolysis capacity of approx. 190 MW for hydrogen production). In total, the energy required to operate the ammonia plant incl. NGU and ancillary plants is 9.8 MWh as a first approximation.

For the following determination of the **production costs of e-ammonia** in Table 24 it is assumed for the case study Northern Europe that cheap renewable electricity from hydropower plants is available for the operation of the water electrolysis, i.e. the plant can be operated continuously overall (and not fluctuating as with the use of wind or solar energy).

In summary, the case study for Northern Europe proves that e-ammonia is already a suitable energy storage and carrier medium for renewable energy producers under the mentioned boundary conditions.

[318] TIC: Total Installed Cost

Note: The calculations are based on the status in 2021. Investors, operators and plant constructors are currently confronted with extreme uncertainty with regard to the availability of materials and equipment, for example, but also with regard to business and contractual conditions, which generally make investments uncertain or even uneconomical. In the medium to long term, it is assumed that a scenario comparable to the situation in 2021 will arise.

Table 24: Overview of ammonia production costs

Energy costs per tonne of e-ammonia (30 €/MWh x 9.8 MWh):	295 €/t ammonia
Financing costs (TIC = € 585 million, 30 % equity, 70 % loan with 5 % interest, 10 years repayment):	122 €/t ammonia
Estimated total cost of ownership:	50 €/t ammonia
Total production costs:	467 €/t ammonia

2.6.2 Production of low-carbon ammonia

It is obvious to synthesise the low-carbon H_2 produced with the also very pure N_2 (nitrogen) produced as a by-product in the ASU (Air Separation Unit) to low-carbon ammonia (see second figure in chapter 2.4.2) (e.g. the patented technology AdWinAmmonia® of the company GasConTec[175]). In the production of this low-carbon ammonia, the following KPIs (Key Performance Indicators) are particularly important:

- CO_2 recovery rates of up to 99 % are achievable
- The CO_2 emissions per ton of low-carbon ammonia are correspondingly lower than for "green" ammonia.
- The CO_2 has a high purity (exceeds required pipeline specifications)
- The production costs per tonne of low-carbon ammonia are even lower than for grey ammonia - and thus many times cheaper than "green" ammonia will ever be.

A corresponding large-scale commercial plant for the production of 3,500 t/d low-carbon ammonia is currently (2022) being realised by the company Nutrien in the USA[319] . The CO_2 recovery rate in this project is > 90 %; higher recovery rates can also be achieved subsequently through simple modifications.

[319] Cf. ThyssenKrupp (2022)

2.6.3 Use options for low-carbon and e-ammonia

Low-carbon ammonia is becoming increasingly important as an energy storage medium and especially as a carrier medium for energy. In addition to the KPIs mentioned above, key drivers for this development are the already existing market and infrastructure - built for its grey fossil-based sister. Furthermore, the high energy density of the chemical makes it advantageous compared to liquefied hydrogen, especially for long-distance transport and long-term storage.

Preferred locations for e-ammonia production plants due to the key factors mentioned above are e.g. regions in Australia, South Africa, Chile, Norway, USA and China.

Preferred locations for plants for the production of low-carbon ammonia are countries where there is cheap natural gas and possibilities for cost-effective storage of CO_2, as well as a legal framework that rewards the comparable or even lower CO_2 emissions per ton of ammonia compared to "green" ammonia. Preferred locations for plants for the production of low-carbon ammonia are accordingly e.g. the USA and regions in the Middle East.

Target markets are countries that consume a relatively large amount of energy, but at the same time have less favourable conditions for the production of low-carbon ammonia. Examples are Japan, South Korea, Germany and Eastern Europe (see Figure 108).

