Synthetic Natural Gas: green fuel for today's engines

Paul Erik Olli

February 2022

1. Introducing synthetic natural gas

The fuels of tomorrow are typically not fully compatible with our existing infrastructure: for example, a ship engine designed for burning diesel cannot switch to ammonia fuel without an engine re-build. A gas turbine powered by natural gas cannot change to running 100% hydrogen. While both ammonia-powered marine engines and hydrogen-fueled gas turbines are being developed, it is tempting to ask: which of the green fuels require least modifications of our existing infrastructure, i.e., vehicles, pipelines, gas stations, or even factories? The clear winner here is **synthetic natural gas (SNG)**. SNG has all the traits of a green fuel but can be transported hassle-free using the existing natural gas transmission network and is **interchangeable with conventional natural gas** (NG) in every use case (Fig. 1).

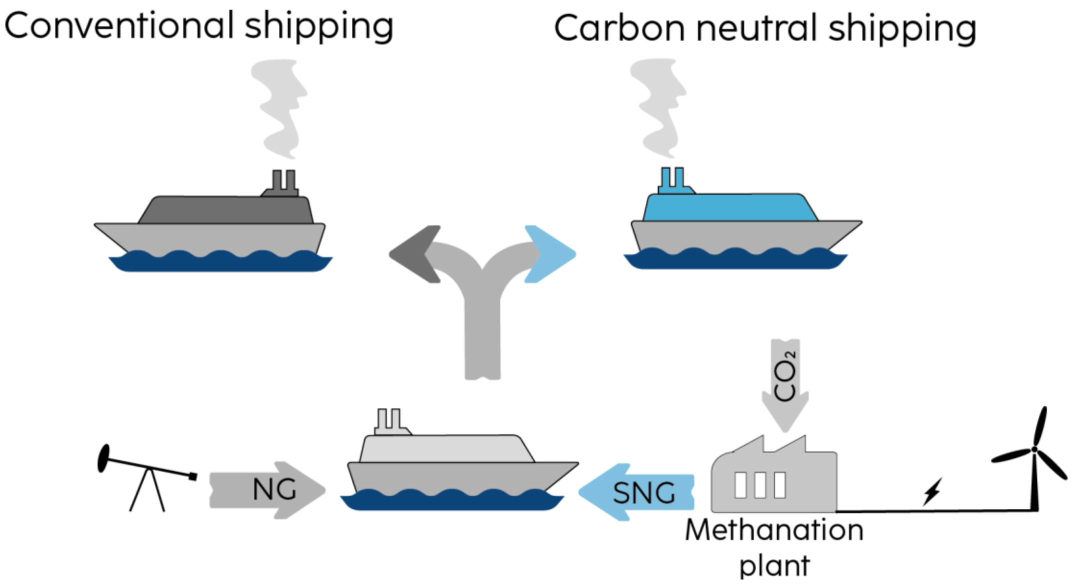

Figure 1. Synthetic natural gas (SNG) is a drop-in replacement for conventional natural gas (NG). A marine vessel with a gas engine can switch from NG to SNG, while requiring no modifications to the engine itself. SNG is carbon neutral: the amount of CO_2 emitted by the engine is equal to the amount of CO_2 bound in SNG during SNG synthesis in a methanation plant.

SNG vs conventional natural gas

The main difference between SNG and conventional natural gas is the production method. Natural gas is a fossil fuel extracted from underground reservoirs, where millions of years old organic matter has been converted into methane and other hydrocarbons via anaerobic decay. Post extraction, natural gas is cleansed of major impurities. In contrast, SNG is natural gas's green relative, and **is produced by converting carbon dioxide and green hydrogen into methane in a process called methanation**. Green hydrogen is in turn produced by electrolysis using low-carbon electricity (more details will be given in Section

2). Both SNG and conventional natural gas consist mainly of methane (CH_4). Therefore, SNG can be converted into liquefied natural gas (LNG) and compressed natural gas (CNG) in exactly the same way as natural gas.

Natural gas will be phased out

Compared to oil or coal, natural gas is a relatively low-carbon fossil fuel and is thus often referred to as a transition fuel, i.e., an intermediate step between today's largely fossil-based economy and the future economy based on renewables. However, the availability and cost of natural gas remain uncertain.

Firstly, the European Union imports about 91% of natural gas that is consumed within its borders and more than 70% of this imported gas comes from non-OECD countries [1]. This results in a significant supply risk and price volatility.

