Scenarios for PtX symbioses in Kalundborg

Report

September 2023

Danish Board of
Business Development

THE EUROPEAN UNION
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Funded as part of the Union's response to the COVID-19 pandemic

Investing in your future

NIRAS

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Introduction

Introduction

This report is developed by NIRAS for Knowledge Hub Zealand from June to September 2023. The report identifies and analyses possible scenarios for implementing a Power to X (PtX)-production in Kalundborg.

The purpose of this work is to demonstrate the main conditions for PtX-symbioses in Kalundborg, based on selected scenarios. The scenarios aim at showing orders of magnitude of energy, masses and economy coupled to different types of PtX-productions. The scenarios are therefore not limited by existing infrastructure and supply of e.g., energy in Kalundborg.

As part of the work, NIRAS has identified scenarios constituting examples of different PtX-symbioses with relevance for Kalundborg.

The scenarios are developed with the purpose of representing the following conditions:

- The scenarios represent different scales of production and timelines for implementation.
- The main output(s) meet an expected demand in the market.
- The material flows in and out of the PtX-production are as far as possible coupled to existing companies in Kalundborg.

Futhermore, the scenarios identify possible roles for the five companies in PtX-Cluster Zealand (Unibio, Algiecell, G2B, Dynelectro, Nordphos). As part of this, the electrolysis technology implemented in the scenarios is assumed based on Dynelectros Solide Oxide Electrolyzer Cell (SOEC) technology.

The following three examples on PtX-scenarios are analyzed in this report:

1. Medium-scale additional methane production
2. Medium-scale jet fuel production
3. Large-scale methanol production fuel production

For each scenario, mass and energy balances and business cases are shown. Also, the necessary conditions and barriers for implementing the scenarios are described, as well as timelines for implementation.

Kalundborg Symbiosis has delivered information about existing material and energy flows to and from companies in the Symbiosis. This information is investigated further through interviews with selected companies.

In addition, data is based on standard sources such as the Danish Energy Agency's price assumptions and the technology catalogue.

The report is funded by PtX Cluster Zealand (REACT RF-22-0068).

PtX Cluster Zealand

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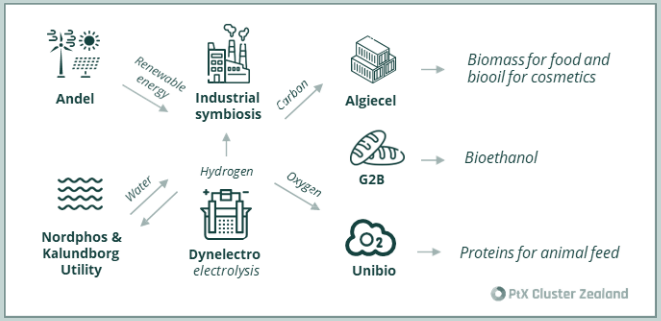
Background: PtX Cluster Zealand[1]

PtX Cluster Zealand is an innovation project aiming to mature, test and scale up new technologies that may enable highly efficient electrolysis – and contribute to the construction of a more commercially viable business case around PtX.

The project also closely examines the opportunities to optimise green energy supply for PtX facilities and the potential value of PtX facilities' excess resources.

The project is being conducted by a broad consortium of private and public partners. Key actors include five high tech companies who, drawing on their own technology, help to build the PtX business case. The technology partners are supported by a broader group of utility companies, knowledge institutions and business promotion officers (including Business Hub Zealand, Knowledge Hub Zealand, Kalundborg Symbiosis and Energy Cluster Denmark).

The project runs from April 2022 to August 2023. It has received around EUR 3.3 million in funding from The European Regional Development Fund.



1. Source: Irisgroup: Biosolutions and Power-to-X, Sector Coupling in a World Leading Industrial Symbiosis in Greater Copenhagen

Key project activities

The focal point of the project is the construction of a 20 feet electrolysis prototype (30 KW) in Kalundborg and the testing of a patented electrolysis technology developed by the university spinout Dynelectro. The technology enables a mix of alternating current (AC) and direct current (DC) for electrolysis, which prolongs life expectancy of the so-called

"SOE-stacks" used in electrolysis – and, hence, reduces hydrogen production costs by 20 %. Aside from Dynelectro, four other tech companies, which either take or supply resources to the PtX plant, participate in the project. These are:

- **Unibio:** uses oxygen from electrolysis in production of proteins in animal feed.
- **Nordphos:** delivers ultra-clean water and purified cooling water for electrolysis.
- **Algiecel:** captures carbon and transforms it into biomass for food and dietary supplements and bio-oil for cosmetics.
- **G2B:** plans to establish a biorefinery plant in Kalundborg for sustainable ethanol production.

Beyond these actors, the remaining partners contribute resources, including expertise knowledge, project management and resource flows, in order to ensure effective project implementation and long-term anchoring.

The utility companies Kalundborg Utility and Andel deliver water and energy to the PtX plant. Ørsted investigates potential infrastructures for CCUS in the Kalundborg area, and the Chemical Engineering department at the Technical University of Denmark (DTU) helps project partners to explore ways to adapt and integrate each others' technologies.

Finally, Business Hub Zealand and Knowledge Hub Zealand act as project managers and focus on a combination of business development, technology commercialisation and the integration of PtX in Kalundborg's existing industrial symbiosis.

The PtX scenarios described in this report do not have a direct connection with the project mentioned above, but the scenarios identify the possible roles for the mentioned companies in PtX Cluster Zealand.

Executive summary

Executive summary

The report builds on analysis of mass and energy balances and business cases for three scenarios for PtX-production in Kalundborg, coupled to relevant companies in the Kalundborg Symbiosis and PtX Cluster Zealand.

The scenarios are developed with the purpose of representing the following conditions:

- The scenarios represent different scales of production and timelines for implementation.
- The main output(s) meet an expected demand in the market.
- The material flows in and out of the PtX-production are as far as possible coupled to existing companies in Kalundborg.

The main inputs and outputs for each scenario are shown in the following illustration.

Scenario 1 - medium-scale additional methane production:
This scenario shows how e-methane can be produced on the basis of CO_2 (from upgrading of raw biogas) through methanation. The raw biogas is produced by Kalundborg Biogas and Novozymes.

The scenario demonstrates a medium-scale PtX-production that will be relatively simple to implement within a short time frame.

The production of methane in this scenario has a negative business case under current methane prices at 2.20 DKK/Nm^3 where total losses over a 20-year period has a net present value of 1.59 bn. DKK. The business case is still negative at 1.25 bn. DKK if the maximum future subsidy of 4.75 DKK/Nm^3 is obtained.

Scenario 2 – medium-scale jet fuel production: This scenario describes and demonstrates a medium-scale PtX-production of sustainable aviation fuel (SAF). In the scenario, bioethanol is upgraded to jet fuel through hydrogen treatment in a process known as alcohol-to-jet (ATJ).

Kalundborg-based Meliora can deliver around 10 % of the bioethanol required for a standard ATJ-plant. The scenario therefore requires additional suppliers of bioethanol.

The scenario could be implemented within a relatively short time frame, given a sufficient supply of bioethanol. The ATJ technology exists, the market for ATJ is established, and demand is expected to rise. The Danish Government has set a target of 100 % green fuel in Danish domestic flight by 2025. ATJ is an available and implementable technology for producing green fuel for aviation.

The main challenge for ATJ production will be the framework conditions for the SAF market and the willingness to pay for SAF.

The production of jet fuel in this scenario has a negative business case under current jet fuels prices at 4,500 DKK/ton where total losses over a 20-year period has a net present value of 11,97 bn. DKK. The business case is still negative at 7.64 bn. DKK if the price of jet fuel is 10,000 DKK/ton.

Scenario 3 – large-scale methanol production:
This scenario describes and demonstrates how a large-scale methanol production plant could be established in Kalundborg. In this scenario, methanol is produced by combining hydrogen from an electrolysis plant with CO_2. The scenario is scaled as a 1GW electrolysis plant and illustrates the need for supply of energy, water and CO_2 to a large-scale PtX-production facility.

The electricity required for 1 GW electrolysis equals the production capacity of a large offshore wind farm. The energy supply is therefore a main barrier in this scenario. The construction of the necessary energy capacity for a large-scale methanol production is unlikely to happen, given the current national energy framework. These conditions results in an unknown and probably long-term horizon for implementation.

Other main conditions for this scenario are development of scale of SOEC-electrolysis technology, establishment of infrastructure and handling of wastewater from the water purification prior to electrolysis.

The main challenge for the methanol production will be the framework conditions for the market for green fuels in the marine industry and finally the willingness to pay for green fuels.

The production of methanol in the scenario has a negative business case under current methanol prices at 2,800 DKK/ton where total losses over a 20-year period has a net present value of 45.5 bn. DKK. However, the business case may be positive if the market value of green methanol, as with other green alternatives, is above the value of fossil methanol - or the future costs of sourcing green CO_2 is negative, i.e., the plant is paid to utilize the CO_2 as an alternative to the cost of storing it along with fossil CO_2. However, the future market value of green and fossil CO_2 is uncertain.

Overall conclusions: The report shows interesting opportunities for establishing medium-scale PtX-symbiosis in Kalundborg and thereby exploiting flows from local based companies in production of e.g., e-methane and green fuels. In establishing PtX, Kalundborg can take advantage of close locations of wastewater, electricity and CO_2 facilities and of Kalundborg's experience in working in symbiosis.

PtX in Kalundborg will not be limited by water supply, since the supply of wastewater is sufficient. On the contrary, energy supply will be a main barrier for large-scale PtX production.

Neither of the business cases shown are viable on pure commercial terms. To make the business cases positive, the value of the green alternatives produced (the willingness to pay) must remain significantly above the fossil alternatives for a long period of time. It must be taken into consideration, that the prices included in the business cases are associated with uncertainties – present as well as future prices.

3 scenarios

	Scenario 1: Medium-scale additional methane production	**Scenario 2:** Medium-scale jet fuel production	**Scenario 3:** Large-scale methanol production
Capacity	13.6 Mw_{el} electrolysis	6 Mw_{el} electrolysis	1 GW_{el} electrolysis
Input	65.4 GWh electricity	29 GWh electricity	4,800 GWh electricity
	16.3 GWh heat	7 GWh heat	1,200 GWh heat
	27,040 m^3 treated wastewater	11,900 m^3 treated wastewater	2,000,000 m^3 treated wastewater
	9,900 tons of CO_2	100,000 tons of ethanol	970,000 tons of CO_2
Output	5,000,000 Nm^3 methane	55,000 tons of ATJ + 20,000 tons of diesel	700,000 tons of methanol
	14,400 tons of oxygen	6,300 tons of oxygen	1,070,000 tons of oxygen

Scenarios

PtX Scenario 1

Medium-scale
additional methane
production

PtX Scenario 1: Medium-scale additional methane production

Description

CO_2 + H_2 = CH_4

Carbon dioxide + Hydrogen = Methane

This scenario describes and demonstrates how additional methane can be produced on basis of the existing biogas production in Kalundborg through a PtX-process called methanation.

The upgrading of raw biogas to biogas leads to a surplus of CO_2. This CO_2 can be methanized by adding hydrogen, which results in the production of additional e-methane.

The scenario is investigated as it demonstrates a PtX-production that will be relatively simple to implement within a short time frame. There is an existing market and infrastructure for methane and the scenario is based on resources currently available in Kalundborg and proven technology.

Input
The scale of the scenario is based on the amount of CO_2 available from the upgrading of raw biogas from by Kalundborg Biogas and Novozymes.

An electrolysis plant placed at Kalundborg Biogas will produce the hydrogen for the methanation of CO_2 from raw biogas. The following methanation requires a methanation plant, also placed at Kalundborg Biogas. The scenario therefore requires transport of CO_2 from Novozymes to Kalundborg Biogas.

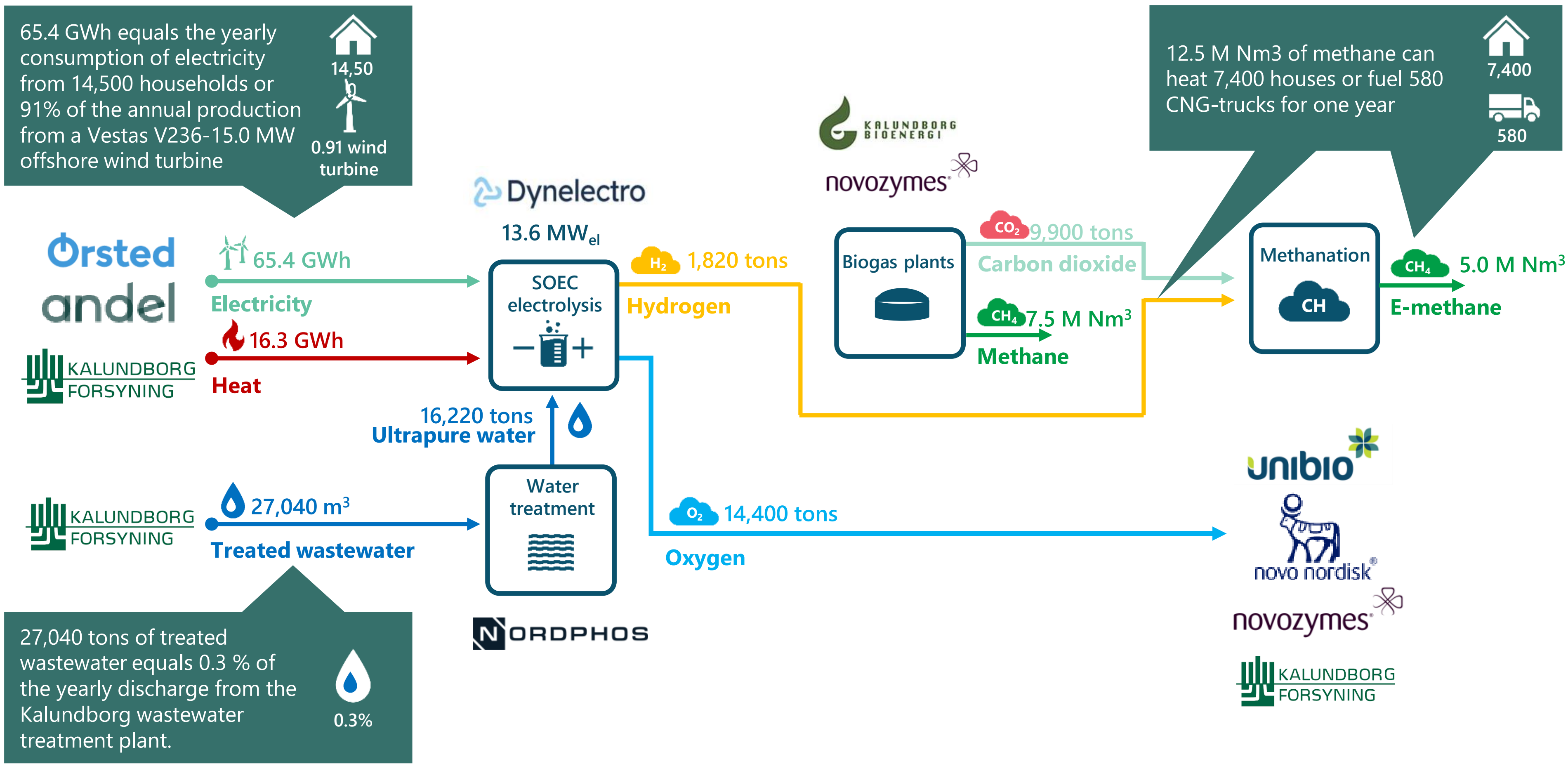
The electrolysis process requires electricity, which can be supplied by Ørsted or Andel. The Solide Oxide Electrolyzer Cell (SOEC) technology also requires heat, which can be supplied by Ørsted. The water for the electrolysis can be supplied from treated wastewater from Kalundborg Forsyning, where Nordphos could contribute to the water purification prior to electrolysis.