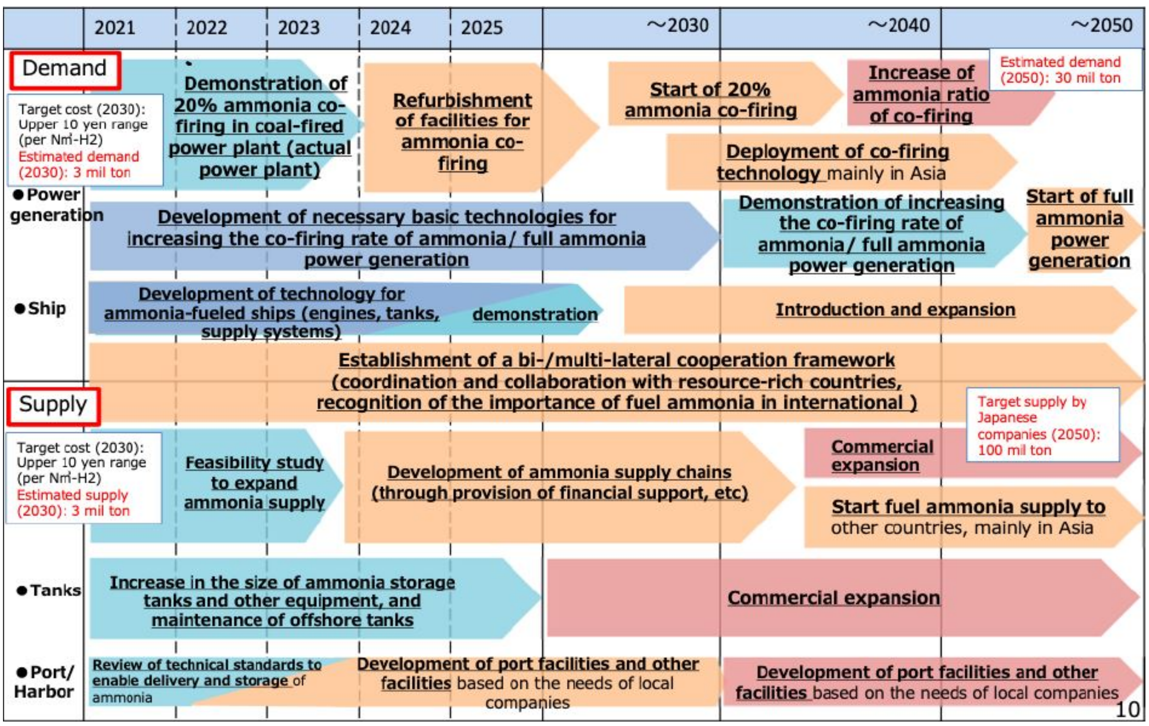

Figure 108: Target markets for e-ammonia: Japan's "Road Map for Fuel Ammonia" plant concept as an example.[320]

Source: Meti (2020)

[320] Cf. Brown (2021)

E-ammonia is becoming increasingly important as an energy storage and especially as a carrier medium for renewable energy. A key driver for this development and advantage is the already existing market and infrastructure - built for its grey fossil-based sister. In addition, the chemical's high energy density makes it advantageous compared to liquefied hydrogen, especially for long-distance transport and long-term storage of renewable energy.

Similarly, low-carbon ammonia has a very great potential to revolutionise many different industrial sectors and transform previously grey processes into climate-neutral ones.

Over 75 % of the ammonia produced worldwide is used for the production of fertiliser (mainly urea), other applications include fibres (nylon) and nitric acid and derivatives.

Urea is one of the few "CO_2 -consuming" products in its production. The summary reaction equation - starting from natural gas - is:

$3\,CH_4 + 4\,N_2 + 2\,H_2O + CO_2 \rightarrow 4\,(NH_2)_2CO$

For each ton of urea, 180 kg of CO_2 are required, which corresponds to 36 Mt of CO_2 for 200 Mt of global production, which is of course released again at some point through decomposition processes when used as fertiliser. Urea fertiliser is therefore not a real CO_2 sink.

Figure 109: Viking Energy of the Norwegian shipping company Eidesvik with ammonia fuel cell propulsion.[321]

Especially for marine fuels (with the IMO's target to reduce annual GHG emissions from international shipping by 50% by 2050) the use of ammonia is a promising substitute for oil.[322] One

[321] CleanThinking (2021)
[322] Cf. International Maritime Organization, n.d.

study predicts that this additional market for e-ammonia will grow from 10 Mt per year in 2025 to 150 Mt per year in 2050.[323] For example, the Norwegian shipping company Eidesvik's offshore utility Viking Energy is already being converted to ammonia fuel cell propulsion.

MAN (AEngine project in cooperation with Eltronic FuelTech DK and Den Norske Veritas[324]), among others, is working on the development of a (2-stroke) marine engine with downstream exhaust gas treatment (NO_X removal). A prototype should be available in 2024.

One example of the use of ammonia as an energy carrier medium is the gas turbine for ammonia developed by Mitsubishi. With an output of 41 MW, it generates up to 70 t of steam per hour (see Figure 110).

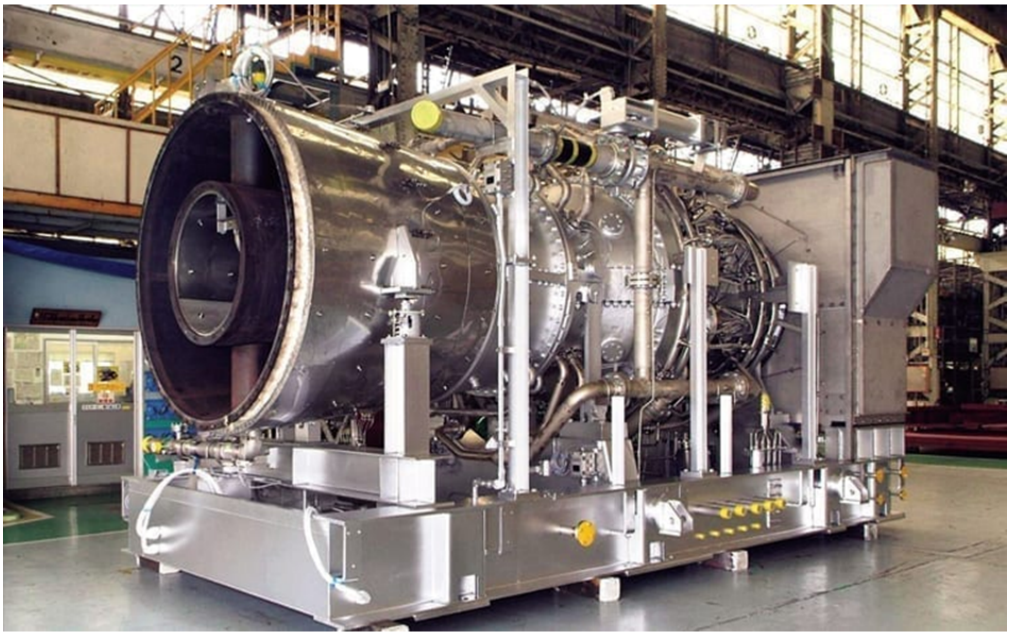

Figure 110: Mitsubishi: Ammonia-capable gas turbine.