Second, the cost of natural gas is determined to steadily increase due to EU legislation and increasing carbon taxation. Since 2021 the annual EU greenhouse gas linear reduction factor has increased from 1.74% to 2.2% [2]. The diminishing pool of CO_2 trading units is determined to drive the price of CO_2 on the European Emission Trading System (ETS) to new heights.

Furthermore, newly proposed additional taxation strongly favors green fuels over fossil fuels. The revised Energy Taxation Directive (ETD), to come into effect in 2023, will place natural gas in the second highest taxed energy category [3]. In addition to the ETD scheme, the updated ETS will also apply to the hitherto excluded maritime sector, presently a growing market for natural gas.

Considering the global push towards full decarbonization, it is clear that **all fossil fuels, including natural gas will have to be phased out**.

SNG as a drop-in replacement fuel

While most industrial sectors face a potentially challenging conversion to new types of fuels and energy carriers, **the consumers of methane can make the green transition simply by replacing natural gas with SNG** (Fig. 1). In other words, SNG is a prospective drop-in replacement for applications that today rely on natural gas.

Natural gas consists of 95% of methane (CH_4), 4% of ethane (C_2H_6) and traces of higher hydrocarbons and minor impurities [4]. SNG typically consists of over 99% of methane. Higher purity enables cleaner combustion and lower particulate emissions, which gives SNG an edge over conventional natural gas. However, fugitive emissions of SNG have a global warming potential identical to that of natural gas, and thus the positive climate impact of SNG relies on solutions that avoid any leaks of CH_4 into the atmosphere.

An overview of the key similarities and differences between SNG and natural gas is provided in Table 1.

Zero emissions. There is no other way.

Table 1. Side-by-side comparison of the properties of SNG and natural gas (NG).

SNG	NG
Carbon neutral production using green electricity	accounts for 22% of global emissions [5]
Price is dependent on cost of input electricity	Price is dependent on political situation and is subject to high CO_2 taxes
Production can be delocalized	Production is dominated by a few large companies
Higher methane content	Additional chemical impurities
Can be compressed or liquefied and are interchangeable in use	

Zero emissions. There is no other way.

Growing demand for methane

In Europe, the need for methane in road transport (either in the form of CNG, LNG or compressed/liquefied SNG) is estimated to **grow by more than a factor of 7 by 2030** to 15 billion cubic meters (Bcm) of methane, with heavy freight accounting for most of the growth [6]. The growth is catalyzed in part by a soaring demand in trucking, where the number of LNG-powered vehicles is thought to increase from 25,000 in 2018 to 280,000 by 2030. Importantly, SNG is projected to meet seven per cent of the transportation sector energy demand in Europe by 2050 [6].

Furthermore, the EU owns 40% of the global shipping fleet and that increases the importance of LNG in the maritime sector over road transportation. **The global use of LNG as maritime fuel is expected to grow** from 15 Bcm of methane in 2020 to 110 Bcm of methane in 2050 (Fig. 2) [8].

In our view, the demand for methane as CNG and LNG will see a sharp increase in the next few years, but the fossil-based gases will in the long term be replaced by SNG-based alternatives.

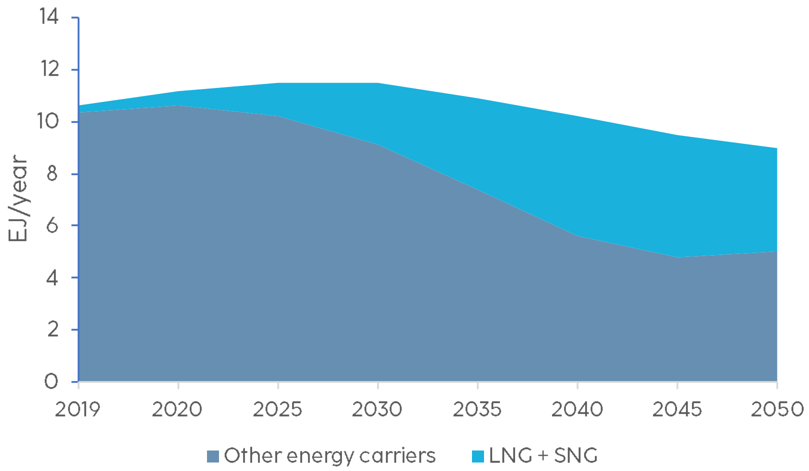

Figure 2. Global maritime fuel use forecast, highlighting the role of LNG+SNG. Source: DNV's Maritime Forecast to 2050 [7]

