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CO2 INFRASTRUCTURE IN NORTHWEST ZEALAND

Feasibility Study of CO2 Infrastructure in Northwest Zealand

WP5 in PtX Cluster Zealand
European Regional Development Fund Project
REACT-EU grant: 22-0068

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Develop understanding and investigate feasibility of the CO_2 infrastructure potentials in Northwest Zealand

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1 OBJECTIVE AND SCOPE

The objective of this project is to perform a feasibility study of a potential CO_2 infrastructure in the Northwest Zealand. The feasibility study considers transporting of CO_2 between Asnæsværket in Kalundborg and the storage sites in Stenlille and Havnsø, as well as analysing potential PtX synergies in the area and the socio-economic benefits and perspectives of the envisioned infrastructure. This study will therefore support as an early phase concept development study for possibilities within the area, interfacing infrastructure solutions and areas and uncertainties to investigate further in the maturation phase.

The initial scope of the feasibility study has evolved during the project period from focusing mainly the CO_2 volumes in the Northwest Zealand area and the according infrastructure concept, to accommodating larger volumes of imported CO_2, enable export of CO_2 and handling CO_2 volumes from the Copenhagen area.

In this feasibility study the Northwest Zealand is considered as the area North and West of the Stenlille storage site; while the East Zealand area is used for the areas east of the Stenlille storage.

The feasibility study considers four work scopes:

- **Mapping of prerequisites:**

  Identification and mapping of CO_2 emissions potentials and CO_2 consumers in the area including identification of emission type (fossil / biogenic) and CO_2 quality. Investigate the storage capacities and operational envelope, identification of relevant existing infrastructure and investigating integration with district heating infrastructure.

  CO_2 pipeline infrastructure:

  Technical feasibility and project feasibility of a CO_2 pipeline transportation concept. The assessments consider design of a CO_2 pipeline for transportation of CO_2 capture potentials to the Stenlille and Havnsø storage sites. Further the assessment considers the concepts for handling CO_2 volumes from Copenhagen and CO_2 volumes imported in Kalundborg.

  The design activities include route considerations, hydraulic and capacity assessments, legislative and permitting aspects, and details of required pipeline system facilities including a CAPEX and OPEX evaluations.

- **Potential future integration with PtX infrastructure:**

  Assessment of current infrastructure visions that have an impact on future integration of CO_2, H_2, electricity grid infrastructure.

  Mapping and analysis of announced PtX projects on Zealand and further mapping of optimal location of future PtX plants. Mapping and quantifying of the expected and potential hydrogen production on Zealand and analysis of the potential of hydrogen infrastructure on Zealand and impact on other PtX activities.

  Analysis of potential synergies between CO_2 pipelines and hydrogen pipelines.

- **Perspectives and realization of the potentials in the area:**

  Analysis of socio-economic perspectives and impacts on jobs, climate targets and GDP.

  Development of a scenario for potential production of hydrogen and assessment of other possible value streams from PtX activities on Zealand and the implications hereof.

  Impacts of an integrated CO_2 pipeline infrastructure connecting Western part of Zealand with a pipeline infrastructure in Greater Copenhagen area.

2 EXECUTIVE SUMMARY

A feasibility study of a CO_2 infrastructure in Northwest Zealand has been performed, consisting of an analysis of the prerequisites in the Northwest Zealand, development of concepts for CO_2 infrastructure, an assessment of the future integration with PtX infrastructure and a socio-economic assessment of a CO_2 infrastructure in the area.

The feasibility study has been an iterative process with stakeholders of the project to define potential infrastructure solutions in the Northwest Zealand area. The study covers multiple scenarios of CO_2 volumes and routes of CO2 transport with high dependencies to interfacing concepts outside the scope of this feasibility study as shipping import/export, storage sites and a pipeline from the Copenhagen area.

Further maturation work is required for each concept in the following phases of developing a CO_2 infrastructure, with focus on safety, permitting and overall confirmation of premises used in this early phase study.

Mapping of prerequisites:

The prerequisites for the infrastructure concepts have been analysed, where volumes and location of CO_2 emission points and CO_2 consumption points for Northwest Zealand (and outside this area) were identified for potential CCS and potential CCU purpose. The CO_2 emission potentials have been identified from the Danish Energy Agency data and market research, considering emissions from power plants, refineries, biogas plants and production companies. The relevant CO_2 potentials for CCS are further sorted for relevance for a CO_2 pipeline infrastructure between Kalundborg, the Stenlille storage site and the Havnsø storage site, showing the main capture potentials being located in Kalundborg local area. The sorted potentials have been analysed further with respect to peak production rates and biogenic/fossil compositions. It was further clear that no clear consumption was identified, hence an infrastructure facilitating storage or export is required.

In addition to the Northwest Zealand CO_2 potentials, the added CO_2 volumes from the Copenhagen area and from shipping import have been identified for incorporation into the CO_2 infrastructure concepts.

Further, the existing infrastructure in the areas have been assessed and mapped considering operation and capacity of storage sites, waste heat integration potentials, port facilities and existing route corridors for pipeline route considerations.

CO_2 pipeline infrastructure:

The concepts for a CO_2 transportation network in the Northwest Zealand area have been developed considering the mapped prerequisites of CO_2 potentials in the Northwest Zealand area, the Copenhagen CO_2 volumes and the ship imported volumes. The required capacity, operational parameters, pipeline dimensions, pipeline material, routes, and crossings of the dense phase pipeline infrastructure have been analysed for the Kalundborg Hub – Stenlille connection, the Kalundborg Hub – Havnsø connection and the Stenlille – Havnsø connection with sensitivity studies for various capacity requirements.

These concepts have further been developed to include the required facilities in the Kalundborg Hub, considering the gas phase gathering network, compressor stations, liquefaction facilities, intermediate storage, pumps and facilities required for shipping. Furthermore, the booster station requirements for increasing the pressure of the CO_2 potentials from the Copenhagen area have been included.

A CAPEX and OPEX cost of each concept function have been outlined and incorporated into four main design cases, with added sensitivity cases, for a CAPEX and OPEX estimation of each design case.

The project feasibility of the envisioned pipeline infrastructure has further been assessed in terms of a project development schedule for a low and high-risk approach, with and identification of the identified project risks.

All four design concepts resulted in achievable pipeline dimensions, with standard material choices, standard wall thicknesses and therefore considered feasible designs. It is although noted that uncertainties on routing, risk and safety aspects and the according permitting process are considered project risks that should be addressed early in the maturation of these concepts.

The analyses of the pipeline costs for case 3A, 3B and 3C have shown minor difference in CAPEX cost for establishing a pipeline handling 5, 9 or 12 MTPA, which show the benefits of choosing a higher capacity pipeline with low financial risks associated with over-dimensioning the pipeline system.

Potential future integration with PtX infrastructure:

The potential future integration with PtX infrastructure has been analysed, through identification of announced PtX projects on Zealand along with the expected CO_2 demand, showing only limited immediate plans for PtX facilities in the area of the envisioned CO_2 pipeline infrastructure in the Northwest Zealand area.

The potential locations for future PtX projects have further been investigated by analysing the power grid, transportation and local offtake possibilities, bi-product offtake and access to CO_2 and water. These analyses have identified Kalundborg, Vordingborg and the Copenhagen area as the most favourable locations for a company to establishing PtX projects.

An outlook of the CO_2 and H2 infrastructure visions have been investigated along with discussion of possible integrations and synergies.

Perspectives and realization of potentials in the area:

The perspectives and realization of the potentials in the Northwest Zealand area are analysed by assessing how the envisioned CO_2 pipeline infrastructure can facilitate the efficient transport of CO_2, as well as benefit and create value for a range of other CO_2 emitters and industries in Zealand that use CO_2 in their production processes. This analysis has been performed with a high level qualitative socio-economic cost-benefit analysis, based on the findings of preceding work of this feasibility study.

Here the investment cost, operating cost, environmental costs, climate effect, additional income, sector coupling, GDP and jobs are quantitatively assessed for three of the various design cases, where especially the climate effects and GDP and job creation shows positive impacts.

It is further identified that the high CO_2 volume case (design case 3) considering imported CO_2 have the most favourable combined score, where the additional incomes and GDP/Jobs are differentiators compared to the base case and no import scenarios.

3 INTRODUCTION

3.1 Background

Ørsted Bioenergy & Thermal Power A/S are in collaboration with the consortium PtX Cluster Zealand investigating the potential for establishment and development of a CO_2 infrastructure in Northwest Zealand to support future development of climate friendly technology and industry, hereunder collecting, storage and usage.

This study is a part of the development of a Danish energy system that supports a transition to sustainable energy production, and as part of the development of an industrial cluster that builds on already existing collaborations in Northwest Zealand, including the Kalundborg Symbiosis.

3.2 Abbreviations

CCS	Carbon capture storage
CCU	Carbon capture utilization
DAC	Direct air capture
DEA	Danish Energy Agency
EPC	Engineering Procurement Construction
FEED	Front end engineering design
GDP	Gross Domestic Product
GSD	Gas Storage Denmark
GEUS	"De Nationale Geologiske Undersøgelser for Danmark og Grønland"
HAZID	Hazard identification
HDD	Horizontal directional drilling
LCO_2	Liquid carbon dioxide.
LED	Light-emitting diode
MAOP	Maximum operating pressure
MSL	Mean sea level
MT	Million ton
MTPA	Million tonnes per annum
PBR	Photo Bio Reactor
PIG	Pipeline Intervention Gadget (Devices used for cleaning and inspection of pipelines)
PLR	PIG Launcher Receiver (Launching and receiving facilities for PIG's)
PtX	Power to X
QT	Quenched and tempered
RFNBO	Renewable fuels from non-biological origin
SAF	Sustainable aviation fuels
SAWL	Submerged arc-welding longitudinal
SG	Specific gravity
SMYS	Specified minimum yield strength
SMTS	Specified minimum tensile strength
TEN-E	Trans-European Network for Energy
TJ	Terajoule
TMCP	Thermo-mechanical controlled process pipes
TOP	Top of pipe
TPA	Ton per annum

4 MAPPING OF PREREQUISITES

The mapping of the prerequisites for the CO_2 infrastructure feasibility study is the basis for assessing and developing a suitable concept for a CO_2 infrastructure in Northwest Zealand. The process involves identifying and analysing:

– the location and potential of CO_2 emitters in the area

– potential CO_2 consumers

– capacity and operational requirements for the Stenlille and Havnsø geological storage sites

– existing infrastructure relevant for integration with a CO_2 pipeline transport system in Northwest Zealand.

The CO_2 infrastructure is also to be integrated with CO_2 volumes outside the Northwest Zealand areas, hence these sources and volumes are further identified.

4.1 Mapping of emitters in Northwest Zealand

4.1.1 Methodology / data sources

The CO_2 emission data presented in this section is established based on market research, including various production and emissions sources along with supporting dialog with project stakeholders, Danish Energy Agency (DEA), and selected facility representatives. The area considered for the mapping of emitters are for the geographic areas with postal codes 40XX, 41XX, 42XX, 43XX, 44XX,45XX and 47XX. The CO_2 emitters considered for this study is divided into:

- Emission potential above 10 000 TPA and all biogas upgrading facilities,
- Emission potential above 1000 TPA and below 10 000 TPA (included in Appendix A).

The energy overview for various facilities is extracted for year 2021 from the "Energiproducenttælling" [1] provided by the Danish Energy Agency, which details the energy production in Terajoules (TJ) for various fuel types at electricity and district heating producers. This energy production overview is converted to tons CO_2 emissions via emission factors from the Danish Energy Agency [2], see Table 4-1.

Table 4-1 Emission factors

Fuel	Emission factor	Unit
Natural gas	56	ton CO_2 / TJ
Fuel oil	79	ton CO_2 / TJ
Gas oil / diesel oil	74	ton CO_2 / TJ
Coal	94	ton CO_2 / TJ
Waste	106	ton CO_2 / TJ
Biogas	84	ton CO_2 / TJ
Straw	100	ton CO_2 / TJ
Wood	112	ton CO_2 / TJ
Bio-oil and other liquid bio-fuels	80	ton CO_2 / TJ

The emissions from production units not included in [1] are extracted from the reported CO_2 emission to the EU Emissions Trading System (EU ETS) provided by the Danish Energy Agency [3].

The biogas plants exporting gas to the natural gas grid are not included in [1] or [3], hence these are collected separatly. Biogas consist of 35-40% of CO_2 and 60-65% of CH_4. To fulfill the required gas quallity of the Danish natural gas grid the CO_2 needs to be seperated in an upgrading facilitiy [4]. The CO_2 emission from upgrading the biogas is estimated based on the yearly production of biogas and a CO_2 content of 40%.

