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Feasibility study for
Power-to-X production on Bornholm

WP3 Market for products

Authors:
Maja Felicia Bendtsen, Rønne Havn
Torben Jørgensen, Bornholms Energi & Forsyning
Jörgen Edström, Bornholms Energi & Forsyning

Review by partners:
Skovgaard Energy
Ramboll

RESUME

On and around Bornholm there is a market for both e-fuels like ammonia, hydrogen, and methanol as well as side streams from Power-to-X production like oxygen and waste heat.

Looking at e-fuels the largest market is within ship traffic, which can be split in two types of customer segment. One segment is the traffic in and out of Port of Roenne, where there is a potential market for e-fuels to respectively ferries and offshore wind installation projects. This market could amount to as much as 300 GWh of energy of which the majority would be for the ferry operation, which is expected to be CO2e-emission free latest from 2030 and because of the conditions around the operation the ferry operation is not likely to be battery electric, which is seen for a number of other ferry routes.

Secondly, vessels passing by Bornholm could in time develop into a significant market for e-efuels. Every year 60.000 vessels pass close by the island of Bornholm and the introduction of EU ETS for shipping as well as FuelEU Maritime will push for the implementation of efuels like ammonia and methanol for shipping. Estimated there could be a market of 170 GWh of energy in 2040. For shipping the displacement price for fossil fuels are expected to be 804 DKK/MWh in 2030.

Smaller markets exist locally in respectively industry and heavy transportation. These markets will likely be converted to either biogas or hydrogen, where the displacement price for fossil fuels will range between 795 and 929 DKK/MWh in 2030. The market for industrial use is expected to be as little as 9 GWh of energy per year, as the current 18,5 GWh can be halved through both electrification and efficiency improvements. For heavy road transportation the current market is quite significant with an annual consumption of 155 GWh of energy. However again direct electrification will cover a large part of this market, and hence the market for heavy road transportation locally on Bornholm is expected to be in the magnitude of 50 GWh energy.

Besides e-fuels there is also side streams of both oxygen and waste heat from a Power-to-X production, which could potentially be sold and utilized by other actors.

The largest known potential user of oxygen is wastewater treatment, which utilize around 3.000 ton of oxygen per year. The alternative for a wastewater treatment plant is continuing as today, using atmospheric air, however an introduction of oxygen could reduce the need for pumping air by almost 80%. This saving would have to be used for both purchasing oxygen and building the necessary equipment to use oxygen instead of atmospheric air. Another potential future user of large amounts of oxygen could be aquaculture, producing fish in fish farms, however this potential has not been quantified.

Bornholm has a widespread distribution of district heating with five different areas of supply. There are considerations to establish a connection between four of these areas, which combined sell 317 GWh of heat to customers. This heat could potentially be partly supplied by waste heat from a Power-to-X production facility. The substitution price for district heating is currently 93 DKK/GJ or 335 DK/MWh, however here it is important to note that this will not be the full value of the waste heat from Power-to-X production, as the temperature is typically around 60°C, and this needs to be raised to approx. 90°C before it can be utilised in the district heating system.

In addition to utilization of waste heat in district heating systems, there is also potential for utilization in new industries, which at the same times could create new jobs for Bornholm. However, the potential for offsetting waste heat in new industries has not been quantified.

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1 MARKET INVESTIGATION

Before assessing the market for the individual fuels, which can potentially be sold from a Power-to-X production facility it is relevant to identify the possible future consumers and their combined need for energy. There are four potential offtake markets for efuels, namely a) local industry, b) local heavy transportation, c) ship traffic to and from Bornholm and d) ships passing by and served in Bornholm Bunker Hub

1.1 Energy consumption in local industry

From the work with the Bornholm Energy Strategy it is estimated that the local industry on Bornholm is using process energy [1] equivalent to 18 465 MWh of energy or 4 435 tons of CO_2e

The main users of process energy on Bornholm are

- Danish Crown

- Bornholms Andelsmejeri
- Victor Vask
- Jensen Danmark (Rønne)
- Hasle Refractories
- Small Batch Bornholm
- Svaneke Bryghus
- Ole Almeborg A/S
- PL Beton
- Beck Pack

Today the users are using LPG as fuel to cover their need for process energy. This fuel could in future either be replaced by non-fossil LPG, biogas, hydrogen or electrification of processes. The Danish government have in 2019 established 14 partnerships for the decarbonization of different sectors. The partnership for the production industry has made some recommendations how the sector can reduce their emissions by 95% in 2030 compared to 1990 [2]. Approx. half of the reductions should come from efficiency gains and further electrification, while the reminder should be reduced through a change in fuel. In the work of the partnership this change is anticipated to be for biogas.

Converting to either biogas or hydrogen would require changes in the technical infrastructure of the companies as both biogas and hydrogen have different properties for storage and transport than LPG. Hence the industrial sector on Bornholm will have to make a new business case to establish which of the three solutions would be the most viable for the individual companies.

However, seen from an overall perspective, it is anticipated that the 18 465 MWh of energy used today in the form of LPG will in future be reduced up to half of the current consumption based on the potential from efficiency gains and electrification [2].

None of the mentioned companies representing the main industrial activity on Bornholm are included in the EU Emission Trading System [3] (ETS). The Danish government have decided to apply a CO_2e tax on the industry and other sectors not currently included in the ETS, taxation will commence from 2025.

For the companies on Bornholm the tax will be 350 DKK/ton CO_2e in 2025 and increase to 750 DKK/ton CO_2e in 2030 [4]. LPG emits 2900 kg CO2 pr ton of LPG, which therefore will have an additional cost of 2 175 DKK in taxes in 2030.

LPG contains 12,78 MWh/ton and delivered at Bornholm LPG has a price of 9 700 DKK/ton[1]. Hence the cost of using LPG is (9 700 DKK+2 175 DKK)/12,78 MWh, and therefore the competitive price for green solutions to displace LPG is 929 DKK/MWh.

1.2 Fuel consumption in local heavy transportation

Heavy transportation encompasses both vans, trucks, bus services and machines used in farming. According to the Bornholm Energy Strategy [1] heavy transportation on Bornholm uses energy equivalent to 155.000 MWh of energy or 15.500 m^3 of diesel, which is the dominant fuel in heavy transportation.

These numbers are valid for transportation companies and activity with a base on Bornholm, such as

For trucks: BHS Logistics, Ole Holm Transport, HGN Transport, Fugato

Bus services: BAT, Åkirkeby Turisttrafik, Gudhjem Bus, Jan-Oles Turisttrafik, Nexø-Svaneke Bus

Van services: Borntrans, GLS, Bring, PostNord

[1] 2030 projection of current price

When possible local truck transport companies avoid sending their trucks to the mainland, instead they only send the semitrailer with the ferry. Therefore, the consumption of fuel for heavy transportation is likely higher than reported in the Bornholm Energy Strategy, as the ferries on an annual basis bring approx. 5.000 trucks[2] back and forth to the island, and a number of these truck will be from companies, which does not have a base on Bornholm. In comparison the ferries bring approx. 17.000 semitrailers back and forth.

Heavy transportation can be further divided into the different types of vehicles as can be seen in Figure 1.