Source: Patel, (2021).

Another potential target market is the use of low carbon and e-ammonia as a transport medium for the corresponding downstream product hydrogen. This requires the ammonia to be split back and the nitrogen separated, as shown in Figure 111 schematically shown.

[323] See Alfa Laval et al, (2020).
[324] Vg. MAN Energy Solutions (2020)

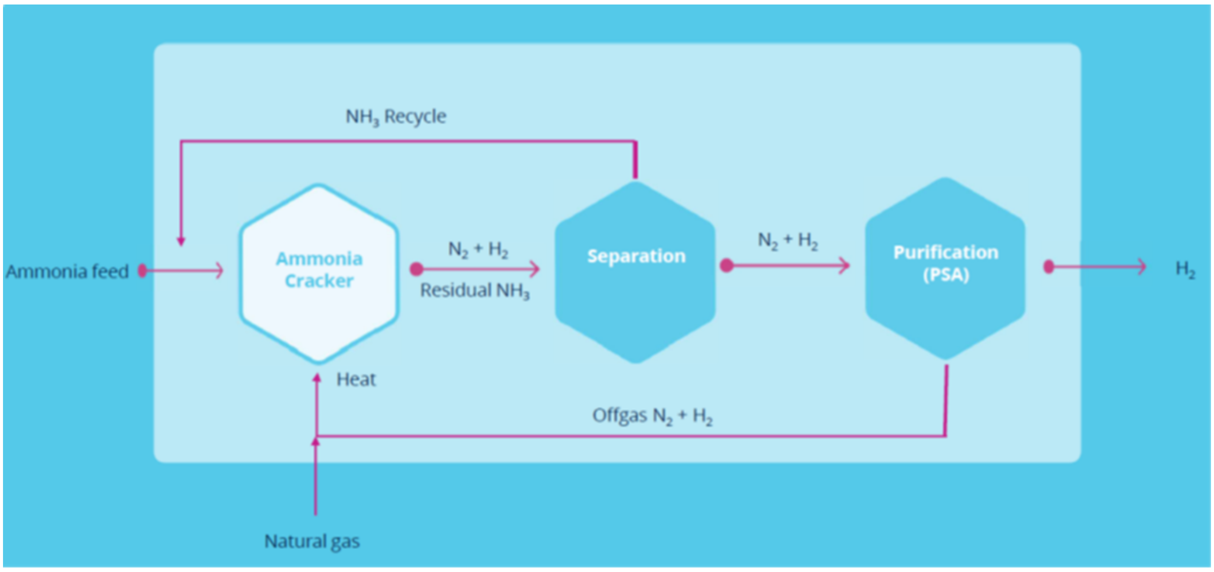

Figure 111: Recovery of hydrogen from ammonia by catalytic cracking.

Source: Nielsen (2021)

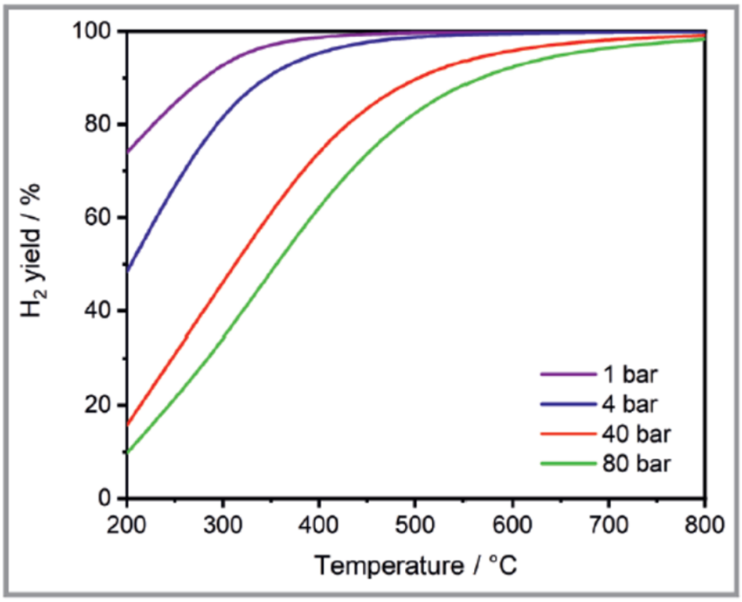

Figure 4. Equilibrium yield of hydrogen in ammonia decomposition at 200–800 °C for 1, 4, 40, and 80 bar (calculated with Aspen Plus software).

Figure 112: Equilibrium concentrations of hydrogen as a function of pressure and temperature due to ammonia splitting back.