2. The production of SNG

Production method

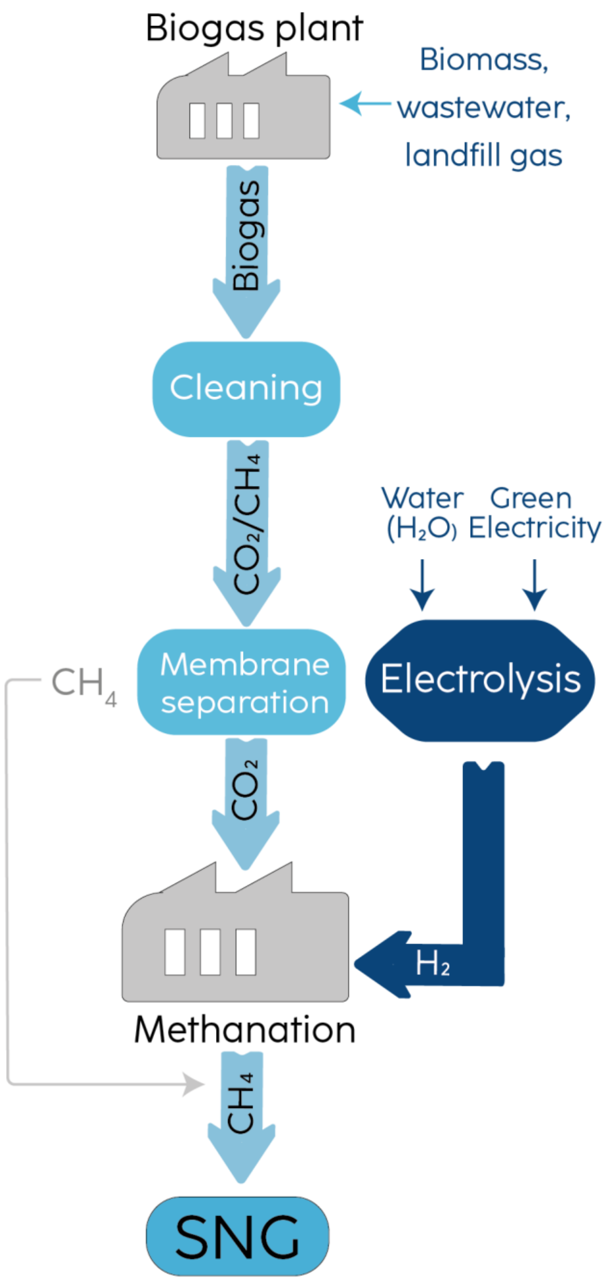

Figure 3. The production pathway of SNG. The produced biogas is first cleaned of impurities. Clean CO_2 is then combined with green H_2 in a methanation reactor to form methane. Previously separated CH_4 is added to the produced SNG. Electrolysis accounts for an estimated >96% of energy requirements of the entire process.

For the production of SNG, two main inputs are required - carbon dioxide (CO_2) and green hydrogen (H_2). As direct capture of CO_2 from the atmosphere is currently over three times more expensive than CO_2 capture from point sources, such as fermentation, cement, ammonia or power plants [9], then in the following description, we choose to only consider CO_2 capture from concentrated point sources. In general, two distinct types of CO_2 can be used:

- the **CO_2 present in flue gas**, i.e., CO_2 emitted as the result of burning biomass, coal, or any other carbon-containing fuel, or
- the **CO_2 present in biogas**, i.e., a mixture of methane and CO_2 of biological origin.

Regardless of the origin of the CO_2, the first step in the process involves thorough cleaning of the gas. In case of biogas, common detrimental impurities include sulfur and nitrogen compounds. These compounds tend to poison the membranes that are used to separate the two main components of biogas, CO_2 and CH_4 from each other [10, 11]. Commonly, sulfur and nitrogen impurities are removed from the biogas with the help of various adsorbing agents or membranes, which are periodically replaced to avoid break-through [10]. The exact ratio of CO_2 to CH_4 in the biogas can vary considerably from source to source, but ratios ranging from 40:60 to 60:40 are most common.

Similarly, the CO_2-rich gas emitted by thermal power plants must be cleaned of corrosive impurities capable of poisoning downstream catalysts. Here, due to the higher concentration of impurities, the corresponding desulfurization and denitrogenation processes may be much more extensive and may be needed to be carried out in multiple steps. The typical CO_2 content in the flue gas of a coal fired plant, a biomass combustion unit, or a natural gas combustion unit is around 12%, 10%, and 4%, respectively, with nitrogen being the main constituent of the flue gas.