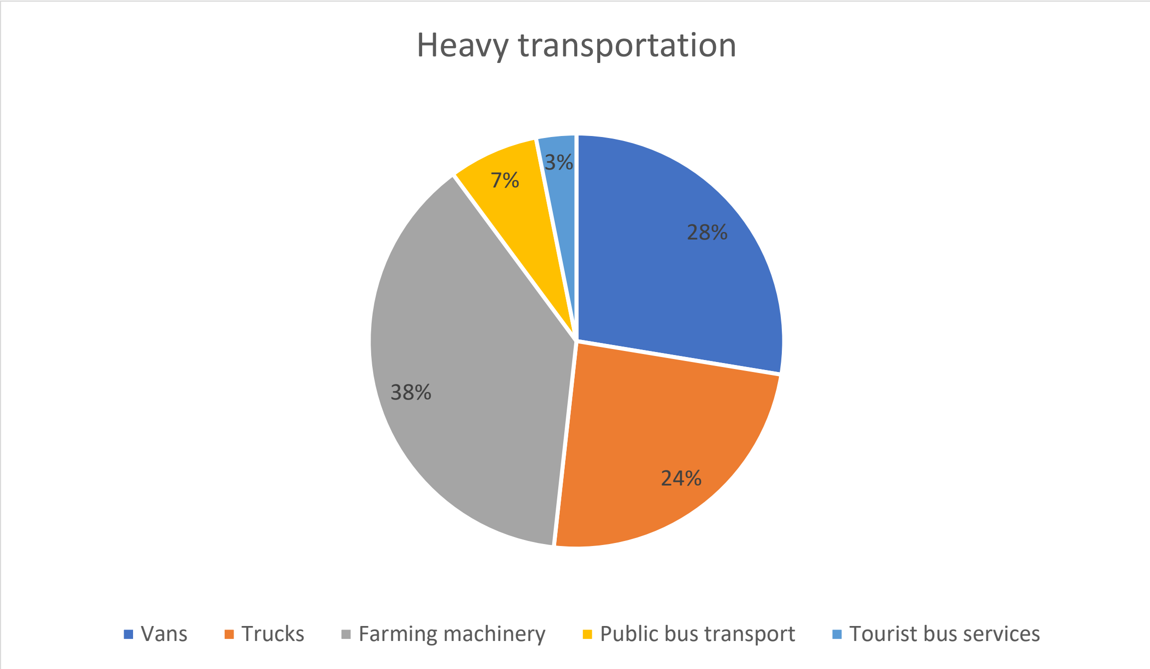


Figure 1 Distribution of segments in heavy transportation on Bornholm [5]

It is expected that vans will primarily be electrified, and therefore they are not given further consideration. A large share of the public bus transportation is also expected to be electrified and therefore the investigation of the potential local market for green fuels will focus on trucks, farming machines and tourist busses.

Through discussions with local actors within the transport industry is evident that they to a large extent prefer to have trucks and busses on solutions, which requires green fuels. With their driving patterns and especially need for flexibility in operations they do not consider direct electric vehicles as the optimal solution for their company. This viewpoint is supported by the logistic industry on a national level [6]. Similarly, most farming machinery will likely be driven by green fuels, again because the utilization of farming machinery requires an extremely high utilization rate a few weeks per year, in which there is very limited time for the necessary recharging of the machinery.

Hence the estimated need for green fuels for heavy transportation on Bornholm could in an conservative estimation be half of the consumption for Trucks (24%), Tourist bus services (3%) and Farming Machinery (38%) of the 155.000 MWh of energy, which the heavy transportation on Bornholm is using. This is equivalent to 50.375 MWh of energy, or 5.038 m3 of diesels. In general diesel engines for heavy transportation operates

[2] Statistics on the number of vehicles using the ferries in Denmark https://www.statistikbanken.dk/SKIB31 and https://www.statistikbanken.dk/SKIB32

with an energy efficiency of around 40-45% [7], which should be taken into account when transforming the estimated consumption to alternative fuels, depending on the drivelines to be used.

From 2027 road transportation will together with buildings be included in the Emission Trading System (ETS) of EU. This mean that the providers of fuels for transportation will be forced to purchase CO2e emissions in the ETS, and this higher price will be reflected on the price that transport companies will pay. By 2030 the emissions from road transportation should be reduced to 45% of the 1990-level [8]. As the ETS for road transportation and buildings is new, it is unknown what the price of CO2 emission will be, however the current price is approx. 92 € pr ton CO2e [9], which has risen from approx. 20 € in the years 2018-2020. Additionally, the Danish Governments has decided to add additional tax on CO2 emissions with a level of 375 DKK/ton CO2e emitted from 2030 [10].

One liter of diesel emits 2,66 kg, and hence the additional cost of using diesel in 2030 due to taxes and the EU ETS is 2,66 kg CO2/l*(0,375 DKK/kg CO2+0,750 DKK/kg CO2) = 2,99 DKK tax/l of diesel[3]. For comparison the current CO2 tax on diesel is approximately 0,44 DKK/l [11]. 2,99 DKK/l of diesel in additional tax is equivalent to 795 DKK/MWh of diesel energy.

1.3 Bornholm Bunker Hub

Port of Roenne have launched the project Bornholm Bunker Hub in cooperation with Ramboll, Ørsted, Topsoe, Bunker Holding, Molslinjen, Wärtsilä and Bureau Veritas in spring 2021 with the ambition of providing green fuels for some of the +60.000 vessels passing by Bornholm every year as well as green fuels for the local ferry service.

Consumption for local ferry operation and other vessels in Port of Roenne

The ferry operation to and from Bornholm emits approx. 93.000 ton CO2 each year [1], which is equivalent to 29.000 ton of marine gas oil, which because of the SECA area [12] is the dominant fuel in the Baltic Sea, and the fuel, which all the ferries use. The ferry service to and from Bornholm is subsidized by the Danish state and it is expected that emission-free operation will be a requirement from the start of the next contract period from 2030. The Danish state have already had such requirement for the public tenders on the routes to and from Samsø and Bøjden-Fynshav [13].

Because of the size and type of ferries servicing Bornholm they will likely not be fit for direct electrification [14], which was the winning technology for the bids on the routes to Samsø and Bøjden-Fynshav. The large high-speed ferry sailing between Rønne and Ystad sails at speeds up to 36 knots and has an engine power of 36 MW. Additionally, there is also a conventional ferry sailing goods to and from Bornholm. This ferry has a service speed of 18 knots and 9,8 MW engine power with a crossing time of 5,5 hours.

Besides the ferry operation, Port of Roenne have in recent years worked as an offshore installation port for wind park projects in the Baltic Sea. More and more wind park owner, such as Ørsted, Copenhagen Infrastructure Partners, RWE, Vattenfall and others begin to set targets for green transportation and installation of their wind parks. By 2040 Ørsted [15] requires their supply chain to be CO2-neutral and the same goes for RWE, who also aims for a 30% reduction in the supply chain by 2030 [16]. Hence it is very likely that vessels visiting Port of Roenne in relation to offshore wind project will request to have green fuels available. Given the number of available ports with purpose-built infrastructure for offshore wind, it is estimated that there will be installed 1 GW offshore wind out of the port each year from 2025 to meet the targets in the Baltic Sea. This amount to approximately 1100 ton of fuel for the installation vessel and 600 ton for the cargo vessels per year for each 1 GW project. Detailed calculations can be found in Appendix 1.

Potential market in the Baltic Sea

[3] Based on the assumption that the ETS price in 2030 will be 100 €/ton CO_2, which equivalates to 750 DKK

Helcom, an intergovernmental organization established in 1974 to protect the marine environment of the Baltic Sea from all sources of pollution, make yearly reports of the fuel consumption in the Baltic Sea [17]. This report shows that the most fuel consuming segments are RoPax, RoRo, Cargo, Container and Tankers as can be seen in Figure 2. Definition of the vessel segments can be found in Appendix 2. Combined the vessel segments consume 4.360.000 ton of fuel or approximately 43.600 GWh of energy.