It shall be aknowledged that the collected emission potentials are based on emission estimates for 2021. The capture potential and emission potential over time is not included in this overview and will be adressed in section 4.2.

4.1.2 CO_2 emitter potentials

Emitters in the considered area with CO_2 emission potential over 10 000 TPA and all relevant biogas plants are listed in Table 4-2. Reference is made to section 4.1.1 for methodology and data sources.

Table 4-2 CO_2 emitter potentials above 10.000 tons CO_2 / year and all biogas upgrading facilities - listed by location.

ID	Facility	Postal code, City	Emission (TPA)	Ref.
255	ARGO Roskilde Kraftvarmeværk	4000, Roskilde	385 943	[1], [2]
1680	Ringsted Halmvarmeværk, Ringsted Fjernvarme	4100, Ringsted	35 254	[1], [2]
-	Ringsted Biogas ApS	4100, Ringsted	5236	[5]
178	Halmvarmeværket Borup	4140, Borup	13 312	[1], [2]
2421	Sorø Bioenergi	4180, Sorø	16 600[1]	[1], [2]
279	SK-Varme A/S- Slagelse Kraftvarmeværk	4200, Slagelse	96 985	[1], [2]
2204	SK Varme A/S, Trafikcenter Allé 32	4200, Slagelse	30 002	[1], [2]
2359	Halsskov halmvarmeværk	4220, Korsør	23 503	[1], [2]
661	Hashøj Kraftvarmeforsyning A.m.b.a.	4261, Dalmose	11 041	[1], [2]
238	Høng Varmeværk, Banemarken 8	4270, Høng	14 762	[1], [2]
2015	Hvalsø savværk varmeværk	4330, Hvalsø	10 685	[1], [2]
277	Asnæsværket	4400, Kalundborg	220 231	[1], [2]
307	Kalundborg Refinery	4400, Kalundborg	534 231	[3]
345	Gyproc A/S	4400, Kalundborg	16 423	[3]
-	Kalundborg Bioenergi ApS	4400, Kalundborg	23 000	[6]
343	Faxe Kalk, Ovnanlægget Stubberup	4640, Faxe	46 136	[3]
317	Ardagh Glass Holmegaard A/S	4684, Holmegaard	51 283	[3]
250	Næstved Affaldsenergi SYD	4700, Næstved	151 680	[1], [2]
2131	Vordingborg Kraftvarme	4760, Vordingborg	66 347	[1], [2]
447	Stege Halmvarmeværk	4780, Stege	12 325	[1], [2]

1) The Sorø Bioenergi emission data from 2021 is a partial dataset considering 2.5 months of production in fall/winther months (4150 TPA). The emission data are therefore extrapolated to estimate the full year potentials.

Table 4-3 CO_2 emitter potentials above 10.000 tons CO_2 / year and all biogas upgrading facilities – listed by emission potential.

ID	Facility	Postal code, City	Emission (TPA)	Ref.
307	Kalundborg Refinery	4400, Kalundborg	534 231	[3]
255	ARGO Roskilde Kraftvarmeværk	4000, Roskilde	385 943	[1], [2]
277	Asnæsværket	4400, Kalundborg	220 231	[1], [2]
250	Næstved Affaldsenergi SYD	4700, Næstved	151 680	[1], [2]
279	SK-Varme A/S- Slagelse Kraftvarmeværk	4200, Slagelse	96 985	[1], [2]
2131	Vordingborg Kraftvarme	4760, Vordingborg	66 347	[1], [2]
317	Ardagh Glass Holmegaard A/S	4684, Holmegaard	51 283	[3]
343	Faxe Kalk, Ovnanlægget Stubberup	4640, Faxe	46 136	[3]
1680	Ringsted Halmvarmeværk, Ringsted Fjernvarme	4100, Ringsted	35 254	[1], [2]
2204	SK Varme A/S, Trafikcenter Allé 32	4200, Slagelse	30 002	[1], [2]
2359	Halsskov halmvarmeværk	4220, Korsør	23 503	[1], [2]
-	Kalundborg Bioenergi ApS	4400, Kalundborg	23 000	[6]
2421	Sorø Bioenergi	4180, Sorø	16 600[1]	[1], [2]
345	Gyproc A/S	4400, Kalundborg	16 423	[3]
238	Høng Varmeværk, Banemarken 8	4270, Høng	14 762	[1], [2]
178	Halmvarmeværket Borup	4140, Borup	13 312	[1], [2]
447	Stege Halmvarmeværk	4780, Stege	12 325	[1], [2]
661	Hashøj Kraftvarmeforsyning A.m.b.a.	4261, Dalmose	11 041	[1], [2]
2015	Hvalsø savværk varmeværk	4330, Hvalsø	10 685	[1], [2]
-	Ringsted Biogas ApS	4100, Ringsted	5236	[5]

1) The Sorø Bioenergi emission data from 2021 is a partial dataset considering 2.5 months of production in fall/winther months (4150 TPA). The emission data are therefore extrapolated to estimate the full year potentials.

4.1.3 CO_2 emitter map

The CO_2 emitter potentials listed in Table 4-2 are shown Figure 4-1 along with the storage locations Stenlille and Havnsø. Also the CO_2 emitters below 10 000 TPA listed in Appendix A are included for reference.

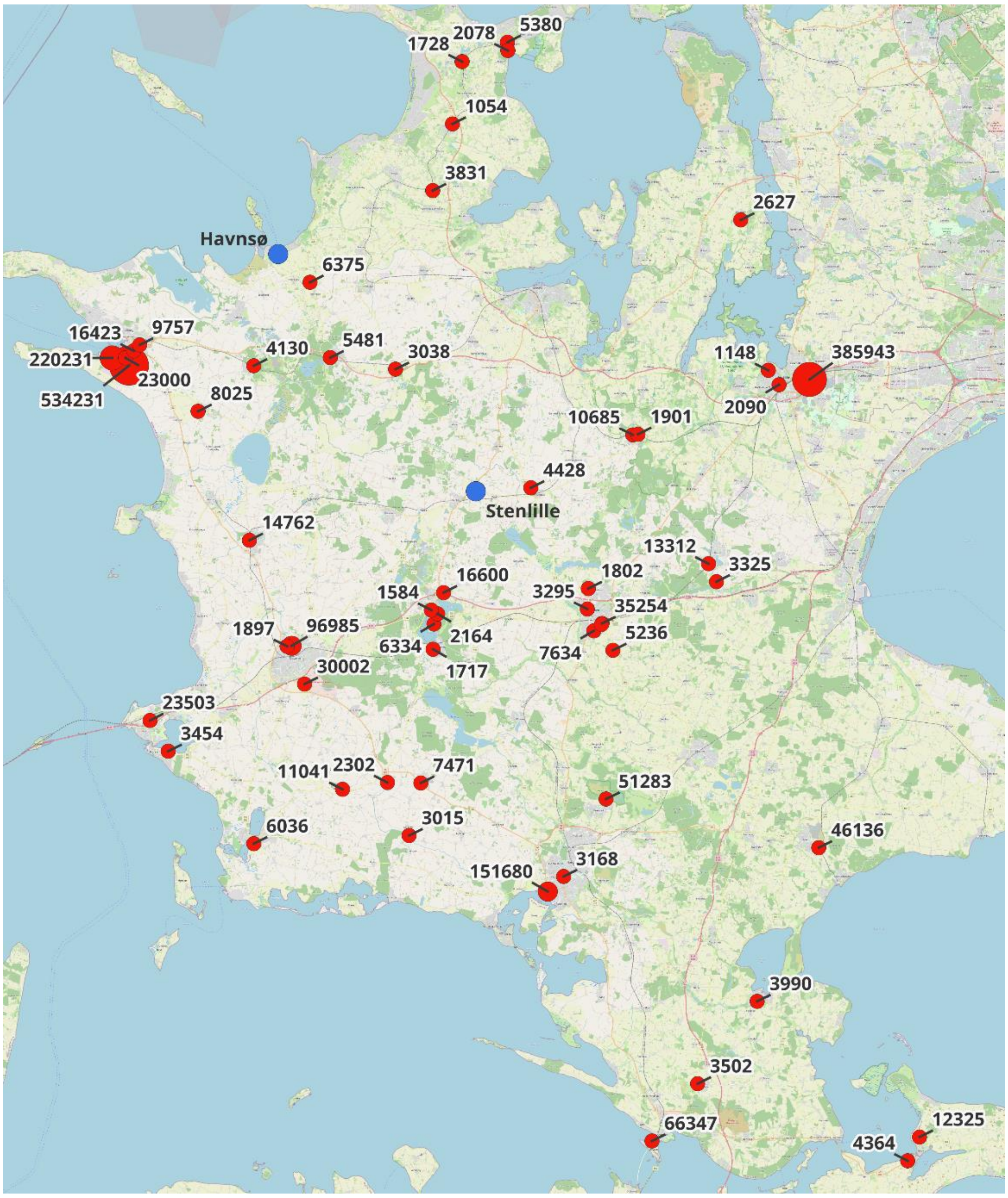


Figure 4-1 Visual representation of CO_2 emitters with corresponding CO_2 emission rate in TPA; blue dots marks the potential CO_2 storage locations at Stenlille and Havnsø

4.2 CO_2 emitters sorted for integration with a CO_2 pipeline

The CO_2 emitters listed in Table 4-2 are sorted based on:

- **The CO_2 potential:** For this study the main sources are based on a minimum of 10 000 TPA. This is not the case for biogas upgrade facilities where the CO_2 gas already is extracted in the upgrading process, hence lower emissions are relevant to consider here.

  The emitters below 10 000 TPA have been included in the overview, to investigate clustered areas with a combined potential or if located close to the envisioned route, but generally not considered feasible to utilize in this study (except for one listed in Table 4-4).

Biogas upgrading facilities are already separating the CO_2 from the gas stream before and will therefore not require a new Carbon Capture plant to be installed, hence lower CO_2 potentials are considered for biogas upgrading facilities.

- **The capture potential:** The sorted potential is further reduced by 10%, which is the efficiency of a typical amine capture plant. This is not the case for biogas upgrade facilities where the CO_2 gas already is extracted in the upgrading process. [7]

  The actual viable capture potential will depend on individual capture technology and emission points for each facility. This will therefore require further investigation of the selected emission points.

  It is noted that the potentials in Table 4-2 and Table A-1 are based on emission data for each facility from 2021. A lower bound estimate is relevant to consider for defining the expected emissions in the future. For this study the feasibility of CCS for the current potential is considered for dimensioning of the pipeline system for accommodating the current potential.

- **Geographical location:** The sources location in relation to the main considered route corridor from Kalundborg to Stenlille and Havnsø is considered. Hence, emitters not located near the potential route corridor are excluded. Whether the CO_2 will be transported by pipeline or truck will require further analyses of CAPEX & OPEX. CO_2 emissions points of less than 50.000 ton/year potentials are assumed transported by truck in this feasibility study unless located in cluster.

Based on the identified CO_2 emitters and above criteria, the emitters considered most relevant for developing a pipeline infrastructure in Northwest Zealand are identified and presented in Table 4-4. The estimated capture potential for each emitter is further listed taking the efficiency of a typical amine process into consideration. Further, the type (biogenic/fossil) of the CO_2 stream for each of the sorted emitters are presented.

Table 4-4 Sorted emitter potential with details on emission amount and type

Facility	**CO_2 emissions tons / year**	**CO_2 emissions tons/year (90%)**	**Type of CO_2 emission**	
			Biogenic [1)]	**Fossil** [2)]
Asnæsværket	220 231	198 208	99.9%	0.1%
Kalundborg Refinery	534 231	480 808	0%	100% [5)]
Gyproc A/S	16 423	14 781	0%	100%
Kalundborg Bioenergi ApS	23 000 [3)]	23 000 [4)]	100%	0%
Miljø Teknik (Novozymes A/S)	97 57	8781	100%	0%
Hvidebæk Fjernvarmeforsyning	8025	7223	100%	0%
Høng Varmeværk	14 762	13 286	100%	0%
Total	**826 429**	**746 087**	**34%**	**66%**

1) Biogenic fuels: Biogas, straw, wood chips, wood- and biomass waste, wood pellets, bio-oil.
2) Fossil fuels: Coal, fuel oil, gas oil, natural gas, waste.
3) The potential listed is the current potential. The company is looking on the potential of expansions, which could lead to 30.000 to 40.000 tons CO_2 / year.
4) The capture potential is not reduced for biogas plants.
5) Kalundborg Refinery, Bæredygtighedsrapport 2022, p. 26-27. Primary energy sources in 2022: Fuel gas (85.7%), which is a leftover from the refinery process, diesel oil (7.7%) and electricity (6.6%).