Source: Ristig (2022)

Since the re-splitting of ammonia is a high-temperature process similar to ammonia synthesis, further development work is aimed at better splitting catalysts that enable lower process temperatures and thus improve economic efficiency. Figure 112 shows the output of hydrogen during the splitting of ammonia. Although low pressures and low temperatures seem to be advantageous here for setting the equilibrium on the H_2 side, the catalysts are not active enough at low temperatures. On the other hand, they coke at high temperatures, so that a suboptimal compromise in pressure and temperature is currently necessary for the cleavage.

2.6.4 Production of low-carbon methanol

Large methanol plants with a capacity of 5,000 tonnes of methanol per day and more are relatively cost-effective thanks to optimised technologies (e.g. above-mentioned synthesis gas production by partial oxidation) and economies of scale, but still have high greenhouse gas emissions. At a capacity of 5,000 tonnes methanol/day, emissions are up to 3 Mt CO_2 /year! Even in the best case ("ATR only"), a natural gas-based plant with a capacity of 5,000 tons methanol/day emits about 600 kt CO_2 /year!

For the production of methanol with a low-carbon footprint (low-carbon methanol), this "ATR only" methanol technology was further optimised in analogy to the previously described developments for low-carbon ammonia. The patented AdWinMethanol Zero® technology from GasConTec[325] is based on an innovative process configuration. In this process, the CO_2 produced at various points (cf. Figure 107) is almost completely converted into methanol. In addition to the natural gas, low-carbon H_2 is required as a feedstock, which as shown in Figure 113 for example by means of water electrolysis powered by renewable energy (see chapter 2.4).

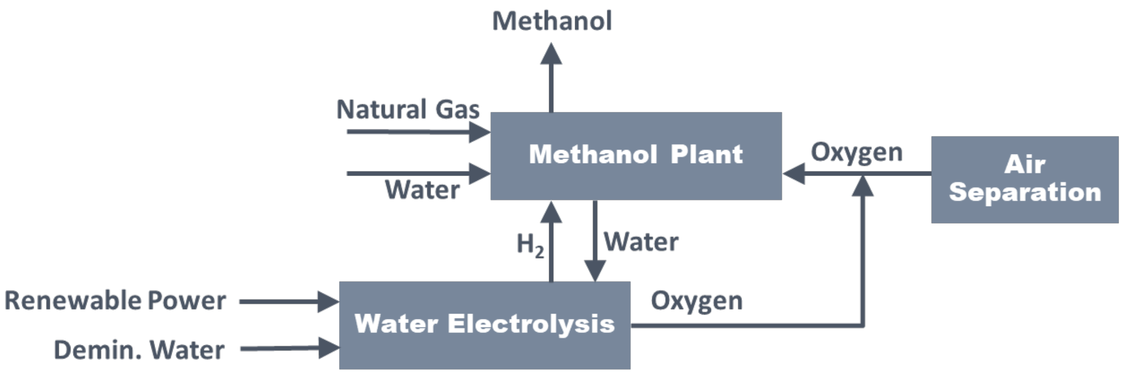

Figure 113: Simplified concept of a low-carbon methanol plant; Source: Author

Alternatively, this low-carbon H_2 can also be produced by partial oxidation with subsequent CO_2 capture and storage.

In the production of this low-carbon methanol, the following KPIs are particularly noteworthy:

- CO_2 recovery rates of up to 99 % are achievable
- CO_2 emissions per tonne of low-carbon methanol are correspondingly lower than for "green" methanol

[325] Cf. GasConTec (n.d.)

- Production capacity is increased by almost 25 % through the use of the resulting CO_2
- The production costs per tonne of low-carbon methanol are therefore comparable to those for grey methanol - and thus many times cheaper than "green" methanol will ever be.

A corresponding large-scale commercial plant for the production of more than 6,000 t/day of low-carbon methanol is in the planning stage (almost all project development activities incl. basic engineering and financing have been completed), FC (financial close) is expected in 2023. It should be emphasised that both the investment costs (CAPEX) and the operating costs (OPEX) and thus the IRR (Internal Rate of Return) are comparable to grey methanol - and this with a CO_2 recovery rate of approx. 99 %!

2.6.4.1 Use options for low-carbon methanol

Low-carbon methanol is becoming increasingly important as an energy storage and especially as a carrier medium for energy. In addition to the KPIs mentioned above, key drivers for this development are the already existing market and infrastructure - built for its grey fossil-based sister. Furthermore, the high energy density of the chemical makes it advantageous compared to liquefied hydrogen, especially for long-distance transport and long-term storage.

Preferred locations for plants for the production of low-carbon methanol are countries where there is cheap natural gas as well as a legal framework that rewards the comparable or even lower CO_2 emissions per tonne of methanol compared to "green" methanol. Preferred locations for plants for the production of low-carbon methanol are accordingly e.g. the USA and regions in the Middle East.

Target markets are countries that consume a relatively large amount of energy, but at the same time have less favourable conditions for the production of low-carbon methanol. Examples are Japan, South Korea, Germany and Eastern Europe.