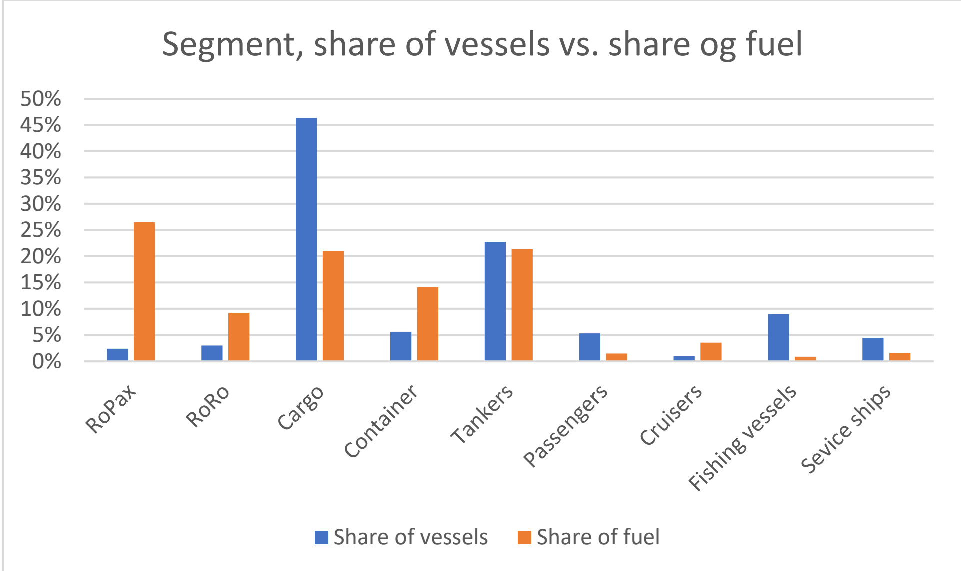


Figure 2 Distribution of fuel consumption and number of vessels on different segments

The Baltic Sea can be divided into different geographic areas defined by crossing lines and thereby it is possible to identify the share of different segments of ships in different areas of the Baltic Sea. The crossing lines 3 Sundet syd (Southern Øresund), 5 Kadet Fairway (Femernbælt), 6 North of Bornholm, 7 South of Bornholm, 8 West of Gotland and 9 East of Gotland can be seen on Figure 3.

Figure 3 Different crossing lines and geographic areas in the Baltic Sea

To identify the potential market for Bornholm Bunker hub and hence potential offtake from a local Power-to-X plant it is relevant to focus on the types of ships passing by Bornholm. This can be done by looking at the distribution of segments on the crossing lines. Figure 4 shows that the segments primarily passing the waters around Bornholm is Cargo, Container and Tankers, while Passenger/RoPax and RoRo is fairly limited.

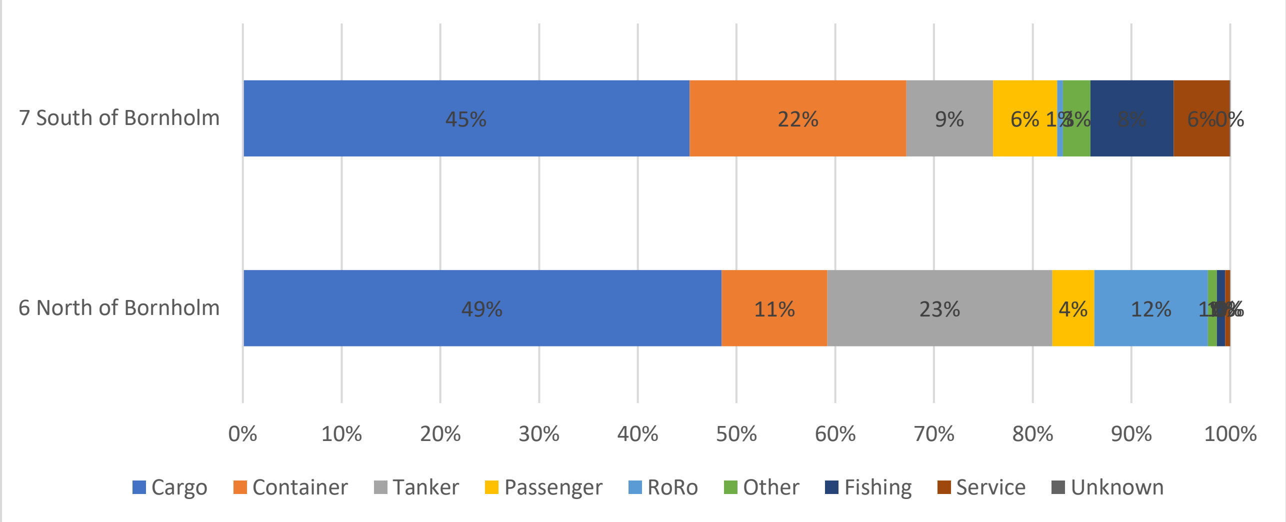


Figure 4 Distribution of segments on crossing lines in the Baltic Sea around Bornholm

Every year 60.000 vessels pass by Skagen [18]. Of these around 3500 vessels stop and bunker a total of 1.000.000 ton of fuel [19]. A similar number of vessels pass close by Bornholm every year, and if it is estimated that 0,1% of these vessels stop and refuel green fuels from Bornholm Bunker Hub in 2030, this equivalates to 60 vessels bunkering around 17.100 ton of fuel. This number can seem unrealistic high, however with the recent agreement of the Fuel EU Maritime directive [20], shipping industry is required to use a minimum of 1% so-called RFNBOs (Renewable Fuels of Non-Biological Origin) by 2030. RFNBOs is the same as e-fuels produced using Power-to-X technology and with a 1 % consumption in 2030, it is equivalent to 43.600 ton of fossil fuel used in the Baltic Sea, which will have to be replaced by e-fuels for RoPax, RoRo, Cargo, Container and Tankers vessels. In 2040 the CO2e emissions will have to be reduced by 38%, which is much higher than the 6% in 2030. It will not be all of this reduction which will be reduced by using RFNBO, but it could be reasonable to believe that RFNBOs should at least be doubled in 2040, and hence expected Bornholm Bunker Hub could sell 34.000 tons in 2040.

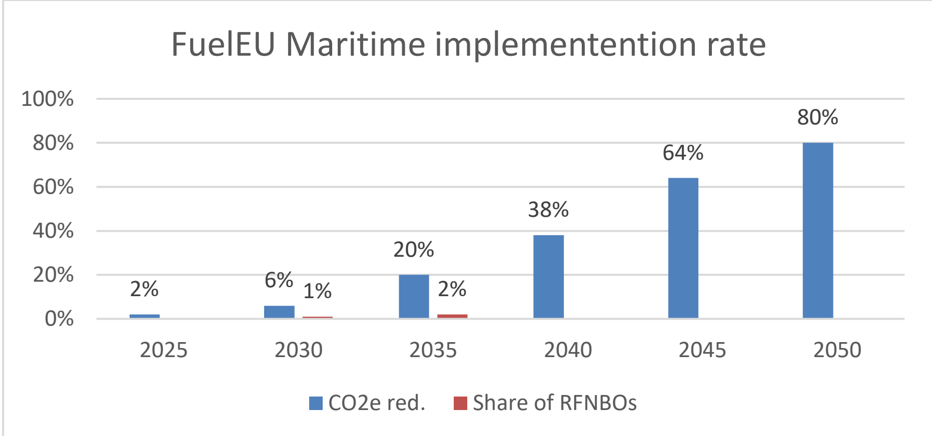


Figure 5 FuelEU Maritime implementation rate for respectively reduction in CO2e emissions and implementation of RFNBOs, also known as eFuels [20]

Price for fossil fuels vs. green fuels

Most vessels in the Baltic Sea use MGO (Marine Gas Oil) as fuel. The price of the fuel varies around the world and is typically more expensive in the smaller ports. Fuel prices are also very volatile and deeply dependent of geopolitical events. Figure 6 show the development in price of MGO in the last three years [21]. Currently MGO has a price of 860 $/ton. From 2026 all vessels above 5000 GT will have to report all their CO2e emissions in the EU ETS (Emission Trading System), and emission from intra EU travel account for 100%, while sailing between an EU and non-EU port accounts for 50%. Vessels will have to pay the price of the European Carbon Market for all their emissions. Over the years the amount of CO2e in the EU ETS system will be lowered, starting with 2% in 2022, 6% in 2030 and further until there is a reduction in emissions of 75% in 2050 [20]. This will drive up the price for CO2e on the EU Carbon Market.

