



Source: Port of Skagen

Feasibility Study of Green Methanol Production in the Port of Egersund

Authors: Kjetil Nedrebø, Prosjektil AS

Mohammad Mansouri, Prosjektil AS

Hugo Eugen Hernes, Prosjektil AS

Date: 2024-10-02

Version: Final report

REDII Ports | Interreg North Sea | Co-funded by the European Union

Executive summary

The main objective of this report is to support decision-making for further investigation and planning for production of green methanol using locally available resources at Kaupanes in the Port of Egersund. Two main pathways that are considered in this report are e-methanol production from hydrogen and carbon dioxide, and bio-methanol production using biomass resources. The study shows that both pathways seem to be feasible in the study area in terms of the resources (feedstocks) that are either available in the study area or will be available due to existing development plans. It is important to mention that along with both pathways, there are important technical and economic challenges that have a high impact for decision-making process in this regard. For the e-methanol pathway, assuming that there will be future large investments in CO_2 capture in the study area, a remaining challenge seems to be natural seasonal variations in CO_2 emissions from the sources, i.e. the fish processing factories. This will require consideration of large storage or import options. For the bio-methanol pathway, an important aspect will be the competition with the current use of the biomass resources in the study area, such as for energy production, or material re-use. Interesting areas that require more investigation, and are not covered in this study, is to study an alternative pathway, a bio-e-methanol facility (combining several resources in other pathways), and to analyze the potential for improvement in the business cases of all these pathways using options for circularity including, but not limited to, recovery of waste heat in the study area.

Content

List of figures

List of tables

1 Introduction

The current report presents a summary of a feasibility study conducted to evaluate the potential of setting up a green methanol production facility at the Port of Egersund considering locally available resources.

1.1 Main goals

The main objective of this report is to support decision-making for further exploration and planning for production of green methanol from locally available resources at Kaupanes in the Port of Egersund via conducting a feasibility study in this regard. The primary goal is to evaluate the potential of using green hydrogen and CO_2 captured from nearby emission sources to produce e-methanol or using biomass (mainly wood chips) to produce bio-methanol, as an alternative renewable fuel for ships. The feasibility study will give Egersund Næring og Havn KF (ENH) a solid foundation for deciding whether to invest in green methanol production or not. The study is intended to be performed into two phases, with a decision point before proceeding to the second phase. Different milestones expected for each phase are listed below.

Phase 1 – Milestones

- Estimate the amount and availability of CO_2 emissions from industrial sources in the study area and identify applicable methods for capturing them.
- Estimate the production capacity of e-methanol assuming locally available resources, i.e., captured CO_2 from industrial sources and green hydrogen.
- Estimate the amount of available biomass resources (only wood chips) in the study area.
- Estimate the production capacity of bio-methanol assuming locally available resources, i.e., wood chips.

Phase 2 – Milestones

- Explore the logistics and infrastructure for transporting, storing, and utilising resources for green methanol production, if sufficient resources are available (or will be available due to existing development plans).
- Select an optimal site for the methanol production facility.
- Analyse the economic viability, potential for industrial symbiosis and environmental benefits of green methanol production.

1.2 Scope

The purpose of this feasibility study is to evaluate the potential of producing green methanol from local resources near Kaupanes and the Port of Egersund. The study will only consider resources that are within 4-5 km from Kaupanes. The source of hydrogen will be Kaupanes Hydrogen AS, a local hydrogen producer at Kaupanes that is a low-carbon hydrogen facility using water electrolysis fed by renewable power. Possible CO_2 sources are industries that currently have CO_2 emissions and might have carbon capture facilities to reduce their CO_2 emissions in the future. For biomass resources, mainly treated and untreated waste wood are considered. These resources are currently managed and handled by several actors in the study area including Geminor AS, NORTØMMER AS, and IVAR IKS. There is also a brief reference to use of part of the municipal solid waste (MSW) that is currently produced and handled in the region and its potential for blending with waste wood resources for bio-methanol production.

1.3 Methodology

This study has been conducted using high level information available in the literature, as well as data, consultation and feedback received from relevant local stakeholders in the study area.

1.4 Study area

The Port of Egersund is a major and vital port in Norway, situated in Egersund municipality in Rogaland. It has a strategic position at the gateway to the North Sea and serves various industries, such as fisheries, offshore, industry and trade, with modern and efficient port services. The Port of Egersund also boasts a rich history that goes back to the Middle Ages when it was a significant trading hub for stockfish. Nowadays, the Port of Egersund is a progressive and innovative port that fosters economic growth and employment in the region. The study area is illustrated in Figure 1.

Figure 1. The area of this feasibility study

1.4.1 Enterprises in the study area

In this part of the report, different enterprises[1] that are in the study area are listed in Table 1, below. Note that possible sources of either hydrogen or carbon dioxide as necessary resources for methanol production are also marked in the table.

[1] The sources for this overview are the Central Coordinating Register for Legal Entities (Enhetsregisteret), https://data.brreg.no/enhetsregisteret/oppslag/enheter.

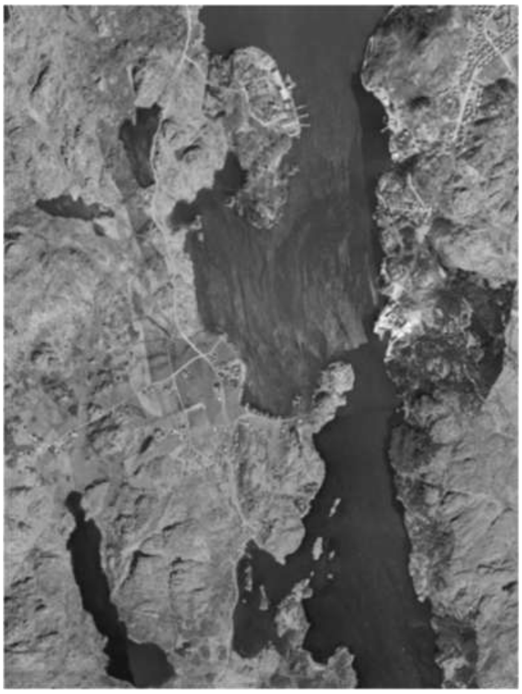
Table 1. List of different enterprises within the study area

#	Business	Description
1	Aker Solutions (Egersund)	Construction of ships and floating structures
2	Badnor AS	Wholesale of building materials not elsewhere classified
3	Bertelsen & Garpestad (Egersund)	Landscaping
4	Dalane Energi AS	Production of electricity from hydropower
5	Kaupanes Hydrogen AS [a]	Production of industrial gases
6	Egersund Group AS	Wholesale of fish and shellfish
7	Egersund Group Fiskeri	Fishing in sea and coastal waters
8	Egersund Eiendom	Rental of own or leased real estate
9	Eigerøy båt & Motor AS	Retail sale of boats and boat engines
10	Egersund Landstrøm	Production of electricity from wind power
11	Egersund Betongindustri AS	Production of concrete elements for construction and civil engineering
12	Egersund Næring og Havn KF	Port and waterway authority
13	Egersund Næringspark AS	Rental of own or leased real estate of item #12
14	Energy Innovation	Other research and development work in natural science and technology
15	Egersund Slipp AS	Repair and maintenance of ships and boats
16	Evrik Shipping	Sea and coastal transport of goods
17	Geminor AS [a]	Waste management
18	Hermod Teigen AS (Egersund)	Production of fishmeal and fish oil
19	H E Seglem AS	Sea and coastal transport of goods
20	Hovland Båt AS	Construction of ships and floating structures
21	Fonn Holding AS	Activity related to holding companies Production of fishmeal and fish oil, production of beer Rental of own or leased real estate otherwise
22	New Kaupang	Other research and development activities in natural sciences and engineering
23	Pelagia Egersund Seafood AS	Production of fishmeal and fish oil
24	Pelagia Egersund Sildoljefabrikk [a]	Production of fishmeal and fish oil
25	Prima Protein AS [a]	Production of fishmeal and fish oil
26	Prima Seafood AS	Wholesale of fish and shellfish
27	PonEnergy Rental	Rental and leasing of machinery and equipment for construction and civil engineering without personnel otherwise
28	Statnett	Transmission of electricity
29	StoneShip AS	Sea and coastal transport of goods
30	Stornes Slipp & Mek Verksted AS	Repair and maintenance of ships and boats

[a] The enterprise has some resources useful for production of low-carbon methanol (either CO_2 emissions, wood chips, or H_2).
[b] Several enterprises are combined in this item including Fonn Holding AS, Fonn Egersund AS, Fonn Egersund, Fonn Fabrikker AS, Fonn Eigeroy AS, Fonn Brygger AS, and Fonn Eiendom AS.