4.2.1 Seasonal trends of emissions

The seasonal trends are assessed based on yearly full working hours estimated in [2] for waste incineration plants (6000 full working hours), industrial plants (7000 full working hours) and biogas plants (8500 full working hours).

The yearly full working hours for each facility are used to translate the yearly emissions to peak emission rates per hour, thereby defining the required capacity for a pipeline to accommodate peak emission periods. In this study the full working hours of each facility are assumed to occur simultaneously defining the maximum CO2 flow rate to design the system for. This yields a pipeline capacity design volume of approximately 1 MTPA, which is used as base for the concepts in section 5.

4.2.2 Detailed mapping overview for pipeline design

The detailed overview of the selected emitters is presented for the Northwest Zealand area in Figure 4-2 and separately for the Kalundborg Hub in Figure 4-3. The presented emitters are selected based on size of CO_2 potential and the location in relation to Kalundborg, Stenlille and Havnsø infrastructure considered for this feasibility study.

The emission potentials outside Kalundborg (Hvidebæk Fjernvarmeforsyning and Høng Varmeværk) are expected to be transported by truck to Kalundborg, hence no separate pipelines are considered here for transporting CO_2 to Kalundborg.

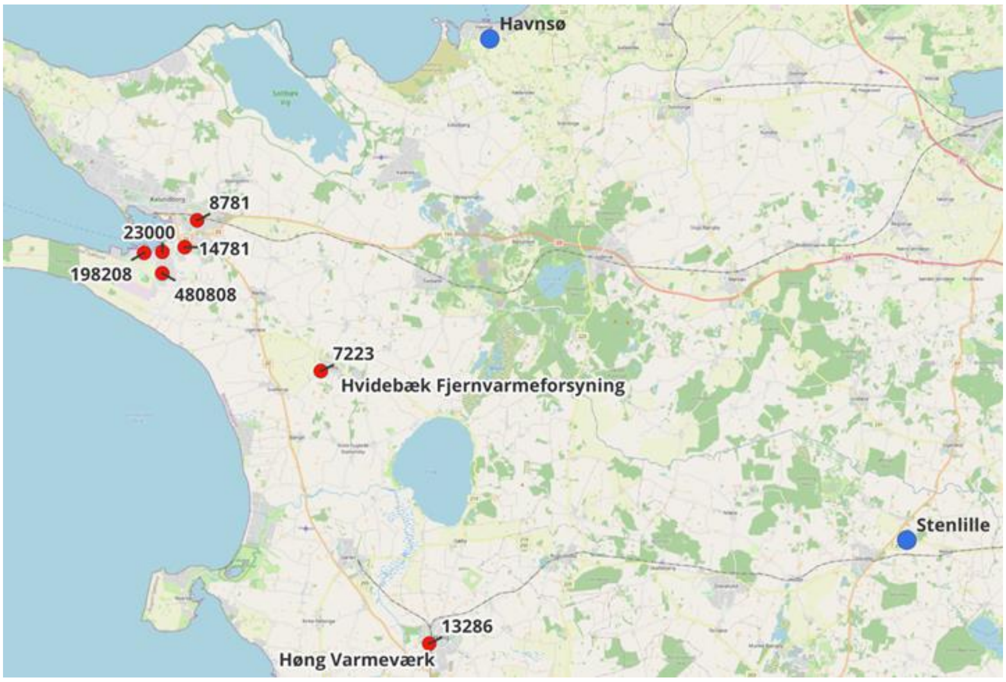


Figure 4-2 Overview of CO_2 emitters in Northwest Zealand. Emitters are presented by CO_2 tons emission (TPA)

Figure 4-3 Overview of identified CO_2 emitters within Kalundborg. Emitters are presented by CO_2 emission in TPA. Locations are not aligned with actual coordinates of emission points on each site.

4.3 CO_2 sources outside Northwest Zealand

In agreement with the project stakeholders further CO_2 sources are identified relevant to consider in a Northwest Zealand CO_2 infrastructure.

- **Copenhagen Hub:** Volumes in the order of 3 MTPA [8] from the larger Copenhagen area is identified. In agreement with the project stakeholders, the Northwest Zealand CO_2 infrastructure must take these volumes into account in the concept development and design. The pipeline system shall be designed with a capacity accommodating peak production hours for the Copenhagen Hub facilities, hence the design volumes of 4 MTPA are defined in dialog with study stakeholders. The infrastructure in Northwest Zealand has to enable transport of these volumes from Stenlille to Kalundborg, alternatively to Havnsø with and extension to Kalundborg. The CO_2 volumes are 90% biogenic and 10% fossil according to [9].
- **Shipping import:** The envisioned CO_2 infrastructure in Northwest Zealand is also to take into account potential imported CO_2 via shipping for permanent storage at Havnsø. These volumes are difficult to estimate at this point in time, hence capacity requirements for imported CO_2 are agreed upon with the project stakeholders to handle import of 4-7 MTPA LCO_2. Whether the imported volumes will be biogenic or fossil, is at current stage unknown. The CO_2 volumes are assumed 50% biogenic and 50% fossil in agreement with the project stakeholders.

4.4 Mapping of CO_2 Consumers

A CO_2 value chain in North Zealand is foreseen to mainly support permanent storage (CCS) to reduce national emissions. Still, CO_2 also has potential as a valuable resource, where it can be utilized in different industrial processes (CCUS). The potential CO_2 consumers in the Northwest Zealand area are mapped for a possible integration with a CO_2 pipeline infrastructure.

4.4.1 Potential consumers

In the consortium PtX Cluster Zealand there is one consumer of CO_2 with a concept that can be implemented at the emitter location. This is the company ALGIECEL ApS. The concept needs to be matured further to confirm the perspectives.

ALGIECEL has developed a microalgae PhotoBioReactor (PBR), which captures CO_2 emissions and transform it using LED light via photo synthesis into a microalgae biomass. This biomass can then be further separated into defatted biomass and biooil. ALGIECEL´s primary target markets for the application of biomass and bio-oil are aquaculture feed and human food supplement. In both markets, ALGIECEL´s products substitute alternatives with higher environmental impacts such as fish oil or fishmeal. ALGIECEL estimates that a medium-sized Danish biogas plant will require 30 ALGIECEL PBRs, which will then solve its CO_2 problem. [10] To produce 1 ton biomass, 1.8 ton CO_2 is consumed. The target is to fixate 1 ton of CO_2 per PBR per day. [11]

For Algiecel it is expected to have a requirement for food grade CO_2 as the end products are aquaculture feed and human food supply. ALGIECEL targets biogas plants as their main market area. With the requirement to CO_2 quality this concept may not be feasible from an economic perspective for larger CO_2 emitters or emitters that can be clustered in a CO_2 hub when comparing to CO_2 storage sub-surface.

A huge demand can potentially also come from the production of synthetic fuels for aviation, shipping or other e-fuels, or in the current refining process as the renewable energy directive has a minimum requirement of 42% hydrogen consumption in industry should be green by 2030 going to 60% in 2035. The potential use of carbon or CO_2 for PtX purposes will be examined in greater detail in section 6.

4.5 Storage

In this feasibility study the captured CO_2 gas is considered to be transported for permanent storage at Stenlille and Havnsø, and/or import/exported via ship. The CO_2 storage onshore and nearshore is in an early phase, and currently the Danish Energy Agency, DEA, is performing an environmental assessment of the proposed Executive Order covering licensing of storage of up to 0.1 MT CO_2 for research and development or pilot project. It is expected that the final round of public hearing will take place mid-2023 [12].

4.5.1 Stenlille storage

The Stenlille gas storage facility is a facility for natural gas, and from a political agreement, "Rammevilkår for CO_2-lagring i Danmark", it is decided to use Stenlille as a pilot project in order to increase the knowledge regarding CCS and increase the development of CO_2 storage in Denmark. [13]. The operational parameters informed by Gas Storage Denmark:

- Capacity: 10 Mt CO_2 [14]
- Injection pressure: The expected injection pressure is expected to be 100-120 bara. [15]
- Flowrate: The expected flowrate is 0.4 MTPA, which maybe increased to 0.5 MTPA.

4.5.2 Havnsø storage

The Havnsø structure is a potential CO_2 storage reservoir, located approximately 15 km northeast of Kalundborg and 30 km northwest from the Stenlille structure. In 2020 GEUS performed an estimation of the storage capacity based on the available data. The storage capacity is estimated for the probability of exceedance (P) of 90, 50 and 10 percentage to account for the uncertainties in the available data [16]:

- P90 – 204 Mt CO_2
- P50 – 294 Mt CO_2
- P10 – 423 Mt CO_2

During 2022 and 2023 GEUS is conducting further seismic surveys to provide a better estimation of the potential capacity. [17].

4.6 Relevant existing infrastructure

The infrastructure relevant for establishing a CO_2 infrastructure in the Northwest Zealand area is identified to aid an optimal concept development, utilizing potential synergies and for identifying potential existing pipelines for CO_2 conversion existing route corridors.

The existing natural gas distribution grid is identified in 4.6.1 and district heating network in 4.6.2.

Other relevant infrastructure in relation to integration of future PtX facilities will be examined in detail such as water and electricity in section 6.

4.6.1 Natural gas distribution grid

Kalundborg area is connected to Stenlille gas storage facility with a gas pipeline. The gas pipeline route from Stenlille gas storage facility is south of Stenlille and Dianalund to a MR station south of Ruds-Vedby where the line splits into line to Gørlev to the West and Kalundborg to the northwest. East of the lake Tissø there is a split in a line to Kalundborg in the northwest and Jyderup in the northeast. The line towards Kalundborg is routed just north of the lake Tissø. Reference is made to Figure 4-4.

The natural gas distribution grid is operated by Evida. Converting the natural gas pipeline between Kalundborg to Stenlille will cut of the natural gas supply for the cities Dianalund, Ruds-Vedby, Gørlev and Kalundborg as well as the option to utilize bio natural gas from Kalundborg in the distribution grid, hence is not considered feasible.

The pipeline route is relevant to consider when routing of a new CO_2 pipeline between Kalundborg and Stenlille as there are areas with environmental restrictions.

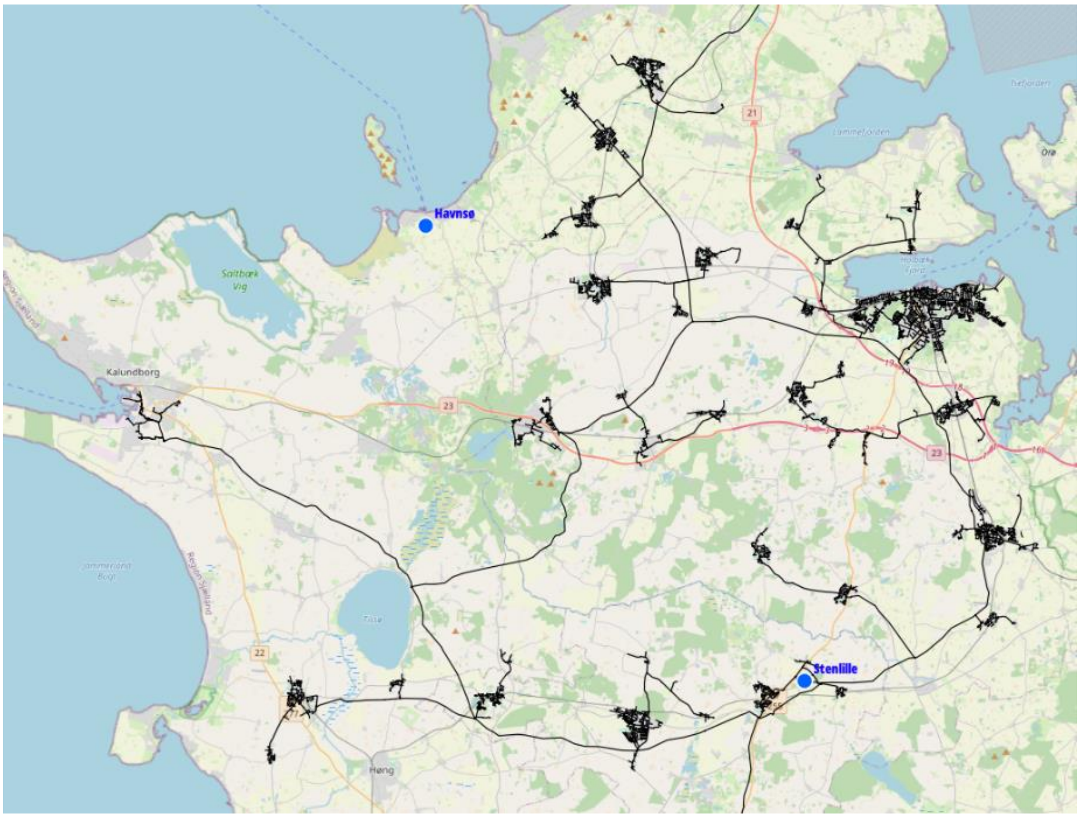


Figure 4-4 Existing natural gas pipeline grid in NW Zealand [18]

4.6.2 District heating network

The process of pressurizing CO_2 for transportation and injection will create heat which can be utilized in a district heating network. Following conclusions are made from dialog with the industry:

- in Kalundborg there is district heating grid with Asnæsværket as the main heat contributor.
- in Stenlille and neighbour-city Dianalund there is no district heating network, however in both cities there is an ongoing dialogue about a connection to Sorø district heating network.
- there is no existing infrastructure setup and agreements for utilizing compressor heat in the district heating network at the Stenlille storage site which can be utilized for this CO_2 project.