Low-carbon methanol has a very great potential to revolutionise many different industrial sectors and transform previously grey processes into climate-neutral ones. As an energy source, energy storage and especially as a fuel, experts expect drastic market growth for low-carbon methanol! In addition to LNG (Liquefied Natural Gas) and low-carbon ammonia (see above), low-carbon methanol is also an important substitute fuel for marine fuel applications.

It is particularly noteworthy that low-carbon methanol can be added to conventional liquid fuels or used to fuel 100 % methanol-based propulsion systems. Furthermore, low-carbon methanol can be converted into petrol in MTG (methanol-to-gasoline) plants. The low-carbon petrol obtained in this way has the same properties as e-gasoline (see chapter 2.4), except that production costs are much lower - much lower than e-gasoline will ever be!

2.6.4.2 Case Study Northern Europe

The investment costs for a plant with a capacity of 250 t e-methanol/day (or 85,000 t e-methanol/year) in Northern Europe amount to € 250 million on the basis of a "class 5" investment cost estimate (+/- 50%) according to the rules of the AACE (American Association of Cost Engineers). With an estimated owner's cost of approx. 30 %, the TIC (Total Installed Cost) amounts to € 325 million.

Various ancillary systems are required for the operation of an e-methanol plant (see Figure 114). In addition to the auxiliary materials cooling water, demineralised water, nitrogen, air, etc., a complex steam system is used, among other things, for heat integration and the generation of electrical energy (e.g. for the compression of the H_2 and CO_2 required for methanol synthesis). In the following calculations, it is assumed as a rough approximation that the associated energy costs roughly balance each other out.

For the production of e-methanol from renewable hydrogen and CO_2, 2,100 Nm³ hydrogen and 700 Nm³ CO_2 are required per tonne of e-methanol at 100% conversion. If, in the best case, 4.5 MWh are required per 1,000 Nm³ of hydrogen, 9.4 MWh are needed to produce 1 t of e-methanol. Based on this, a 100 MW water electrolysis can produce 10.6 t e-methanol/h or 85,000 t e-methanol per year. 10.6 t e-methanol/h require 14.6 t CO_2.

For the following determination of the production costs of e-methanol, it is assumed for the case study Northern Europe that cheap renewable electricity from hydropower plants is available for the operation of the water electrolysis, i.e. the plant can be operated continuously overall (and not fluctuating as with the use of wind or solar energy).

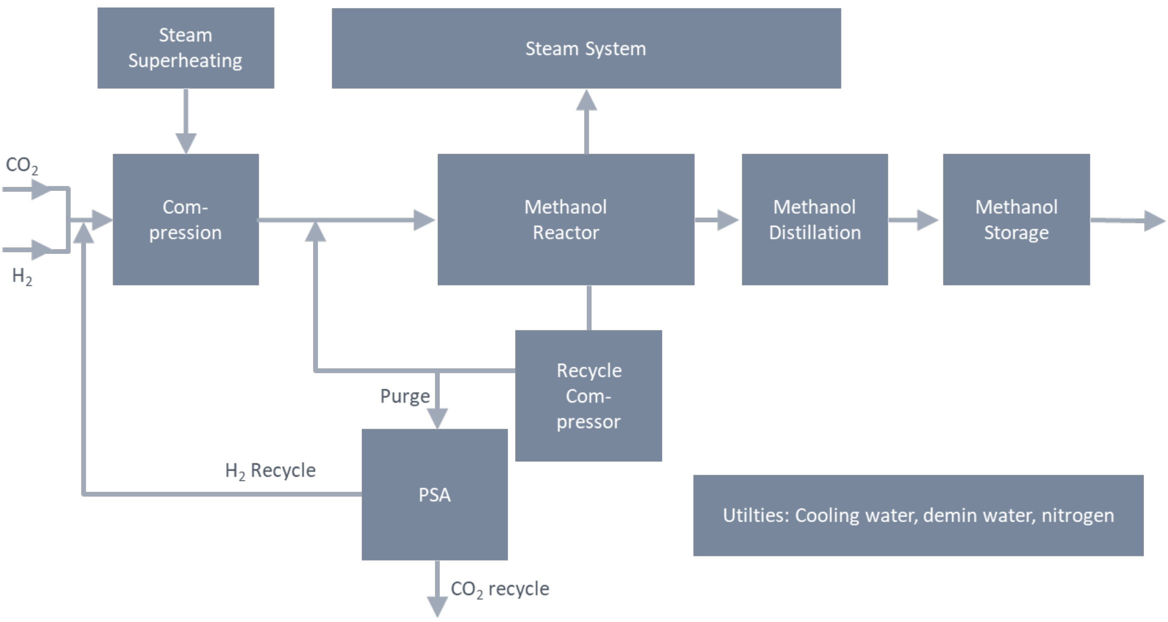

Figure 114: Block flow diagram of the synthesis of an e-methanol plant

Source: Author

Table 25: Overview of the costs for methanol production

Energy costs per tonne of e-methanol (30 €/MWh x 9.4 MWh):	282 €/t methanol
Costs per tonne of CO_2	55 €/t methanol
Financing costs (TIC = € 320 million, 30 % equity, 70 % loan with 5 % interest, 10 years repayment):	132 €/t methanol
Estimated total cost of ownership:	50 €/t methanol
Total production costs:	519 €/t methanol

In summary, the case study for Northern Europe proves that e-methanol is already a suitable energy storage and carrier medium for renewable energy producers under the above-mentioned boundary conditions. For comparison: IRENA estimates the production costs of e-methanol at 400 - 700 USD/t.[326]

Note: The calculations are based on the status in 2021. Investors, operators and plant constructors are currently confronted with extreme uncertainty with regard to the availability of materials and equipment, for example, but also with regard to business and contractual conditions, which generally make investments uncertain or even uneconomical. In the medium to long term, it is assumed that a scenario comparable to the situation in 2021 will arise.