Output
The additional e-methane produced through methanation is sold as biogas in the existing gas network, which requires a certification as biogas.

The oxygen production from the electrolysis process could e.g. be used by Novozymes and Novo Nordisk in their existing fermentation processes or by Kalundborg Forsyning in treatment of drinking water or waste water. Oxygen could also be used by Unibio in a possible future production in Kalundborg, however, the Unibio production will require much larger quantities of oxygen.

The energy and mass balances and the relationship between these and the mentioned companies are illustrated on the next page.

PtX Scenario 1: Medium-scale additional methane production



Location (example)

The map shows the locations of companies and facilities involved in the scenario. The location of the methanation plant is a preliminary suggestion and the physical conditions are not fully investigated.

The facilities involved could possibly be located relatively close. This is an advantage when establishing PtX-symbiosis. Novozymes is an exception, and the scenario assumes transportation of CO_2 from Novozymes to the methanation plant.

PtX Scenario 1: Medium-scale additional methane production

Assessment of necessary conditions

The main necessary conditions and barriers for implementing the scenario are assessed in the following table, addressing status and barriers for supply of energy and water, infrastructure, development of technology and market as well as authority permits.

The timeline for implementing the scenario is shown afterwards, with NIRAS' assumptions of the time needed to establish conditions, overcome barriers, and construct the plant.

The assessment and the following timeline are based on generalized categories to reduce complexity, and the list of conditions is therefore not exhaustive.

Overall findings

The assessment shows that implementing the production is relative uncomplicated. There is a need for technological development of SOEC-electrolysis and for obtaining relevant authority permits, but the overall complexity of the project is low, resulting in a relative short timeline for implementation.

The e-methane is sold as biogas in the existing gas network, which requires a certification as biogas. Since the hydrogen has to be considered as renewable, the electricity supply must comply with the EU-regulation for renewable hydrogen setting minimum standards for the average proportion of renewable electricity in the grid.

PtX Scenario 1: Medium-scale additional methane production

Conditions

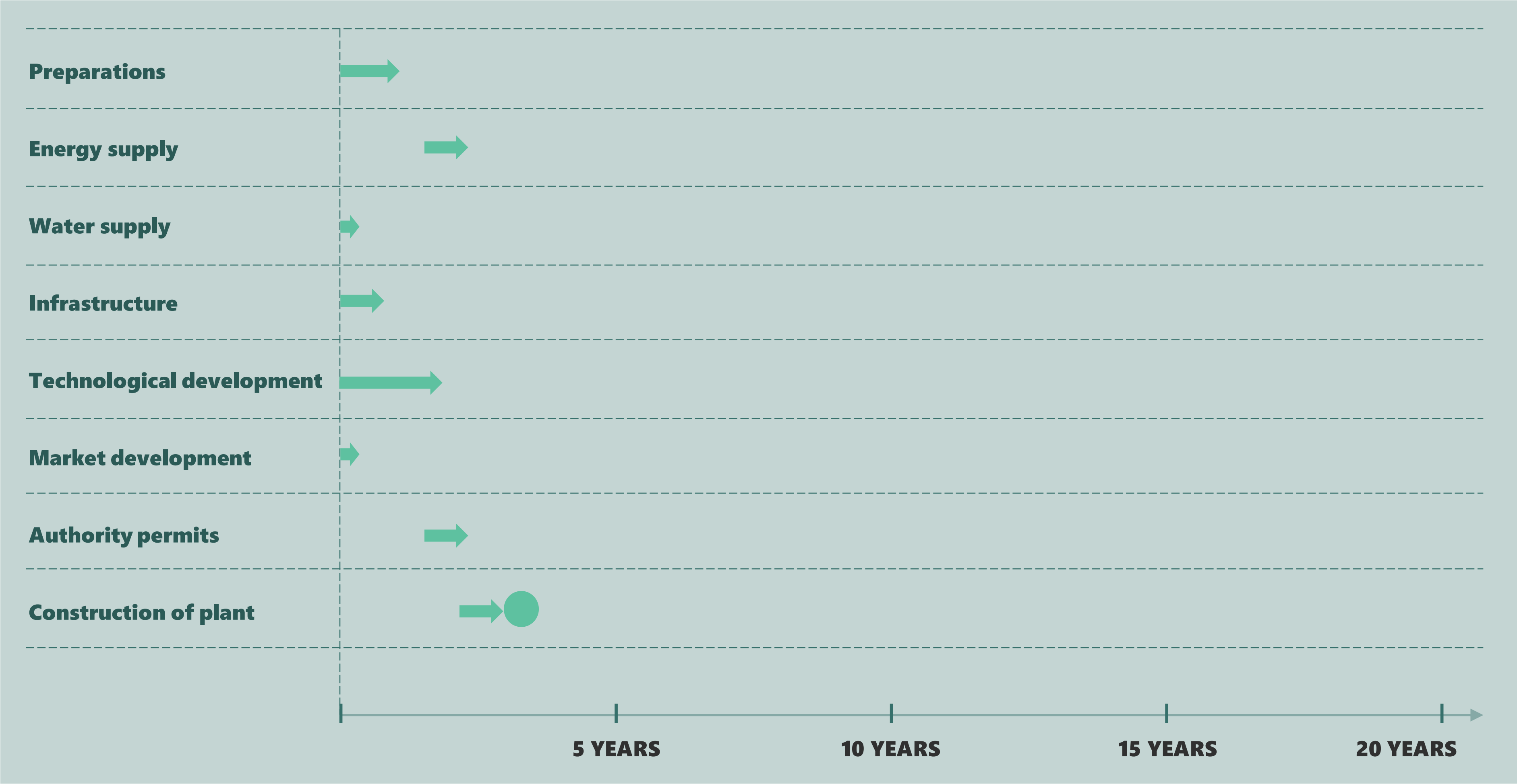
(√) **ENERGY SUPPLY**	A new transformer station could be required to support electricity supply. If the hydrogen (and biogas) is to be considered as renewable, the electricity supply must comply with the EU-regulation for renewable hydrogen, setting minimum standards for the average proportion of renewable electricity in the grid*. It has to be investigated further, if local heat supply has the demanded quality for the SOEC-electrolysis.
√ **WATER SUPPLY**	Water consumption equals 0,3 pct. of the yearly discharge from Kalundborg Renseanlæg.
(√) **INFRASTRUCTURE**	The need for infrastructure for waste water, reject water and CO2 from Novozymes to Kalundborg Biogas requires further investigation.
(√) **TECHNOLOGICAL DEVELOPMENT**	SOEC-technology needs development (likely to be ready in 2025). Other technologies for electrolysis are ready for implementation now.
√ **MARKET DEVELOPMENT**	Market for biogas is established. The e-methane must be certified as biogas to be sold as biogas. The requirements for certification have to be explored further.
(√) **AUTHORITY PERMITS**	Requires authority permits for etablisment of plant and pipeline. The permit for the plant may be given as a supplementary approval to the biogas plant (app. 200 days from when full application has been send).

√ = Conditions are available
(√) = Conditions need development
÷ = Conditions need massive development

"Fuel producers may count electricity taken from the grid as fully renewable if the installation producing the renewable liquid and gaseous transport fuel of nonbiological origin is located in a bidding zone where the average proportion of renewable electricity exceeded 90 % in the previous calendar year and the production of renewable liquid and gaseous transport fuel of non-biological origin does not exceed a maximum number of hours set in relation to the proportion of renewable electricity in the bidding zone" (Delegated regulation on Union methodology for RNFBO's, 7 February 2023).

PtX Scenario 1: Medium-scale additional methane production

Timeline

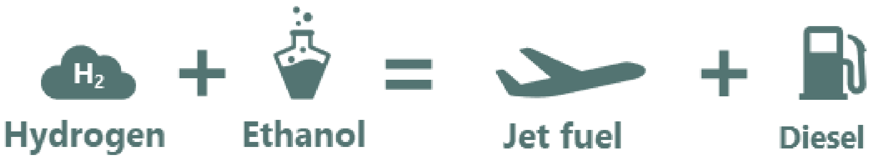


PtX Scenario 2

Medium-scale jet fuel production

PtX Scenario 2: Medium-scale jet fuel production

Description



This scenario describes and demonstrates a medium-scale PtX-production of sustainable aviation fuel (SAF). In the scenario, bioethanol is upgraded to jet fuel through hydrogen treatment in a process known as alcohol-to-jet (ATJ).

The scenario is very relevant to explore since there is an increasing demand for SAF in the green transition of the aviation industry. The Danish Government has set a target of 100 % green fuel in Danish domestic flight by 2025. ATJ is an available and implementable technology for producing green fuel for aviation.

The scenario is also interesting, because the Kalundborg based company Meliora has an existing production of bioethanol and the PtX-Cluster Zealand company G2B has the potential to develop additional bioethanol production.

The scenario demonstrates a medium-scale PtX-production that could be implemented within a relatively short time frame. The ATJ technology exists, the market for ATJ is established, and demand is expected to rise.

Standardized ATJ plants are in development. The smallest ATJ units have an expected annual production capacity of around 50,000 ton ATJ fuel. A generic bioethanol plant (also known as a lignocellulosic plant) comparable to the size of Meliora's, can deliver around 10 % of the bioethanol needed for this scale of production. The scenario therefore requires additional suppliers of bioethanol.

Input
Bioethanol is the main input to the production. Meliora is assumed to deliver 10 % of the bioethanol for the production, while 90 % is assumed delivered from suppliers outside of Kalundborg.

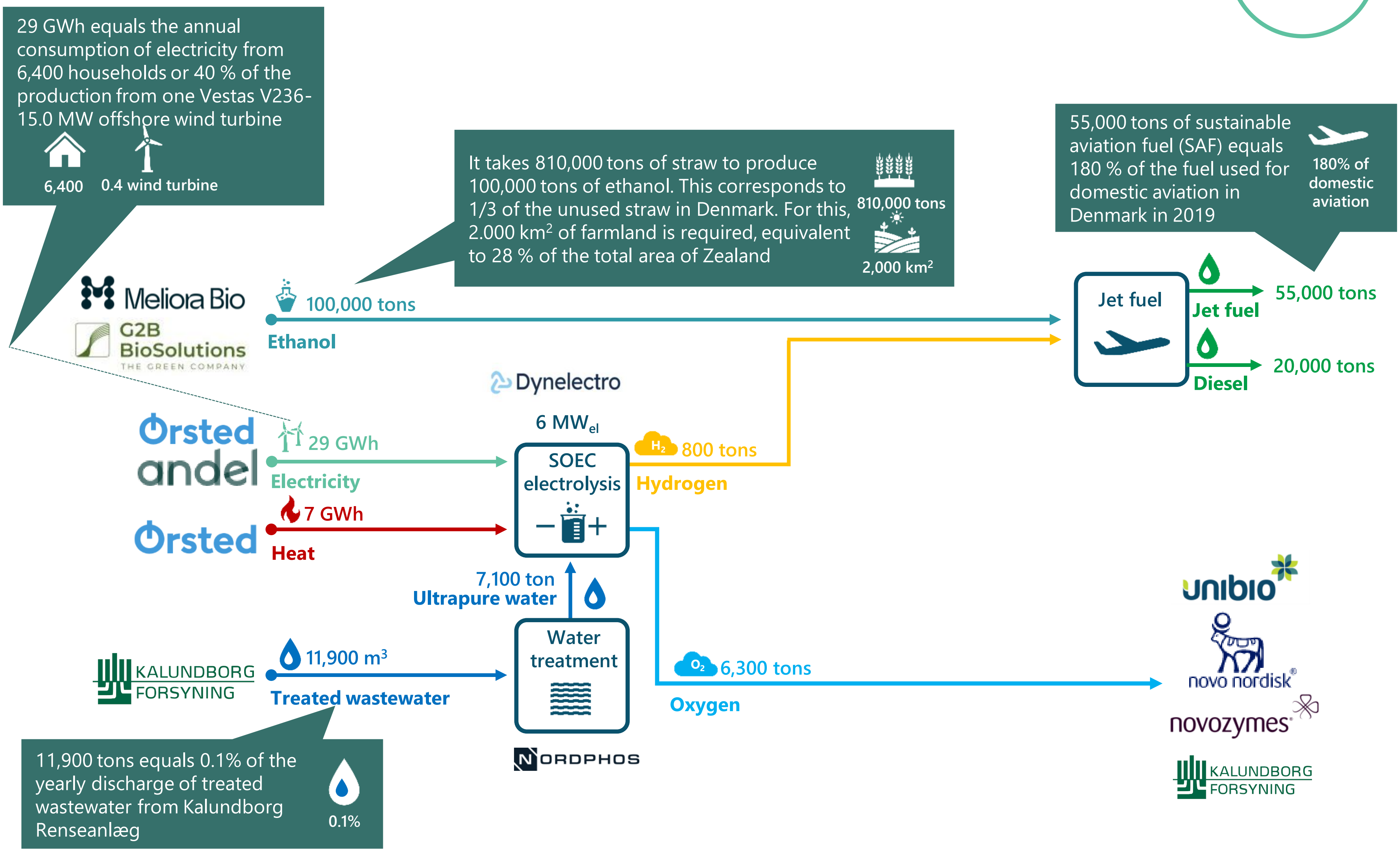
An electrolysis plant close to Meliora will produce the hydrogen for the ATJ production. The electrolysis process requires electricity, which can be supplied by Ørsted or Andel. The SOEC-electrolysis technology also requires heat, which can be supplied by Ørsted. The water for the electrolysis can be supplied from treated wastewater from Kalundborg Utility, where Nordphos could contribute to the purification prior to electrolysis.