1.4.2 Historical images

The study area is in Eigerøy, an island that is in the south-west coast of Norway with a size of approximately 20 km^2, and a population of about 2 500 persons. The study area has a typical prevailing climate in the south-west coast of Norway that is very much influenced by the coast with relatively high temperatures in winter and low temperatures in summer and with high wind speeds[1]. During the recent years and in the coming years, new industries have already established or to be established on the island of Eigerøy, specifically around the study area, i.e., harbour area at Kaupanes. The new industries are mainly from fish industry (e.g., fish food producers), and they resulted already in an increased energy demand on the island. One of such industrial actors is Prima Protein AS that started their operation in 2019[2]. It should be noted that some of the industries in the study area are dependent on fossil fuel consumption to supply their processes with necessary thermal energy requirements (for example in terms of process steam). As it will be explained later, such fossil fuel uses will result in CO_2 emissions, a resource that can be further utilised for methanol production if it is captured.



(1967)

(2003)

[1] The island of Eigerøy, https://www.robinson-h2020.eu/the-islands/eigeroy/

[2] https://primaprotein.no/en/production/

(2012) (2022)

Figure 2. The development history in the study area.

1.4.3 Available land area

As for establishing a green methanol facility in the study area, availability of land area is an important requirement. The study area in Kaupanes (also including northern part) have almost 92 000 m^2 available for new industry, as shown in Figure 3. As of this available land, 7 700 m^2 is labelled as ISPS[1] at the quayside (coloured by blue in Figure 3) that can be easily expanded to the west by another 19 000 m^2 (coloured by turquoise blue in Figure 3). Another 65 000 m^2 is located on the northern part of Kaupanes, out of which 50 000 m^2 is coloured by orange in Figure 3, and another approximately 15 000 m^2 to the north of this orange block is not shown in the figure but it is available for new industrial activities. Note that all the available area has gone through all regulatory processes and is ready to build for industry.

[1] International Ship and Port Facility Security

Figure 3. Available land for industry in the study area[1].

[1] Egersund Næring og Havn KF (ENH), Plan map and available plots of Kaupanes Port and Industry Park ("Plankart og tilgjengelige tomter, Kaupanes Havn og Næringspark" in Norwegian), https://kaupanes.no/fasiliteter/tilgjengelig-areal/

2 Background on resources

As mentioned earlier, the objective of this study is to evaluate the feasibility of producing green methanol using locally available resources of hydrogen, carbon dioxide (when captured) or biomass. It is therefore important to briefly touch upon these resources, and then methanol and its production pathways.

2.1 Green hydrogen (H_2)

Green hydrogen is a form of hydrogen that is produced using renewable power, such as solar, wind or hydropower in an electrolysis process. Green hydrogen is an energy carrier that does not emit greenhouse gases or pollution when used. Green hydrogen can be used to store (specifically when produced from variable renewable energy sources) and transport energy, as well as to replace part of the fossil fuels used in various sectors, such as in industry and transport. Green hydrogen has a great potential to help reducing emissions and reaching climate targets, while matching energy supply and demand in an energy system predominantly based on variable renewable energy sources.

2.2 Carbon dioxide (CO_2)

Carbon dioxide is a chemical compound that is a gas at room temperature. Carbon dioxide is formed when carbonaceous substances such as fossil fuels or biomass are burned or via respiration. Carbon dioxide is also an essential part of the Earth's climate system because it is a greenhouse gas (GHG) that absorbs and re-emits infrared radiation. This helps keep the Earth's surface temperature stable and liveable. Despite its importance, increased carbon dioxide concentration in the atmosphere due to human activities since the Industrial Revolution has become a problem. This has led to global warming threatening the natural climate and ecosystems of the earth. Some of the consequences of global warming may include more extreme weather, sea level rise, melting of glaciers and polar caps, loss of biodiversity and reduced food production.

One of the options to mitigate CO_2 emissions is to use carbon capture and storage (CCS). CCS can be seen as a chain of different processes starting with trapping (separating) CO_2 emitted due to fossil fuel combustion or other industrial processes before it can enter the atmosphere, transporting the capture CO_2, and eventually storing it in geological formations underground or under seabed[1]. This GHG mitigation option is specifically considered for tackling emissions from sectors that are difficult to decarbonise. It should be noted that implementing CCS is associated with significant energy loss and requires extensive infrastructure. An alternative pathway until availability of an extensive infrastructure of pipelines and large-scale CO_2 storage sites is to utilise the captured CO_2 emissions either directly (i.e., not chemically altered) or indirectly (i.e. transformed) in various products such as for synthesis of different chemical compounds (or fuel). This is referred to as carbon capture and utilisation – CCU[2].

---

[1] UNDP, 2023, The climate dictionary - Speak climate fluently, United Nations Development Programme, https://www.undp.org/publications/climate-dictionary

[2] IEA, 2024, CO_2 capture and utilisation, https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/co2-capture-and-utilisation

There exist different techniques for CO_2 separation from flue gases of industrial units using different solvents (absorption), solid materials (adsorption), membranes, and other technologies.

2.3 Biomass

Biomass is an organic renewable energy source that can cover a wide variety of organic components. There can be various resources (feedstocks) listed as biomass[1] as listed below:

- Forestry residues: These are biomass that are not harvested or used in commercial forest processes and include materials from dead and dying trees.
- Agricultural crops: These include cornstarch and corn oil, soybean oil and meal, wheat starch, and vegetable oils that generally yield sugars, oils, and extractives.
- Agriculture crop residues: Biomass materials consisting primarily of stalks and leaves that are not used for commercial use, such as corn stover (stalks, leaves, husks, and cobs), wheat straw, and rice straw.
- Dedicated energy crops: These herbaceous energy crops are perennials that are harvested after reaching maturity including grasses like switchgrass, miscanthus, bamboo, sweet sorghum, tall fescue, kochia, wheatgrass, and others.

Note that animal wastes, aquatic biomass resources like algae, as well as organic component of municipal, and industrial wastes and the fuel produced from food processing wastes, such as used cooking oil are also considered as biomass.

[1] Kanoglu, M., Çengel, Y.A., Cimbala, J.M. 2023. Fundamentals and Applications of Renewable Energy", 2nd Edition, McGraw Hill Education, p. 510.

3 Methanol

3.1 Properties of methanol

Methanol is the simplest alcohol (CH_3OH), a colourless, water-soluble liquid with mild alcoholic odour and a polar chemical compound that is acid-base neutral, and generally considered non-corrosive. Some properties of methanol are listed in the following Table 2. There are about 90 methanol production plants in the world that produce approximately 110 million metric tons of methanol annually[1], mostly via use of natural gas reforming processes, but also via coal gasification. Other than fossil fuels, different organic feedstocks like biomass, biogas, or organic municipal waste can also be used as feedstock to produce methanol (or bio-methanol).

Table 2. Properties of methanol [2] [3]

Properties	**Remark/Value [Unit]**
Chemical formula	CH_3OH
Other names	Methyl alcohol, and wood alcohol
Molecular weight	32.04 [g/mol]
Melting point	-97.6 [°C]
Boiling point	64.6 [°C]
Density at 20°C	791 [kg/m^3]
Higher heating value (HHV)	22 677 [kJ/kg]
Lower heating value (LHV)	19 920 [kJ/kg]
Energy of vaporisation	9.2 [kcal/mol]
Flash point	11 [°C]
Explosive limits in air	7-36%
Auto ignition temperature	455 [°C]

Methanol is considered as a building block for several products (including plastics, construction materials, vehicle parts etc.). This widely utilised chemical compound is increasingly considered as an "energy carrier" in different sectors, such as in the transportation, and heat and power production sectors in different technologies e.g., in internal combustion engines or fuel cells. Using methanol as an energy

[1] Deka, T.J., Osman, A.I., Baruah, D.C., Rooney, D.W. 2022. "Methanol fuel production, utilization, and techno-economy: a review." Environmental Chemistry Letters 20: 3525-3554. doi: https://doi.org/10.1007/s10311-022-01485-y

[2] Cheng, W-H, and Kung, H.H. 1994. Methanol Production and Use. New York, NY, USA: CRC Press.

[3] Kanoglu, M., Çengel, Y.A., Cimbala, J. 2020. Fundamentals and Applications of Renewable Energy. 1st Edition, McGraw-Hill Education, p. 398.

carrier is typically considered as part of various decarbonisation scenarios together with hydrogen or ammonia.