CO_2 separation methods

A variety of technologies can be used for separating CO_2 from the rest of the initial gas mixture, be it biogas or the flue gas of a power plant.

The main CO_2 separation technologies include **amine-based absorption, water scrubbing, cryogenic distillation, various adsorption technologies, and membrane-based separation** [10, 12, 13]. Water scrubbing and amine-based processes are most common but the exhaust gas from these processes is a mixture of CO_2 and H_2S and requires further cleaning. Amine-based absorption also requires pre-cleaning of gas from SO_x and NO_x which irreversibly bind amines [14]. Membrane based separation is dry and compact and, depending on the type of membrane selected, may not need pre-purification [10, 12]. The choice of separation technology depends on energy, water and space availability, and requirements on the purity of the resulting CO_2.

Methanation

Finally, the resulting clean and concentrated CO_2 is routed to methanation. Methanation is a process where CO_2 and H_2 are converted to CH_4. The process is best performed under ambient pressure, at a temperature of 300°C, and in presence of a nickel-based catalyst. The reaction ($CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$) is highly exothermic, and the heat generated by the reaction can be used to pre-heat the CO_2 and H_2 to process temperature [15].

Electrolysis

In this production step, green hydrogen is produced in an electrolysis unit using green electricity as input. **Alkaline electrolysis is the best suited electrolysis technology thanks to its proven reliability and technical maturity**. In an alkaline electrolysis cell, electrochemical water splitting is carried out under strongly alkaline conditions, in a solution of concentrated potassium hydroxide. Water reacts at the negative electrode (cathode) to form hydroxide ions and hydrogen (Fig. 4). The hydroxide ions are transported through the separator onto the positive electrode (anode), where oxygen is released. The separator acts as a barrier to prevent gases from mixing. The overall reaction can be written as $2\ H_2O \rightarrow 2\ H_2 + O_2$. According to our calculations, hydrogen production step accounts for >96% of the total energy requirement in the SNG production process.

Zero emissions. There is no other way.

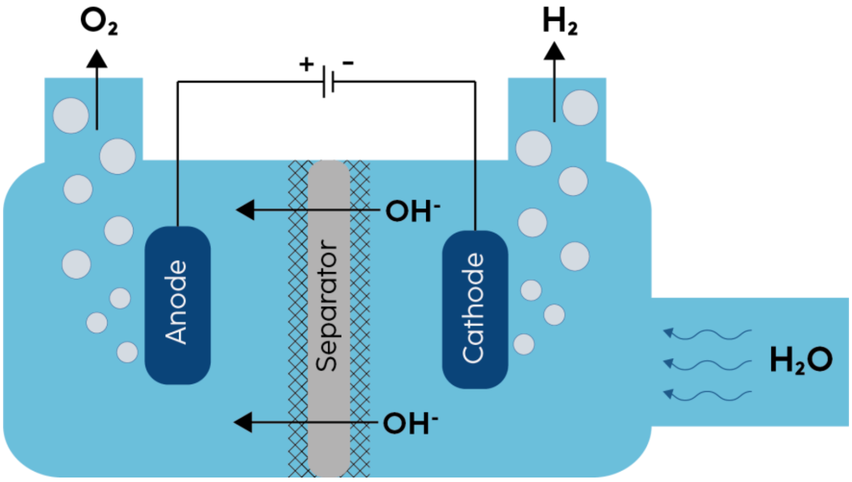

Figure 4. The working principle of an alkaline electrolyzer.

Alkaline hydrogen electrolyzers are easily scalable and the most proven electrolysis technology. Stargate Hydrogen offers alkaline electrolyzers with attractive CAPEX figures and high process efficiency, resulting in a competitive OPEX. Our electrolyzers are ideally suited for being incorporated into an SNG production process. For technical details, please refer to our product portfolio.

3. The economics of SNG

Plant size

The size of an SNG plant is typically determined by the availability of the CO_2 at the point source, as well as the availability of green electricity that is used to run the electrolyzer. The average historical SNG plant size tripled from 118 kW to 390 kW in the years 2012 to 2015 [16]. The number of SNG production facilities has increased exponentially since 1990 and this trend is continuing (Fig. 5) [16]. In contrast to many other chemical processes, **SNG production does not require huge plant sizes to reach high efficiencies**. SNG production processes can thus be successfully integrated with local biogas plants. A demonstration site in Falkenhagen (576 kW) reported a 69% of process efficiency including the re-use of heat [17]. However, large-scale SNG production plants may enjoy the advantages related to potentially closer integration with district heating and power plants.