Output
The end-product in Scenario 2 is jet fuel, however, a significant side stream of diesel is also produced.

The oxygen side stream from the electrolysis process could e.g. be used by Novozymes and Novo Nordisk in their existing fermentation processes or by Kalundborg Utility for the treatment of drinking water. Oxygen could also be used by Unibio in a possible future production in Kalundborg which, however, will require much larger quantities.

The energy and mass balances and the relationship between these and the mentioned companies are illustrated on the next page.

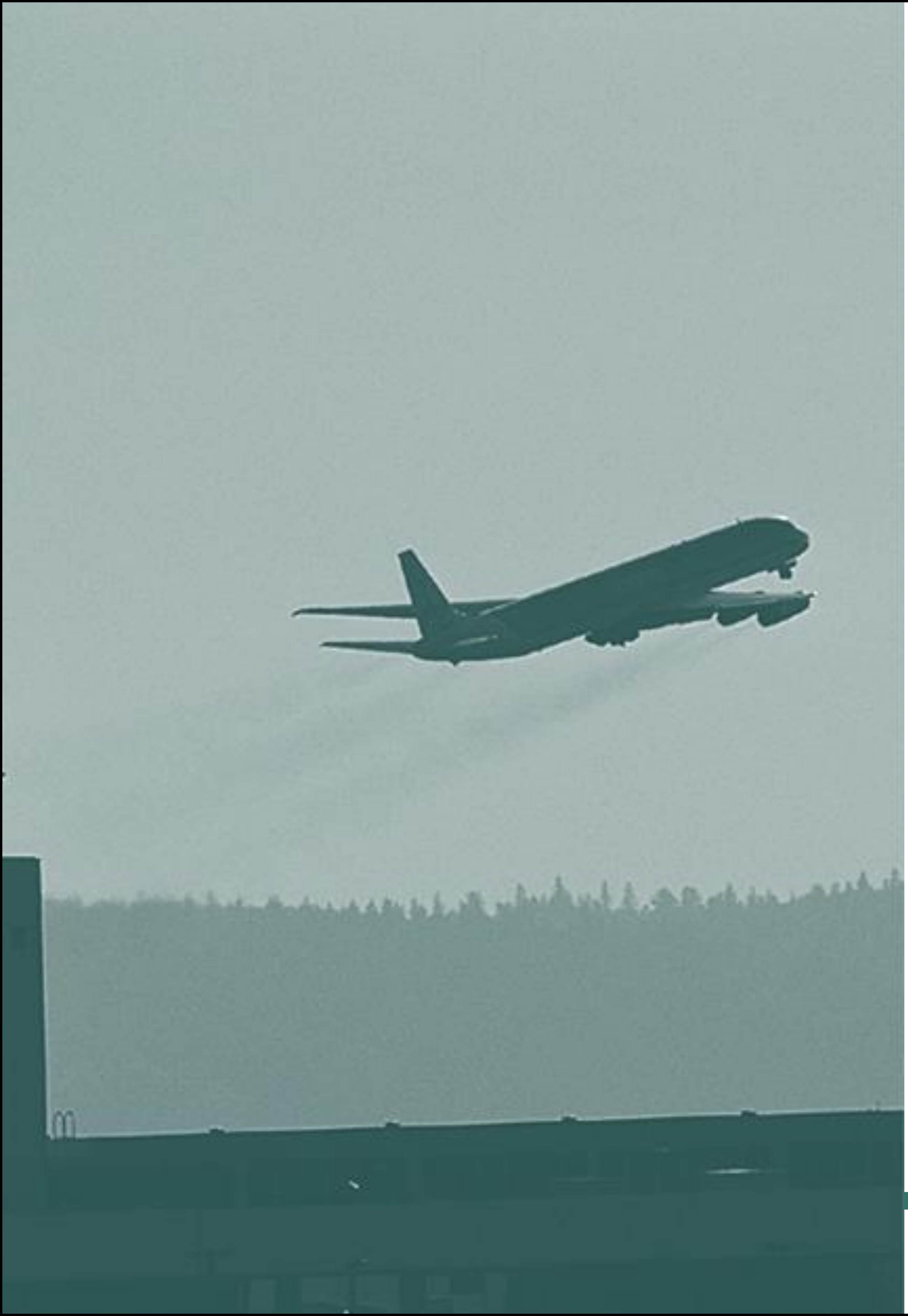
PtX Scenario 2: Medium-scale jet fuel production



Location (example)

The map shows the locations of companies and facilities involved in the scenario. The location of the Alcohol-to-Jet plant is a preliminary suggestion and the physical conditions are not fully investigated.

The facilities involved could possibly be located relatively close. This is an advantage when establishing PtX-symbiosis.



PtX Scenario 2: Medium-scale jet fuel production

Assessment of necessary conditions

The assessment of status for main necessary conditions for implementing Scenario 2 follows the same procedure as described for Scenario 1, using the same categories and setup.

Overall findings

The scenario depends on bioethanol supply from the market, as Meliora can deliver only 10 % of the needed amount. The total amount of bioethanol needed requires a large supply of straw, which is currently available in e.g. Denmark, but could be challenged by competitive uses of straw in a future market.

The supply situation for energy and water seems reasonable and no significant need for establishing new infrastructure has been identified.

If the hydrogen (and thereby ATJ) is to be considered as renewable, the electricity supply must comply with the EU-regulation for renewable hydrogen, setting minimum standards for the average proportion of renewable electricity in the grid. The ATJ requires a certification to be sold as a sustainable jet fuel.

There is a need for technological development of SOEC-electrolysis and for obtaining relevant authority permits. The storage of large quantities of bioethanol and jet fuel implies a SEVESO risk permit.

PtX Scenario 2: Medium-scale jet fuel production

Conditions

ENERGY SUPPLY	√	A new transformer station could be required to support electricity supply. If the hydrogen (and AtJ) is to be considered as renewable, the electricity supply must comply with the EU-regulation for renewable hydrogen, setting minimum standards for the average proportion of renewable electricity in the grid*. It has to be investigated further, whether local heat supply has the demanded quality for the SOEC-electrolysis.
WATER SUPPLY	√	Water consumption equals 0,1 pct. of the yearly discharge from Kalundborg Renseanlæg
INFRASTRUCTURE	(√)	The need for infrastructure for waste water and reject water requires further investigation.
TECHNOLOGICAL DEVELOPMENT	(√)	SOEC-technology needs development (likely to be ready in 2025).
MARKET DEVELOPMENT	√	The market for AtJ is established and the demand is expected to increase. The AtJ requires a certification to be sold as a sustainable jet fuel.
AUTHORITY PERMITS	÷	The construction requires permits for etablisment of facilities, planning process and Environmental Impact Assessment. Furthermore, a SEVESO risk document most likely will be required. (1½-3 years in total)

√ = Conditions are available
(√) = Conditions need development
÷ = Conditions need massive development

**"Fuel producers may count electricity taken from the grid as fully renewable if the installation producing the renewable liquid and gaseous transport fuel of nonbiological origin is located in a bidding zone where the average proportion of renewable electricity exceeded 90% in the previous calendar year and the production of renewable liquid and gaseous transport fuel of non-biological origin does not exceed a maximum number of hours set in relation to the proportion of renewable electricity in the bidding zone" (Delegated regulation on Union methodology for RNFBO's, 7 February 2023).*

PtX Scenario 2: Medium-scale jet fuel production

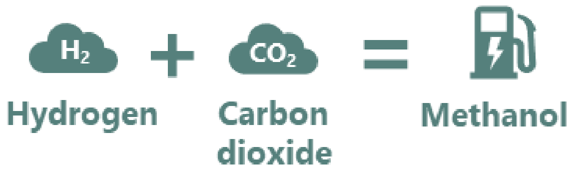
Timeline

PtX Scenario 3

Large-scale
methanol
production

PtX Scenario 2: Medium-scale jet fuel production

Description



This scenario describes and demonstrates how a large-scale methanol production plant could be established in Kalundborg. In this scenario, methanol is produced by combining hydrogen from an electrolysis plant with CO_2.

The scenario is relevant to explore, because it illustrates energy and mass balances and economy of a large-scale PtX plant. Furthermore, methanol is an interesting output, because the green transition of the marine industry demands development of green fuels as methanol. As a result, Mærsk recently presented its first containership moving on methanol.

The scenario is scaled as a 1GW electrolysis plant, since this matches the size of other planned large-scale PtX plants in Denmark. The scenario thereby illustrates the needed for supply of energy, water and CO_2 to a large-scale PtX-production facility.

This is a long-term scenario. The electricity required for 1 GW electrolysis equals the production capacity of a large offshore wind farm. At the moment, there are no planned wind farms of this size and scale in the vicinity of Kalundborg.

Input
The production of hydrogen through electrolysis requires large amounts of electricity. A 1 GW electrolysis plant has an annual consumption of 4,800 GWh which equals the production from 67 15.0 MW wind turbines.

The methanol synthesis requires a large CO_2 volume, which could be supplied from e.g., Fidelis or other CO_2 handlers, if an infrastructure for CO_2 to Kalundborg is established. The CO_2 must be certified biogenicic or from biogenicic origin. Kalundborg Biogas and Novozymes produce biogenicic CO_2 from upgrade of biogas, but the volume is very small compared to the demand.

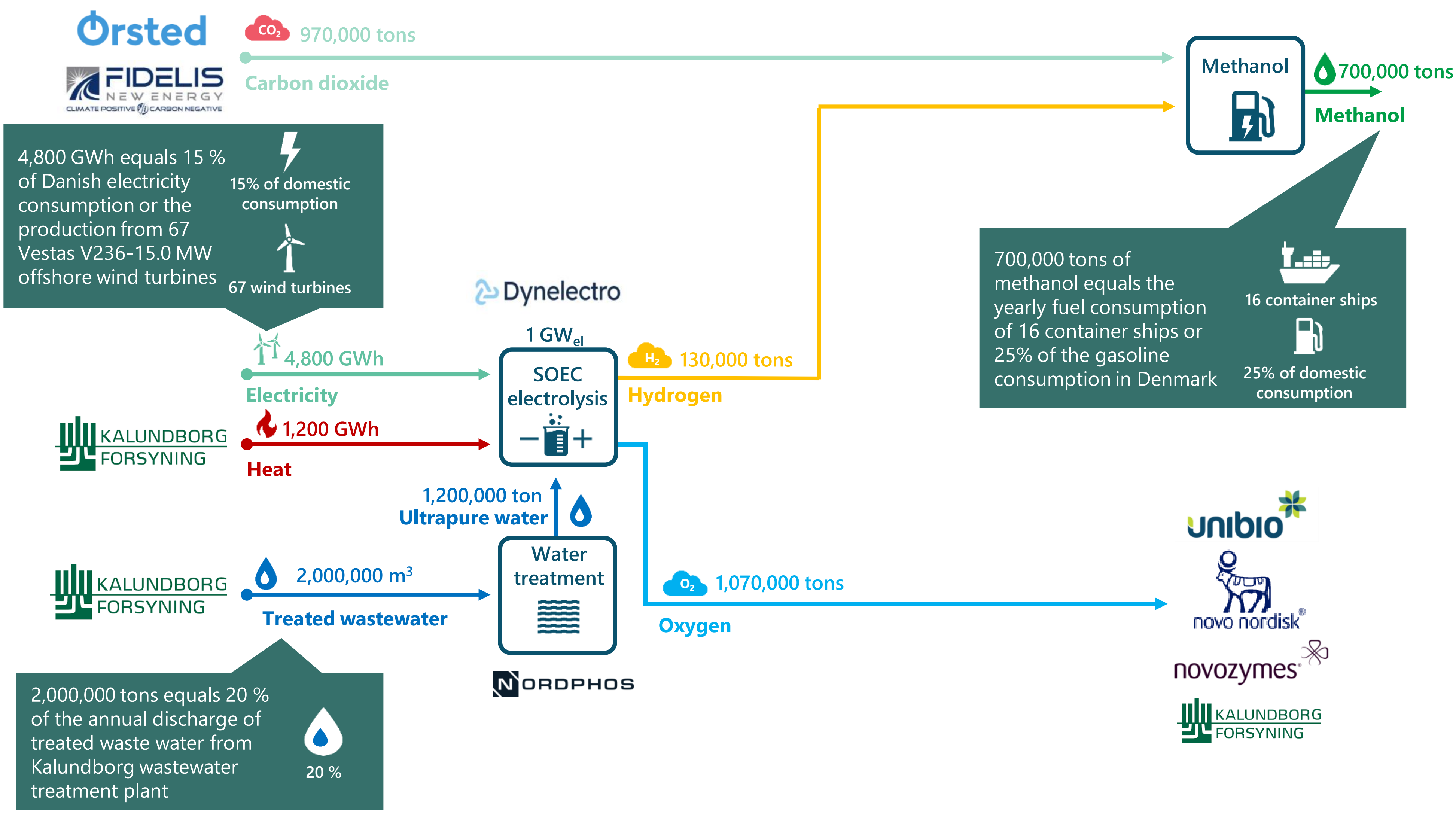
The SOEC-electrolysis technology also requires heat, possibly supplied by Ørsted. The water for the electrolysis is supplied from treated wastewater from Kalundborg Utility, where Nordphos could contribute to the purification prior to electrolysis.