Methanol that is produced in an alternative production process via use of carbon dioxide (captured from air or other sources), and a low-carbon hydrogen produced from electrolysis process can also referred to as e-methanol. Both e-methanol and bio-methanol (or collectively called green methanol) can be considered as a low-carbon fuel (or carbon-neutral fuel under certain conditions) that have some advantages over other alternative energy carriers. For example, low-carbon methanol can be stored and transported in a simple way and using existing infrastructure, unlike hydrogen or ammonia. In addition, it has a higher energy density than conventional batteries[1], making it suitable for long distances.

Due to advantages of low-carbon methanol and its potential to reduce emissions, several shipping companies have plans to use it as fuel for their ships, such as Maersk and DFDS. It should be noted that there are already some ships using methanol as fuel, but most of them use fossil-based methanol.

3.2 Methanol production

As mentioned earlier, methanol can be produced using different feedstocks and different pathways but today the production is done almost exclusively from fossil-based options (i.e., coal and natural gas) through reforming or gasification. A summary of several different methanol production pathways made by the International Renewable Energy Agency (IRENA) is shown in Figure 4. A qualitative carbon intensity of these pathways is also shown on the right side of this figure. One should pay attention that the term “Green Methanol” used in this report falls in the green-blue region of the CO_2 intensity region of Figure 4. This is because the CO_2 that is considered in this study is mainly considered to be the supplied from the CO_2 emissions sources in the study area (refer to Section 4 – Mapping and identifying the main resources).

[1] Burhan, H., Cellat, K., Yilmaz, G., Sen, F., 2021, Direct Liquid Fuel Cells – Fundamentals, Advances and Future, Academic Press, pp. 71-94, https://doi.org/10.1016/B978-0-12-818624-4.00003-0

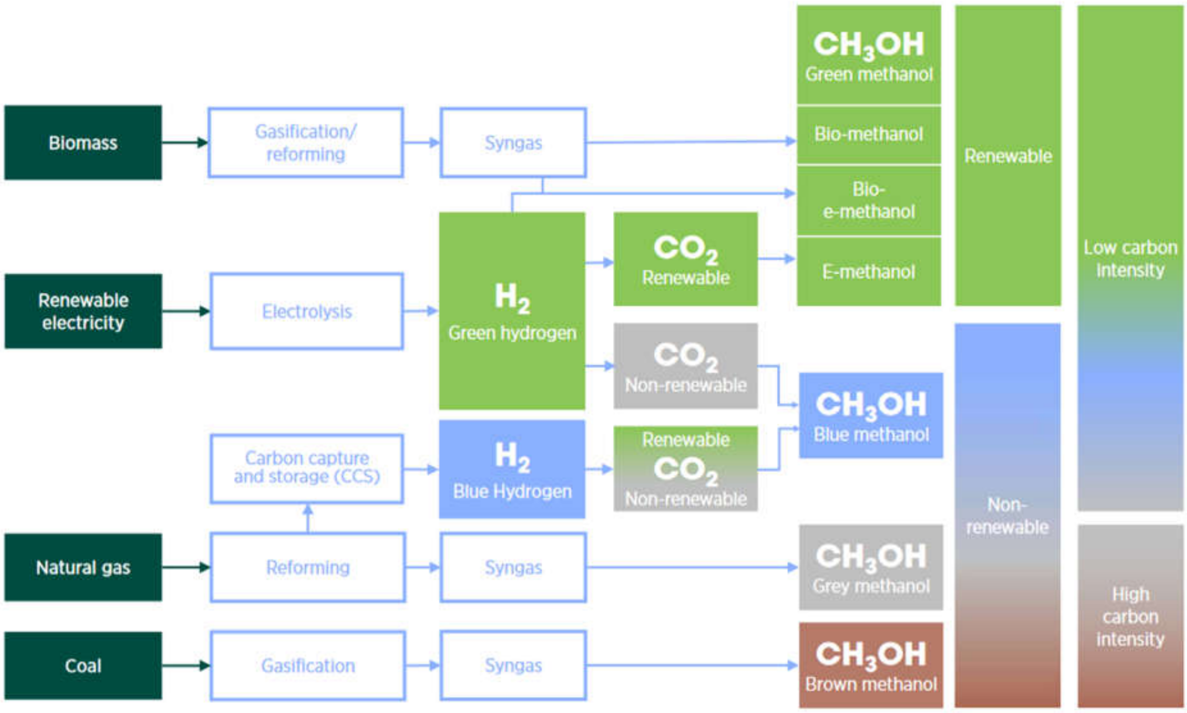


Figure 4. Main methanol production pathways[1].

3.2.1 Conventional methanol production

Conventional methanol production (using natural gas, coal, or organic feedstock) is performed in three main steps including, synthesis gas (syngas) production, methanol synthesis[2], followed by a methanol purification step[3], as also shown in Figure 5. Each of the mentioned steps can be completed using different technologies based on the desired application and purity.

[1] International Renewable Energy Agency (IRENA) and Methanol Institute (MI), 2021, Innovation Outlook Renewable Methanol, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf.

[2] Bromberg, L., and Cheng, W.K. 2010. Methanol as an alternative transportation fuel in the US: Options for sustainable and/or energy-secure transportation. Cambridge, MA, USA: Energy Efficiency & Renewable Energy, U.S. Department of Energy.

[3] Aasberg-Petersen, K., Nielsen, C.S., Dybkjær, I., Perregaard, J. 2009. Large scale methanol production from natural gas. Haldor Topsøe.

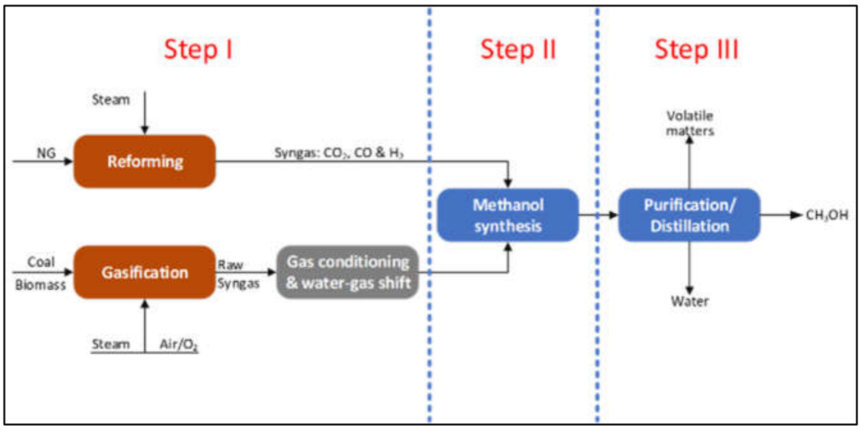


Figure 5. Conventional production methods of methanol.

The first main step in conventional methanol production is to convert the feedstock into a synthesis gas (syngas). Syngas consists mainly of CO, H_2 (but also some CO_2, N_2, and other trace components). If natural gas (NG) is used as feedstock, syngas production is typically carried out via catalytic reforming and steam. The overall steam reforming reaction for methane (CH_4), as the principal constituent of natural gas, is an endothermic reaction requiring energy input (heat) to proceed, as shown below:

$$CH_4 + 3\,H_2O \;\rightarrow CO + CO_2 + 7\,H_2$$

When coal is used as feedstock, syngas production is performed via gasification using air (or other oxidisers like oxygen) and steam, followed by a water-gas shift (WGS) reaction. During gasification, partial oxidation is first performed, and then syngas is produced in a water-gas shift reaction, as follows:

$$C + {}^{1}/_{2}\,O_2 \;\leftrightarrow CO \qquad \text{(Partial oxidation)}$$

$$C + H_2O \;\leftrightarrow CO + H_2 \qquad \text{(Water-gas reaction)}$$

$$CO + H_2O \;\leftrightarrow CO_2 + H_2 \qquad \Delta H^0_{298} = -41\ kJ/mole \qquad \text{(WGS reaction)}$$