As one ton of MGO emits 3,2 ton CO2e [22] the cost of purchasing CO2e emissions is expected to be ~2.400 DKK/ton MGO in the EU ETS. For vessels sailing in Danish waters there will be a further tax of 375 DKK/ton CO2e [23], adding additional 1.200 DKK/ton. Hence the additional taxes in 2030 will be 9.460 DKK/ton MGO used. This is equivalent to 804 DKK/MWh of energy from MGO.

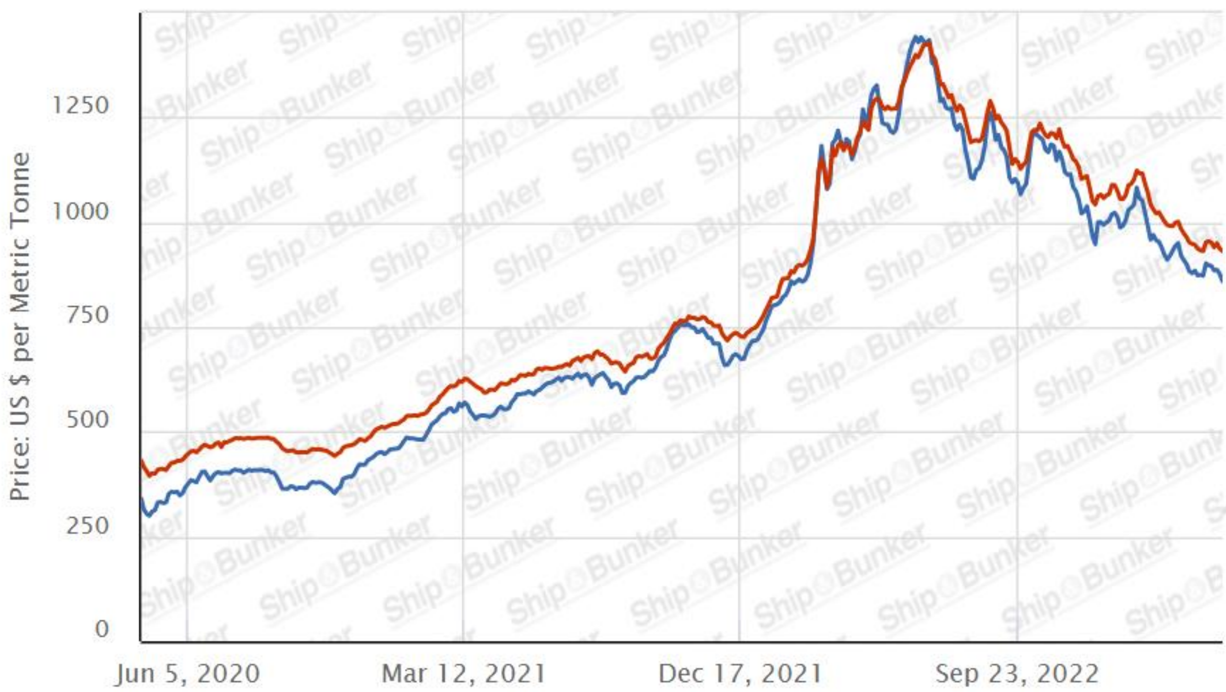


Figure 6 Fuel price for MGO in $/ton. The red curve is the global average, and the blue curve is the EMEA average

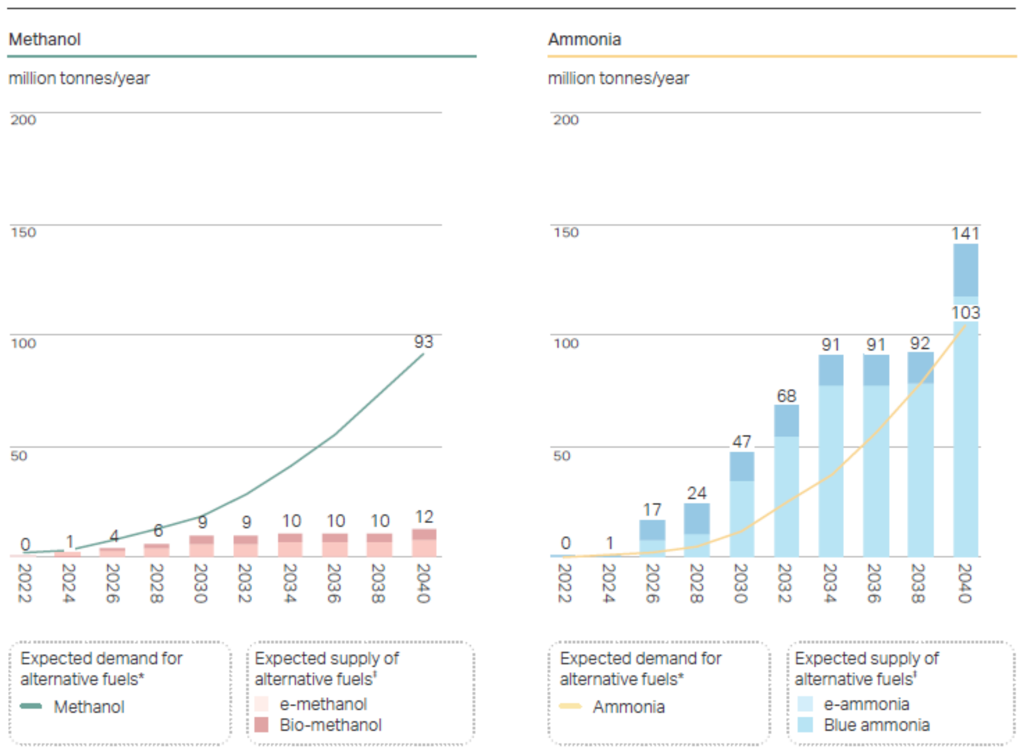
2 MARKET FOR AMMONIA

Ammonia is a commonly used chemical for both production of fertilizer and used as a cooling agent in many cooling systems. Annually X ton of ammonia is produced on a global scale. In future the annual production of ammonia could grow to even larger amounts, as ammonia is both a potential zero-carbon fuel for the shipping industry and also a very likely candidate to be the energy carrier of the future.

The world is moving towards a green hydrogen-based economy, as hydrogen is a very potent fuel to replace fossil fuel. However, due to the properties of hydrogen with especially low volumetric energy densities for both compressed and liquid hydrogen [24], and the challenges of handling liquid hydrogen at minus 250

°C, hydrogen as chemical is a challenging energy carrier, and therefore it is foreseen that ammonia will be produced in large quantities in areas with low energy costs and then transported to energy consuming areas, where ammonia can be cracked in to the hydrogen, which society need.

As for the use of ammonia as a marine fuel there are significant challenges to overcome before ammonia is a generally used fuel. The primary challenges are related to safety, as ammonia is a poisonous chemical. The challenges can likely be overcome, but it means that the implementation of ammonia as fuel for the shipping industry will be slower than the similar implementation of methanol. This is also portrayed in Figure 7, where the global demand for respectively methanol and ammonia is projected from 2022 to 2040.



*Source: MAN Energy Solutions, Shipping en route to Paris Agreement Overshoot, 2022
‡Source: Cumulative global production capacity based on announcements aggregated by MMMCZCS. Announced production is not targeted to shipping industry.

Figure 7 Projected demands for methanol and ammonia as fuel for the shipping industry [25]

As it can be seen in Figure 7 the demand for ammonia as marine fuel is projected to be slightly higher than methanol in 2040. The main reason for this is that ammonia is projected to have lower fuel cost than methanol [25]. However, as it can also be seen in 2030 the split between ammonia and methanol is opposite.

Looking at the possible market for ammonia out of Port of Roenne in 2030 it could be 40% of the potential 17.000 tons, which could be delivered to vessels passing by, hence 6.800 tons.