Production cost

Green electricity is the most important input for the SNG production process. Therefore, the production costs of SNG are determined to a large degree by the cost of input electricity (Fig. 6). Below, we have estimated SNG production costs as a function of input electricity price. The calculation includes contributions arising from CO_2 separation, the electrolyzer, the methanation process, as well as electrolysis and methanation maintenance, hydrogen and CO_2 storage, and CO_2 compression as part of OPEX. In the calculation, we assumed that the CO_2 originated from a point source (a biogas plant) and that membrane-based CO_2 separation was used for separating CO_2 from CH_4.

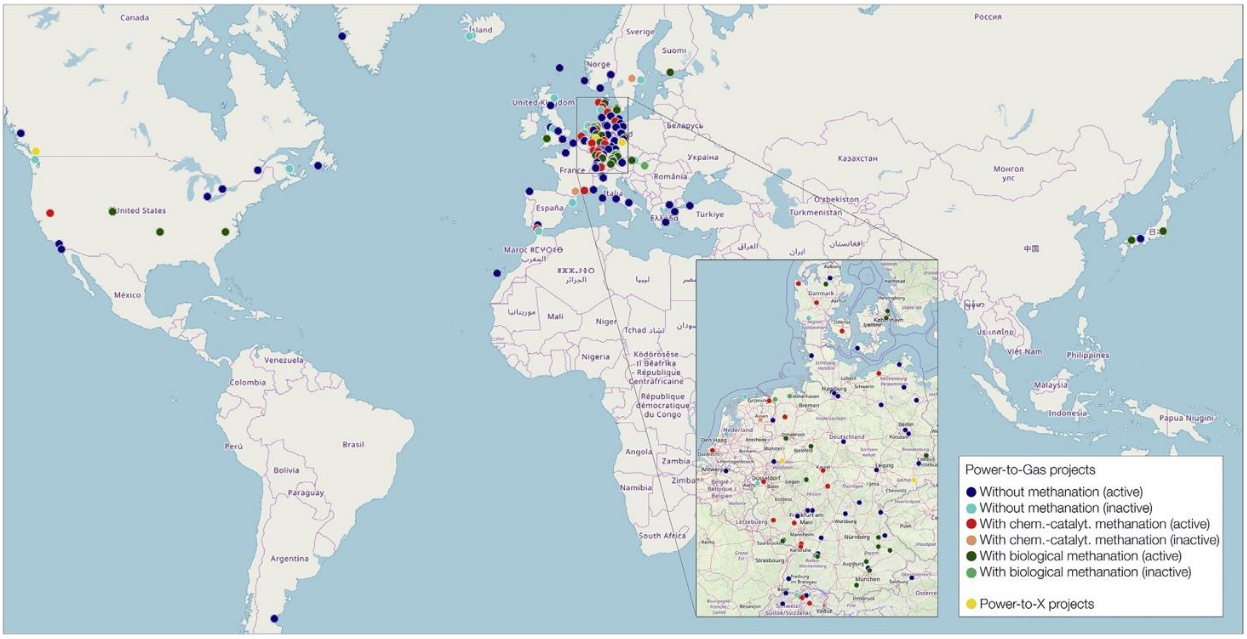

Figure 5. A map of power-to-gas projects as of 2020. Methanation plants are marked in red, orange, and green. Reproduced from [16] with permission from Elsevier under Creative Commons Attribution License.