Output
The main output is methanol, which can be sold to the marine industry as a sustainable fuel.

The large oxygen production from the electrolysis process could e.g., be used by Unibio in a possible future production in Kalundborg, since Unibio's production is based on large amounts of oxygen. Smaller amounts could be used by Novozymes and Novo Nordisk in existing fermentation processes and by Kalundborg Utility in treatment of drinking water.

The energy and mass balances and the relationship between these and the mentioned companies are illustrated on the next page.

PtX Scenario 3: Large-scale methanol production



Location (example)

The map shows the locations of companies and facilities involved in the scenario. The location of the methanol plant is a preliminary suggestion and the physical conditions are not fully investigated.

The facilities involved could possibly be located relatively close. This is an advantage when establishing PtX-symbiosis.

The source of CO_2 is unknown and it could be sourced from outside Kalundborg, especially if an infrastructure for CO_2 to Kalundborg is established.

PtX Scenario 3: Large-scale methanol production

Assessment of necessary conditions

The assessment of main necessary conditions and barriers for implementing Scenario 3 follows the same procedure as described for Scenario 1 and 2, using the same categories and setup.

Overall findings

The energy supply is a main barrier in this scenario and the construction of the necessary energy capacity for a large-scale methanol production (e.g. an offshore wind farm) is unlikely to happen, given the current national energy framework.

Furthermore the resulting waste water volume from the UPW plant can be difficult to handle for existing waste water facilities, since the UPW will enhance the waste water volume in Kalundborg with around 10 %.

Another barrier is the development of scale of the SOEC-technology. Though the timeline for this development is probably shorter than for the development of energy supply, and the SOEC-technology could be replaced by other electrolysis technologies.

The methanol requires a certification to be sold as a sustainable fuel.

Worth mentioning is also the need for authority permits. The storage of large quantities of hydrogen and methanol implies a SEVESO risk permit.

Altogether, these conditions results in an unknown and probably long time horizon for implementation.

PtX Scenario 3: Large-scale methanol production

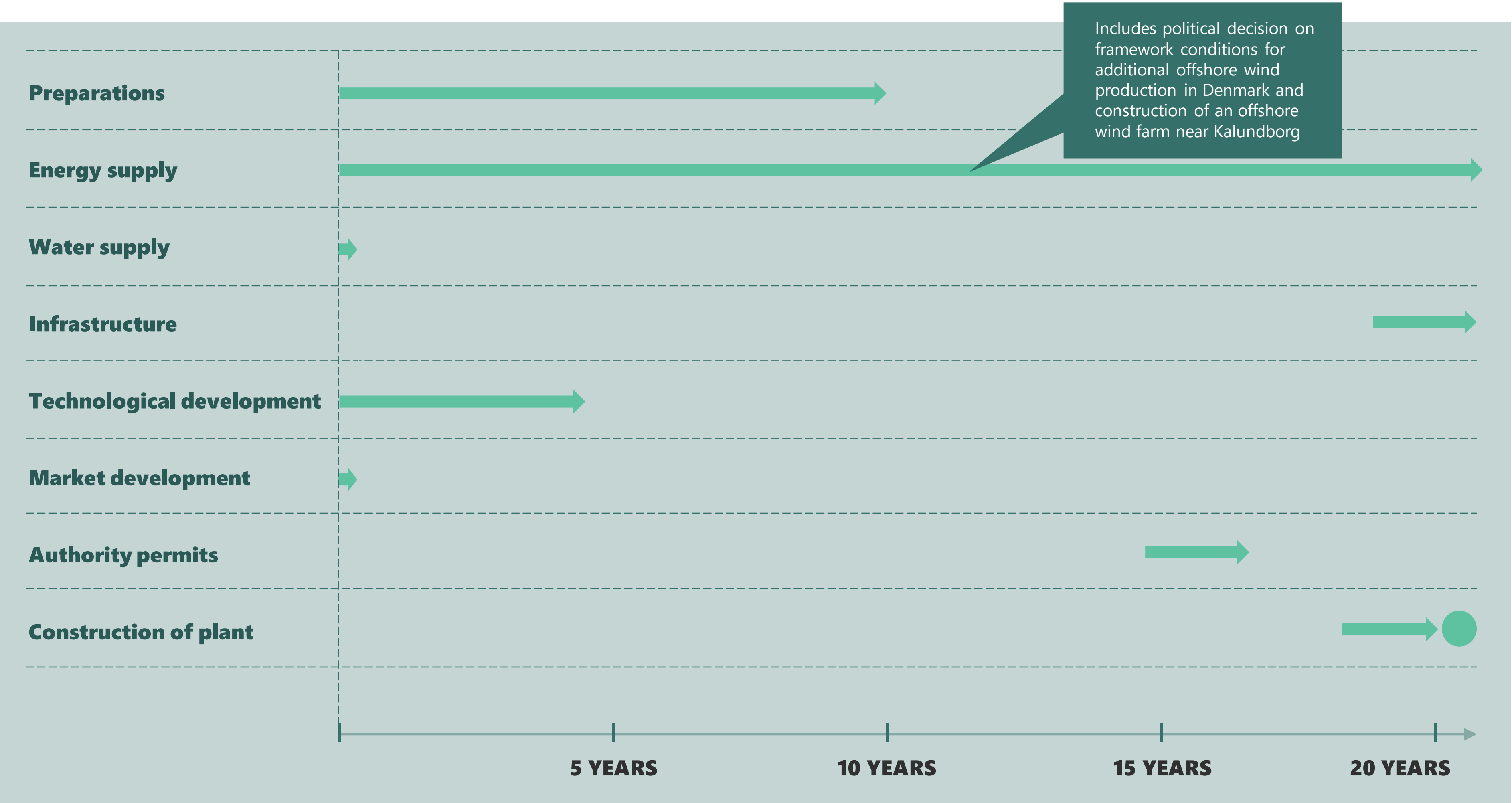
Conditions

÷ ENERGY SUPPLY	Requires massive development of energy supply, corresponding to the production from an offshore wind farm
√ WATER SUPPLY	Water consumption equals 20 % of the yearly discharge from Kalundborg Renseanlæg
÷ INFRASTRUCTURE	The production and handling of materials requires pipelines for waste water, CO_2, oxygen and methanol and storage facilities for methanol at Kalundborg Harbour. The waste water from UPW in this volume can be dificult to handle for existing waste water facilities.
÷ TECHNOLOGICAL DEVELOPMENT	SOEC-technology needs development of scale.
√ MARKET DEVELOPMENT	Mærsk has ordered 19 container ships that sail on methanol for delivery in 2023-2025 and the market is expected to develop rapidly. The methanol requires a certification to be sold as a sustainable fuel.
÷ AUTHORITY PERMITS	The construction requires permits for etablisment of facilities, planning process and Environmental Impact Assessment. Furthermore, a SEVESO risk document will most likely be required. (1½-3 years in total).

√ = Conditions are available
(√) = Conditions need development
÷ = Conditions need massive development

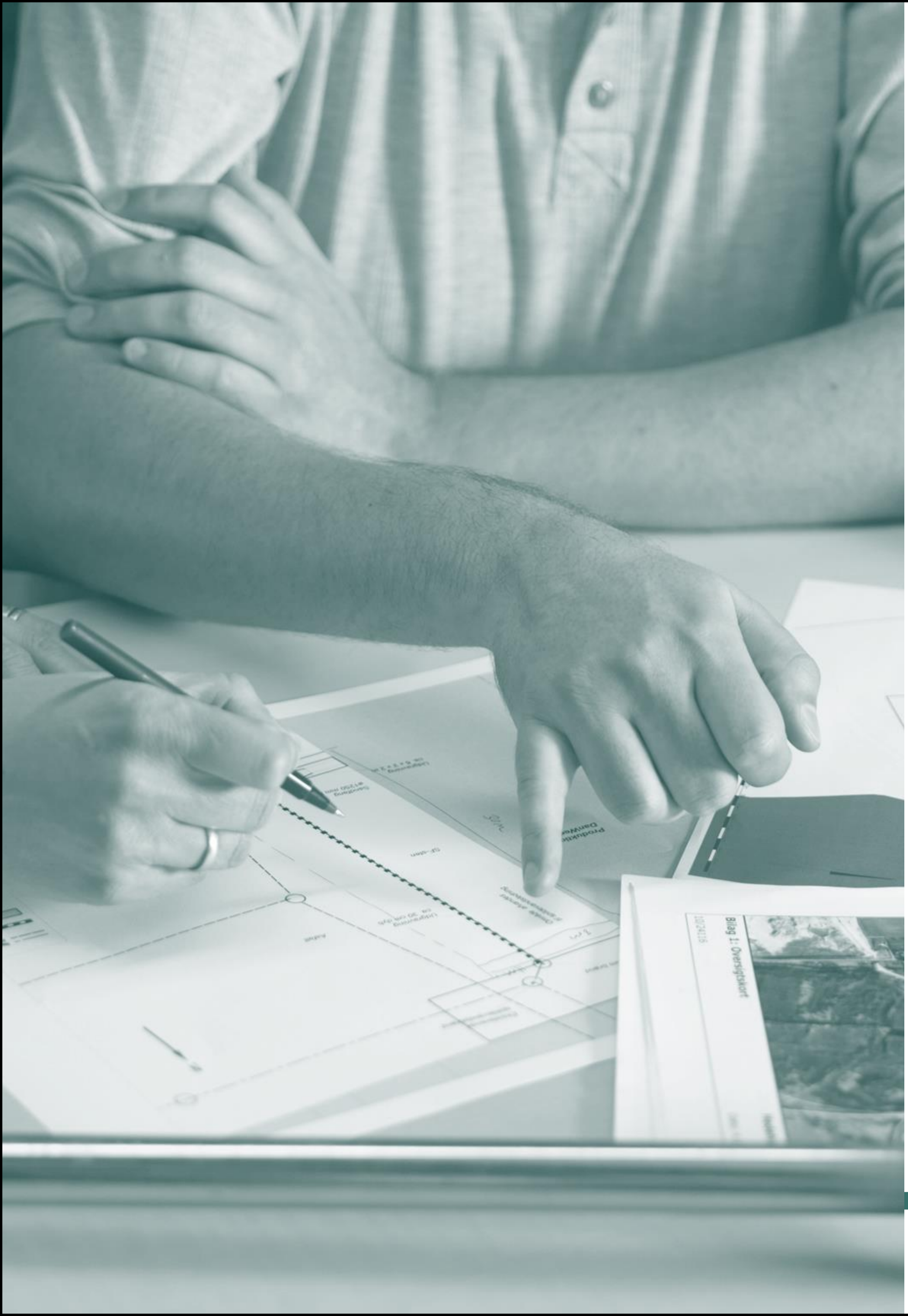
PtX Scenario 3: Large-scale methanol production

Timeline



Business cases

Inputs, methodology and results



Introduction and conclusions

Introduction
In this section, the main inputs and drivers for the business cases are presented.

Furthermore, detailed business cases are calculated and presented for the three scenarios[1].

Conclusions
Neither of the business cases are viable on pure commercial terms.

Value creation from side streams, such as oxygen or heat, can contribute to the business cases, but it is not sufficient to make the business cases positive.

To make the business cases positive, the value of the green alternatives produced must remain significantly above the fossil alternatives for a long period of time. Alternatively, government subsidies must be in place.

1. Please note that the business cases are illustrative only. The business cases are based on key figures, assumptions and projections that may deviate from other industry players' estimates and expectations. There is probably significant room for optimization of the technical solutions and business cases.

Future price of hydrogen

Main assumptions

In all three scenarios the end-product is produced from hydrogen produced at a local plant. We compare the cost of producing hydrogen in Kalundborg with the expected future hydrogen price to assess the competitiveness of the local hydrogen production.

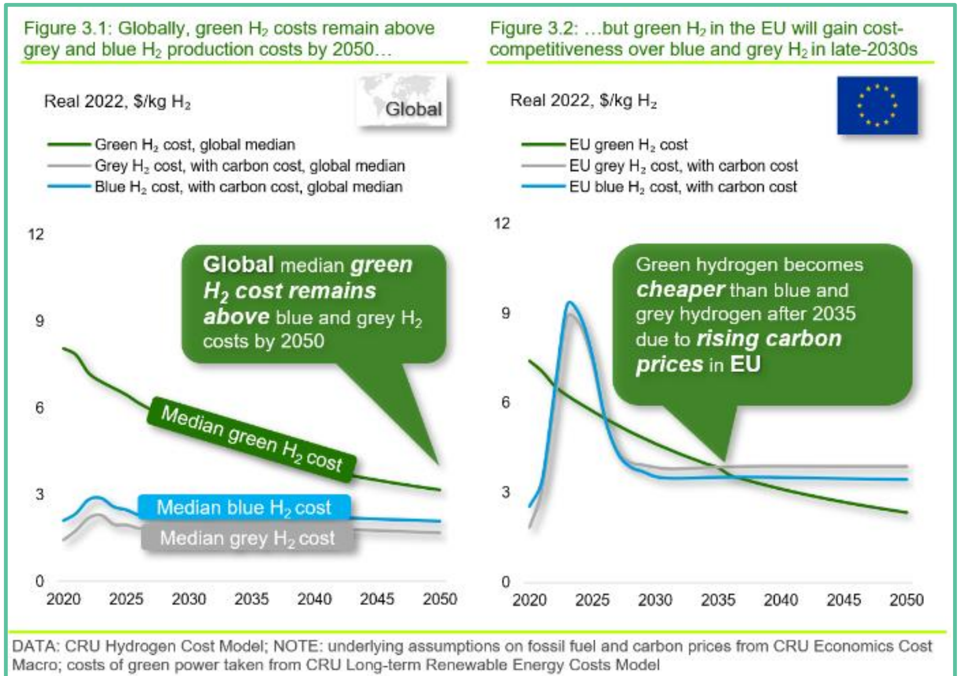
The future hydrogen price is uncertain but expected to fall compared to today's price. From the opening speech by President von der Leyen at the European Hydrogen Energy Conference 2022[1]: *"With the current rise in gas prices, green hydrogen can already be cheaper than grey hydrogen. Our target is to bring its cost well below 1.8 euros per kilo by 2030. And this goal is within reach."*

NIRAS expects the statement above to be optimistic in line with other industry observers like e.g., the example shown from CRU. NIRAS expects a reduction in green hydrogen prices from currently 7-8 EUR/kilo to 3-4 EUR/kilo in 2030.