$$CO_2 + C \;\leftrightarrow 2\,CO$$

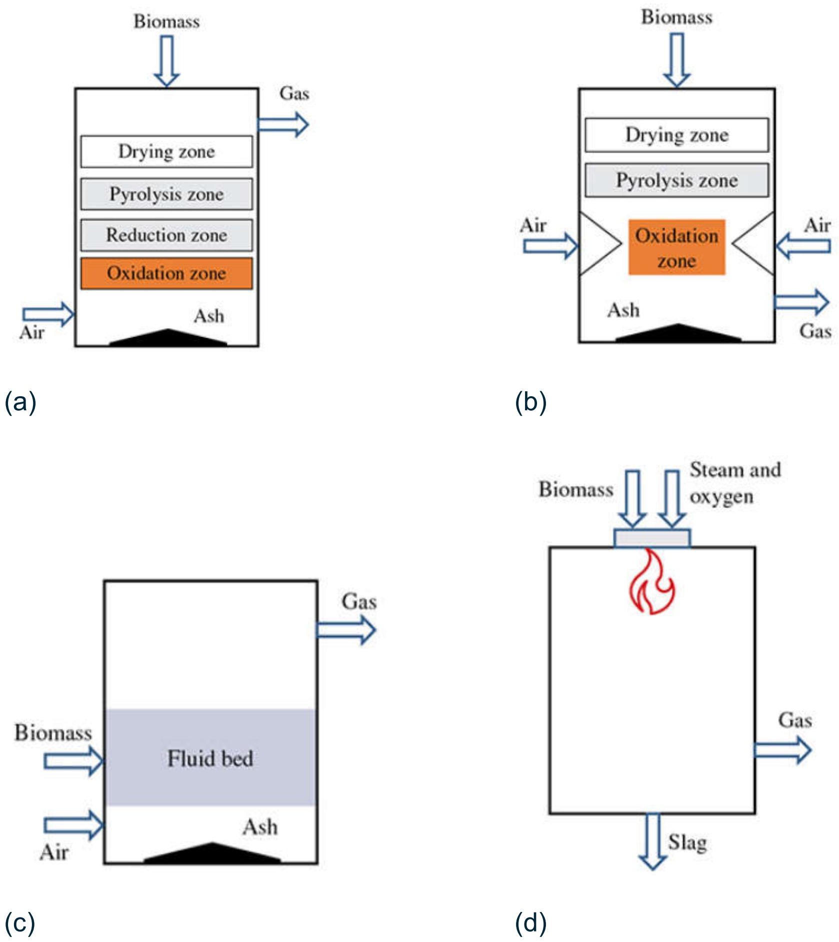
When syngas is produced, the second step should be accomplished that is the catalytic synthesis of methanol from the produced syngas. The last step of a methanol production plant is purification of the raw methanol that is produced in the methanol synthesis reactor. The raw methanol should be distilled to meet the final specifications. The purification is accomplished by one to three columns, where the first one is used a stabiliser for removal of dissolved gases (and volatile compounds like CO_2), and the latter ones are used for water removal. There are two main grades of methanol available[1]. These include "Chemical grade AA" that requires removal of essentially all water and byproducts to meet the composition of 99.85wt.% of MeOH, 0.1wt% water, and higher alcohols at ppm levels, as well as "Fuel grade methanol" that has a more relaxed requirements than the previous grade with the composition of 97wt.% of MeOH, 1wt.% water, 1.5wt.% alcohols, and 0.5wt.% of process oil.

[1] Aasberg-Petersen, K., Nielsen, C.S., Dybkjær, I., Perregaard, J. 2009. Large scale methanol production from natural gas. Haldor Topsøe.

3.2.2 Bio-methanol production

As mentioned earlier, in addition to natural gas or coal, organic feedstocks such as biomass (e.g., wood chips), biogas, or organic municipal waste can be used to produce bio-alcohols like methanol. Solid organic feedstocks such as biomass are converted into syngas by a similar process described for coal, i.e., gasification. However, in this case, raw materials need a pretreatment (such as drying and chipping)[1], and then the syngas produced needs to be treated to produce a syngas with low methane content, and proper H_2-to-CO ratio[2].

There are three main types of gasifiers based on the flow characteristics of the syngas produced including fixed bed (both updraft and down draft), fluidized bed, and entrained flow, as shown in Figure 6. Among them, fixed bed gasifiers are more prevalent for small-scale implementations than other types, while fluidized bed are more viable for large scale applications. It should be noted that typical efficiency range of common gasification systems is about 70-80% of the thermal energy of the biomass used.



[1] Deka, T.J., Osman, A.I., Baruah, D.C., Rooney, D.W., 2022, Methanol fuel production, utilization, and techno economy: a review, Environmental Chemistry Letters 20: 3525-3554. https://doi.org/10.1007/s10311-022-01485-y.

[2] Bromberg, L., and Cheng, W.K., 2010, Methanol as an alternative transportation fuel in the US: Options for sustainable and/or energy-secure transportation, Cambridge, MA, USA: Energy Efficiency & Renewable Energy, U.S. Department of Energy.

Figure 6. Main types of biomass gasifiers including (a) updraft fixed bed (b) downdraft fixed bed (c) fluidized bed and (d) entrained flow[1].

It should be noted that in addition to losses due to the gasification process, there are other energy losses during methanol synthesis and purification that reduces the energy efficiency of such a plant to somewhat lower than 60% [[2], [3], [4]], defined as the energy input (total MWh of feedstock used) divided by energy output (lower heating value of methanol produced). However, in methanol production, there are various potentials for energy optimization including recovering part of generated heat that is otherwise wasted for district heating or use of high temperature waste heat for electrical power production.

3.2.3 e-methanol production

In addition to the conventional production processes of methanol (and bio-methanol), hydrogenation of CO_2 (either from bio-origin, direct air CO_2 capture, or emission sources) via hydrogen produced from renewable energy has gained attention. A simple schematic of this process is shown in Figure 7.

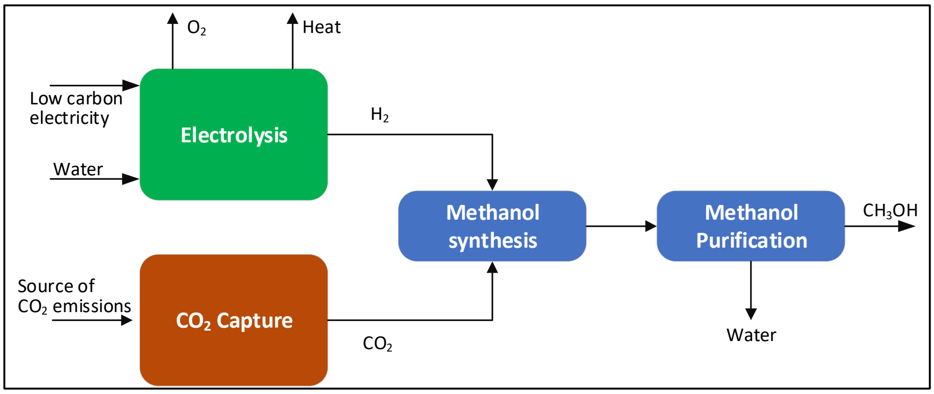


Figure 7. Methanol production using CO_2 hydrogenation.

There are different catalysts that can be used for hydrogenation of CO_2 for methanol production as overviewed by Ganji et al.[5], and the most studied and used ones are copper-based (Cu) metal catalysts that are commercially available Cu-ZnO-Al_2O_3 for the selective formation of methanol from the hydrogenation of CO_2.

Catalytic CO_2 hydrogenation involves mainly three equilibrium reactions leading to production of methanol and water:

---

[1] Kanoglu, M., Çengel, Y.A., Cimbala, J.M. 2023. Fundamentals and Applications of Renewable Energy", 2nd Edition, McGraw Hill Education, p. 510.

[2] Andersson, J., Lundgren, J., Marklund, M. 2014. Methanol production via pressurized entrained flow biomass gasification – Techno-economic comparison of integrated vs. stand-alone production, In Biomass and Bioenergy, Volume 64, 2014, Pages 256-268, ISSN 0961-9534, https://doi.org/10.1016/j.biombioe.2014.03.063.

[3] Danish Technology Institute. 2011. GreenSynFuels. EUDP project journal number: 64010-0011. https://energiforskning.dk/files/slutrapporter/greensynfuels_report_final.pdf.

[4] Clausen, L. 2014. Integrated torrefaction vs. external torrefaction – A thermodynamic analysis for the case of a thermochemical biorefinery. Energy, Volume 77, Pages 597-607. https://doi.org/10.1016/j.energy.2014.09.042.

[5] Ganji, P., Chowdari, R.K., Likozar, B., 2023, Photocatalytic reductionof carbon dioxide to methanol: Carbonaceous materials, kinetics, industrial feasibility, and future directions, Energy & Fuels 37: 7577-7602. https://doi.org/10.1021/acs.energyfuels.3c00714.