[326] Irena and Methanol Institute (2021)

2.6.4.3 Target markets

E-methanol, as explained, is becoming increasingly important as an energy storage medium and especially as a carrier medium for renewable energy. A key driver for this development and advantage of the sustainable fuel is the already existing market and infrastructure - built for its grey, fossil-based sister. In addition, the chemical's high energy density makes it advantageous compared to liquefied hydrogen, especially for long-distance transport and long-term storage of renewable energy.

Preferred locations for e-methanol production plants are countries where there is a lot of renewable energy and a regulatory framework that promotes renewable energy and its conversion into chemicals, e.g. regions in Australia, South Africa, Chile, Norway, USA, China.

Target markets are countries that consume a relatively large amount of energy, but at the same time have less favourable conditions for the production of e-methanol and have few fossil resources of their own (at least relevant for a transition phase). Examples are countries like Japan, South Korea, Germany and Eastern Europe.

In addition to LNG (Liquefied Natural Gas) and e-ammonia, e-methanol is also considered a substitute fuel for marine fuel applications.[327] It can also be added to conventional liquid fuels or used to fuel 100% methanol-based propulsion systems. E-methanol has great potential to revolutionise many different industrial sectors and transform previously grey processes into climate-neutral ones. As an energy source, energy storage or marine fuel, experts expect drastic market growth for e-methanol: forecasts indicate a tripling of the market volume!

2.6.5 E-methane

Methane is the main component of natural gas. Under normal conditions, it is a combustible, colourless and odourless gas. There are very large deposits in countries like Russia, the USA or the Middle East, which has made it a very attractive source of energy. It is transported through pipelines. Alternatively, it can be liquefied by cooling (this is also the desired method for obtaining pure methane) and transported as liquefied natural gas (LNG) by tankers. Methane is often used as a heating gas and is the starting material for the large-scale industrial production of hydrogen, ammonia and methanol in the chemical industry.

Besides occurring in natural gas, very large quantities of methane are found bound as methane hydrate on the seabed and in permafrost areas.

Methane is produced where organic material is decomposed in the absence of air, e.g. in agriculture and forestry, sewage treatment plants and landfills.

[327] Cf. NOW (2023)

As a greenhouse gas, methane has a high global warming potential. It contributed to global warming in the history of the climate and influences current global warming.

2.6.5.1 Production of e-methane

Methanisation or the Sabatier process is a process for producing synthetic methane. In this process, carbon monoxide and/or (today especially) carbon dioxide is catalytically converted with hydrogen to methane. This reaction was discovered in the 19th century by Paul Sabatier:

$$CO_2 + 4\ H_2 <-> CH_4 + 2\ H_2O\ (\text{exothermic})$$

The reaction has been implemented primarily in the removal of traces of carbon monoxide and carbon dioxide, which act as catalyst poisons in some processes. Today, methanation is a climate-friendly technology for the production of synthetic methane ("natural gas") and thus long-term storage for excess electricity produced by wind and solar power plants: Low-carbon H_2 from water electrolysis powered by renewable energy reacts with CO_2 to produce e-methane (see. Figure 115). This process is referred to as "power to gas".

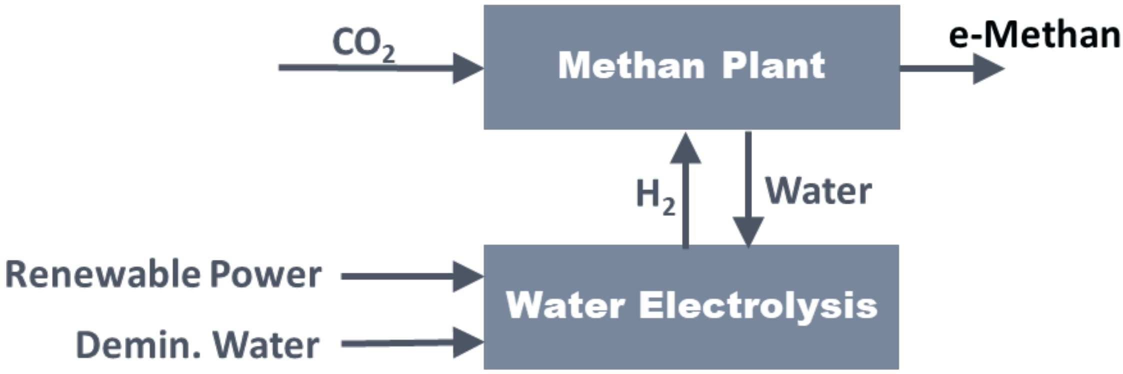

Figure 115: Simplified concept of an e-methane or power-to-gas plant

Source: Author

The carbon dioxide required for methane synthesis is recovered from biogas or other fermentation plants, from all kinds of applications such as flue and exhaust gases from chemical and petrochemical complexes, cement works or steel mills. By retaining and "recycling" this greenhouse gas from the atmosphere, the production process can make a further positive contribution to climate protection.