The current and expected future hydrogen prices are not part of the business cases, but illustrates the competitiveness of local hydrogen production on slide 45.

1. Source: https://ec.europa.eu/commission/presscorner/detail/en/SPEECH_22_3185
2. Source: https://sustainability.crugroup.com/article/energy-from-green-hydrogen-will-be-expensive-even-in-2050

Some estimated future hydrogen prices[2]



Future price of power

Main assumptions

Power is one of the main resources needed to produce hydrogen.

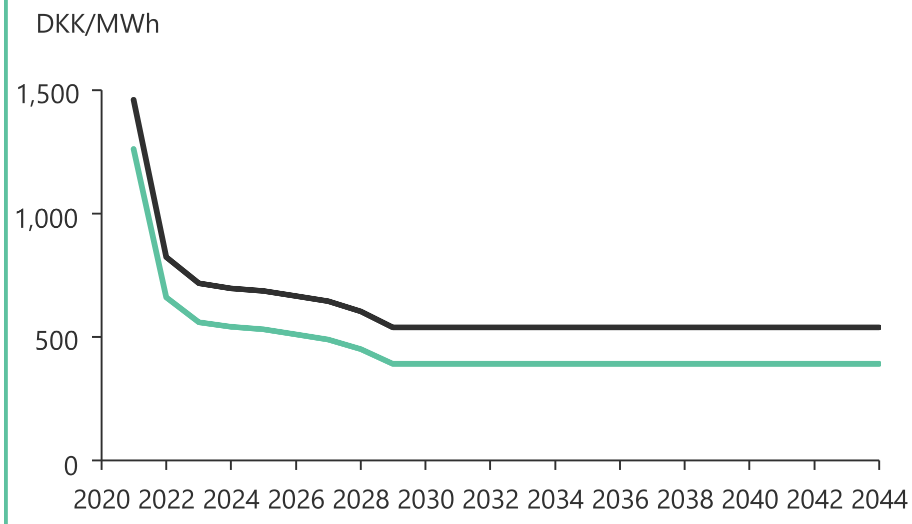
In Scenario 3, we assume that power is sourced from a dedicated wind farm nearby at production cost. Hence the "raw" socioeconomic power price is used for this scenario.

In Scenario 1 and 2, we assume that power is sourced from the power grid. Hence, we need to add costs of grid loss, transportation costs (tariffs) and producer profits.

The Danish Energy Agency projects the future power prices for different usages and situations including the above. Based on the average power prices in the period 2025-2045 and adjusting for operating time results, the following future power costs are estimated:

- Scenario 1 and 2: 419 DKK/MWh.
- Scenario 3: 309 DKK/MWh

Price of power[1]



The prices shown in the diagram are further adjusted to reflect the fact that the plants are operated only when prices are low. The adjustment factor for plants operating 50-55 % of the time is 0.74.

1. Source: Danish Energy Agency.

Future price of methane

Main assumptions

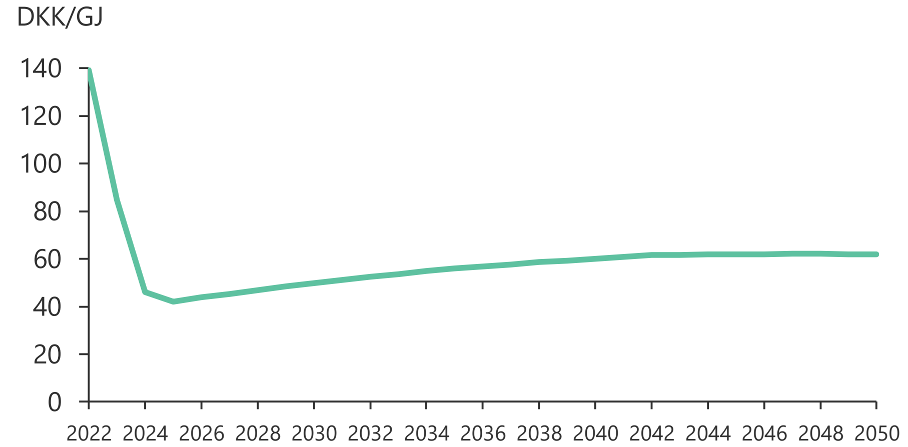
The end-product in Scenario 1 is methane. The methane is produced from upgrading CO_2 from the current biogas (methane) production. The resulting additional methane produced is injected into the gas grid alongside the biogas produced today.

The Danish Energy Agency projects the future natural gas prices. The average expected price 2024-2050 is 55.6 DKK/GJ which translates to the 2.2 DKK/Nm^3.

Production of biogas is currently subsidized with 87.4 DKK/GJ. However, the subsidy scheme ends in 2023. As of 2024, the subsidy will be decided in a competitive bidding process, where the maximum allowed subsidy is 120 DKK/GJ, which translates to approximately 4.75 DKK/Nm^3. Hence, the expected maximum value of methane is 6.95 DKK/Nm^3. However, the authorities do not expect subsidy levels at this level. Hence, the methane price incl. possible subsidies is only shown for illustrative purposes on slide 42.

- The methane price used in the business case for scenario 1 is 2.2 DKK/Nm^3.

Expected natural gas price[1]



Current subsidies for natural gas (ends in 2023)[2]

Opgradering

Pristillæg	2019	2020	2021	2022	2023
Grundtillæg 82,2 Kr./GJ	82,2	82,6	82,8	83,6	87,4
Naturgastillæg 21 Kr./GJ	23,4	43,8	51,7	0,0	0,0
Total		126,4	134,5	83,6	87,4

1. Source: Danish Energy Agency.
2. Source: https://ens.dk/ansvarsomraader/bioenergi/stoetteudbud-til-biogas-og-andre-groenne-gasser

Future prices of jet fuel and diesel

Main assumptions

The end-product in Scenario 2 is jet fuel, however, a significant side stream of diesel is also produced.

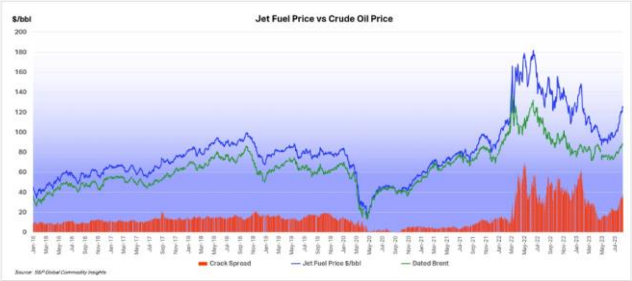
Fossil jet fuel and diesel prices are tightly correlated with crude oil prices. The spread to crude oil reflects the refinery margin which depends on the market situation. Spreads are currently unusually high and volatile. Before COVID and the Ukraine War, the jet fuel spread was around 10-20 USD/bbl, ie. approximately 825 DKK/ton. The diesel spread was around 5-15 USD/ton, ie. approximately 70 DKK/ton.

The Danish Energy Agency projects the future crude oil prices. Adding the spreads to this result in the following prices, which are used in the business case for scenario 2:

- Fossil jet fuel price: approximately 4,450 DKK/ton.
- Diesel price: approximately 3,700 DKK/ton.

The current price of green jet fuel is 2,500-3,500 USD/ton. In 2040, the price may be as low as 1,000-2,000 USD/ton, i.e. 7,000-14,000 DKK/ton. A possible future green jet fuel price of 10,000 DKK/ton is illustrated on slide 43.

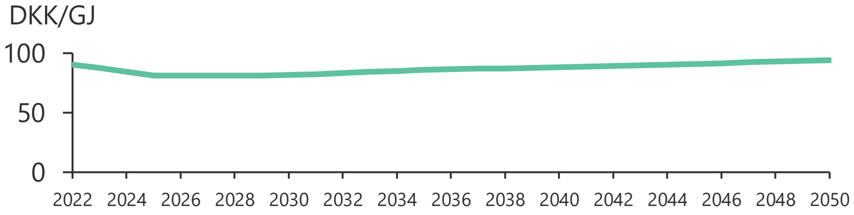
Jet fuel prices and spread to crude oil[1]



Diesel spread to crude oil[2]

Note: Northwest European diesel barge refining margins in $/tonne
Source: Refinitiv

Expected crude oil price[3]



Future price of ethanol

Main assumptions

The process of producing jet fuel is based on ethanol. Hence, the price of ethanol is one of the main drivers of the business case along side the cost of hydrogen.

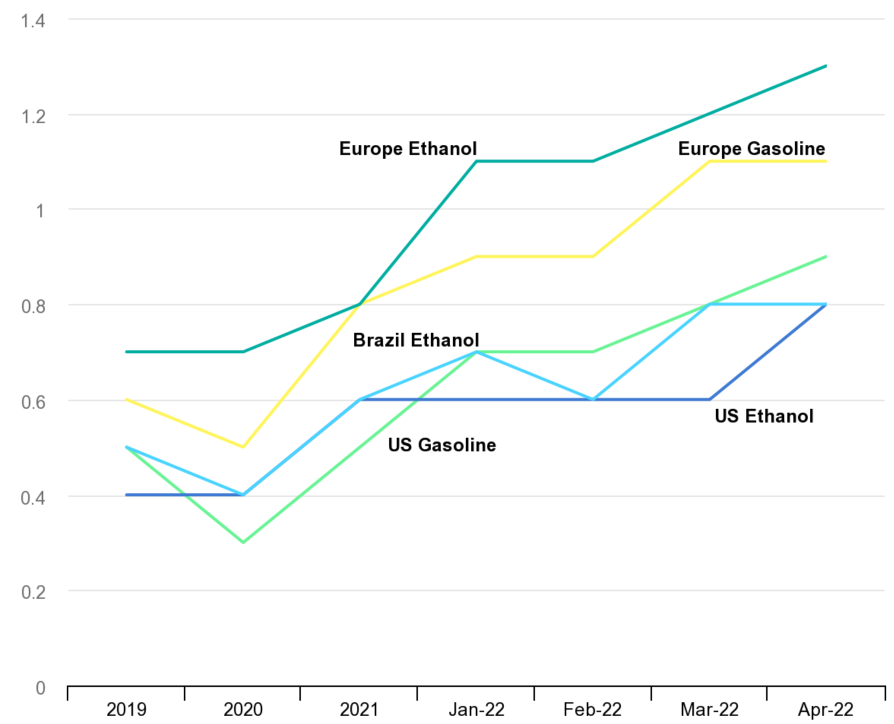
The EIA has published data on historical ethanol prices in Europe. The price was approximately 1.3 USD/litre in April 2022. Data from other sources suggest that this is equivalent with price projections for the near future also.

1.3 USD/litre translates to approximately 9,100 DKK/ton.

Adding transportation costs and a margin at a total of 10 % on top of the commodity price would result in an ethanol cost in line with NIRAS market intelligence at approximately 10,000 DKK/ton.

- The ethanol price used in scenario 2 is 10,000 DKK/ton.

Expected ethanol prices[2]



1. Source: https://www.iea.org/data-and-statistics/charts/ethanol-and-gasoline-prices-2019-to-april-2022

Future price of methanol

Main assumptions

The end-product in Scenario 3 is methanol. Methanol is produced from CO_2 and hydrogen.

Methanol is traded on regional spot markets as well as on contracts. Current prices are at approximately 400 EUR/ton which translates to around 2,800 DKK/ton.

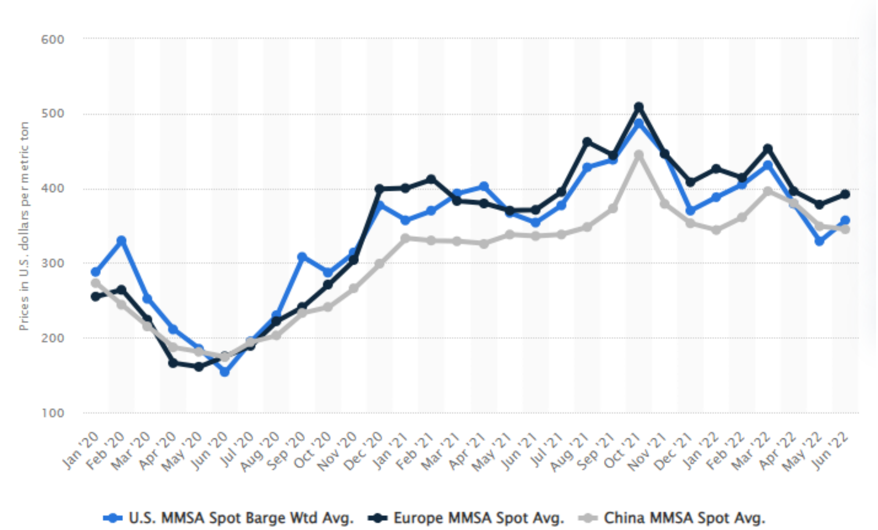
It is expected that the demand for methanol will increase in the future due to investments in methanol freight ships, e.g., by Maersk and other shipping companies.

Production of methanol – in particular, green methanol - will need to increase to meet demand. However, shipping companies are pursuing a strategy, where they source green methanol directly through contracts with investors in methanol plants. The price in this market is not public and its impact on the price of methanol traded on the world market is unknown.

- The methanol price used in scenario 3 is 2,800 DKK/ton.

Expected methanol prices[1]

The European methanol spot prices were on average at around 400 USD/ton in 2021 and 2022. Other sources and more recent data show that the prices remains at this level in 2023.



1. Source: hhttps://www.statista.com/statistics/1323381/monthly-methanol-spot-prices-worldwide-by-region/ and

Other primary inputs

Main assumptions

CO_2
CO_2 is priced at 0 DKK in the analyses. The future regulatory regime for biogenic CO_2 is unknown and the price may be positive or negative depending on supply and demand. If the alternative to using the CO_2 is to incur the cost of storing it, the price of CO_2 may be in the range of 90-220 DKK/ton[1]. The effect on the business cases of being paid to utilize CO_2 is explored in the sensitivity analyses.