There is also a potential market for the vessels visiting the port. However, as the major consumer of fuel in Port of Roenne is the ferry operation, and that ferries will likely not be the early adapters of ammonia as fuel, it is likely not possible to sell relevant amounts of ammonia to vessels in Port of Roenne as of 2030.

3 MARKET FOR HYDROGEN

Besides the expected European and global market for hydrogen, which is so large that Power-to-X production on Bornholm will only constitute a smaller part of the consumption on European level. Hence, should there be established a pipeline from Bornholm to Germany, as there are considerations to do [26], it will be the production price of the hydrogen and not the quantity that sets the limit.

Therefore, the focus on market for hydrogen in this report will be the local market. As described in sections 1.1 and 1.2 the expected consumption in local industry will be equivalent to half of 18 465 MWh. This could be provided in form of ~282 ton of hydrogen; however, it could potentially also be delivered as biogas.

4 MARKET FOR METHANOL

As shown in Figure 7 the projected consumption for methanol and ammonia for shipping will have approximately the same share of the market in 2030 and 2040. In 2030 the consumption of methanol will be higher than ammonia, because of faster implementation rate for methanol. However, towards 2040 ammonia will slowly overtake methanol. More specifically, as described in sections 0 and 2, the ferry operation to and from Bornholm will likely be a candidate for using methanol as a fuel from 2030. Today the operation of the ferries to and from Bornholm consumes approx. 29.000 tons of MGO a year and given the lower energy density of methanol compared to MGO [27], it will equivalate to approx. 62.000 tons of methanol.

Furthermore, the offshore wind installation project out of Port of Roenne is potential candidates for using methanol, as the offshore installation industry is moving in the direction of methanol with orders of both installation vessels and SOVs [28], [29], [30]. According to experience an offshore installation project of 1 GW could use 1.100-1.700 ton of MGO or 2.360-3.650 ton of methanol. With the planned expansion of Port of Roenne and offshore wind installation projects in the pipeline, there will likely be installed 1,5 GW offshore wind annually out of Port of Roenne. This could mean an additional annual consumption of 3.540-5.475 ton of methanol, latest from 2040 and onwards.

5 MARKET FOR OXYGEN

5.1 The oxygen marked on Bornholm today and logistics of supply

Today, there are only a handful of oxygen consumers on Bornholm:

- **Industrial use**: Producers of metal constructions / machines, eg. The Jensen group, and Almeborg, some of the largest employers on the Island. The estimated oxygen completion is low however, **less than 1 tons O2/year**.
- **Medical use**: The local Hospital is the largest current consumer of Oxygen, about **3,5 tons O2** in 2022, to a price of at app. 10 €/kg (personal communication with Bornholms Hospital)

Logistics: Oxygen is transported to the Island by ferry in tank lorries (or gas cylinders) and filled into local tanks placed at the consumer sites.

Figure 8 Bornholm's hospital

5.2 Potential Oxygen market on Bornholm

The potential market for Oxygen at Bornholm consists in exchanging use of air for water treatment with Oxygen:

Waste Water Treatment Plants (WWTPs) has a large consumption of Oxygen, and they have the largest potential for a future market of Oxygen at Bornholm. The Oxygen demand for WWTP's today is fulfilled by using atmospheric air (with an Oxygen content of app. 21%). Compression of air for the diffusors in the process tanks of WWTPs is the most electricity consuming part of waste water purification. The Oxygen demand per m3 of wastewater depends on the content of organic matter and nitrogen. The value of Oxygen for WWTPs consists in reduced need for electricity for compressors, more than. 80% reduction of the electricity demand. Thus, the saved electricity costs will be related to the price of Oxygen that WWTPs are willing to pay.

"PO (pure oxygen) increases the driving force for oxygen transfer and the degree of oxygen saturation possible – its partial pressure is 4.7 times of that of its atmospheric counterpart. It improves the OTR (Oxygen transfer rate) and maintains high DO (dissolved Oxygen) concentrations at lower flowrates even if high strength or toxic wastewaters must be treated. Compared with air, PO provides higher gas phase oxygen concentrations, improves biokinetics and allows for faster treatment rates at higher MLSS concentrations and shorter hydraulic residence times (HRTs). Systems employing PO aeration are simple and compact and allow for easy gas storage and handling. They handle foul condensates without stripping, so they reduce odor and volatile organic compound emissions, decrease sludge production as more complete oxidization to CO_2 is achieved, and minimize sludge bulking and biomass foaming problems. PO ensures system stability at reduced power consumption rates and lower sludge disposal costs, (Neerackal et al., 2016, Zhuang et al., 2016b, Larrea et al., 2014, Calderón et al., 2013, Rodríguez et al., 2012b, Paice et al., 2003, Brindle et al., 1998, Shelef and Green, 1980)."[31]

The electricity consumption for compressors on Rønne WWTP was about 450.000 kWh/year in 2022, and the average price of electricity inclusive grid-fees was 2,115 kr./kwh. Thus, the potential savings on electricity costs by using O2 instead of air can be estimated to more than (80% * 450.000 * 2,115) kr. = 760.000 kr. for Rønne WWTP alone, in 2022.

Figure 9 Rønne Waste water treatment plant

The estimated consumption of oxygen for all WWTPs on Bornholm is app. **3,000 tons O2/year**, based on the correlation between the biological oxygen demand at the WWTPs on Bornholm, and oxygen consumption is estimated to app. 2 kg oxygen per kg BOD (as BI5). In Figure 10 ("Bornholm map") the calculated consumption of oxygen for the different WWTPs is shown (the smallest plants: Svaneke and Vestermarie is omitted). The future structure of the WWTPs on Bornholm is currently reviewed, and one scenario is to replace the existing plants with one large new plant located at Boderne, near the planned Energy Island Transformers.

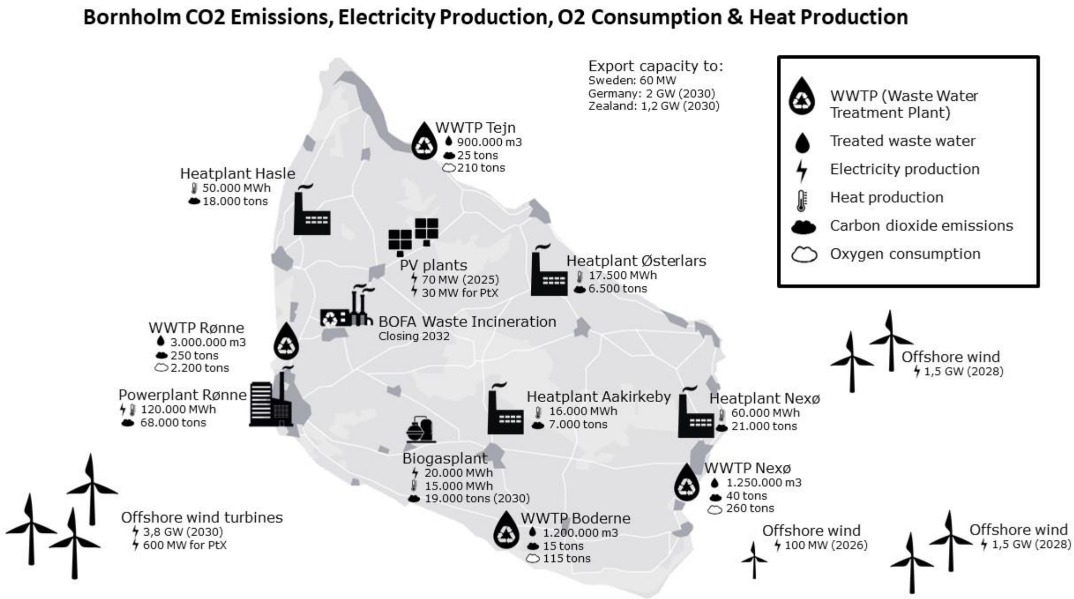


Figure 10 Map of BEOF utilities on Bornholm and planned OWE capacity

Drinking Water plants / Water Works In Denmark all drinking water is produced from ground water (except on Christians Ø). Ground water is usually anoxic and needs oxygen sparking and filtration to obtain drinking water quality. Traditionally atmospheric air is used to produce drinking water, but for new facilities it is common to use pure oxygen, for hygienic reasons.