1) $CO + 2\,H_2 \leftrightarrow CH_3OH$ $\quad \Delta H^0_{298} = -90.8\ kJ/mole$

2) $CO_2 + H_2 \leftrightarrow CO + H_2O$ $\quad \Delta H^0_{298} = +41.2\ kJ/mole$ (revers WGS reaction)

3) $CO_2 + 3\,H_2 \leftrightarrow CH_3OH + H_2O$ $\quad \Delta H^0_{298} = -49.2\ kJ/mole$

Among these reactions, revers WGS reaction is an endothermic one, hence temperature increase is favourable for it. Note that temperature increase has negative impact for the other two reactions. Equilibrium. Therefore, based on the other reactions (1 and 2), lower temperatures and higher pressures result in higher methanol yields. According to Kiss et al.[1], in a process having all three components (CO_2, CO, and H_2) in the feed, the mole fractions must be adjusted to reach an optimal stoichiometric number (SN) of 2. The SN number (or sometimes referred to as, Module S) is calculated as follows:

$$SN = \frac{y_{H_2} - Y_{CO_2}}{y_{CO} + Y_{CO_2}}$$

This shows that when only CO_2 and H_2 are present in the feed, a H_2:CO_2 ratio of 3:1 ensures an SN of 2.

[1] Kiss, A.A., Pragt, J.J., Vos, H.J., Bargeman, G., de Groot, M.T., 2016, Novel efficient process for methanol synthesis by CO2 hydrogenation, Chemical Engineering Journal 284: 260-269. http://dx.doi.org/10.1016/j.cej.2015.08.101.

4 Mapping and identifying the main resources

An important step of this feasibility study is to identify the locally available resources that can be used as feedstocks to a green methanol production facility. A summary of these resources including green hydrogen, CO_2 that can be captured from industrial sources, and biomass (mainly in form of wood chips), as well as the enterprises that can supply such resources are described in this section.

4.1 Hydrogen from Kaupanes Hydrogen AS

Kaupanes Hydrogen[1] is a company that produces and supplies hydrogen for various purposes. They have a factory in Egersund that uses electrolysis to make hydrogen from water and renewable electricity. The hydrogen produced at Kaupanes Hydrogen's facility can alternatively be used as a feedstock for methanol production. It is worth noting that Kaupanes Hydrogen is in collaboration with the ROBINSON project (see Figure 8) and two of the partner enterprises (Dalane Energy AS and Egersund Næring og Havn KF) are also members of the EU ROBINSON project.

Figure 8. Kaupanes Hydrogen production facility at Kaupanes[2]

As of now, Kaupanes Hydrogen is considered as a relatively small production facility with a 1 MWel input and nominal production capacity of 390 kg H_2 per day that gives an estimated yearly production of 135-140 tonnes of compressed hydrogen. Kaupanes Hydrogen has plans of expanding their production to 21 MW electrical input using a new configuration. This could potentially increase their production to about 2 800-2 900 tonnes of H_2 per year.

[1] Kaupanes Hydrogen, Accessed online on 01.05.2024, https://www.kaupaneshydrogen.no/en-gb

[2] Photo credits to Pål Christensen from Stavanger Aftenbladet (https://www.aftenbladet.no/okonomi/i/kElOqA/minister-paa-hydrogen-blir-man-ikke-frelst-av-dette-er-det-ikke-haap)

4.2 Carbon dioxide from the emissions of the fish industry

The main emission sources in the study area are Pelagia Egersund Sildoljefabrikk and Prima Protein that are listed in Table 3 with the total CO_2 emissions of more than 20 700 tonnes in 2023.

Table 3. Carbon dioxide emissions in the study area[1]

Emission source	Year	Annual emissions to air
Pelagia Egersund Sildoljefabrikk	2023	8 990 tonnes
Prima Protein	2023	11 714 tonnes
Total CO_2 emissions	**2023**	**20 704 tonnes**

4.2.1 Pelagia Egersund Sildoljefabrikk AS

Pelagia Egersund Sildoljefabrikk is a leading producer of pelagic fish products for human consumption, and an important supplier of essential ingredients in all types of fish and animal feed, protein concentrate, fish meal and fish oil. The factory was founded in 1921 as Egersund Sildoljefabrikk. The factory has a great potential to reduce emissions from the production of fishmeal and fish oil and can be considered as a CO_2 resource via carbon capture implementation.

Annual CO_2 emissions from Pelagia Egersund Sildoljefabrikk for the recent years is shown in Table 4. It is important to note that the emissions from the factory have been declined from 19 031 tonnes in 2016 to 8 990 tonnes in 2023. This reduction in emissions is mainly due to reduced activities.

Pelagia Egersund Sildoljefabrikk plans to build a new factory at Kaupanes and move production from the old factory (refer to Figure 1). In their new premises, they are planning a more modern solution to cover their energy needs but have not yet landed a solution. Pelagia will not be able to be a resource for CO_2 in the short term but could be a possible resource in its new premises when it is completed. The new factory will have estimated emissions of 20 000 tonnes of CO_2 per year.

Table 4. Carbon dioxide emissions from Pelagia Egersund Sildoljefabrikk

Year	CO_2 emissions (tonnes)	Year	CO_2 emissions (tonnes)
2023	8 990	2019	14 626
2022	9 717	2018	17 101
2021	10 875	2017	18 646
2020	15 372	2016	19 031

[1] Data source; Accessed online on 27.03.2024, Norwegian Environment Agency, Land-based industry emissions to air in Norway, https://www.norskeutslipp.no/en/Industrial-activities/?SectorID=600

4.2.2 Prima Protein AS

With the aim of being a market leader in the production and sale of high-quality marine proteins and marine oils (pelagic production) in Norway and abroad, Prima Protein was established in 2017. Construction of the factory on Eigerøy in Egersund started in February 2018 and the state-of-the-art processing plant was completed in February 2019 (see Figure 9). In the same month (i.e., February 2019), they received the first delivery of pelagic fish, and the production started. The company has a goal to expand and produce more products beyond ingredients for fish and animal feed[1].

Figure 9. Industrial area at Kaupanes – Prima Protein[2]

In parallel with focusing on more products, Prima Protein has been active in supporting research and development activities; an example being their participation as the demonstration site for the EU Horizon 2020 ROBINSON project that aims for islands' decarbonisation via demonstrating innovative energy solutions. Figure 10 shows the ROBINSON concept that will be demonstrated at Kaupanes, inside (or in the vicinity of) the Prima Protein premises.

[1] Prima Protein AS, Accessed online on 27.03.2024, https://primaprotein.no/en/about-prima-protein/

[2] Photo credits to Eigersund Næring og Havn KF, https://dalaneenergien.no/egersund-er-forst-ut-med-hydrogenproduksjon-i-rogaland-gir-store-muligheter/

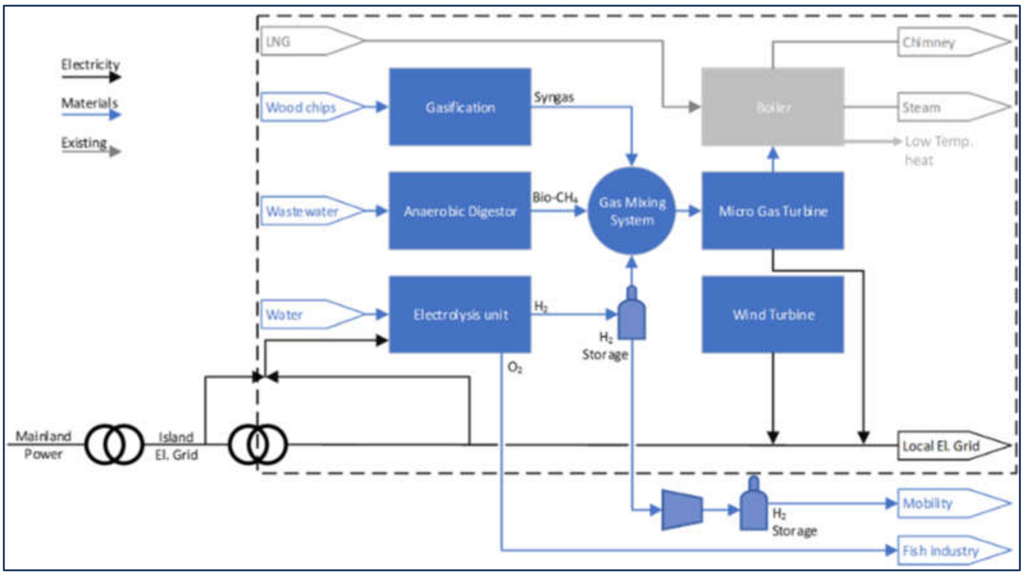


Figure 10. Original ROBINSON concept (inside the dashed box) to be demonstrated at Kaupanes[1].

The factory has had yearly average CO_2 emissions of 9 300 tonnes since the first reporting in 2020, as listed in Table 5, and the most recent data shows approximately 11 700 tonnes of CO_2 emissions in 2023.