Oxygen
Oxygen is priced at 0 DKK in the analyses. However, there is a potential opportunity for selling oxygen. The effect on the business cases of exporting oxygen is explored in the sensitivity analyses.

Heat sales
Excess heat produced is priced at 0 DKK in the analyses, as there is already significant amounts of unused excess heat in Kalundborg. The effect on the business cases of selling the heat to Holbæk is explored in the sensitivity analyses.

1. Energistyrelsen, 2021. https://ens.dk/sites/ens.dk/files/CCS/markedsanalyse_af_co2-lagring_i_danmark.pdf

Steam
For Scenario 1, it is assumed that the steam is generated by an electric boiler, and for Scenario 2 and 3, it is assumed that the steam is supplied by Asnæsværket. For Scenario 1 and 3, the steam is priced at the electricity price, and for Scenario 2, the steam is priced at the electricity price minus 100 DKK/MWh.

Wastewater
The current wastewater tariffs in Kalundborg are:

- 0-500 ton: 39.44 DKK/ton
- 501-20,000 ton: 31.55 DKK/ton
- >20,000 ton: 15.78 DKK/ton

These tariffs are used in Scenario 1 and 2. However, in Scenario 3 the amounts of wastewater is well above 20,000 ton, indicating that a specific price and conditions may need to be negotiated. Hence, a wastewater tariff of 10 DKK/ton is used in Scenario 3.

Operation
An annual operation of 4,800 equivalent full-load hours is assumed for all scenarios corresponding to the expected production of offshore wind turbines as stated by the Danish Energy Agency.

Business case methodology and output

Introduction

The purpose of the business cases is to illustrate the financial flows related to the possible investments in hydrogen production of different scale and usage of the hydrogen in a symbiosis.

The business cases are calculated as standard cash flow analyses of costs and revenues during the lifetime of the plants from the perspective of the owner, i.e., out-of-pocket values are negative whereas revenues are shown as positive values.

No terminal value is included in the business cases, i.e., it is implicitly assumed that there is no further value to be created after the first 20 years of operation and no costs if the plant is abandoned.

Financial costs and taxes are not included in the business case as these depend on the investor's situation (i.e., credit worthiness and opportunities for tax optimization) and not the actual investment.

An interest rate of 3.5 % has been applied for the discounting of the cash flows. This is in line with the social discount rate recommended by the Danish Ministry of Finance. However, commercial investors would normally require a WACC[1] of 8-12 % or higher for investments with a similar risk profile.

Business case reporting

The results of the business cases are shown in a waterfall diagram showing the net present value (NPV) over 20 years of the different cost and revenue items. The diagram shows which items contributes most significantly to the business case.

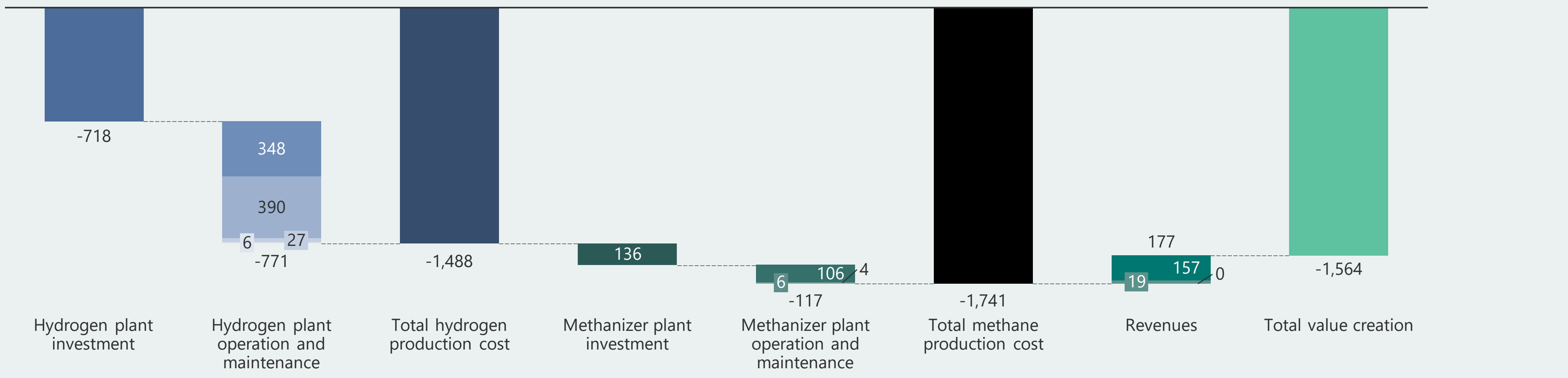
The waterfalls show the cost of hydrogen production separately (blue coloured items) and cost of production of the end product (grey coloured items). Revenues are shown with a green legend colour. Negative total value creation is shown with a red legend colour.

The revenues are calculated based on the value of the fossil version of the end products. These figures are supplemented with estimated revenues if a "green premium" is obtained, based on the prices of green alternatives today. Furthermore, the requirements for additional revenues from e.g. sales of oxygen and heat to break even is calculated.

Please note that the business cases are illustrative only. The business cases are based on key figures, assumptions and projections that may deviate from other industry players' estimates and expectations. There is probably significant room for optimization of the technical solutions and business cases.

Scenario 1 – Additional methane production (13.7 MW electrolysis)

Value creation, NPV, MDKK[1]



Conclusion

- The cost of hydrogen production is the main cost component. The total hydrogen production costs in the 20-year period corresponds to an average cost of the hydrogen produced of 57,691 DKK/ton. The current market prices of green hydrogen is 7-8 EUR/kg corresponding to 52,500 – 60,000 DKK/ton. However, the market price is expected to fall to about 3-4 EUR/kg in the future.
- The production of methane has a negative business case under current methane prices at 2.20 DKK/Nm^3 where total losses over a 20-year period has a net present value of 1.59 bn. DKK. The business case is still negative at 1.25 bn. DKK if the maximum future subsidy of 4.75 DKK/Nm^3 is obtained.

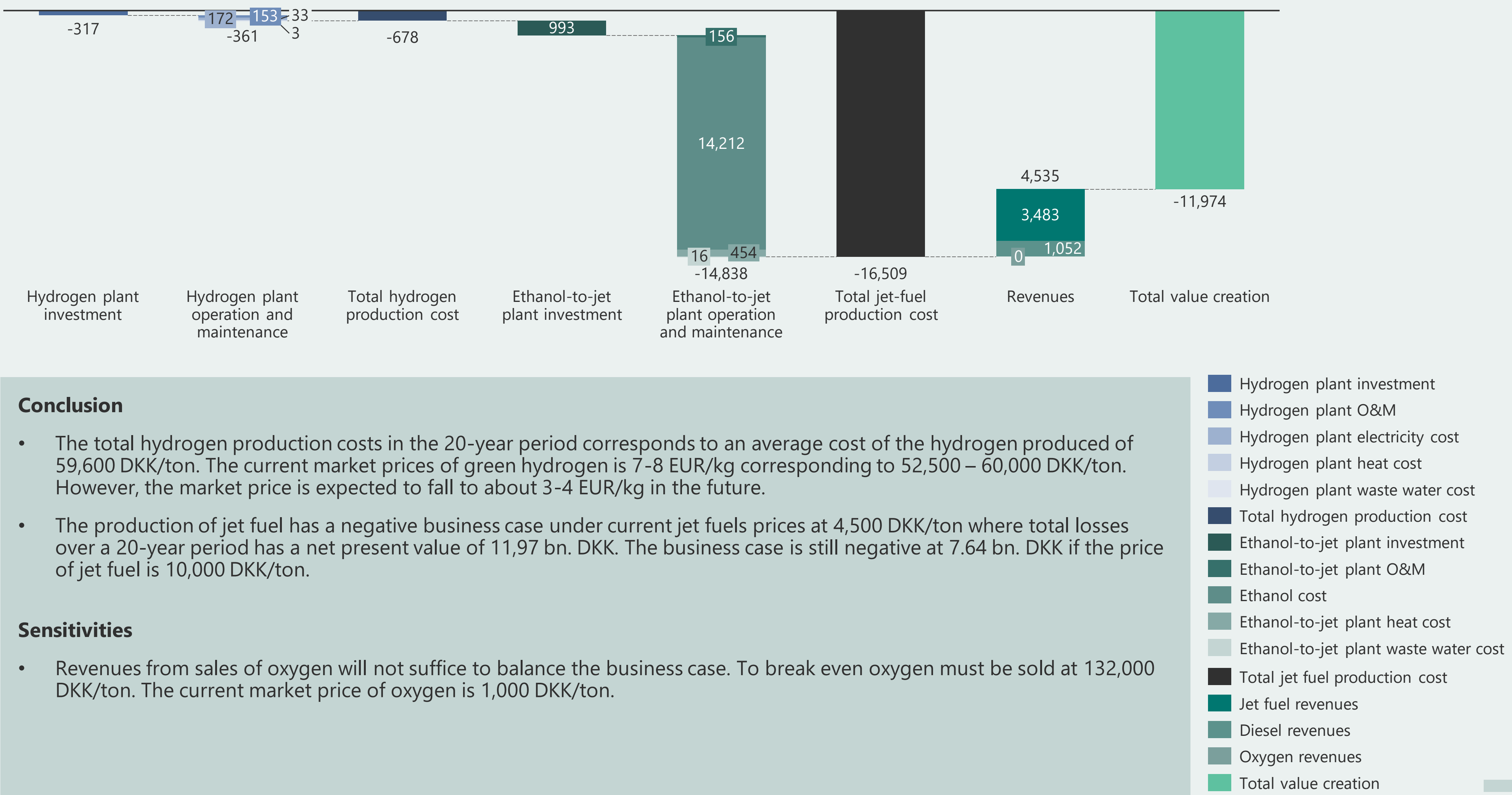
Sensitivities

- Revenues from sales of heat and oxygen will not suffice to balance the business case even if the maximum subsidy is obtained. To break even, either heat must be sold at 43,000 DKK/MWh compared to a current district heating price at 670 DKK/MWh or oxygen must be sold at 6,000 DKK/ton. The current market price of oxygen is 1.000 DKK/ton. Selling the oxygen at this price would amount revenues with a net present value of 205 MDKK. However, selling oxygen at this price would still requires heat to be sold at 36,000 DKK/MWh to balance the business case.

1. NPV calculated with 3,5% interest rate. Estimates of investment cost and operation and maintenance cost primarily based on Energistyrelsen but adjusted by NIRAS to reflect the case.

Scenario 2 – Jet fuel production (6 MW electrolysis)

Value creation, NPV, MDKK[1]



Conclusion

- The total hydrogen production costs in the 20-year period corresponds to an average cost of the hydrogen produced of 59,600 DKK/ton. The current market prices of green hydrogen is 7-8 EUR/kg corresponding to 52,500 – 60,000 DKK/ton. However, the market price is expected to fall to about 3-4 EUR/kg in the future.
- The production of jet fuel has a negative business case under current jet fuels prices at 4,500 DKK/ton where total losses over a 20-year period has a net present value of 11,97 bn. DKK. The business case is still negative at 7.64 bn. DKK if the price of jet fuel is 10,000 DKK/ton.

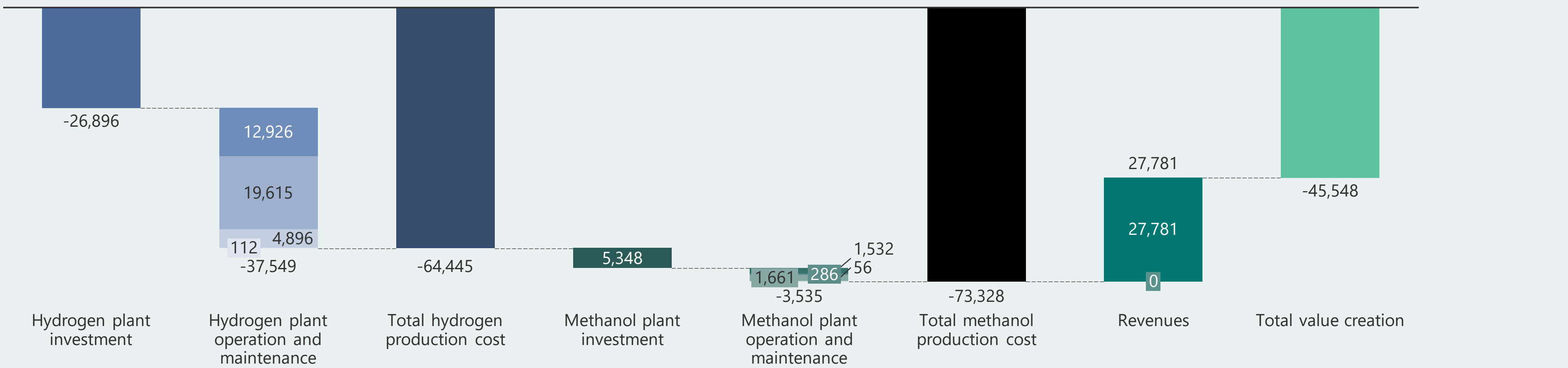
Sensitivities

- Revenues from sales of oxygen will not suffice to balance the business case. To break even oxygen must be sold at 132,000 DKK/ton. The current market price of oxygen is 1,000 DKK/ton.

1. NPV calculated with 3,5% interest rate. Estimates of investment cost and operation and maintenance cost primarily based on Energistyrelsen but adjusted by NIRAS to reflect the case.