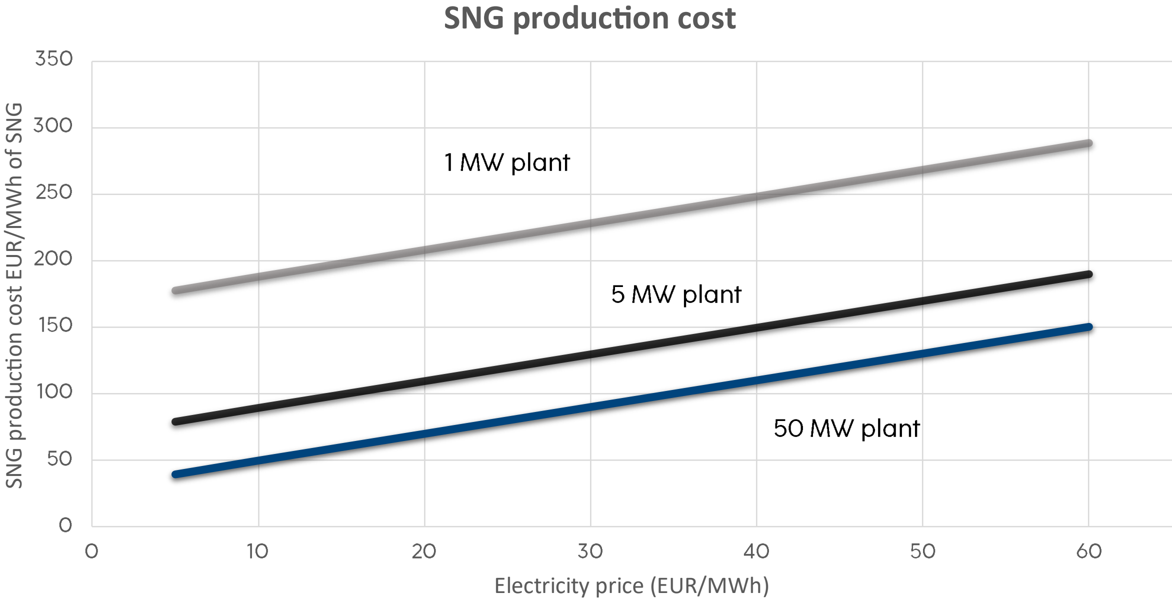

Figure 6. Estimated production cost of SNG as function of plant size and input electricity price. The cost is comprised of fixed OPEX and a variable OPEX based on electricity cost. Fixed OPEX is 18,5% of CAPEX and covers the maintenance and running costs of electrolysis, hydrogen storage, methanation, CO_2 storage and compression, gas grid injection, and SNG storage. Variable OPEX covers energy requirement of methanation, electrolysis, and CO_2 separation from biogas, and is a function of electricity price. [10, 15, 17, 18]

The competitiveness of SNG production improves as the size of the plant increases. At a fixed electricity price of 40 EUR/MWh, a 50-MW SNG plant can reach an SNG production cost of 110 EUR/MWh. Due to increased CAPEX per unit gas produced, the production costs of smaller units are higher: e.g., a 5-MW SNG plant can reach an SNG production cost of

150 EUR/MWh and a 1-MW plant approximately 250 EUR/MWh under otherwise identical conditions. According to some estimates, the OPEX of small-scale SNG plants with a production capacity of 20 MW ranges from 173 EUR/kWh to 1490 EUR/kWh [19]. Alternatively, OPEX can be estimated as a percentage of the total plant CAPEX and is currently about 23% of CAPEX, decreasing to 13% by 2050 [18].

Technical advancements will drive down costs in the future. For example, the efficiency of electrolysis, currently around 65%, is projected to increase to 75% in 2030 and 78% in 2050, resulting in considerable positive impact on the cost of SNG. The production costs in 2030 are in the range of 42 EUR/MWh for an electricity price of 0 EUR/MWh and 85 EUR/MWh for an electricity price of 25 EUR/MWh. In 2050, the respective costs are projected to be 20 EUR/MWh and 61 EUR/MWh. [18]

While SNG is unlikely to be taxed in any near-future, the long-term legal opinion is yet to be clarified. Possible regulations and taxation may increase the cost of SNG. However, the costs of SNG production are expected to fall significantly thanks to decreasing investment costs and the ever-increasing availability and declining cost of renewable electricity. [17]

CAPEX

CAPEX depends greatly on the size of the plant. The precise cost of the system depends further on several additional parameters, such as the plant location, the chosen CO_2 source, plant integration, etc. and is therefore very dependent on project specifics. A 5-MW pilot plant in Falkenhagen, Germany using chemical methanation reported a CAPEX of 1430 EUR/kWh (Fig. 7). According to some estimates, an optimized 50 MW SNG plant could have a CAPEX as low as 360 EUR/kW.