- All the facilities at Bornholm use atmospheric air today, and there are 14 facilities supplying drinking water on Bornholm, with a total water producition of app. 3,5 mio. m3/year. The largest facility, Smålyngsværket near Pedersker, produces app. 1 mio. m3/year water.
- The demand of oxygen for drinking water production is much lower than for wastewater treatment: App. 11 g O2/m3 (personal communication with HOHcon) – this means that the potential marked for oxygen for production of drinking water on Bornholm (3,5 mio. m3/year) is app. **40 tons O2/year**.
    -

Possible other future consumers If oxygen from electrolysis becomes very cheap on Bornholm, industry with demand of oxygen can be attracted to establish production facilities on the island, this could be e.g.: Aquaculture, to allow more fish to be raised or kept in a given size of pond or tank.

Figure 11 Water plant Smålyngsværket

6 MARKET FOR WASTE HEAT

6.1 Background

The task focus on potential markets for waste heat from a Power-to-X plant including amounts and expected prices of heat. Markets where waste heat can be utilized are for example district heating (DH) or industries with a need for heat for the processes.

In Bornholm, the waste heat could most likely be used for district heating, which is widely implemented on the island. The total amount of heat produced to the DH system is around 330 GWh per year, and a large part of this could be replaced by waste heat depending on necessary investments and location.

The potential for utilizing the waste heat in existing industries on Bornholm is assessed as marginal.

Another possibility is the establishment of new industries, which use heat in the production process. The amount of waste heat is substantial and the need in new industries would mostly be at a small scale but nevertheless interesting due to other beneficial aspects such as new jobs created, and local brand and identity supporting the PtX facility as well as the new industries. The willingness to pay from these new potential industries will vary, and the cost for the industries to access the heat at required temperatures would be a critical factor.

6.2 Waste heat from PtX

As defined in WP2 the waste heat from PtX will amount to either 72 GWh (51 MW AEC electrolyzer) or 435 GWh (567 MW AEC electrolyzer) per year. When utilizing waste heat, the temperature will be of importance as well as the load profile. It is in the following paper assumed that the temperature of the waste heat will be divided with about 90% at a temperature of about 60°C, and the last 10% at about 30°C.

6.3 The district heating system on Bornholm

The existing district heating system (DH-system) on Bornholm is characterized by being separated in 5 DH-systems without interconnections. The heat production is centered in each DH-system on one primary location typically supported by peakload units on the same site or at an alternative site.

The total production of district heating on Bornholm is about 335 GWh/year. This of course varies with weather conditions and can be both higher and lower. The total netgrid losses are approximately 25% in the existing district heating systems but will also vary with sales and increase in years with low demand and decrease in years with high demand.

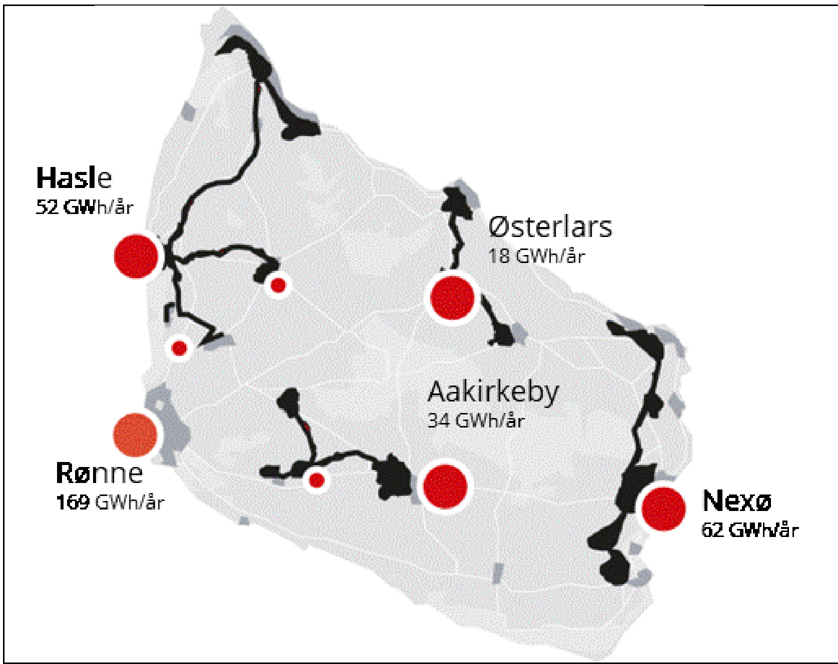


Figure 12 Production of district heating in 2021

There is a prognosis from the municipality that the number of inhabitants is expected to increase. This increase will partially result in more m² heated houses in the existing DH-systems.

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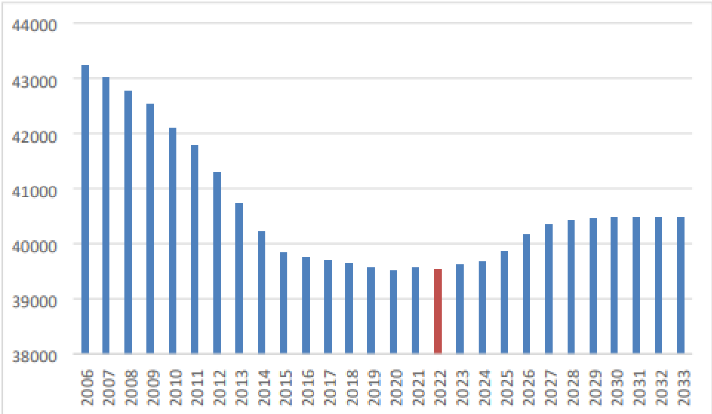

Figure 13 Bornholm Municipality, population forecast 2022-2033

There is also an expectation that the heat demand will rise in the coming years due to more houses converting from individual oil heating or direct electricity heating to district heating in the current DH systems. New areas where district heating will be established is not expected.

In the coming years there is also an assumption that the costumers will continue to try to save heat and that the overall DH-systems will be more efficient.

All in all, we expect the total heat demand to be stable in the coming years.

When it comes to utilizing waste heat in the DH systems the placement of a PtX facility is crucial. It is assessed as feasible to establish connections between four different DH systems and thereby secure a larger use of waste heat.

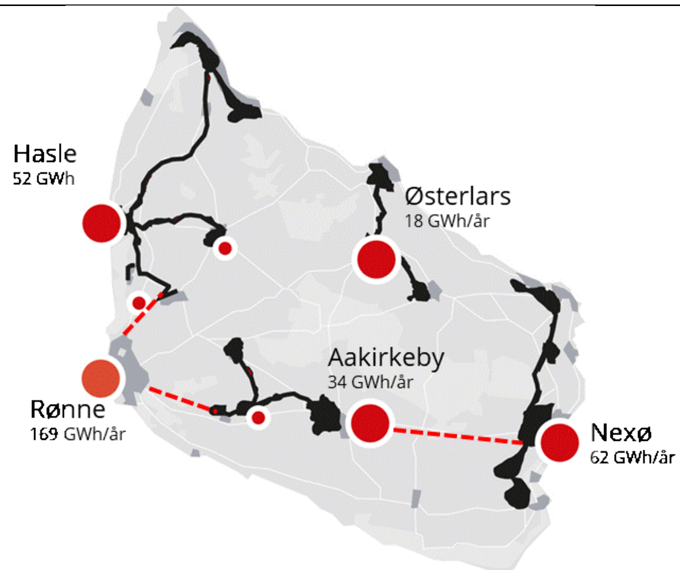

Figure 14 Possible connections between the DH systems on Bornholm

Temperatures and load

The temperature from the production facility (heat-plants) placed inside or close to the DH-system will typically deliver at a temperature range of 70-80°C varying depending on the weather conditions and the costumer's performance. If the DH-system is placed with some distance from the production facility and the

DH system is old the delivery temperature can be as high as 85-95°C depending on the distance and the energy losses in the DH system.