Plants for the production of e-methane are usually demonstration plants such as the STORE&GO project: "Methanisation technology as gas storage technology" with a capacity of approx. 1,500 Nm³ e-methane per day. [328] However, studies have already been carried out for

[328] Cf. https://www.storeandgo.info/about-the-project/index.html

plants with capacities of 25,000 Nm³ of e-methane per day and more. For each tonne of e-methane, approx. 2.7 tons of CO_2 and 0.5 tons of hydrogen are required; in parallel, 2.2 tons of water are produced. The main cost drivers are, in particular, the availability and costs of renewable energy, the investment costs and, if applicable, the costs for CO_2 (incl. transport). Overall, this results in high costs for e-methane. Estimates expect e-methane to cost more than 170 €/MWh in Europe in 2030 and more than 120 €/MWh in 2050. The envisaged cost reductions require substantial early and continuous investments (e.g. expansion of the globally installed power-to-gas/power-to-liquid capacity to about 100 gigawatts). This means that the production costs for e-methane are permanently many times higher than those of its fossil alternative.

2.6.5.2 Target markets

E-methane, as explained, is becoming increasingly important as an energy storage medium and especially as a carrier medium for renewable energy. A key driver for this development and advantage is the already existing market and infrastructure – built for its grey fossil-based sister. In addition, the high energy density makes it advantageous compared to liquefied hydrogen, especially for long-distance transport and long-term storage of renewable energy.

Partly due to the very well-developed natural gas grid in Germany, for example, and the associated natural gas storage facilities, power-to-gas therefore nevertheless offers application options as a long-term energy storage facility for storing large quantities of (renewable) energy in the natural gas grid, as a flexibility option for grid management (sector coupling), as a renewable heat source, as a raw material in industrial production and as a fuel for mobility. With an increase in affordable renewable energy, e-methane could thus also be produced in large quantities on the basis of wind or solar power, geothermal energy or hydropower.

Preferred locations for e-methane production plants are countries where there is a lot of renewable energy and a legal framework that promotes renewable energy and its conversion into chemicals, e.g. regions in Australia, South Africa, Chile, Norway, USA, China.

Target markets are countries that consume relatively much energy, but at the same time have less favourable conditions for the production of e-methane and have few fossil resources of their own (at least relevant for a transition phase). Examples are countries like Japan, South Korea, Germany and Eastern Europe.

2.6.6 Consideration of the downstream products like e-gasoline

Traditionally, the production of petrol, diesel and paraffin is based on the processing of crude oil in oil refineries, and to a much lesser extent on the use of natural gas or coal as feedstock. Thanks to decades of research and development, many of these oil refineries are largely energy and residue o202ptimised. Economies of scale make plants with a capacity of 10 million tons per year and more relatively cost-effective, but high greenhouse gas emissions cannot be avoided.

2.6.6.1 Production of e-gasoline

Climate-friendly technologies for the production of petrol (or diesel and paraffin) are based, for example, on the production of low-carbon H_2 from water electrolysis operated with renewable energy and subsequent conversion of the low-carbon H_2 produced in this way with CO_2 to fuels (alternatively, fuels can also be produced by using renewable raw materials, see Chapter 2.7). The route via the intermediate product methanol has been commercially realised on an industrial scale: The low-carbon H_2 is synthesised with CO_2 to methanol (see above) and then converted into petrol in an MTG plant (methanol-to-gasoline) (see Figure 116).

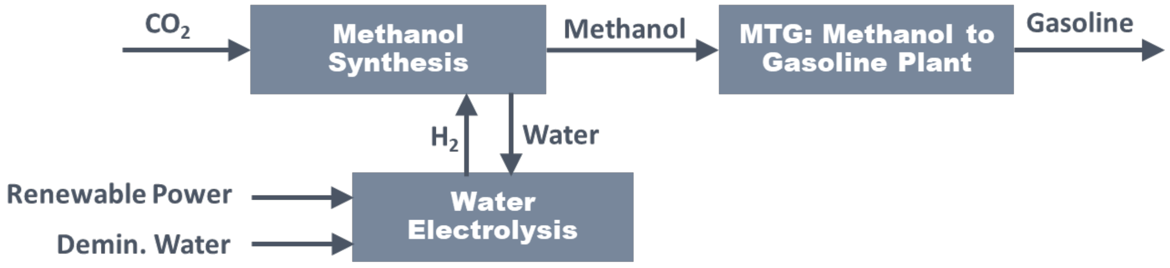

Figure 116: Simplified concept/mass balance of an e-gasoline system

Source: Author

An alternative route for the production of gasoline (or diesel/kerosene) is based analogously on the production of low-carbon H_2 from water electrolysis powered by renewable energy and the use of CO_2 by means of subsequent Fischer-Tropsch synthesis. The production of fuels based on Fischer-Tropsch synthesis has been realised commercially on an industrial scale for synthesis gas consisting of H_2 and CO (not CO_2). The products are liquid, low-sulphur synthetic fuels, synthetic motor oils and long-chain hydrocarbons as a raw material base for the chemical industry (waxes). The by-products are oxygenated hydrocarbons such as ethanol and acetone as well as ethene, propene and higher olefins and alcohols. Accordingly, the processing of these various reaction products of a Fischer-Tropsch synthesis is significantly more complex than the "diversions" via the intermediate product methanol and subsequent MtG plant. According to our analyses, the economic efficiency is therefore somewhat worse.