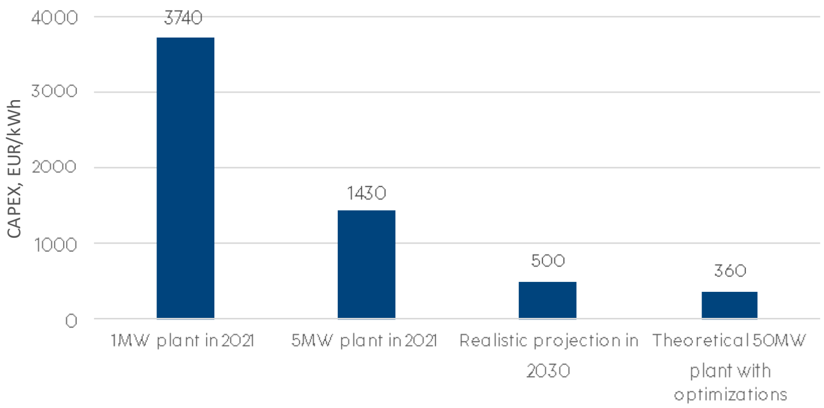

Figure 7. The CAPEX of different SNG plants. [17]

Moreover, the electrolyzer, compressor and hydrogen storage costs dominate SNG plant CAPEX, while methanation accounts for less than 5% of hydrogen production system [19]. Therefore, the **choice of the electrolyzer unit is the most important decision** that the owner of an SNG production facility needs to make. The technical lifetime of the systems should be greater than 25 years [19].

If systems can be manufactured in standardized sizes and in a modular fashion, the CAPEX for SNG plants would decrease further [18]. Every time the installed power-to-gas capacity doubles, the investment costs are expected to decrease by 13%. Considering the current exponential growth in the number and capacity of SNG facilities, plant CAPEX is projected to reach 500 EUR/kWh in 2030 [16, 20]. The cost is projected to further decrease to 130 EUR/kWh by 2050 [16]. Hence, we expect to see a strong decline in plant CAPEX in the coming years.

4. SNG – energy carrier of the future

Thanks to its excellent physical properties, we envision that SNG will not remain only as a transition fuel replacing natural gas but will become **one of the major energy carriers of the future energy economy** alongside green hydrogen, ammonia, and methanol. SNG exhibits an exceptionally high volumetric energy density compared to hydrogen (Fig. 7). Additionally, the compression of SNG is much less energy intensive.

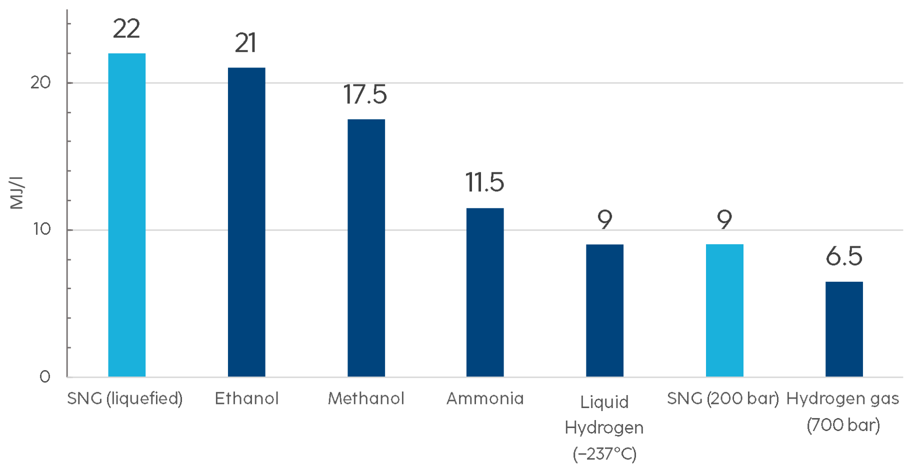

Figure 7. The energy density of different fuels for maritime application [7].

Furthermore, SNG can be transported using the already existing natural gas infrastructure. This enables SNG to be used as a means for seasonal energy storage, allowing stabilizing the highs and lows in the annual energy consumption. By the end of 2018, the European Union already had enough LNG terminals to cover 45% of annual natural gas consumption [21]. With 25 large-scale terminals operational, 3 being constructed, and 8 more being planned, the storage capacity is set to further increase in the future [21]. SNG could be handled and stored in existing terminals, enabling seasonal storage of green energy.

5. Takeaway messages

As the climate crisis deepens, the push for complete phase-out of fossil fuels becomes increasingly stronger. SNG offers sectors presently relying on natural gas to reduce emissions and to continue operations without the need for major CAPEX investments in e.g., engine refurbishments. There is a wide consensus in the academic literature that **production costs of SNG will decrease rapidly in the coming years** [16, 18, 20]. The cost of SNG production is mainly determined by the cost of input green electricity, but other factors, such as plant size and electrolyzer efficiency also affect costs. SNG is presently witnessing rapid scale-up and has the potential to become one of the major energy carriers of the future. **First-movers in SNG production will secure their position and be the first to take advantage of this carbon-neutral fuel**.