The return temperature will preferable be as low as possible in the range of 35-45°C depending on the costumer's performance.

The DH load varies and is at its highest in the winter.

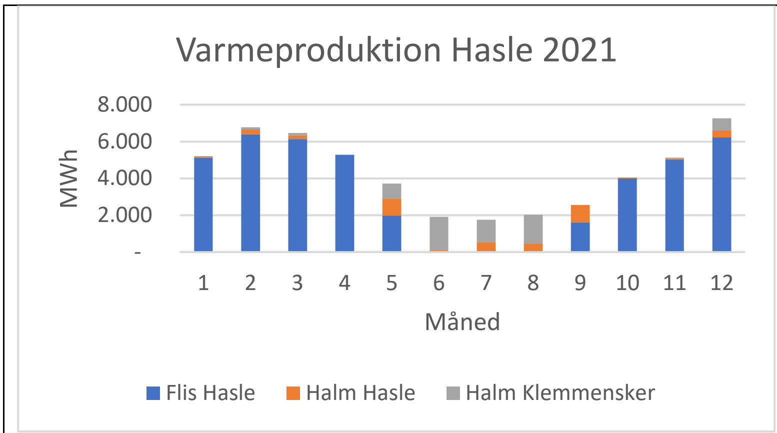

Figure 15 Production in the Hasle DH system per month in 2021

Investments to utilize waste heat into the DH-system

There will be a need to invest in transmission lines, heatpumps and storage facilities to utilize the waste heat on the DH side as well as investments to deliver the waste heat is needed from the PtX facility.

Price for excess heat

Prices for excess heat delivered to district heating is regulated in the Heat Supply Act and is applicable for both the DH company and for the PtX facility. §20 in the Heat Supply Act regulates the heat prices and the purpose is to protect heat costumers from high prices. The DH company and the PtX facility can agree on a contract for delivering waste heat, but the agreed price must be lower than both the price cap announced by The Danish Energy Authority and the substitution price [32], [33], [34].

The price cap is announced yearly and for 2023 the cap is 93 DKK/GJ. There is a possibility to get approval from The Danish Energy Inspectorate for a higher price cap in the first years of operation against an equivalent reduction in the successive years. The investments the DH company must establish to utilize the waste heat is part of the calculation under the prices cap.

The substitution price reflects the alternative price for the DH company either by producing the heat in their own facilities or buying it from another party. The substitution price is calculated concretely in relation to the heat that is substituted and the actual conditions regarding the substituted production. There is furthermore a principle regarding marginal price especially when the heat only partially covers the district heating demand. The DH company will calculate the price with starting a point in marginal costs in that that the excess heat does not reduce fixed costs. This reflects the issue of security of supply and the load profile from the producer of waste heat regarding the value of the heat for the DH company.

An indication of the substitution price for excess heat on Bornholm is the price for woodchips and straw. The figure below shows expected price development for straw (halm), woodchips (træflis) and wood pellets (træpiller).

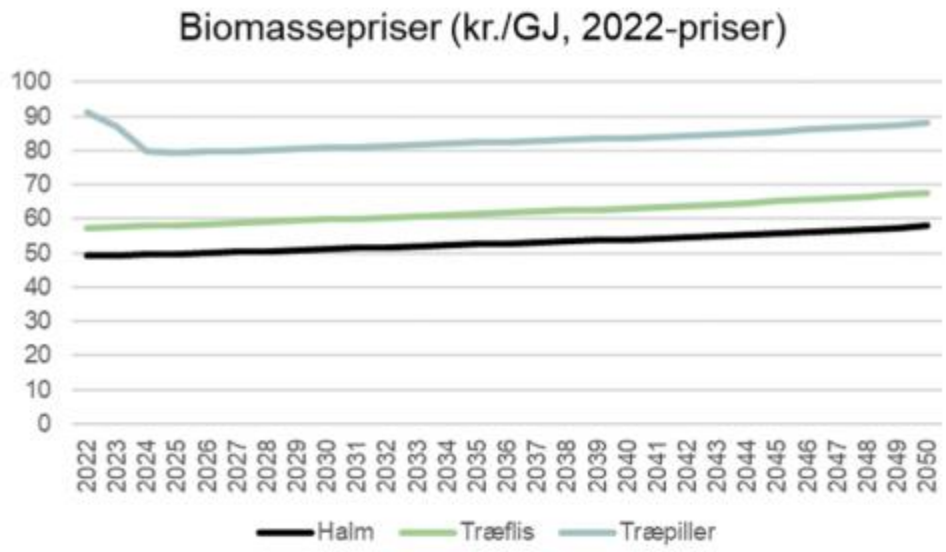

Figure 5: Expected biomass prices at central power stations (kr/GJ, 2022-prices, ex taxes), Energistyrelsen, 2023

From the regulators point of view the overall price for waste heat can at no time be higher than either the yearly price cap or the substitution price but there are no obstacles for the prices to be lower.

Having this as a background it is important to have a picture of the costs for each party to be able to utilize the waste heat. This can indicate the possible range of price and the framework for a contract between to two parties concerning heat price.

6.4 Potential in existing industries

The large potential for utilizing waste heat on Bornholm is the DH-system. There are some industries that use process heat but the majority use higher temperatures and therefore use propane gas to produce heat or steam. The potential to use low temperature heat in existing industries is assessed as low.

6.5 Potential in new industries

Below is a brief review of ideas for new industries developed at an innovation workshop organized by Nationalt Center for Grøn Energi on the 7th of February 2023, and further developed by a group of students from DTU [35], [36], [37], [38], [39].

The amount of waste heat that can be utilized in new industries is for the majority at a small scale but nevertheless interesting due to other beneficial aspects such as new jobs created, and local brand and identity supporting the PtX facility as well as the new industries. The willingness to pay from these new potential industries will vary, and the cost to access the heat at required temperatures would be a critical factor.

Algae cultivation

Algae production in bioreactors will use heat mainly in drying the algae, and the cost for heat would in this production be a substantial part of operation costs. The algae can be used as protein source for humans or livestock, or as raw material for different industries.

Thermal desalination

The primary input to hydrogen production is electricity and water. The water use for hydrogen production is substantial and the water resource can e.g., be wastewater or seawater. As the water in the Baltic Sea has a low salinity membrane technology could be relevant to produce water for hydrogen production. Low-grade waste heat can drive low temperature boiling and evaporation processes such as MED, humidification dehumidification HDH, membrane distillation MD, and adsorption desalination AD. Waste heat can be used to drive other desalination processes, which are either mechanically driven or electrically driven. Membrane distillation could use from 90-1.000 kWh waste heat pr. produced m^3 desalinated water and could thereby potentially use large amounts of excess heat.

The Paleo Dome

NaturBornholm is a science center located near Aakirkeby on Bornholm. The main idea would be to establish a Paleo Dome which reflects the climate on Bornholm 145-66 mio. years ago, where the summer temperature was 27°C and winter temperature was 15°C, and the atmosphere contained 2.000 ppm CO_2 compared to 415 ppm today. NaturBornholm is a popular destination, attracting around 50-60,000 visitors annually, with approximately one-third being school visits. It is the most visited educational site among Bornholm's cultural institutions. Since opening in May 2000, the center has received 1.3 million visitors, with between 25 and 30% of them being school children from other parts of Denmark. NaturBornholm has received several awards and recognitions for its innovative approach to education and sustainability. The center has also collaborated with various organizations and institutions to promote environmental awareness and education.