4.6.3 Harbour facilities and truck terminal

Harbour facilities and truck terminal are identified in Kalundborg at Asnæsværket premises. The harbour has a depth of 15 m and considered as a viable port for export and/or import of CO_2 [19], also considering vessel size larger than the 7500m^3 first generation Northern Lights. Larger ship sizes will likely be required for the Medium and High design cases of section 5 (case 3B and 3C) considered for the Havnsø reservoir.

Figure 4-5 The Asnæsværket harbour in Kalundborg [19]

4.7 CO_2 properties and quality requirements

4.7.1 Properties of pure CO_2

CO_2 is a non-polar chemical compound composed of two oxygen atoms covalently bonded to a single carbon atom (O=C=O). The molecule has a linear shape and zero dipole moment. At ambient pressure and temperature pure CO_2 appears colorless, and at low concentration an odorless, gas. CO_2 occurs naturally in the earth's atmosphere at a concentration of typically 0.040% by volume and is naturally dissolved in the oceans. High purity CO_2 also exists in geological formations. Further reference is made to DNV-RP-F104, section 2 [20].

4.7.2 Quality requirements for CO_2 stream

A CO_2 stream is a stream that primarily consist of CO_2 but also other chemical components. Depending on the volume of these other components the CO_2 stream may vary from the physical properties of pure CO_2 and will have implications on both pipeline design and operation. The acceptable amount of other chemical components relates to techno-economic optimization not limited to a pipeline but also including the facilities at the pipeline upstream and downstream battery limits.

A techno-economic optimization will evaluate the cost-benefit of a lenient CO_2 quality specification with less purification, with the cost of a more challenging environment for CO_2 infrastructure and storage. A strict CO_2 quality specification will increase the need for purification, but with the positive outcome that the more common materials can be used as well as the integrity of the wells will not be compromised.

It is acknowledged that the composition of CO_2 captured from the various sources listed in Table 4-5 may vary in terms of type and level of impurities. It is foreseen that this will also depend on the selected capture process for each emitter.

The requirements to CO_2 purification (removal of impurities) need consideration, also when co-mingling CO_2 from different emitters into a transport value chain. For transport concepts involving transport of liquefied CO_2 (LCO_2), e.g. ship or truck, it is foreseen that the liquid CO_2 will be 99.X% CO_2, given by the nature of the liquefaction process. For pipeline transport, higher levels of non-condensable components and other impurities may be generally accepted from an operability perspective.

One of the most recent CO_2 storage projects is the Northern Lights project, where the quality specification is presented in Table 4-5.

Table 4-5 Northern Light CO_2 qualification specification for impurities in the CO_2 stream [21]

Component, impurities	Concentration, ppm (mol)
Water (H2O)	≤ 30
Oxygen (O2)	≤ 10
Sulphur oxides (SOx)	≤ 10
Nitric oxide/Nitrogen dioxide (NOx)	≤ 10
Hydrogen sulphide (H_2S)	≤ 9
Carbon monoxide (CO)	≤ 100
Amine	≤ 10
Ammonia (NH3)	≤ 10
Hydrogen (H2)	≤ 50
Formaldehyde	≤ 20
Acetaldehyde	≤ 20
Mercury (Hg)	≤ 0.03
Cadmium (Cd), Thallium, (TI)	Sum ≤ 0.03

The CO_2 quality requirements for Stenlille storage facility will follow the Northern Lights specification. Gas Storage Denmark is although investigating the possibility to deviate from this quality standard. The Havnsø storage site is not evaluated with regards to CO_2 quality requirements due to the immature state of the storage site

The CO_2 quality requirements for this project should be evaluated based on the actual emitters, storage facilities and infrastructure. However, it should be noted that the Northern Light project has been evaluated as feasible and it may end up setting the industry standard for CO_2 quality requirements for geological storage of CO_2.

For the purpose of investigating scenarios for infrastructure for transport of CO_2, it is in this feasibility study assumed that each emitter would deliver CO_2 to the infrastructure according to the Northern Light specification.

5 CO_2 PIPELINE INFRASTRUCTURE

5.1 General

It is the intention of this report to reflect possible alternative options for transporting CO_2 between Kalundborg and the permanent storage facilities at Stenlille and Havnsø, also taking into consideration possible volumes of CO_2 arriving from East Zealand and volumes arriving by ship at Kalundborg. It should be noted that for each of the transport cases considered in this report, only selected functions are applicable for each cases. Figure 5-1 provides an overview of all concept options covered in this report. Note that schematics in grey colour is only included to illustrate the larger picture, including the reference case for ship export/import and inclusion of potential CO_2 volumes transported by truck either from inside Kalundborg area or from outside. Hence, Figure 5-1 is mainly intended for illustration.

On a high level the following main pipeline transport concepts are considered:

- CO_2 pipeline transport system from Kalundborg to Stenlille, enabling transport of CO_2 from emitters within the Kalundborg area for permanent storage at Stenlille. The pipeline concept is foreseen to include a low pressure CO_2 gas gathering network inside the Kalundborg area to a location where the CO_2 can safely be compressed and transported in a dense phase pipeline to Stenlille. The concept is to be designed in terms of transport capacity to also accommodate "reverse flow" of CO_2 arriving Stenlille from East Zealand (e.g. Copenhagen area) to Kalundborg for either ship export or through alternative dense phase pipeline to Havnsø.
- CO_2 pipeline system from Kalundborg to Havnsø, enabling transport of CO_2 from emitters locally in Kalundborg, CO_2 arriving from East through the Kalundborg-Stenlille pipeline, import by ship or from local emitters by truck to the Kalundborg area. The pipeline concept is intended to be uni-directional from Kalundborg to Havnsø, and designed to accommodate larger CO_2 volumes imported by ship that is foreseen required for development of the Havnsø storage.
- CO_2 pipeline system connecting Stenlille to Havnsø, allowing for direct routing of CO_2 arriving at Stenlille through a potential pipeline form East Zealand (e.g. Copenhagen area).

The concept description intends to include a minimum of specifications for utility functions required to conditioning the CO_2 to required state throughout the value chain, considering transitions between gas phase, dense phase and liquid phase for ship transport.

To visualize what technical installations are required and to enable CAPEX/OPEX assessments, the different pipeline transport concepts are described by the required functions provided in Table 5-1 and the premises listed in section 5.3. It should be acknowledged that on the current concept stage several premises are based on assumptions that will require justification and detailing in future design stages. Section 5.4 provides a minimum description at concept level of the facilities and functions required to enable the pipeline transport concepts with corresponding CAPEX estimates in Section 5.5. A summary and comparison of each pipeline transport concept is provided in Table 5-1.

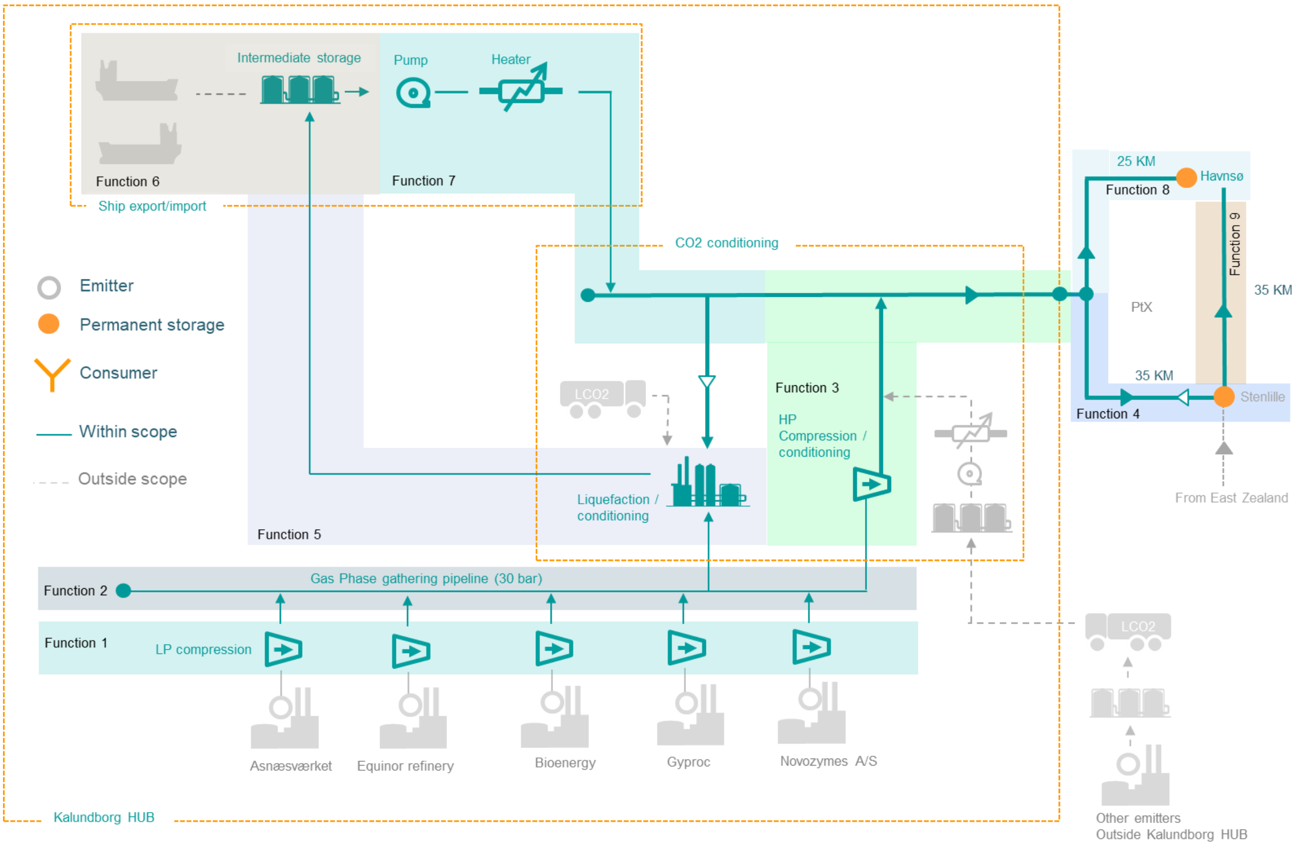


Figure 5-1 Concept layout and definition of functions

5.2 Functions

The transport concept is divided in the functions shown in Figure 5-1 and described in Table 5-1. Equipment sizing and corresponding CAPEX/OPEX estimates per function are provided for the selected concept design cases listed in Table 5-3 and described in 5.4.