Zero emissions. There is no other way.

References

[1] Natural gas supply statistics. Eurostat. October 2021. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Natural_gas_supply_statistics#Supply_structure

[2] Start of phase 4 of the EU ETS in 2021: adoption of the cap and start of the auctions. European Commission. November 2021. https://ec.europa.eu/clima/news-your-voice/news/start-phase-4-eu-ets-2021-adoption-cap-and-start-auctions-2020-11-17_en

[3] Energy Taxation Directive. KPMG. August 2021. https://assets.kpmg/content/dam/kpmg/xx/pdf/2021/09/energy-taxation-directive.pdf

[4] Learn About Natural Gas. Enbridge. 2017. https://www.enbridgegas.com/about-enbridge-gas/learn-about-natural-gas

[5] CO_2 emissions. IEA. 2021. https://www.iea.org/reports/global-energy-review-2021/co2-emissions

[6] A review of prospects for natural gas as a fuel in road transport. The Oxford Institute for Energy Studies. April 2019. https://www.oxfordenergy.org/wpcms/wp-content/uploads/2019/04/A-review-of-prospects-for-natural-gas-as-a-fuel-in-road-transport-Insight-50.pdf

[7] Maritime Forecast to 2050. DNV. 2019. https://sustainableworldports.org/wp-content/uploads/DNV-GL_2019_Maritime-forecast-to-2050-Energy-transition-Outlook-2019-report.pdf

[8] 2019 Annual Report on CO_2 Emissions from Maritime Transport. European Commission. 2020. https://ec.europa.eu/clima/system/files/2020-05/swd_2020_82_en.pdf

[9] Position Paper Fuel Option Scenarios. Mærsk. October 2021. https://cms.zerocarbonshipping.com/media/uploads/documents/Fuel-Options-Position-Paper_Oct-2021_final.pdf

[10] Membrane gas separation technologies for biogas upgrading. Chen, Cinh-Thang, Ramirez, Rodrigue, Kaliaguine. RSC advances. 5, 24399. 2015. 10.1039/C5RA00666J

[11] Ullmann's Encyclopedia of Industrial Chemistry. Biogas. 2000. 10.1002/14356007.a16_453.pub2

[12] Upgrading biogas to biomethane using membrane separation. Vrbová, Ciahotny. Energy & Fuels. 31 (9), 9393. 2017. 10.1021/acs.energyfuels.7b00120

[13] Comparison of energy consumption for different CO_2 absorption configurations using different simulation tools. Øi, Kvam. Energy Procedia. 63. 1186. 2014. https://doi.org/10.1016/j.egypro.2014.11.128

[14] – $DeNO_x$, $DeSO_x$, and CO_2 Removal Technology for Power Plant. Kikkawa, Ishizaka, Kai, Nakamoto. September 2008.

[15] A Cost Estimation for CO_2 Reduction and Reuse by Methanation from Cement Industry Sources in Switzerland. Baier, Schneider, Heel. Frontiers in Energy Research. 6. 2018. 10.3389/fenrg.2018.00005

[16] Power-to-Gas: Electrolysis and methanation status review. Thema, Bauer, Sterner. Renewable and Sustainable Energy Reviews. 112. 775. 2019. https://doi.org/10.1016/j.rser.2019.06.030

[17] Renewable Power-to-Gas: A Technical and Economic Evaluation of Three Demo Sites Within the STORE&GO Project. Schlautmann, Böhm, Zauner, Mörs, Tichler, Graf, Kolb. Chemie Ingenieur Technik. 93(4). 568. 2021. 10.1002/cite.202000187.

[18] Production costs for synthetic methane in 2030 and 2050 of an optimized Power-to-Gas plant with intermediate hydrogen storage. Gorre, Ortloff, Leeuwen. Applied Energy. 253. 113594. 2019. https://doi.org/10.1016/j.apenergy.2019.113594.

[19] Technology Data – Renewable Fuels. Danish Energy Agency and Energinet. 2017. https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf

[20] Necessity and Impact of Power-to-gas on Energy Transition in Germany. Thema, Sterner. Energy Procedia. 99. 392. October 2016. 10.1016/j.egypro.2016.10.129

[21] Finding a home for global LNG in Europe. The Oxford Institute for Energy Studies. January 2020. https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/01/Finding-a-home-for-global-LNG-in-Europe-NG-157.pdf

Zero emissions. There is no other way.