Low temperature Direct Air Capture

DAC is under development but can be an important technology in the future and has the potential to provide CO_2 to PtX industries on Bornholm. A solid sorbent system of the type under development requires low-temperature heat (<150 °C), making it feasible to use waste heat from industrialized applications coupled with heat pumps. Operationally, low temperature systems are least energy-intensive, particularly those that utilize waste heat. The energy demand for DAC is high. It is estimated that around 1 MWh is used per ton CO_2 captured. It is important to stress that this is a technology under development and there are demonstrations carried through, but the economy and the energy demand are also obstacles to be addressed in future development.

Greenhouse

The possibility for a substantial greenhouse farming on Bornholm could be developed as a niche production. In Denmark most of the green houses is on Fyn and there is especially focus on potted plants. The industry is dependent on good transport infrastructure, and it is assessed that Bornholm being an island will not have the possibility to compete in larger scale in these markets. There could be a niche opportunity when it comes to new product such as medical plants. The access to excess heat could be a competitive advantage that makes this possible.

Wastewater Treatment

Low temperature heat can improve the processes at WWTP (Waste Water Treatment Plant) on Bornholm and thereby improve the purification of waste water. The future structure of the WWTPs on Bornholm is currently reviewed, and one scenario is to replace all the existing plants with one large new plant located at Boderne, near the Energy Island Transformers. If a stable heat supply from P2X is anticipated, a new WWTP can be reduced significantly in size and volume, by increasing the temperature of the wastewater inflow, and thereby the processes in the WWTP. So, the synergies between WWTP's and P2X are obvious. Heat and oxygen for processes in WWTP's and partly purified wastewater from WWTP's as water source for P2X, and CO2 from WWTP's as carbon source for P2X.

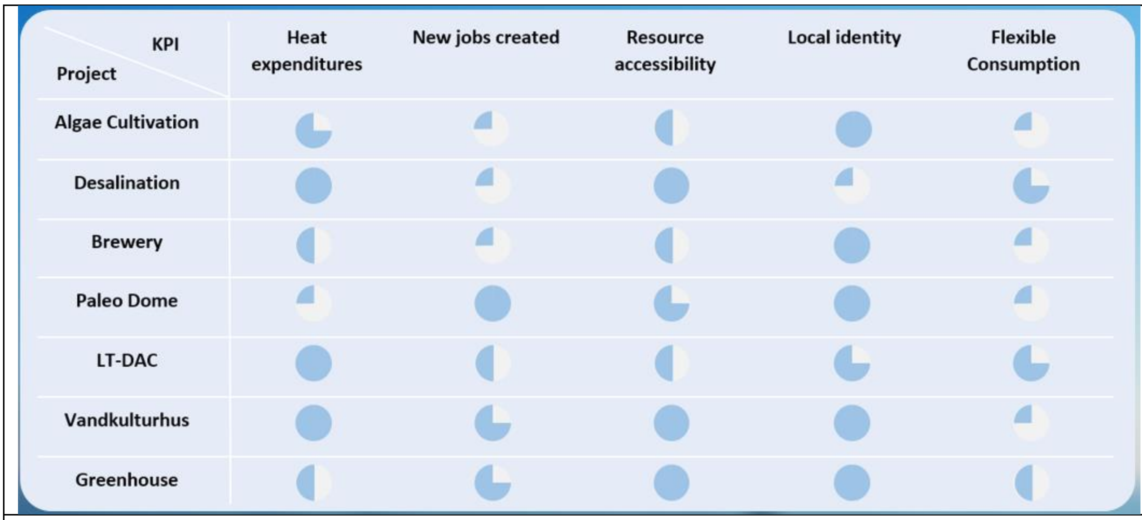

Figure 16 Overview of possible utilization of waste heat in relation to KPI's [39]

7 REVENUE FROM SYSTEM SERVICES AND BALANCING OF POWER GRIDS

In the project, it has been chosen to make the analysis of potential Power-to-X production on Bornholm based on so-called behind-the-meter-power, meaning that there is a direct connection between power production and Power-to-X plant. However, there is also possibilities of connecting a Power-to-X production on Bornholm to the grid and hence provide services, such as for example balancing by being able to ramp fast up and down with the electrolyzers and hence help stabilize the power system. This has been tested in another Danish project called HyBalance [40], just at it is considered to be an important part of the national Power-to-X strategy [41], where integration with the power system is one of the primary objectives.

There is good reason to work for utilizing the potential of flexible consumption in Power-to-X production. Analysis shows that there is a positive socio-economic effect for Energy Island Bornholm of establishment of Power-to-X production. The effect is even slightly higher of a Power-to-x facility located on Bornholm and located directly to the transformer facility rather than Power-to-X production established on other locations in Denmark [42]. Other analysis show that the there is a market for 623 MW/hour mFRR and 90 MW/hour aFRR ancillary services in DK2[4] in 2030, which is two types of ancillary services, where Power-to-X production would be able to provide services. Introducing Power-to-X production is anticipated to significantly lower the cost of activating ancillary services [43].

In WP2 a LCOE for offshore wind of 58,6 €/MWh has been used in the calculations. In an analysis from 2022 for the Danish Energy Agency EA Energianalyse have made estimations of future price curves in 2030, 2040 and 2050 [44]. The graphs show that the power price on the spot market is expected to be higher that 50 €/MWh around 3000 hours per year, which leaves +5000 hours with prices lower than 50 €/MWh, that could potentially be used for Power-to-X production. It is important to notice, however, that the development of the power prices in 2022 have surprised the entire industry and modelling of future prices should therefore be carefully examined before planning Power-to-X production based on these.

[4] Electricity price area, which will be neighbor to the price area of the Energy Island Bornholm

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9 APPENDIX

9.1 Appendix 1

Calculation of fuel consumption for a 1 GW offshore project

Each offshore wind project has individual parameters affecting the fuel consumption related the transport and installation. However, based on experience the following assumptions can be made for a 1 GW wind park

- The project consists of 66 wind turbines of 15 MW.
- The installation vessel can bring 3 wind turbines on one trip to the installation field, and it can do two trips to the installation field per week -> the duration of the installation is 11-12 weeks.
- Fuels consumption is approx. 100 ton per week for the installation vessel. Hence the total consumption of fuel for the installation is approximately 1100 ton for a 1 GW project
- Parts for the wind turbines are brought in from different locations, some come with towers, some with nacelles and some with blades. On average there is on cargo vessel for each wind turbine, which is transported to the port. Hence there is 66 cargo vessels arriving with parts for a 1 GW project.
- Cargo vessels are approx. 10.000 DWT and ~150 m long and ~25 m wide. They have an engine power of 5 MW and a service speed of 13 knots at 85% MCR.
- The wind turbine parts are typically produced in Denmark, and arrive from different locations such as Aalborg, Nakskov and Odense. Estimating an average travel distance for the elements of 350 km or 199 nm, and a travel speed of 13 knots, the average sailing time for the elements is 15,3 hours.
- The cargo vessels on average use 0,7 m3 or 0,595 ton MGO per hour sailing, hence the trip to Port of Roenne for a cargo vessel consumes 9,1 ton MGO and with 66 cargo vessels for a 1 GW project the total consumption is 600 ton.

9.2 Appendix 2

Definition of vessel segments in data from Helcom

General	Detail
Cargo	General, bulk, other
Container	Container
Fishing	Fishing
Other	Dredger, Tug, Other, Yatch
Passenger	Ropax, cruise, ferry
Rorocargo	Rorocargo, vehicle carrier
Service	Service
Tanker	Oil product, crude oil, gas, chemical

RoPax: Ship that can carry both passengers and vehicles that can drive onboard and of, for example cars and trucks

RoRo: Ship that carry goods that are driven onboard and of, for example trucks and semitrailers. The ship only carry a very limited number of passengers (truck drivers) as it is dedicated to move goods

Cargo: Ships that carry bulk and general goods. Bulk goods are for example, sand, gravel, agriculture products, wood chips and similar. General goods can be goods packed in big bags, single unit goods etc.

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