Table 5-1 Functions - description

Function	Description
Function 1	Compressors at Kalundborg emitters, compressing CO_2 from 2 bara outlet pressure from capturing plant to 30 bara for gas phase CO_2 gathering network in the Kalundborg area
Function 2	CO_2 gas phase gathering pipeline (2km) – within Kalundborg HUB
Function 3	Compression from 20 - 140 bara within Kalundborg HUB for dense phase pipeline transport either to Stenlille (Function 4) or Havnsø (Function 8)
Function 3b	Boosting (pumping) CO_2 in dense phase at Stenlille - CO_2 from East Zealand; assuming boosting (pumping) required to raise pressure from assumed arriving pressure Stenlille of 100 bara
Function 4	Dense phase transport pipeline - Kalundborg to Stenlille; including estimated number of major road crossings (requiring HDD), metering stations and pigging facilities
Function 4b	Dense phase transport pipeline - Stenlille to Kalundborg - Import from Zealand East. This function is the same as Function 4, except for reverse flow direction. Function includes estimated number of major road crossings (requiring HDD), metering stations and pigging facilities
Function 5	Liquefaction and conditioning (composition control) of CO_2 from Kalundborg HUB for intermediate storage and ship export – included in reference Case 1A
Function 6	Intermediate storage of Liquid CO_2 - Kalundborg for ship export (limited to 1 MTPA) – included in reference Case 1A
Function 6b	Intermediate storage of Liquid CO_2 – Kalundborg – included in the cases for larger import volumes for transport to Havnsø
Function 7	Boosting and heating liquid CO_2 arriving at Kalundborg by ship - to dense phase (ambient temperature) pipeline transport conditions
Function 8a	Dense phase transport pipeline - Kalundborg to Havnsø – system capacity for Low case; including estimated number of major road crossings (requiring HDD), metering stations and pigging facilities
Function 8b	Dense phase transport pipeline - Kalundborg to Havnsø – system capacity for Medium case; including estimated number of major road crossings (requiring HDD), metering stations and pigging facilities
Function 8c	Dense phase transport pipeline - Kalundborg to Havnsø – system capacity for High case; including estimated number of major road crossings (requiring HDD), metering stations and pigging facilities
Function 9	Dense phase transport pipeline - Stenlille to Havnsø – alternative pipeline to handle CO_2 from East Zealand to Havnsø; including estimated number of major road crossings (requiring HDD), metering stations and pigging facilities

5.3 Design premises

The pipeline concept is based on the following design premises:

- Moderate elevation differences for all pipeline routes within North Zealand
- Transport pipelines to be designed for dense phase
- Steel line pipe with no internal flow coating, internal roughness default 50 micrometre
- No intermediate pump stations for dense phase pipelines; not required for the moderate pipeline lengths
- Metering station at export and arrival end of all pipelines
- The pipeline system design shall allow operation of PIG's.
- Major road crossings or environmentally sensitive areas requiring horizontal directional drilling (HDD) based on pipeline route
- Ship size – assumed 7 500 m^3 (Current Northern Lights ship size) for volumes up till 1 MTPA and 30 000 m^3 for volumes larger than 1 MTPA – used as basis for estimating required capacity of intermediate LCO_2 storage in Kalundborg. Intermediate storage in Kalundborg for either import or export assumed 1.2 x ship capacity
- CO_2 imported by ship to Kalundborg is in liquid phase
- A dense phase pipeline can reach Kalundborg to a distance within 2-3 km reach of Kalundborg port, considering potential concerns with dense phase pipelines in populated areas. This premise is also applicable to ship import and location of transition between LCO_2 (ship condition) and dense phase pipeline transport, also considering availability for seawater heating medium.
- Each emitter shall ensure CO_2 specification compliant with value chain specification.

5.4 Basis for CAPEX/OPEX estimates

5.4.1 Summary

Input to CAPEX/OPEX estimates are listed in Table 5-2, see subsequent sections for further details.

Table 5-2 Basis for CAPEX/OPEX estimates

Parameter	Value	Note
Pipeline (MEUR / km)	-	Based on pipeline statistic, onshore Europe, see section 5.4.2
Compressors (MEUR / MW)	-	Estimated based on onshore gas compressor statistics, see 5.4.3
Electric energy cost (MEUR / GWh) – input OPEX	0.1	Expected to be in high range, see section 5.4.5
Capital cost (annual % of CAPEX) – input OPEX	5	Assumed, see section 5.4.6
Operation & Maintenance cost (annual % of CAPEX) – input OPEX	6	Assumed, see section 5.4.7
CO_2 metering station CAPEX per unit (MEUR) – input CAPEX	1	High level estimate for complete metering station, see section 5.4.8
Pigging facilities CAPEX per unit (MEUR)	1	High level estimate for complete PLR, see section 5.4.9
Liquefaction plant CAPEX (MEUR / MTPA) – input CAPEX	37.5	Literature data with markup factor of 1.5 [22], see section 5.4.11
Intermediate LCO_2 storage (EUR / m^3) – input CAPEX	3000	Literature data [22], see section 5.4.10
Terminal for offloading/loading 1)	-	Assume use of existing facilities, see section 5.4.13.
Leak detection system	-	Currently limited to low pressure alarms and mass balance, see section 5.4.12.

1) A new dedicated terminal in Kalundborg for handling of volumes larger than 3 MTPA will likely be required; this is currently not included in the CAPEX estimates.

5.4.2 Pipeline

Pipeline CAPEX is based on statistical cost figures for onshore pipeline projects in Europe, including right of way, permitting, design, materials, installation and pre-commissioning. Materials include line pipe and pipeline components such as inline valve stations. Acknowledging that the references pipeline CAPEX statistics is predominantly for onshore Natural gas pipelines, an upper bound on the statistics is applied in terms of CAPEX per kilometer length. It is also acknowledged that the CO_2 pipelines covered in this concept study is relatively short, and likely shorter than an average pipeline length represented by the applied CAPEX statistics. Several of the pipeline costs are fixed per pipeline, independent of length, e.g. design, mobilisation for installation and pre-commissioning, hence using upper bound CAPEX statistics is justifiable. It is also acknowledged that the CO_2 pipelines included in the concept may be first-of-kind dense phase CO_2 pipeline in Denmark, which may justify higher cost associated with the permitting process. Other than selection of upper bound CAPEX values, no additional contingency is added to the CAPEX estimates.

5.4.3 Compressors

CAPEX for CO_2 compressors are estimated based on statistics for onshore natural gas compressors per MW installed. The CAPEX estimates are limited to the cost of compressor, excluding other costs associated with permitting, design, ground work and installation.

5.4.4 Pumps

CAPEX for CO_2 pumps are estimated based on estimate. The CAPEX estimates are limited to the cost of pump per MW installed, excluding other costs associated with permitting, design, ground work and installation.

5.4.5 Electric energy cost

It is assumed that all compressors and pumps will be based on electric drive. Electric energy cost used for input to OPEX is likely to vary by seasons and will also depend on long term contracts. A fixed tariff in EUR / GWh is used for input to OPEX estimate. Energy consumption is based on Installed compressor and pump design capacities and duty.

5.4.6 Capital cost

OPEX associated with CAPEX is assumed a fixed percentage of CAPEX per annum.

5.4.7 Operation & Maintenance cost

Operation and maintenance cost will likely vary across different types of equipment, i.e. compressors, pumps, metering stations, pipelines etc. For the current high-level estimate, OPEX is assumed a fixed percentage of total CAPEX per annum, all equipment included.

5.4.8 Metering station

For each pipeline, metering station is included at both export and arrival end for pipeline operability and leak detection. CAPEX estimates are estimated for complete metering station, calibrated and installed.

5.4.9 Pigging stations

Pigging stations are included for all dense phase pipelines to enable internal inspection.

5.4.10 Intermediate LCO_2 storage – Kalundborg

For the case of CO_2 export from Kalundborg (Case 1A), intermediate LCO_2 storage volume capacity in Kalundborg harbour of 9400 m^3, corresponding to 1.2 times first generation Northern Lights CO_2 carrier (7500 m^3), is assumed. For an export volume of 1 MTPA, two ship arrivals per week is foreseen. At the initial target export of 0.5 MTPA, a ship arrival frequency of once per week is foreseen.

For the import case, larger vessels are required to obtain a reasonable ship frequency. Ship size of 30 000 m^3 is assumed in line with expected CO_2 ship developments. Intermediate storage capacity in Kalundborg of 36 000 m^3 is assumed, corresponding to 1.2 times ship capacity. For the larger storage volumes, a floating storage may be an attractive alternative to onshore storage, considering land use, flexibility and reduced risk of stranded assets. It is possible that the larger ships will operate at lower pressure and temperature compared to the northern lights “medium” pressure/temperature. Other than a slight increase in conditioning cost for pipeline transfer (heating and pumping), the implications for the onshore pipeline concept is foreseen to be moderate.

For the intermediate storage, CAPEX associated with groundwork prior to erection of the storage system is not included. No additional contingency is included. CAPEX for the onshore tank system is estimated to 3000 EUR/m^3 from literature data[1]. It should be acknowledged that these estimates are associated with uncertainty.

5.4.11 Liquefaction plant

CAPEX and OPEX estimate for the liquefaction plant conditioning the CO_2 to medium pressure conditions (approx. -25°C), is based on available literature data [22]. Even though not explicitly stated, it is expected that ground work is not included in the published data. The CAPEX is based on a standard CO_2 liquefaction cycle, consisting of a CO_2 compression train, pre-cooler, liquefier and purge flash, recirculation flash and compressor and ammonia refrigeration cycle. CAPEX associated with groundwork prior to erection of the liquefaction plant is not included. No additional contingency is included.

5.4.12 Leak detection system

Minimum leak detection system is based on low-low pressure alarms and mass balance systems in addition to gas detectors for above ground equipment and pipeline inline valve stations. Hence, a minimum leak detection can be facilitated with the equipment already included for the CAPEX/OPEX estimates for the pipeline. The requirements for pipeline distributed leak detections system (e.g. fibre optics) should be considered for later design stages and may add significant CAPEX to the pipeline.

5.4.13 Terminal facilities

For the current CAPEX estimates it is assumed that existing terminal facilities can be used. CAPEX for modification of existing Kalundborg terminal to accommodate CO_2 load transfer is not included.

It is noted that a new dedicated terminal facility is foreseen required for export/import volumes larger than 1 MTPA. Additional CAPEX for new terminal facility (pier) is not included in the current estimates.

For the 4 MTPA import case (medium), three ship arrivals per week is foreseen. For the 7 MTPA import case (high), five ship arrivals per week is foreseen. The feasibility of these cases needs to be confirmed, considering current/future terminal ship traffic to Kalundborg, pilot requirements etc. No terminal fee is included in the OPEX estimates.

5.4.14 Cooling/heating

It is assumed that seawater is available to meet the cooling capacity for the liquefaction and conditioning facilities in Kalundborg. No CAPEX/OPEX included to accommodate required cooling/heating capacity. Potential limitations to discharge of warm/cold water should be addressed in later design stages. For liquefaction, expected cooling capacity is expected to be in the range of 40 MW / MTPA [22].

[1] Jan Kjärstad et.al., Ship transport - A low cost and low risk CO_2 transport option in the Nordic countries, International Journal of Greenhouse Gas Control 54 (2016) 168-184

5.5 CAPEX per function

Estimated CAPEX per function is summarized in Table 5-3, ref. basis in section 5.4.

Table 5-3 Functions - CAPEX

Function	CAPEX (MEUR)	Note
Function 1	12	Compressors at Kalundborg emitter(s), compressing CO_2 from 2 bara outlet pressure from capturing plant to 30 bara for gas phase CO_2 gathering network in the Kalundborg area; CAPEX estimate for 1 MTPA. It should be noted that the CAPEX for compression as function of MW is based on a non-linear model, taking credit for scaling effects
Function 2	4	CO_2 gas phase gathering pipeline (2km) – within Kalundborg HUB
Function 3	8	Compression from 20 - 140 bara within Kalundborg HUB for dense phase transport either to Stenlille (Function 4) or Havnsø (Function 8); CAPEX estimate for 1 MTPA. It should be noted that the CAPEX for compression as function of MW is based on a non-linear model, taking credit for scaling effects
Function 3b	0.6	Boosting (pumping) CO_2 in dense phase at Stenlille - CO_2 from East Zealand; assuming boosting (pumping) required to raise pressure from assumed arriving pressure Stenlille of 100 bara; Pump CAPEX estimate for 4 MTPA
Function 4	49	Dense phase transport pipeline - Kalundborg to Stenlille; designed to 4MTPA
Function 4b	49	Dense phase transport pipeline - Stenlille to Kalundborg - Import from Zealand East. This function is the same as Function 4, except for reverse flow direction and in principal identical pipeline
Function 5	38	Liquefaction and conditioning (composition control) of CO_2 from Kalundborg HUB for intermediate storage and ship export – included in reference Case 1A; CAPEX/OPEX estimate for 1.0 MTPA
Function 6	28	Intermediate storage of Liquid CO_2 - Kalundborg for ship export (limited to 1 MTPA) – included in reference Case 1A; CAPEX/OPEX aligned to 7500 m^3 vessel size (Northern Lights)
Function 6b	108	Intermediate storage of Liquid CO_2 – Kalundborg – included in the cases for larger import volumes for transport to Havnsø; CAPEX/OPEX aligned to 30 000 m^3 vessel size
Function 7	10	Boosting and heating liquid CO_2 arriving at Kalundborg by ship - to dense phase (ambient temperature) pipeline transport conditions; CAPEX for High case pump capacity (7 MTPA ship import)
Function 8a	39	Dense phase transport pipeline - Kalundborg to Havnsø – pipeline capacity for Low case
Function 8b	42	Dense phase transport pipeline - Kalundborg to Havnsø – pipeline capacity for Medium case
Function 8c	45	Dense phase transport pipeline - Kalundborg to Havnsø – pipeline capacity for High case
Function 9	49	Dense phase transport pipeline - Stenlille to Havnsø – alternative pipeline to handle CO_2 from East Zealand to Havnsø (4 MTPA)

5.6 Comparison of pipeline transport concepts verses reference case

CAPEX/OPEX estimates provided shall be taken as a high-level estimate, considering the current project maturity and the limited industry experience with facilities for handling CO_2 in context of CCS.