The operation of Fischer-Tropsch plants with synthesis gases from H_2 and CO_2 has not been tested on a large scale; however, considerations and trials suggest that the economic efficiency is (still) worse.

2.6.6.2 Production costs of e-petrol

As an exemplary case study, a cement plant is considered, e.g. in Morocco. Cement plants emit large unavoidable amounts of CO_2. As an example, the production capacity of a typical cement plant is 4,000 tons of cement per day, emitting about 3,320 tonnes of CO_2, i.e. about 1,060,000 tons of CO_2 per year. For the utilisation (CCU = Carbon Capture and Use) of this carbon dioxide (assumptions: 830 kg CO_2 per ton of clinker, CO_2 completely separable, losses neglected) for the production of e-gasoline from low-carbon H_2 and CO_2, approx. 0.5 tons of H_2 and approx. 3.6 tonnes of CO_2 are required per tonne of e-gasoline in analogy to above at 100% conversion. According to Figure 117 the CO_2 could thus theoretically be converted into 925 tpd of e-gasoline (approx. 45% of gasoline consumption in Morocco in 2018).

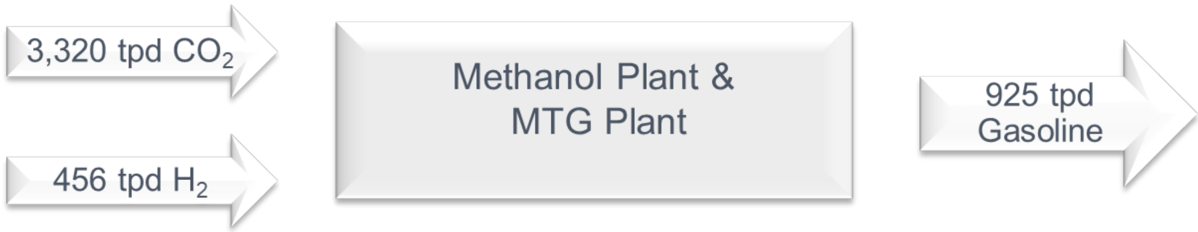

Figure 117: Simplified mass balance of an e-petrol system

Source: Author

The required low-carbon H_2 is generated with a water electrolysis plant with a capacity of 1 GW, which is fed with renewable electricity. The emissions of the corresponding amount of fossil fuels are avoided. To further achieve climate neutrality, activities in the field of nature-based solutions can be used (e.g. approx. 200,000 hectares of afforestation).

Various ancillary systems are required to operate an e-petrol plant (cf. Figure 114). In addition to the auxiliary materials of cooling water, demineralised water, nitrogen, air, etc., a complex steam system is used for heat integration and the generation of electrical energy. In the following estimation, it is assumed as a first approximation that the associated energy costs roughly balance each other out. Under these assumptions, e-gasoline costs about twice as much as a comparable energy quantity of fossil fuel. But with larger production volumes and falling electricity prices, e-fuels could become significantly cheaper, although this would require billions of dollars of investment in production facilities. Optimistic forecasts assume that costs for e-gasoline of 1.00 to 1.40 euros per litre are achievable, excluding transport costs and taxes. This assumes that low-carbon H_2, which today costs around 5 US dollars per kilo, will be competitive with fossil-generated hydrogen (currently 1.5 to 2 US$/kg) (which is expected for 2030 at the earliest).

2.6.6.3 Target markets

E-gasoline is becoming increasingly important as a climate-friendly fuel or, as explained, as an energy storage and carrier medium for renewable energy. A key driver for this development and advantage of the sustainable fuel is the already existing market and infrastructure - built for its grey, fossil-based sister. In addition, the high energy density makes it advantageous compared to liquefied hydrogen, especially for long-distance transport and long-term storage of renewable energy.

Preferred locations for e-gasoline production plants are countries where there is a lot of renewable energy and a legal framework that promotes renewable energy and its conversion into fuels. Target markets are countries that consume relatively much energy, but at the same time have less favourable conditions for the production of e-gasoline and have few fossil resources of their own (at least relevant for a transition phase).

Mobility is a basic human need and an important prerequisite for value creation. In developing and emerging countries in particular, there is a great need to catch up over the coming decades. The mobility of people and goods will therefore increase, if only because of the growing number of people. It is therefore foreseeable that the current stock of 1.3 billion cars and commercial vehicles will continue to increase. The same applies to the use of aircraft and ships. Accordingly, e-fuels have great potential to transform previously grey processes into climate-neutral ones.