Table 5. Carbon dioxide emissions from Prima Protein

Year	CO_2 emissions (tonnes)
2023	11 714
2022	8 520
2021	7 940
2020	9 040

[1] M. Mansouri, H. Madi, P. Breuhaus, Establishment of a baseline integrated energy system to decarbonise geographical islands, Proceedings of the ASME Turbo Expo 2022, Rotterdam, Netherlands, June 2022 (https://doi.org/10.1115/GT2022-82918)

4.3 Biomass resources

4.3.1 Wood chips from Geminor AS

Geminor is a Karmøy[1]-based international recycling company that provides services within waste treatment, material handling, logistics, and waste for energy production. At Holeviga on Kaupanes, Geminor provides services related to wood chips, including receiving, intermediate storage, grinding and shipping. The capacity limitation given by the governor of Rogaland County (Statsforvaltaren i Rogaland) in 2022[2] was to receive maximum 30 000 tonnes of waste per year, specified to 10 000 tonnes/year of sorted waste wood, and grinding 15 000 tonnes/year of wood chips. When required, Geminor can apply for larger volumes, which they normally will receive. Therefore, Geminor can be considered as a relevant supplier of wood chips for a possible bio-methanol production facility at Kaupanes, both in terms of the amount that they are currently receiving and handling in the study area and through the statement that they can provide whatever is required for a bio-methanol facility of wood chips both in terms of quantity (volume) and quality.

It is worth noting that if required, Geminor can transport wood chips from various other ports where they have operations today. Typical loads will be 1 500 to 2 000 tonnes per boat, which is a suitable amount for a weekly call and thereby contributing to a reduced amount of storage capacity at the possible bio-methanol plant.

4.3.2 NORTØMMER AS

NORTØMMER is a national actor operating also in the Port of Egersund, handling the timber that are produced and cut down by several forest owners in and outside the Egersund region. Through this company, there will be available raw waste wood in the form of tree tops and branches.

The availability of raw waste wood in terms of the amount (tonnes) varies with the amount of timber they handle each month/year. The quality of this biomass resource (in terms of energy content and moisture) will most likely vary depending on its source (i.e., type of forests, locations etc.) requiring some pre-treatment (e.g., drying).

4.3.3 Other waste wood actors

In Nord-Jæren, a region north of Egersund, IVAR IKS[3] that is an inter-municipality renovation company is handling approximately 8-10 000 tonnes/year of raw waste wood, which goes to material recycling. This resource is unfortunately thereby not available for bio-methanol production.

Private recycling actors are handling approximately 20-30 000 tonnes/year of waste wood (including Geminor), which is today mainly transported to Sweden for thermal (heating) energy production. These

[1] Karmøy is a municipality in Rogaland County, Norway. It is located approximately 150 km to the northwest of the town of Egersund.

[2] The governor of Rogaland County (Statsforvaltaren i Rogaland), 2022, Permit to operate according to the Pollution Act by Geminor AS in Egersund (Tillatelse til virksomhet etter forurensningsloven Geminor AS - Egersund), https://www.statsforvalteren.no/siteassets/fm-rogaland/dokument-fmro/miljo/soknad-og-loyve/avfall/revidert-tillatelse-til-geminor-as-egersund.pdf.

[3] IVAR IKS, About IVAR, Accessed online on 29.09.2024, https://www.ivar.no/english/.

resources are thus available for a bio-methanol plant, and the cost mainly depends on the energy price in Sweden and transportation costs of waste wood. Currently, the cost of waste wood in the Nord-Jæren region that can be transported to Egersund is estimated to be around 750-850 NOK/tonne for forest waste wood, while 500-600 NOK/tonne for used waste wood (including painted, impregnated wood etc.).

4.3.4 Municipal solid waste (MSW)

In Svåheia (see Figure 11), approximately 13 kilometres southeast of Egersund, the municipal waste is handled for the municipality of Eigersund. Depending on the configurations and cleaning processes chosen for both ash and gasses, it might be possible to partly add some of the MSW that is currently handled by Svaaheia Avfall AS[1] to the other biomass resources that are going to be used for producing bio-methanol.

Figure 11. Svåheia Industry Park hosting the MSW handling in the region[2]

[1] Svåheia Industry Park, Accessed online on 29.09.2024, https://www.svaaheia.no/svaaheia-avfall-as.6531008-576291.html.
[2] Photo credits to Svaaheia eiendom (https://www.svaaheia.no/naeringsutvikling-paa-svaaheia.6624664-578108.html).

5 Preliminary estimation of methanol production

Another important step of this feasibility study is to estimate the amounts of different feedstocks needed to for a green methanol production facility. As a basic assumption, it is estimated that one container vessel requires almost 11 000 tonnes of methanol for one year of operation. Using the amount of fuel for the engines of the vessel, the amounts of different feedstocks are then estimated.

5.1 e-methanol

In this section, using some assumptions, the amount of methanol that can be produced using the available H_2 in the study area is first estimated. The values are then scaled to cover the fuel needed annually to supply energy needed by one container vessel (i.e., 11 000 tonnes of methanol yearly per vessel).

The annual hydrogen production capacity by Kaupanes Hydrogen using 1 MWe of renewable-based power is estimated to be around 135 tonnes. The collected data and assumptions made for H_2 are listed in the following Table 6. Please note that the unit (having ca. 1 MWe input) is consisted of 2 modules, and the data listed (except the total production) are for each electrolysis module.

Table 6. The data collected[1] and assumptions made for hydrogen facility

Parameter	Dimension	Amount
Nominal hydrogen production rate	[kg/h]	8.1
Nominal hydrogen production rate	[Nm^3/h]	90.0
Hydrogen pressure	[bar]	35.0
Hydrogen purity	[%]	>99.998
Oxygen purity	[%]	>99.000
Stack		
Maximum stack power consumption BOL	[kW]	390
Maximum stack power consumption EOL	[kW]	450
Expected stack service life (operational hours)	H	100 000
Max. stack voltage (DC)	[V]	250
Stack current at 100% load	[A]	1 800
Stack water intake at 100% load	[litres/Nm^3]	0.9
Stack efficiency / power consumption at 50% load BOL	[%HHV]	85.2
Stack efficiency at 100% load BOL	[%HHV]	81.8
Stack power consumption at 50% load BOL	[kWh/Nm^3]	4.15
Stack power consumption at 100% load BOL	[kWh/Nm^3]	4.33
Total system container		
Total system efficiency at 100% load BOL	[%HHV]	73.5
Total system efficiency at 100% load BOL	[%LHV]	62.2
Total system power consumption at 100% load BOL	[kWh/kg H_2]	53.6
Total system power consumption at 100% load BOL	[kWh/Nm^3]	4.82

[1] HYPROVIDE® A-Series (A-90), Green Hydrogen Systems®, https://www.greenhydrogensystems.com/electrolysers/hyprovide-a-series-modular-plug-and-play-electrolysers

Total Facility		
Assumed capacity factor of the system	%	0.95
Annual total hydrogen production (consisting of 2 modules)	**tonnes**	**134.8**

* BOL – beginning of life, EOL – end of life, DC – direct current, HHV – higher heating value, and LHV – lower heating value

Table 7. The molar mass data of different process components

Parameter	Molar mass [g/mol]
Hydrogen (H_2) molar mass	2.016
Carbon (C) molar mass	12.011
Oxygen (O_2) molar mass	31.998
Carbon dioxide (CO_2) molar mass	44.009
Molar mass of methanol (CH_3OH)	32.042

Using molar mass given in Table 7, the number of kmol of H_2 produced annually is 66 875 (equivalent to ca. 135 tonnes). Assuming H_2:CO_2 molar ratio of 3:1 (refer to Section 3.2), the amount of CO_2 needed is 22 292 kmol that is equivalent to approximately 981 tonnes of CO_2 per year. Using ca. 135 tonnes of H_2 and 981 tonnes of CO_2, we can produce approximately 714 tonnes of methanol per year.

As mentioned earlier, to supply 11 000 tonnes of methanol fuel to one container vessel and based on the preliminary estimations above, there is a need for 2 078 tonnes of H_2 and 15 123 tonnes of CO_2. This requires approximately a 16 times bigger water electrolysis facility (based on given efficiency, and performance data provided in Table 6), but still in line with expansion plans of Kaupanes Hydrogen up to 21 MW electrical input.

5.2 Bio-methanol

For estimation of biomass resources needed for production of 11 000 tonnes of bio-methanol per year, only untreated white waste wood is considered. For clarification, a common classification of waste wood based on information available from the Wood Recyclers Association (WRA)[1] is listed in Table 8.