A summary of a high-level CAPEX/OPEX estimate for the functions included in the selected concept design cases are summarized in Table 5-3. Input to the CAPEX/OPEX estimates is provided in section 5.4. Based on the estimated annual OPEX, relative transport cost (EUR/T) is calculated, see Table 5-4.

The reference Case 1A is included to enable comparison of CAPEX/OPEX; a ship export concept for the CO_2 volumes within the Kalundborg HUB. See section 0 for further details.

Case 2A, represents transport total of 1 MTPA from Kalundborg HUB to Stenlille, assuming the total volume is gathered from multiple emitters through a low-pressure gas phase network within the Kalundborg HUB and compressed for dense phase transport to Stenlille. It should be acknowledged that the pipeline CAPEX is based on a pipeline sized for Case 2B. See section 5.8 for further details.

Case 2B, represents transport of CO_2 volumes arriving from East Zealand to Kalundborg HUB, for further transport to Havnsø or export via shipping. See section 5.8 for further details.

Case 3A,B,C represents Low, Medium and High case pipeline transport from Kalundborg to Havnsø. For the Case3A, Low case, the transport volumes originate from Kalundborg HUB and East Zealand (through pipeline from Stenlille to Kalundborg). Case 3B and 3C includes additional 4 and 7 MTPA volumes imported by ship to Kalundborg. See section 5.9 for further details.

Case 4A is included as an alternative to Case 2A, with direct pipeline routing from Stenlille to Kalundborg for CO_2 volumes arriving at Stenlille from East Zealand. See section 5.10 for further details.

When comparing the different cases on CAPEX, OPEX and relative transport cost, it should be acknowledged that more or less of the value chain is included, depending on the transport functions required. E.g. for Case 2A, the starting point is CO_2 at low pressure, where the CO_2 is compressed to dense phase for pipeline transport. For comparison, Case 2B assumes CO_2 arriving from East Zealand to Stenlille at 100 bara, hence the power required to boost (by pumping) the pressure from 100 to 140 bara is significantly less at the same time the transfer rate is four times higher than Case 2A. For the reference case 1A with liquefaction of CO_2 from capture plant in Kalundborg for export, significant energy is required for liquefaction. For comparison, Case 3B,C with large import volumes of liquid CO_2, the liquefaction cost is taken outside the current part of the value chain.

Estimated electricity demand is included in Table 5-4. For the reference case, the electricity demand is governed by liquefaction. For the other cases the energy demand is governed by compression and liquid pumping. The available electric energy within the Kalundborg HUB may be an important driver for the feasibility of each concept.

Table 5-4 Summary CAPEX/OPEX for selected cases

Design case	Case description		CO_2 handled (MTPA)	CAPEX (MEUR)	OPEX (MEUR/y)	Transport cost (EUR/Ton)	Electricity demand (GWh/year)
1	A	**Reference case**; no pipelines; liquefaction, intermediate storage and shipping from Kalundborg; Functions [5,6]	0.5	47	12	24	66
2	A	Pipeline transport; compression Kalundborg to 140 bara; pipeline transport Kalundborg to Stenlille; Functions [1,2,3,4]	1	72	17	17	92
	B	Pipeline between Kalundborg and Stenlille; boosting at Stenlille from 100 – 140 bara; transport to Kalundborg; Functions [3B,4B]	4	49	5.4	1.5	6
3	A 1)	Pipeline between Kalundborg and Havnsø, Low case; 1 MTPA from Kalundborg; 4 MTPA from East Zealand; no ship import; Functions [1,2,3,3B,4B,8A]	5	112	22	4.3	98
	B 2)	Pipeline between Kalundborg and Havnsø, Medium case; 1 MTPA from Kalundborg; 4 MTPA from East Zealand; 4 MTPA ship import Functions [1,2,3,3B,4B,6B,7,8B]	9	225	34	2.4	115
	C 3)	Pipeline between Kalundborg and Havnsø; High case; 1 MTPA from Kalundborg; 4 MTPA from East Zealand; 7 MTPA ship import Functions [1,2,3,3B,4B,6B,7,8C]	12	229	34.5	1.9	128
4	A	Isolated pipeline from Stenlille to Havnsø to handle volumes transported by pipeline from East Zealand; boosting at Stenlille from 100 to140 bara; Functions [3B, 9]	4	49	5.4	1.4	6

1) 1 MTPA from Kalundborg + 4 MTPA from East Zealand (via Stenlille)

2) 1 MTPA from Kalundborg + 4 MTPA from East Zealand (via Stenlille) + 4 MTPA ship import to Kalundborg

3) 1 MTPA from Kalundborg + 4 MTPA from East Zealand (via Stenlille) + 7 MTPA ship import to Kalundborg

5.7 Reference concept – ship export

5.7.1 General

A reference case is established to enable assessing the alternative pipeline concepts. The concept design includes facilities for liquefaction and intermediate storage of 0.5 MTPA captured locally within the Kalundborg HUB, from one or more emitters.

5.7.2 Concept design

Concept design for the reference case is shown in Figure 5-2, limited to facilities for liquefaction and intermediate storage of CO_2 within the Kalundborg area. For the CAPEX/OPEX estimates, shipping part is excluded. The reference case is based on liquefaction and shipment of 0.5 MTPA. Shipping of 0.5 MTPA with a typical ship capacity of 7500 m^3 will require 1-2 ship arrivals per week. Intermediate storage is designed to 1.2 times ship capacity to provide some margin.

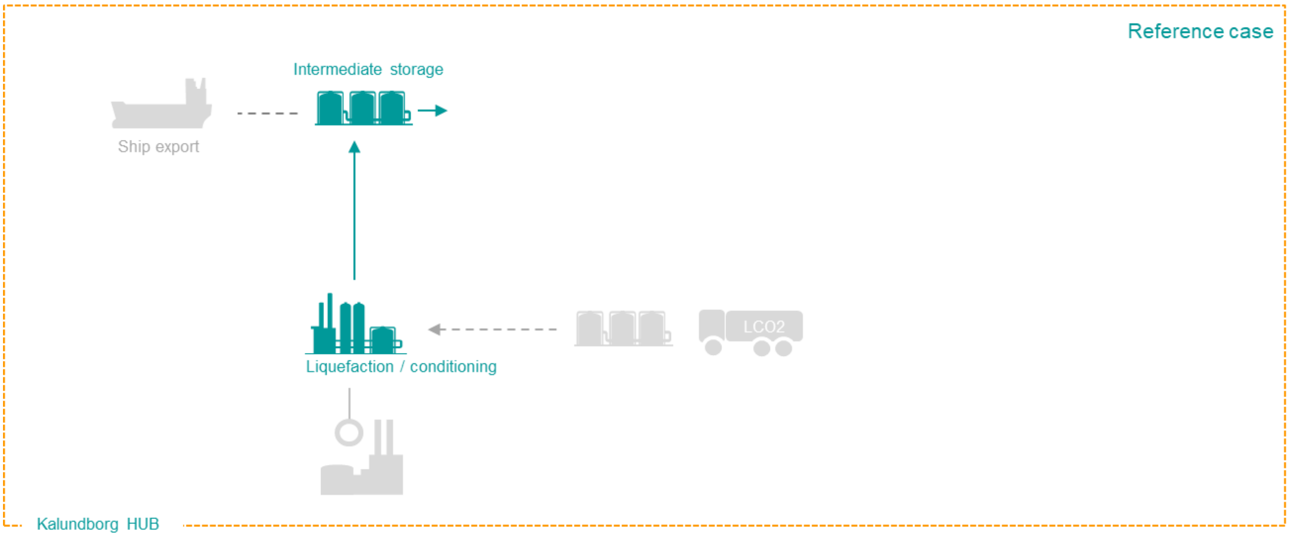


Figure 5-2 Reference case; ship export of Kalundborg volumes

5.7.3 CAPEX/OPEX estimate

CAPEX and OPEX estimates for the reference case is provided in table below. Levelized cost for liquefaction and intermediate storage is estimated to 23 EUR/Ton CO_2.

For this reference case it is assumed only one emitter and that the liquefaction plant and intermediate storage is directly associated with this emitter, hence the local low pressure gas gathering network with associated low pressure compressors is not included.

With regard to the intermediate storage, it shall be acknowledged that the storage volume is aligned with the ship volume, hence not directly proportional to the annual ship export rate. This is based on the assumption that the ship will be fully (not partial) loaded on each docking.

			MTPA	0.5	
			EUR/T	23.4	
Functions enabled in CAPEX/OPEX Estimate					
on/off			**CAPEX (MEUR)**	**OPEX (MEUR)**	**GWh/Y**
0	Function 1	Compressors at Kalundborg emitters, compressing CO2 from 2bara to 30 bara	0	0.0	0.0
0	Function 2	CO2 gas phase gathering pipeline - Kalundborg HUB	0	0.0	0.0
0	Function 3	Compression from 20 - 140 bar within Kalundborg HUB	0	0.0	0.0
0	Function 3B	Boosting (pumping) CO2 in dense phase at Stenlille - CO2 from East Zealand	0	0.0	0.0
0	Function 4	Dense phase transport pipeline - Kalundborg to Stenlille	0	0.0	0.0
0	Function 4B	Dense phase transport pipeline - Stenlille to Kalundborg - Import from Zealand East	0	0.0	0.0
1	Function 5	Liquefaction of CO2 from Kalundborg for intermediate storage and ship export	19	8.6	65.7
1	Function 6	Intermediate storage of Liquid CO2 - Kalundborg Export (limited to 1 MTPA)	28	3.1	0.0
0	Function 6B	Intermediate storage of Liquid CO2 - Kalundborg (for larger import volumes)	0	0.0	0.0
0	Function 7	Boosting and heating liquid CO2 arriving at Kalundborg by ship - to dense phase pipeline transport conditions	0	0.0	0.0
0	Function 8A	Dense phase transport pipeline - Kalundborg to Havnsø - Low case	0	0.0	0.0
0	Function 8B	Dense phase transport pipeline - Kalundborg to Havnsø - Medium case	0	0.0	0.0
0	Function 8C	Dense phase transport pipeline - Kalundborg to Havnsø - High case	0	0.0	0.0
0	Function 9	Dense phase transport pipeline - Stenlille to Havnsø	0	0.0	0.0
Total			**47**	**11.7**	**66**

Figure 5-3 Case 1A; reference case – ship export of Kalundborg volumes

5.8 Concept for CO_2 pipeline between Kalundborg and Stenlille

5.8.1 General

Conceptual design of a CO_2 pipeline between Kalundborg and Stenlille is based on the following functionalities:

A. capacity to transport 1 MTPA of CO_2 from Kalundborg HUB to Stenlille GSD

B. capacity to transport 4 MTPA of CO_2 arriving from Copenhagen HUB at Stenlille to Kalundborg HUB for further transport in pipeline to Havnsø or export via shipping; note this option is only relevant if a pipeline is built from Kalundborg to Havnsø or a shipping solution is arranged for in Kalundborg.

To meet the above functionalities, the pipeline concept shall allow for bi-directional flow, where the line sizing is based on the highest capacity represented by functionality B. Scope of concept design is limited to the pipeline system, i.e. excluding CO_2 backbone pipeline from East Zealand to Stenlille and liquefaction, intermediate storage and shipping within the Kalundborg HUB.