Scenario 3 – Large-scale methanol production (1 GW electrolysis)

Value creation, NPV, MDKK[1]



Conclusion

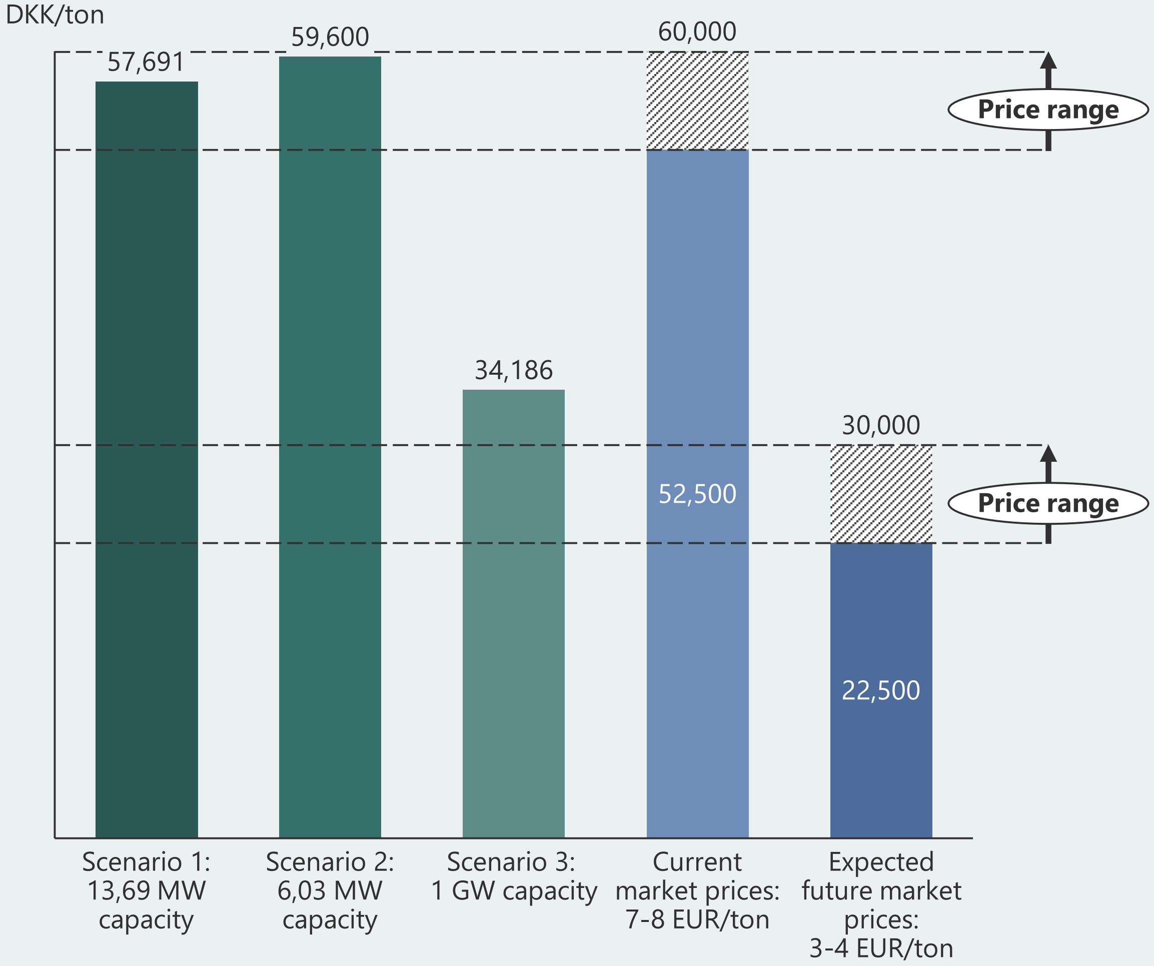
- The total hydrogen production costs in the 20-year period corresponds to an average cost of the hydrogen produced of 34,186 DKK/ton. The current market prices of green hydrogen is 7-8 EUR/kg corresponding to 52,500 – 60,000 DKK/ton. However, the market price is expected to fall to about 3-4 EUR/kg in the future. At this scale, the production of hydrogen is expected to be competitive in the short run, but not in the future.
- The production of methanol has a negative business case under current methanol prices at 2,800 DKK/ton where total losses over a 20-year period has a net present value of 45.5 bn. DKK. It requires a methanol price of 7,400 DKK/ton for the business case to break even, i.e. the "green premium" must be at 4,600 DKK/ton. However, this also rests on the assumption that the CO_2 required is sourced for free (price=0 DKK/ton). The future price of CO_2 is highly uncertain.

Sensitivities

- Revenues from sales of oxygen will not suffice to balance the business case. To break even oxygen must be sold at 3,000 DKK/ton, while the current market price of oxygen is 1.000 DKK/ton.

1. NPV calculated with 3,5% interest rate. Estimates of investment cost and operation and maintenance cost primarily based on Energistyrelsen but adjusted by NIRAS to reflect the case.

Overview of results – hydrogen production at different scales

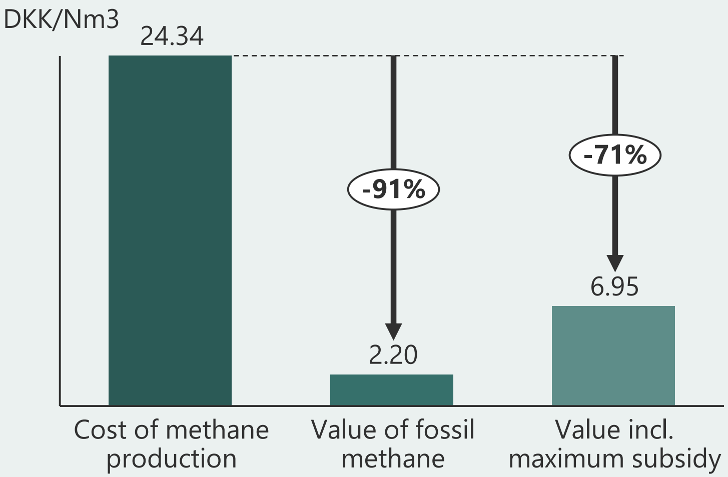


Comments

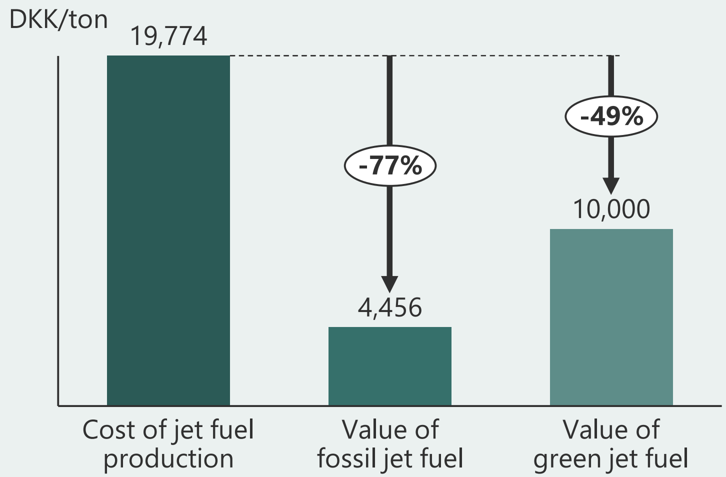
- The basis for each scenario is production of hydrogen. Hence, the production cost of hydrogen must be competitive to ensure that the prices of the end products are competitive.
- There is significant economy of scale in production of hydrogen, i.e. larger plants result in lower costs per output.
- For the small plants in Scenario 1 and 2, the production cost of hydrogen is expectedly high but within the range of the current market price of green hydrogen. However, the production cost is expectedly not competitive in the long run.
- To make hydrogen production competitive also in the longer run requires production at a very significant scale, at or above 1 GW capacity.

Overview of results - end products

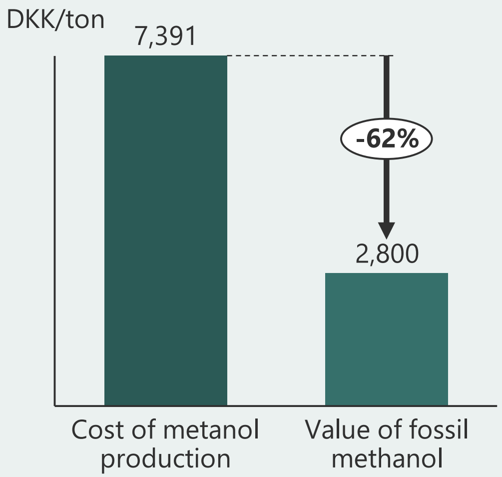
Scenario 1
– Additional methane production



Scenario 2
– Jet fuel production
Production costs incl. revenues from diesel



Scenario 3
– Large-scale methanol production

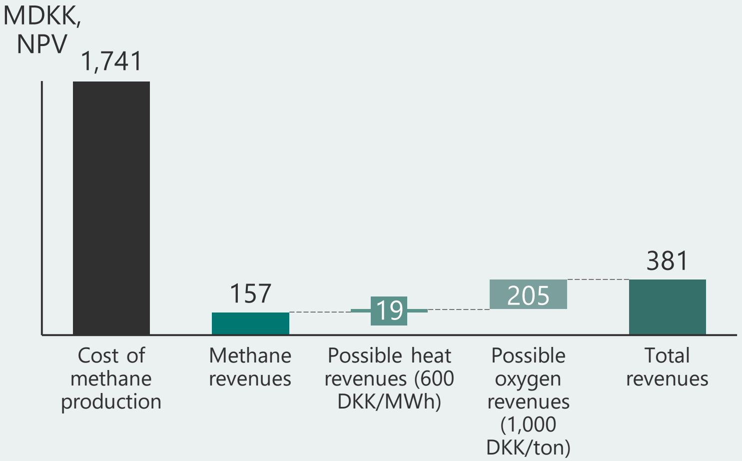


Comments

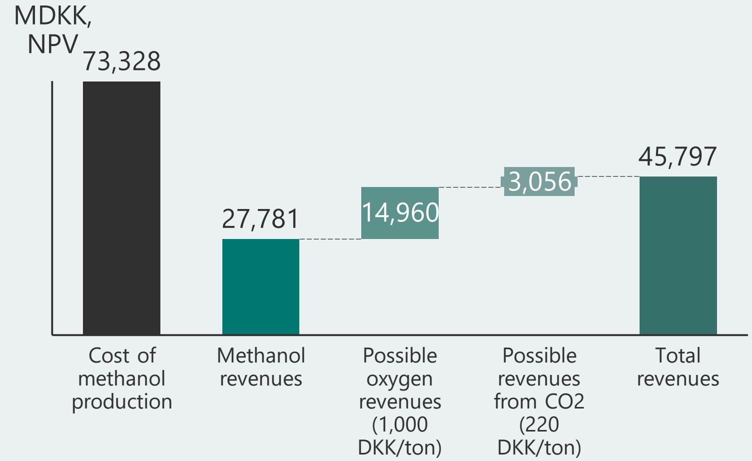
- Additional methane production on biogas plants from CO_2 and own produced hydrogen is expectedly not competitive. The small scale of the hydrogen plant, and hence the high costs of hydrogen, is a significant barrier. However, buying green hydrogen at market price will expectedly not reduce the costs enough to make the business case viable.
- Jet fuel production is expectedly not a viable business case. This is primarily due to the high cost of ethanol, not the production costs of hydrogen.
- Large-scale methanol production will expectedly not be competitive compared to fossil methanol. However, the business case may be positive if the market value of green methanol, as with other green alternatives, is above the value of fossil methanol - or the future costs of sourcing green CO_2 is negative, i.e. the plant is paid to utilize the CO_2 as an alternative to the cost of storing it along with fossil CO_2. However, the future market value of green and fossil CO_2 is uncertain.

Overview of results – additional value creation from side streams

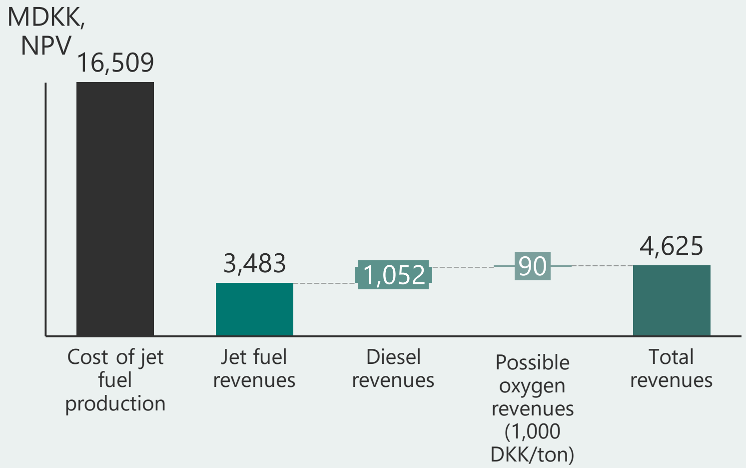
Scenario 1 – Additional methane production



Scenario 3 – Large-scale methanol production



Scenario 2 – Jet fuel production



Comments

- Excess heat produced is priced at 0 DKK in the main analyses, as there is already significant amounts of unused excess heat in Kalundborg. In the sensitivity calculations for Scenario 1, where the excess heat is sold to e.g. Holbæk, a price of 670 DKK/MWh is used. This is the current variable district heating tariff in Holbæk[1] which should cover both heat sourcing costs and other operating and maintenance costs, depreciations etc. Hence, the 670 DKK/MWh used in the sensitivity analysis is a maximum price that the buyer (FORS) can afford. Even at this price, including heat revenues, the results do not change significantly.
- Oxygen is priced at 0 DKK in the main analyses. The oxygen price used in the sensitivities is 1,000 DKK/ton which is equivalent to the average export price of oxygen from the EU[2]. Exporting oxygen probably involves additional costs. Hence, the 1,000 DKK/ton used in the analyses is a maximum value creation.
- CO_2 is priced at 0 DKK in the main analyses. There may be a revenue from utilising CO_2 as an alternative to storing it, but it is not enough for the business case to break even, even if the price of CO_2 (alternative storage cost) is at the most expensive scenario of 220 DKK/ton.