Table 8. Typical grades of waste wood

Types	Description
Grade A	Used untreated white wood including solid softwood and hardwood, packaging waste, scrap pallets, packing cases and cable drums. This class can include low quantity of nails and metal fixings.
Grade B	Industrial waste wood that includes treated and non-hazardous.
Grade C	Mainly municipal waste wood (mostly board products) that includes treated wood with paints but still non-hazardous.
Grade D	Hazardous waste wood that requires disposal at facilities licensed to accept hazardous waste

One important consideration to estimate the amount of biomass resources (specifically waste wood or wood chips) is that the energy content of available resources varies significantly specifically because of seasonal variations in the moisture content. A typical range that can be used for the moisture content is 40-45 mass%, at least the range that is commonly used in the Danish market[2]. For the study area, a water content of 35-40mass% is a good estimation. Using the lower water content range (i.e., 35%), the lower heating value of the waste wood is estimated to be around 3.2 kWh per kg of waste wood (or 11 500 kJ/kg). As mentioned earlier, assuming an energy efficiency of 60 LHV%, almost 32 000 tonnes of waste wood (grade A) is necessary to produce 11 000 tonnes of bio-methanol.

[1] Wood Recyclers Association, Grades of waste wood, Accessed online on 29.09.2024, https://woodrecyclers.org/wp-content/uploads/WRA-Grades-of-Waste-Wood.pdf.

[2] Danish Energy Agency, Biomass Statistics: Wood waste, 2018, Accessed online on 29.09.2024, https://ens.dk/sites/ens.dk/files/Statistik/metode_traeaffald.pdf.

6 Important considerations and preliminary cost indicators

As mentioned in the previous section; to produce 11 000 tonnes of e-methanol[1], it is necessary to have approximately 2 100 tonnes of H_2 and 15 100 tonnes of CO_2. For the same amount of bio-methanol, the amount of biomass needed is 32 000 tonnes per year (given the assumptions made for waste wood). Given the mapping exercise that was performed, as well as reviewing the development plans in the study area, production of methanol in both pathways seem to be feasible. It should be noted that the mapping exercise did not consider significant seasonal variations in CO_2 emissions from the point sources, i.e., Pelagia Egersund Sildoljefabrikk and Prima Protein that can affect e-methanol production. A typical yearly heat demand of these factories can be seen in Figure 12 that is proportional to the processed fish feedstock. As LNG is mainly used to supply the process heat, the CO_2 emissions associated with LNG use is also varying throughout a year with less emissions during winter periods.

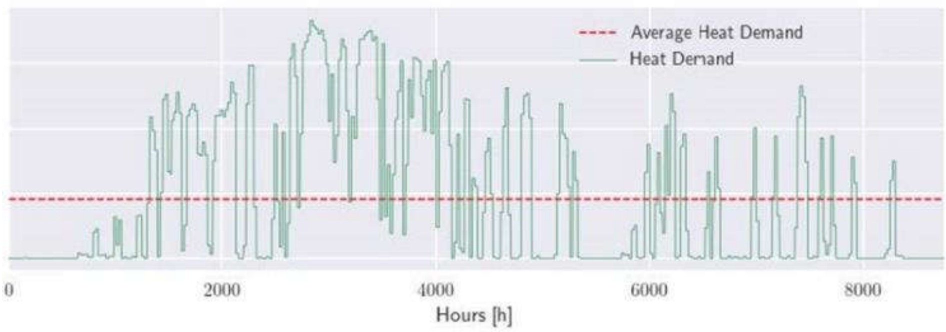


Figure 12. A typical heat demand in the fish industry located in the study area[2]

This variation in CO_2 emissions implies considering either storage of CO_2 during peak production of two factories throughout the year or find a different CO_2 source for approximately 2 500-4 000 tonnes. This is to cover the CO_2 demand for methanol production in December and January and some extra weeks in November and February, if required and is anticipated to vary between the years. A couple of alternatives to fill the CO_2 gaps from the point sources in winter can be listed as:

- Importing CO_2 by ships (or trucks)
- Using direct air CO_2 capture (DAC)

Regarding CO_2 import, Northen Lights in Øygarden[3] in western Norway (that will store CO_2 that is captured in different facilities including the Brevik CCS facility[4]) and other companies that transport CO_2

---

[1] Please note that a grade for methanol purity (whether it on chemical grade or fuel grade) has not been considered.

[2] International Renewable Energy Agency (IRENA) and Methanol Institute (MI), 2021, Innovation Outlook Renewable Methanol, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf.

[2] Madi, H., Lytvynenko, D., Jansohn, P., 2022, Decarbonisation of geographical islands - The role of solar, wind and biomass, 2nd International Conference on Energy Transition in the Mediterranean Area (SyNERGY MED) https://doi.org/10.1109/SyNERGYMED55767.2022.9941442.

[3] Northern Lights, Accessed online on 01.05.2024, https://norlights.com/what-we-do/

[4] Brevik CCS – World's first CO_2-capture facility in the cement industry, Accessed online on 01.05.2024, https://www.brevikccs.com/en

by ships for different purposes (e.g., the food industry) passing by Egersund can be considered. Northern Lights[1] transports CO_2 in liquid phase (-25°C and 17 bar) with ships[2], and each ship has two cylindrical cargo tanks (each tank with capacity of 3 750 tonnes). Ships for the food industry typically have smaller capacities in the range of 1 500-1 800 tonnes. One should pay attention that there are already some development plans and feasibility projects going on in the region (outside the study area) related to CO_2 capture from waste incineration in Nord-Jæren (IVAR IKS) or in Svåheia that might be beneficial for transporting smaller volumes of CO_2 using trucks. In general, CO_2 import option might have the benefit of a reduced capital expenditure (CAPEX) needed, as compared to building a large storage tank on a possible methanol production site in the study area. However, there are various factors, specifically when considering ship transport, requiring deeper investigation, such as:

- Additional requirements at the harbour for offloading and handling CO_2 including the space and the equipment needed. In this regard, a reception system including storage/buffer tanks, pressure adjustment devices, systems for liquification/evaporation, and other auxiliary systems is needed.
- Additional measures to maintain CO_2 quality for the methanol production facility and for the transport means itself (i.e., ships). One should note that different transport ships contain CO_2 from various suppliers and thereby different CO_2 quality (impurities, water content, temperature, and pressure). Offloading CO_2 from the transport ships to the storage/buffer tanks will increase the risk of undesired elements on both ends[3] (i.e., the ship and the tank).
- Partial versus full de-bunkering of ships. Partial offloading poses higher complexity as opposed to full-tank offloading (this is relevant if a transport ship has a larger capacity than what is needed for a possible methanol production facility and its CO_2 storage/buffer tank, that can be relevant to for example Northern Lights' ships).

Direct air capture of CO_2 can also be an option for either filling the gaps in CO_2 that can be captured from the local point sources, or as a sole supplier of CO_2. In short, DAC systems capture CO_2 using a sorbent materials providing high purity CO_2 streams ready for utilization, or compression if transport and storage is the goal. The core of these systems consists of a cycle of CO_2 sorption, and CO_2 desorption. The CO_2 sorption process happens in air collectors where ambient air (that has a low CO_2 content) is brought in contact with the sorbent materials to which its CO_2 binds either physically or chemically. During CO_2 desorption (or regeneration process), the captured CO_2 is separated from the CO_2-rich (or saturated) sorbent under different operational conditions than those in the air collectors (for more details on the DAC process, readers are encouraged to read different studies, an example being Socolow et al.[4]).

---

[1] Northern Light JV, Accessed online on 30.09.2024, https://norlights.com/who-we-are/.

[2] Northern Lights JV, 2023, Accessed online on 30.09.2024 https://norlights.com/news/northern-lights-enters-charter-agreement-to-expand-fleet-with-a-fourth-co2-ship/.

[3] This is of specific concern when dealing with food quality CO_2.

[4] Socolow, R., Desmond, M., Aines, R., Blackstock, J., Bolland, O., Kaarsberg, T., Lewis, N., Mazzotti, M., Pfeffer, A., Sawyer, K., Siirola, J., Smit, B., Wilcox, J. 2011. Direct air capture of CO_2 with chemicals − A technology assessment for the APS Panel on Public Affairs. American Physical Society - APS Physics.