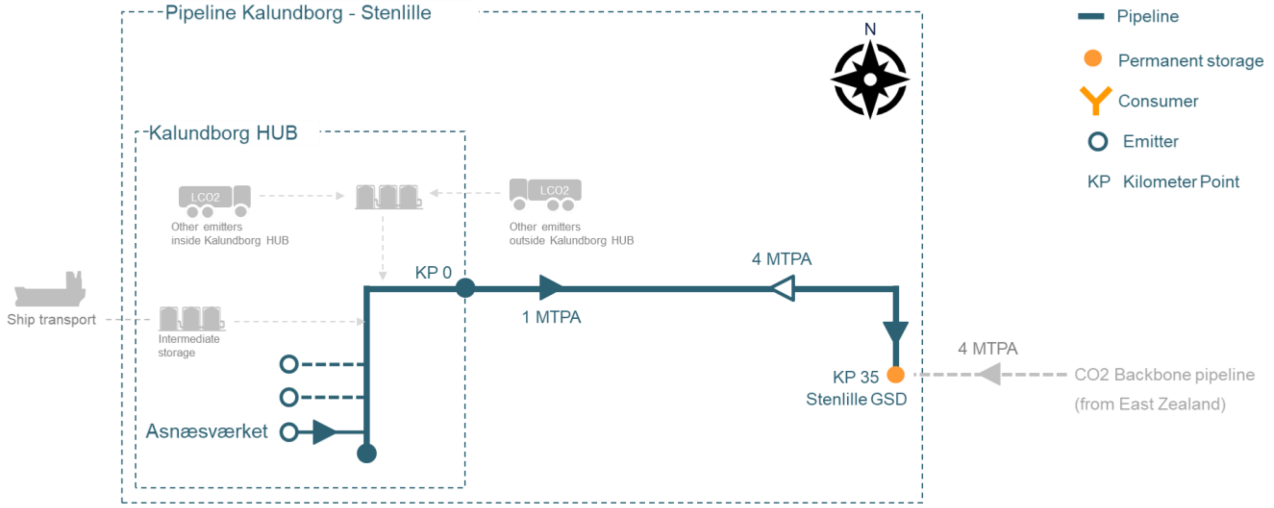


Figure 5-4 Conceptual design of CO_2 pipeline between Kalundborg and Stenlille (GSD)

5.8.2 Concept design

Design parameters for a dense phase pipeline between Kalundborg to Stenlille are listed in Table 5-5. Pipeline sizing is governed by the 4 MTPA case from Stenlille to Kalundborg, requiring an estimated pipeline size of 14". To accommodate 1 MTPA from Kalundborg to Stenlille, a 10" pipeline would be sufficient [2].

Table 5-5 Premises – Dense phase pipeline Kalundborg - Stenlille

Parameter	Kalundborg to Stenlille	Stenlille to Kalundborg
Pipeline system design pressure @ MSL (bara)	150	
Pipeline system MAOP @ MSL (bara)	145	
Pipeline system design temperature max/min (°C)	-29 / 35	
Transfer rate (MTPA)	1	4
Transfer rate (kg/s)	32	127
Pipeline inlet temperature (°C)	15 [2)]	15 [3)]
State of product (-)	Dense phase	Dense Phase
Minimum arrival pressure Stenlille (bara)	100 [5)]	n/a
Minimum arrival pressure Kalundborg (bara)	n/a	100
Burial, TOP (m)	1.2	1.2
Line pipe material (-)	API 5L X65	
Length of pipeline (km)	35 [4)]	
Product SG (1)	0.87 [6)]	0.87 [6)]
Selected pipeline size (inch) [7)]	10 [7)]	14 [7)]
External pipeline diameter (mm)	273.1	355.6
Wall thickness (mm) [8)]	12.7	15.9
Internal diameter (mm)	249.1	325.4
Friction pressure loss (bar)	6	25
Flow velocity (m/s)	0.75	1.8
Required pipeline inlet pressure (bara)	106	125

1) Based on expected arrival pressure at Stenlille (from Copenhagen HUB); booster pump at Stenlille may be required depending on arrival pressure for product from East Zealand at Stenlille
2) Assuming seawater available for cooling post compression Kalundborg, enabling cooling to specified inlet temperature
3) Assuming CO_2 from Copenhagen Backbone pipeline arriving Stenlille close to soil temperature at burial depth (approx. 8°C)
4) Length of pipeline based on envisioned route between Kalundborg & Stenlille in section 5.13.1.1.
5) Based on expected injection pressure at Stenlille in the range of 80 to 100 bara
6) For the line sizing, SG is conservatively based on maximum product temperature and minimum pressure (arrival end)
7) Based on available standard pipe sizes, 8", 10", 12", 14", 16", 18", 20", 24"
8) Conservatively based on location class 5; additional check for fracture arrest

[2] Selecting the 14" pipeline size to accommodate Function B, the flow velocity and corresponding friction pressure loss for the Function A will be marginal. Implicitly, the pipeline will be oversized for Function A.

5.8.3 CAPEX/OPEX estimate

CAPEX and OPEX estimates for Case 2A and 2B is provided in tables below. Levelized cost for liquefaction and intermediate storage is estimated to 17 and 1.4 EUR/T CO_2 for Case 2A and 2B respectively.

Case 2A reflects facilities for transport of 1 MTPA from Kalundborg to Stenlille, including gas gathering network and compression at Kalundborg. Case 2B reflects return of 4 MTPA from Stenlille to Kalundborg, only requiring boosting (pumping) at Stenlille from estimated 100 to 140 bara. The difference in cost per transferred volume (EUR/T) is mainly due to the higher compression cost at Kalundborg. It should be acknowledged that for case 2B, this the compression cost will already be taken in the value chain from Zealand East (Copenhagen).

Functions enabled in CAPEX/OPEX Estimate

			MTPA	1	
			EUR/T	17.2	
on/off			CAPEX (MEUR)	OPEX (MEUR)	GWh/Y
1	Function 1	Compressors at Kalundborg emitters, compressing CO2 from 2bara to 30 bara	12	7.4	61.3
1	Function 2	CO2 gas phase gathering pipeline - Kalundborg HUB	4	0.4	0.0
1	Function 3	Compression from 20 - 140 bar within Kalundborg HUB	8	3.9	30.7
0	Function 3B	Boosting (pumping) CO2 in dense phase at Stenlille - CO2 from East Zealand	0	0.0	0.0
1	Function 4	Dense phase transport pipeline - Kalundborg to Stenlille	49	5.4	0.0
0	Function 4B	Dense phase transport pipeline - Stenlille to Kalundborg - Import from Zealand East	0	0.0	0.0
0	Function 5	Liquefaction of CO2 from Kalundborg for intermediate storage and ship export	0	0.0	0.0
0	Function 6	Intermediate storage of Liquid CO2 - Kalundborg Export (limited to 1 MTPA)	0	0.0	0.0
0	Function 6B	Intermediate storage of Liquid CO2 - Kalundborg (for larger import volumes)	0	0.0	0.0
0	Function 7	Boosting and heating liquid CO2 arriving at Kalundborg by ship - to dense phase pipeline transport conditions	0	0.0	0.0
0	Function 8A	Dense phase transport pipeline - Kalundborg to Havnsø - Low case	0	0.0	0.0
0	Function 8B	Dense phase transport pipeline - Kalundborg to Havnsø - Medium case	0	0.0	0.0
0	Function 8C	Dense phase transport pipeline - Kalundborg to Havnsø - High case	0	0.0	0.0
0	Function 9	Dense phase transport pipeline - Stenlille to Havnsø	0	0.0	0.0
Total			**72**	**17.2**	**92**

Figure 5-5 Case 2A Pipeline transport; compression Kalundborg to 140 bara; 1 MTPA pipeline transport from Kalundborg to Stenlille; Functions [1,2,3,4]

Functions enabled in CAPEX/OPEX Estimate

			MTPA	4	
			EUR/T	1.4	
on/off			CAPEX (MEUR)	OPEX (MEUR)	GWh/Y
0	Function 1	Compressors at Kalundborg emitters, compressing CO2 from 2bara to 30 bara	0	0.0	0.0
0	Function 2	CO2 gas phase gathering pipeline - Kalundborg HUB	0	0.0	0.0
0	Function 3	Compression from 20 - 140 bar within Kalundborg HUB	0	0.0	0.0
1	Function 3B	Boosting (pumping) CO2 in dense phase at Stenlille - CO2 from East Zealand	1	0.1	5.6
0	Function 4	Dense phase transport pipeline - Kalundborg to Stenlille	0	0.0	0.0
1	Function 4B	Dense phase transport pipeline - Stenlille to Kalundborg - Import from Zealand East	49	5.4	0.0
0	Function 5	Liquefaction of CO2 from Kalundborg for intermediate storage and ship export	0	0.0	0.0
0	Function 6	Intermediate storage of Liquid CO2 - Kalundborg Export (limited to 1 MTPA)	0	0.0	0.0
0	Function 6B	Intermediate storage of Liquid CO2 - Kalundborg (for larger import volumes)	0	0.0	0.0
0	Function 7	Boosting and heating liquid CO2 arriving at Kalundborg by ship - to dense phase pipeline transport conditions	0	0.0	0.0
0	Function 8A	Dense phase transport pipeline - Kalundborg to Havnsø - Low case	0	0.0	0.0
0	Function 8B	Dense phase transport pipeline - Kalundborg to Havnsø - Medium case	0	0.0	0.0
0	Function 8C	Dense phase transport pipeline - Kalundborg to Havnsø - High case	0	0.0	0.0
0	Function 9	Dense phase transport pipeline - Stenlille to Havnsø	0	0.0	0.0
Total			**49**	**5.4**	**6**

Figure 5-6 Case 2B Pipeline between Stenlille and Kalundborg; boosting at Stenlille from 100 – 140 bara; 4 MTPA transport to Kalundborg; Functions [3B,4B]

5.9 Concept for CO_2 pipeline between Kalundborg and Havnsø

5.9.1 General

Base case concept design of a CO_2 pipeline from Kalundborg HUB to storage location in Havnsø is based the infrastructure illustrated in Figure 5-7. The pipeline is intended to handle a range in CO_2 flowrates routed through the Kalundborg HUB from:

- Local emitters within Kalundborg HUB (Q1)
- East Zealand (Q2)
- Ship import (Q3)
- Other emitters outside Kalundborg HUB by truck (Q4)

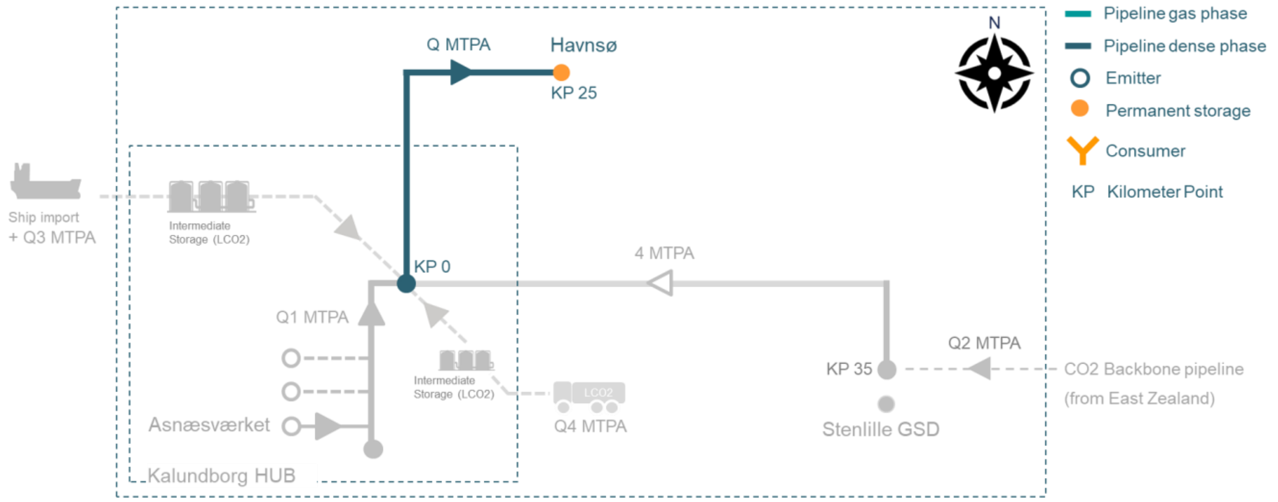


Figure 5-7 Pipeline Kalundborg to Havnsø

The pipeline sizing and corresponding CAPEX/OPEX estimates is based on transport capacities of Q=5 MTPA, 9 MTPA and 12 MPTPA, representing low, medium and high case respectively.

5.9.2 Concept design

Design parameters for a dense phase pipeline between Kalundborg and Havnsø are listed in Table 5-6 for the low, medium and high transport capacities.