1. Source: https://www.fors.dk/wp-content/uploads/2023/07/priser-2023-fors-varme-holbaek-jyderup-omraade-holbaek.pdf
2. Equivalent to 0.2 $/Nm^3$. Source: https://www.globenewswire.com/en/news-release/2022/04/12/2420689/0/en/Oxygen-Market-Report-Size-Production-Trends-and-Forecast-to-2030-IndexBox.html

Conclusions and recommendations

Conclusions & recommendations

The explored scenarios for PtX-symbiosis in Kalundborg are shown to have different potentials and challenges:

- Scenario 1 can exploit existing material flows in Kalundborg when CO_2 from the upgrading of raw biogas is methanized and the scenario and the overall complexity of the project is low, resulting in a relative short timeline for implementation.
- Scenario 2 can exploit the local production of bioethanol in Alcohol-to-Jet production, but it also depends on large amounts of bioethanol from companies outside Kalundborg.
- Scenario 3 is less coupled to local material flows, and the scenario is significantly challenged by lack of energy supply. Thereby this scenario seems very difficult to implement in Kalundborg.
- Neither of the business cases in Scenario 1-3 are viable on pure commercial terms.
- Value creation from side streams such as oxygen or heat can contribute to the business cases, but it is not enough to make the business cases positive.
- What particularly speaks in Kalundborg's favour is the adequacy of water. But there are none of the other side streams that significantly change the business case.
- To make the business cases positive, the value of the green alternatives produced must remain significantly above the fossil alternatives for a long period of time. Alternatively, government subsidies must be in place.
- To make hydrogen production competitive also in the long run requires production at a very significant scale, approaching or above 1 GW capacity. There are no plans for offshore turbine development near Kalundborg and such plans will have a long-time horizon.
- The economic challenges related to all scenarios in this report will most likely be applicable on any PtX-project in Denmark and probably also globally.

Recommendations:

To continue investigating the possibilities for PtX-symbiosis in Kalundborg, the following steps can be made:

- Enter into a deeper dialogue with actors in Kalundborg about testing the solutions included in the report's scenarios.
- Go more in-depth with business cases and future prices of input and output flows.

What speaks for and against PtX in Kalundborg?

+

- Relevant local biogenic input flows for PtX such as raw biogas and bioethanol.
- Sufficient supply of wastewater.
- Waste water, electricity and CO2 facilities are placed close.
- Experience with cooperating in industrial symbiosis.

−

- No large-scale supply of renewable energy, which is the most essential input for PtX.
- No large-scale demand for the sidestream outputs from PtX such as oxygen and heat.

Appendix

Energy og mass balances

Different electrolysis technologies

Energy and mass balance

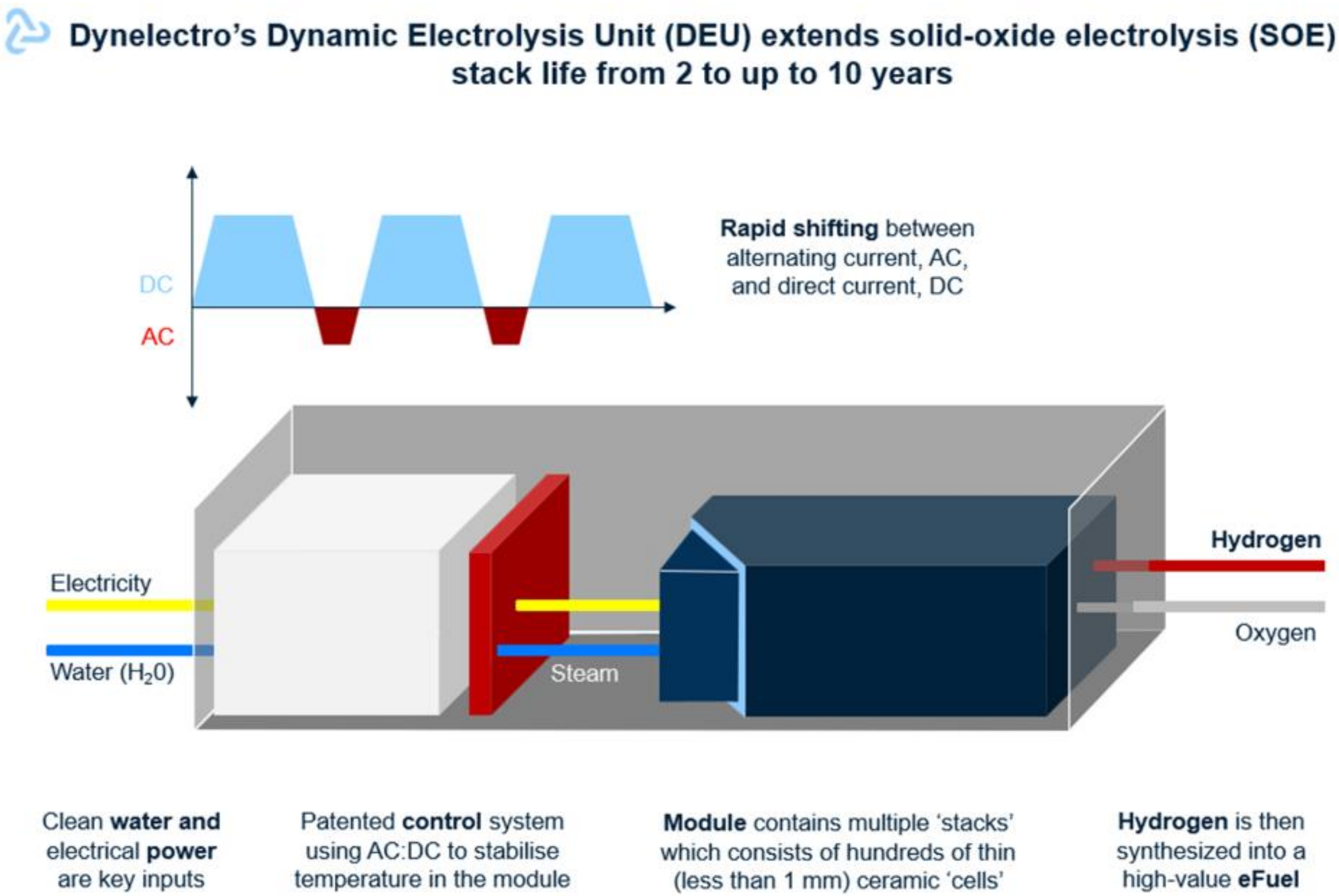
Different electrolysis technologies

The scenarios in this report are analysed with SOEC-electrolysis technology.

The diagrams on the following pages show energy and mass balances for a 1GW PtX plant with different electrolysis technologies: AEC, PEM and SOEC

Most significant differences are:

- SOEC is more energy efficient than AEC and PEM.
- SOEC needs heat and does not produce heat.
- AEC and PEM is implementable today. SOEC needs further development, especially when it comes to large-scale implementation.



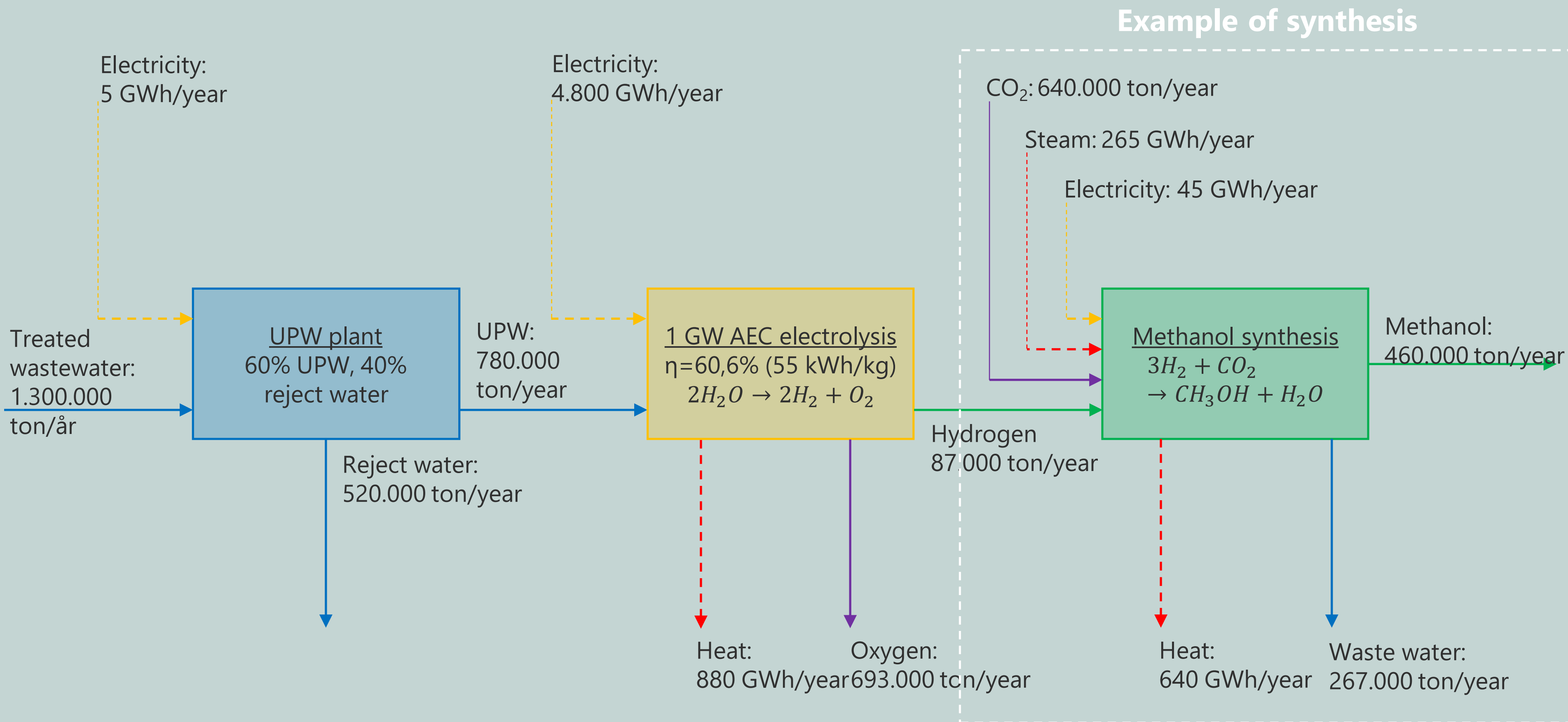
Energy and mass balance

Different electrolysis technologies

	AEC	PEM	SOEC
Input			
Water	8,9 kg	8,9 kg	8,9 kg
Electricity	55,0 kWh	57,0 kWh	36,0 kWh
Heat	0,0 kWh	0,0 kWh	9,0 kWh
Output			
Hydrogen	1,0 kg	1,0 kg	1,0 kg
Oxygen	7,9 kg	7,9 kg	7,9 kg
Heat	10,1 kWh	11,2 kWh	0,0 kWh

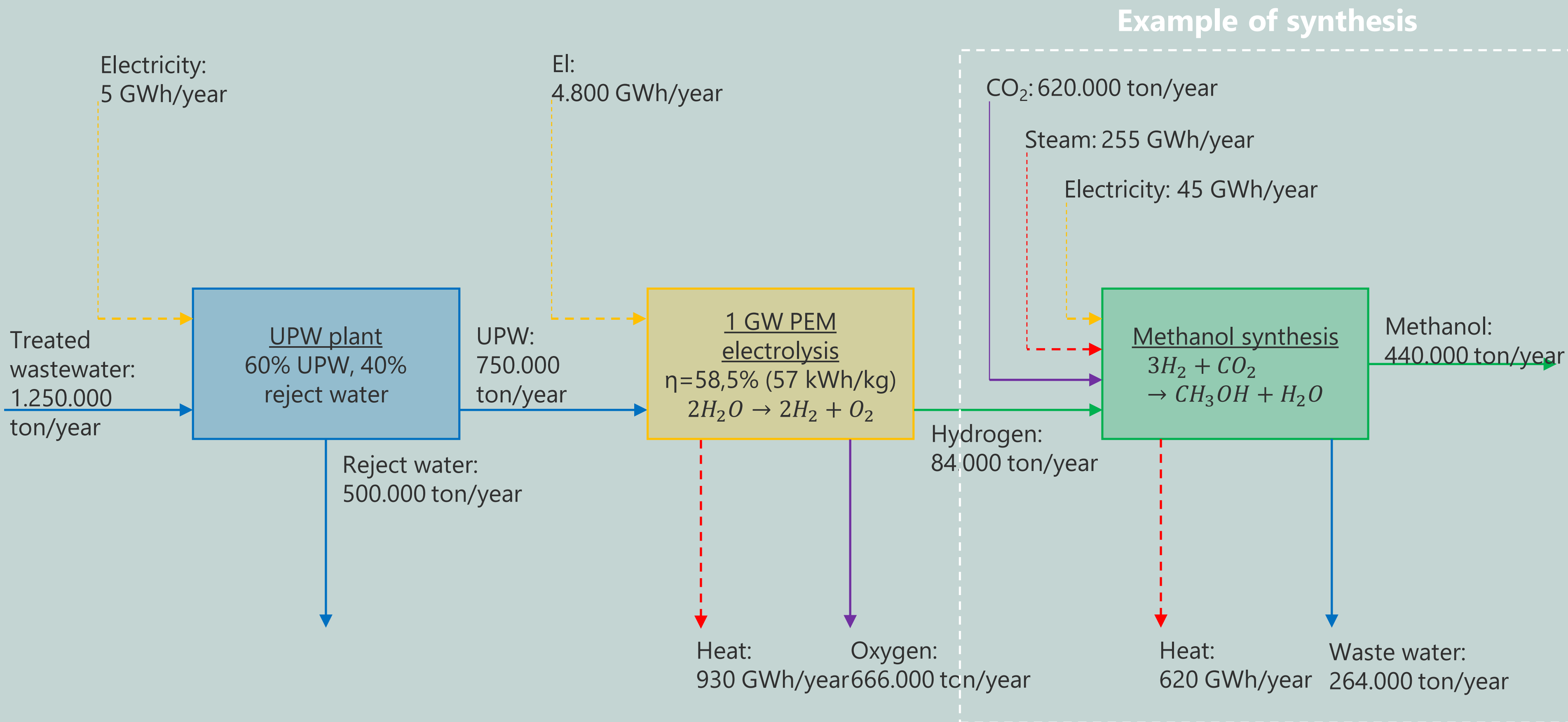
1 GW alkaline electrolysis (AEC)

Energy og mass balance



1 GW proton exchange membrane electrolysis (PEM)

Energy and mass balance



1 GW fast oxid electrolysis (SOEC)

Energy and mass balance