DAC is a technology that is increasingly tested out because of its direct contribution to CO_2 removal from the atmosphere. As compared to other CO_2 capture technologies from point sources, DAC plants offer various advantages including their potential for higher CO_2 purity, modularity (that can result in easier sizing and improved reliability), and siting flexibility. These systems are commonly available with small capacities that can also be seen as one of their advantages. Nevertheless, DAC systems suffer from high CO_2 reduction costs. This is because of their scales, use of newer technology as compared to their competitors (and not so long track records of real life operation), and the fact that the CO_2 concentration in ambient air is very low (with about 420 ppmv) that is significantly lower as compared to e.g., the flue gas of a natural gas fired gas turbine cycle or a coal-fired power plant. Despite the high costs of the technology, an important consideration is the availability of competencies in the region including technology suppliers such as GreenCap Solutions AS[1] with the capability of building and delivering DAC modules of typically 10-20 000 tonnes of CO_2.

Another alternative pathway that was not covered in this report and certainly has potential to be further explored, is production of bio-e-methanol that can be achieved by using biogas as a feedstock. Biogas is a mixture of carbon dioxide and methane, and using steam reforming, syngas can be produced from biogas. If hydrogen is added to the process, a higher conversion of the CO_2 can be achieved. H_2 addition can be seen as a flexibility in this pathway depending on its availability. Certainly, benefitting from this flexibility (via intermittent addition of H_2) requires additional considerations and investment (because of more downstream systems), as the gas composition changes significantly when H_2 is supplied at different quantities and time. Providing a utilization pathway for both H_2 and biomass resources, this alternative pathway can be seen as a bridge between several of the resources that are available in the study areas. Once again availability of actors and technology suppliers is underlined that can provide future collaboration opportunities, as well as knowledge and technology transfer to the study area and beyond. An example here is Glocal Green AS[2] that is currently in the process of establishing a first-of-a-kind facility in Norway in the municipality of Øyer aiming at a production capacity of up to 150 000 tonnes of annual production by 2028.

In addition to considerations mentioned above, various pathways for methanol production offer a wide range of costs. One challenge for cost estimation of renewable-based methanol production is lack of data that is mainly because of low production capacity (as compared to fossil-based production that is almost exclusively practiced globally). In addition, various parameters like conversion efficiency, feedstock costs (and for example electricity price), and capacity factor of the production facility can significantly affect the production costs. International Renewable Energy Agency – IRENA[3] estimates the production costs for different pathways to be:

- E-methanol: 800-1 600 USD per tonne noting that the costs are very much sensitive to the costs of both hydrogen and carbon dioxide the production cost of e-methanol was estimated to be in the range. They assumed a CO_2 cost of 10-50 USD per tonne. Using CO_2 from DAC would

[1] GreenCap Solutions AS, Accessed online on 30.09.2024, https://greencap-solutions.com/about-us/.

[2] Glocal Green AS, Accessed online on 02.10.2024, https://glocalgreen.com/divisjoner/.

[3] International Renewable Energy Agency (IRENA) and Methanol Institute (MI), 2021, Innovation Outlook Renewable Methanol, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf.

increase the e-methanol production costs to a range of 1 200-2 400 USD per tonne assuming 300-600 USD per tonne of CO_2 from DAC. If we focus on the study area and consider DAC as the option to fill to supply lack of CO_2 due to seasonal variations in the point sources, increased CAPEX and OPEX is an inevitable consequence. We should remember that due to some technological advancements in DAC within a couple of years, costs figures of about 100 USD[1] per tonne of CO2 are not impossible to achieve assuming that the DAC unit is in its full load operation. The cost will be higher when the facility is only used for part time production. In case of CO_2 import using container/ship, extra cost for infrastructure needed as for offloading and CO_2 is very uncertain. Nevertheless, using iso-container transporting liquid CO_2 seems to be a simpler and more cost-effective option than bulk transport by ships[2].

- Bio-methanol: 320-770 USD per tonne of methanol with potential for costs reduction down to 220-560 USD per tonne due to technological advancements and even more reduction when much cheaper resources like industrial waste streams or MSW are utilized.
- Conventional fossil-based: 100-250 USD per tonne of methanol using natural gas reforming or coal gasification.

[1] According to personal communication with GreenCap Solutions AS.

[2] According to personal communication with Brevik Engineering AS (https://brevik.com/).

7 Future works and conclusion

Two main pathways that are considered in this report are e-methanol production from hydrogen and carbon dioxide, and bio-methanol production using biomass resources. As for the case of producing e-methanol (using H_2 from water electrolysis and CO_2 from emission point sources) and considering the amount of H_2 and CO_2 needed to produce enough fuel for one container vessel, it seems that the study area has sufficient potential and resources locally. Nevertheless, there are still several factors that need to be considered before starting to investigate appropriate CO_2 capture technologies, the logistics and infrastructure for transporting, storing, and utilising CO_2, optimal site for the e-methanol production facility, and the economic viability and environmental benefits of e-methanol production. Here comes some of these factors that require further investigation:

- In this study, it is estimated that a much larger hydrogen production facility than the one available in Kaupanes is needed to cover the H_2 needed to produce 11 000 tonnes of methanol per year. Practically, the size of such a facility needs to be scaled up to about 16 MWel. This expansion is already in line with the expansion plans of Kaupanes Hydrogen that targets 20 MWel additional capacity. One should note that using larger electrolysis facilities with advanced configurations can result in less inefficiencies and higher specific production of H_2 (kg of H_2 per MWe input).
- As estimated, there is a need for about 15 123 tonnes of CO_2 to produce the required amount of methanol (i.e., 11 000 tonnes). This is less than the amount of CO_2 emissions currently emitted from Pelagia Egersund Sildoljefabrikk AS and Prima Protein AS (20 704 tonnes in 2023, refer to Table 3). As stated earlier, the amount of CO_2 emissions from the future factory of Pelagia Egersund Sildoljefabrikk AS alone with about 20 000 tonnes is estimated to be more than the required CO_2 amount. One might think that the total available CO_2 emissions is even in a range to cover CO_2 needed to produce methanol fuel for two container vessels. However, we should remember that the amount of CO_2 that can be captured will be less than the total sum of CO_2 emissions from the mentioned two factories. Also, it is extremely difficult, energy intensive, and expensive to reach very high carbon capture rate (say above 95%).
- Assuming pessimistic CO_2 capture rates (i.e., low separation efficiencies), there is still enough CO_2 available to produce the required methanol (of course, assuming that there will be enough H_2 available from Kaupanes Hydrogen or in general within the study area). However, an important consideration here is that both factories, i.e., Pelagia Egersund Sildoljefabrikk AS and Prima Protein AS (as sources of CO_2) have similar fluctuations in their seasonal (and even daily) production profiles. Consequently, the amount of CO_2 available is fluctuating (and not stable) and even there is no CO_2 available for some days/weeks when fish stock (as main feedstock to the factories) is unavailable. This issue requires analysis of historical production profiles (and expansion potential) of both factories. Consequently, proper CO_2 storage options need to be considered for periods that there are no CO_2 emissions available to be captured and sent to a possible methanol production facility. To reduce CO_2 storage size, other potential options to supply CO_2 needs to be investigated.

As for the case of producing bio-methanol (using biomass resources), it seems that the study area has sufficient potential and resources locally. Based on high level assumptions, such as an energy efficiency of 60 LHV% for the entire process of bio-methanol facility, almost 32 000 tonnes of waste wood (grade

A) is necessary to produce 11 000 tonnes of bio-methanol. Like e-methanol case, there are some factors that require further investigation:

- As mentioned earlier, the estimation of the feedstock needed (waste wood) is very much sensitive to the quality of the waste wood that is available in the study area or can be brought to the study area. Proper storage of waste wood in the location or high share of imported dryer waste wood can significantly reduce the amount of waste wood needed. In addition, the amount feedstock needed is significantly influenced by the conversion efficiency (energy efficiency) of the resources to methanol.
- Waste wood (or wood in general) has a global market, and as mentioned earlier, part of the available feedstock is currently exported to other countries for re-use or energy production and part of it is used for energy production in the region. Therefore, it is important to estimate the environmental impact (both positive and negative) of using this feedstock in a bio-methanol production facility as compared to the existing uses.

An area that can benefit both e-methanol and bio-methanol cases is to recover part of the waste heat that is generated in both pathways for district heating and other industrial uses. This circularity and increased integration potential in the study area can result in an improved economic viability of both cases. In addition, another alternative pathway that is not covered in this report and certainly has potential to be further explored, is production of bio-e-methanol. This pathway offers an alternative use of H_2 in the study area, combining it with utilization of biomass (and waste) resources for methanol production. All these areas and possible scenarios with higher likelihood can be explored further for the Port of Egersund in the context of REDII Ports project, serving the ports involved in the project with a strong foundation for building synergies and better opportunity to explore circular possibilities.