Table 5-6 Premises – Dense phase pipeline Kalundborg – Havnsø

Parameter	**Low Case**	**Medium Case**	**High Case**
Pipeline system design pressure @ MSL (bara)	150		
Pipeline system MAOP @ MSL (bara)	145		
Pipeline system design temperature max/min (°C)	-29 / 35		
Soil temperature – top of pipe – annual average (°C)	8		
Transfer rate (MTPA)	5	9	12
Transfer rate (kg/s)	159	285	381
Pipeline inlet temperature (°C)	15 [2)]		
State of product (-)	Dense phase		
Minimum arrival pressure Havnsø (bara)	100 [5)]		
Burial, TOP (m)	1.2		
Line pipe material (-)	API 5L X65		
Length of pipeline (km)	25 [4)]		
Product SG (1)	0.87 [6)]		
Selected pipeline size (inch) [7)]	14	16	18
External pipeline diameter (mm)	355.6	406.4	457.2
Wall thickness (mm) [3)]	15.9	15.9	19.1
Internal diameter (mm)	323.8	374.6	419.0
Friction pressure loss (bar)	21	30	32
Flow velocity (m/s)	2.2	3.0	3.2
Required pipeline inlet pressure (bara)[8)]	122	133	133

1) Based on expected arrival pressure at Stenlille (from Copenhagen HUB); booster pump at Stenlille may be required depending on arrival pressure for product from East Zealand at Stenlille
2) Assuming seawater available for cooling post compression Kalundborg, enabling cooling to specified inlet temperature
3) Wall thickness based on Location class 5; additional check for fracture arrest
4) Length of pipeline based on route envisioned in section 5.13.1.2, with contingency of 20%.
5) Based on expected injection pressure at Havnsø in the range of 100 bara
6) For the line sizing, SG is conservatively based on maximum product temperature and minimum pressure (arrival end)
7) Based on available standard pipe sizes, 8”, 10”, 12”, 14”, 16”, 18”, 20”, 24”
8) Inlet pressure is based on hydraulic simulations, indicating what inlet pressure is required to accommodate the specified transfer rate (MTPA)

5.9.3 Case 3A - CAPEX/OPEX

CAPEX/OPEX estimate for case 3A is provided in table below. Levelized cost for CO_2 conditioning/compression/ pumping is estimated to 4.3 EUR/Ton CO_2.

			MTPA	5	
			EUR/T	4.3	
Functions enabled in CAPEX/OPEX Estimate					
on/off			**CAPEX (MEUR)**	**OPEX (MEUR)**	**GWh/Y**
1	Function 1	Compressors at Kalundborg emitters, compressing CO2 from 2bara to 30 bara	12	7.4	61.3
1	Function 2	CO2 gas phase gathering pipeline - Kalundborg HUB	4	0.4	0.0
1	Function 3	Compression from 20 - 140 bar within Kalundborg HUB	8	3.9	30.7
1	Function 3B	Boosting (pumping) CO2 in dense phase at Stenlille - CO2 from East Zealand	1	0.1	5.6
0	Function 4	Dense phase transport pipeline - Kalundborg to Stenlille	0	0.0	0.0
1	Function 4B	Dense phase transport pipeline - Stenlille to Kalundborg - Import from Zealand East	49	5.4	0.0
0	Function 5	Liquefaction of CO2 from Kalundborg for intermediate storage and ship export	0	0.0	0.0
0	Function 6	Intermediate storage of Liquid CO2 - Kalundborg Export (limited to 1 MTPA)	0	0.0	0.0
0	Function 6B	Intermediate storage of Liquid CO2 - Kalundborg (for larger import volumes)	0	0.0	0.0
0	Function 7	Boosting and heating liquid CO2 arriving at Kalundborg by ship - to dense phase pipeline transport conditions	0	0.0	0.0
1	Function 8A	Dense phase transport pipeline - Kalundborg to Havnsø - Low case	39	4.3	0.0
0	Function 8B	Dense phase transport pipeline - Kalundborg to Havnsø - Medium case	0	0.0	0.0
0	Function 8C	Dense phase transport pipeline - Kalundborg to Havnsø - High case	0	0.0	0.0
0	Function 9	Dense phase transport pipeline - Stenlille to Havnsø	0	0.0	0.0
Total			**112**	**21.5**	**98**

Figure 5-8 Case 3A, Low case – CAPEX/OPEX; Pipeline between Kalundborg and Havnsø, Low case; 1 MTPA from Kalundborg; 4 MTPA from East Zealand; no ship import; Functions [1,2,3,3b,4B, 8A]

5.9.4 Case 3B – CAPEX/OPEX

CAPEX/OPEX estimate for case 3B is provided in table below. Levelized cost for CO_2 conditioning/compression/ pumping is estimated to 2.3 EUR/Ton CO_2.

			MTPA	9	
			EUR/T	2.4	
Functions enabled in CAPEX/OPEX Estimate					
on/off			**CAPEX (MEUR)**	**OPEX (MEUR)**	**GWh/Y**
1	Function 1	Compressors at Kalundborg emitters, compressing CO2 from 2bara to 30 bara	12	7.4	61.3
1	Function 2	CO2 gas phase gathering pipeline - Kalundborg HUB	4	0.4	0.0
1	Function 3	Compression from 20 - 140 bar within Kalundborg HUB	8	3.9	30.7
1	Function 3B	Boosting (pumping) CO2 in dense phase at Stenlille - CO2 from East Zealand	1	0.1	5.6
0	Function 4	Dense phase transport pipeline - Kalundborg to Stenlille	0	0.0	0.0
1	Function 4B	Dense phase transport pipeline - Stenlille to Kalundborg - Import from Zealand East	49	5.4	0.0
0	Function 5	Liquefaction of CO2 from Kalundborg for intermediate storage and ship export	0	0.0	0.0
0	Function 6	Intermediate storage of Liquid CO2 - Kalundborg Export (limited to 1 MTPA)	0	0.0	0.0
1	Function 6B	Intermediate storage of Liquid CO2 - Kalundborg (for larger import volumes)	108	11.9	0.0
1	Function 7	Boosting and heating liquid CO2 arriving at Kalundborg by ship - to dense phase pipeline transport conditions	2	0.2	17.4
0	Function 8A	Dense phase transport pipeline - Kalundborg to Havnsø - Low case	0	0.0	0.0
1	Function 8B	Dense phase transport pipeline - Kalundborg to Havnsø - Medium case	42	4.6	0.0
0	Function 8C	Dense phase transport pipeline - Kalundborg to Havnsø - High case	0	0.0	0.0
0	Function 9	Dense phase transport pipeline - Stenlille to Havnsø	0	0.0	0.0
Total			**225**	**33.9**	**115**

Figure 5-9 Case 3B, Medium case – CAPEX/OPEX; Pipeline between Kalundborg and Havnsø, Medium case; 1 MTPA from Kalundborg; 4 MTPA from East Zealand; 4 MTPA ship import; Functions [1,2,3,3b,4B,6B,7,8B]

5.9.5 Case 3C – CAPEX/OPEX

CAPEX/OPEX estimate for case 3C is provided in table below. Levelized cost for CO_2 conditioning/compression/ pumping is estimated to 1.9 EUR/Ton CO_2.

MTPA	12
EUR/T	1.9

Functions enabled in CAPEX/OPEX Estimate

on/off			CAPEX (MEUR)	OPEX (MEUR)	GWh/Y
1	Function 1	Compressors at Kalundborg emitters, compressing CO2 from 2bara to 30 bara	12	7.4	61.3
1	Function 2	CO2 gas phase gathering pipeline - Kalundborg HUB	4	0.4	0.0
1	Function 3	Compression from 20 - 140 bar within Kalundborg HUB	8	3.9	30.7
1	Function 3B	Boosting (pumping) CO2 in dense phase at Stenlille - CO2 from East Zealand	1	0.1	5.6
0	Function 4	Dense phase transport pipeline - Kalundborg to Stenlille	0	0.0	0.0
1	Function 4B	Dense phase transport pipeline - Stenlille to Kalundborg - Import from Zealand East	49	5.4	0.0
0	Function 5	Liquefaction of CO2 from Kalundborg for intermediate storage and ship export	0	0.0	0.0
0	Function 6	Intermediate storage of Liquid CO2 - Kalundborg Export (limited to 1 MTPA)	0	0.0	0.0
1	Function 6B	Intermediate storage of Liquid CO2 - Kalundborg (for larger import volumes)	108	11.9	0.0
1	Function 7	Boosting and heating liquid CO2 arriving at Kalundborg by ship - to dense phase pipeline transport conditions	3	0.4	30.4
0	Function 8A	Dense phase transport pipeline - Kalundborg to Havnsø - Low case	0	0.0	0.0
0	Function 8B	Dense phase transport pipeline - Kalundborg to Havnsø - Medium case	0	0.0	0.0
1	Function 8C	Dense phase transport pipeline - Kalundborg to Havnsø - High case	45	4.9	0.0
0	Function 9	Dense phase transport pipeline - Stenlille to Havnsø	0	0.0	0.0
Total			**229**	**34.4**	**128**

Figure 5-10 Case 3C, High case – CAPEX/OPEX; Pipeline between Kalundborg and Havnsø; High case; 1 MTPA from Kalundborg; 4 MTPA from East Zealand; 7 MTPA ship import; Functions [1,2,3,3B,4B,6B,7,8C]

5.10 Concept for CO_2 pipeline between Stenlille and Havnsø

5.10.1 Concept design

As an alternative to routing potential CO_2 volumes from East Zealand through Kalundborg, a direct pipeline route from Stenlille is considered as a Case 4A. The pipeline length and required transport capacities is similar to the Case 2A. Pipeline concept design parameters are summarized in Table 5-1.

Table 5-7 Premises – Dense phase pipeline Kalundborg - Stenlille

Parameter	Stenlille to Havnsø
Pipeline system design pressure @ MSL (bara)	150
Pipeline system MAOP @ MSL (bara)	145
Pipeline system design temperature max/min (°C)	-29 / 35
Transfer rate (MTPA)	4
Transfer rate (kg/s)	127
Pipeline inlet temperature (°C)	15 [3)]
State of product (-)	Dense Phase
Minimum arrival pressure Havnsø (bara)	100
Burial, TOP (m)	1.2

Line pipe material (-)	API 5L X65
Length of pipeline (km)	35 [4)]
Product SG (1)	0.87 [6)]
Selected pipeline size (inch) [7)]	14
External pipeline diameter (mm)	355.6
Wall thickness (mm) [8)]	15.9
Internal diameter (mm)	323.6
Friction pressure loss (bar)	20
Flow velocity (m/s)	1.8
Required pipeline inlet pressure (bara)	120

5.10.2 CAPEX/OPEX

CAPEX/OPEX estimate for case 4A is provided in table below. The estimate is only included for reference as an alternative to Case 2B where the East Zealand volumes are routed through Kalundborg, not representing a full transport chain. The pipeline from Stenlille to Havnsø is estimated to be of same size and length as Stenlille to Havnsø. CAPEX for the Stenlille to Havnsø is less than from Stenlille to Kalundborg, as no HDD sections are foreseen/included.

			MTPA	4	
			EUR/T	1.1	
Functions enabled in CAPEX/OPEX Estimate					
on/off			**CAPEX (MEUR)**	**OPEX (MEUR)**	**GWh/Y**
0	Function 1	Compressors at Kalundborg emitters, compressing CO2 from 2bara to 30 bara	0	0.0	0.0
0	Function 2	CO2 gas phase gathering pipeline - Kalundborg HUB	0	0.0	0.0
0	Function 3	Compression from 20 - 140 bar within Kalundborg HUB	0	0.0	0.0
1	Function 3B	Boosting (pumping) CO2 in dense phase at Stenlille - CO2 from East Zealand	1	0.1	5.6
0	Function 4	Dense phase transport pipeline - Kalundborg to Stenlille	0	0.0	0.0
0	Function 4B	Dense phase transport pipeline - Stenlille to Kalundborg - Import from Zealand East	0	0.0	0.0
0	Function 5	Liquefaction of CO2 from Kalundborg for intermediate storage and ship export	0	0.0	0.0
0	Function 6	Intermediate storage of Liquid CO2 - Kalundborg Export (limited to 1 MTPA)	0	0.0	0.0
0	Function 6B	Intermediate storage of Liquid CO2 - Kalundborg (for larger import volumes)	0	0.0	0.0
0	Function 7	Boosting and heating liquid CO2 arriving at Kalundborg by ship - to dense phase pipeline transport conditions	0	0.0	0.0
0	Function 8A	Dense phase transport pipeline - Kalundborg to Havnsø - Low case	0	0.0	0.0
0	Function 8B	Dense phase transport pipeline - Kalundborg to Havnsø - Medium case	0	0.0	0.0
0	Function 8C	Dense phase transport pipeline - Kalundborg to Havnsø - High case	0	0.0	0.0
1	Function 9	Dense phase transport pipeline - Stenlille to Havnsø	39	4.3	0.0
Total			**39.5**	**4.3**	**5.6**

Figure 5-11 Case 4A, Alternative transport case for North East Zealand volumes transported in pipeline from Stenlille to Havnsø

5.11 Material Selection

The selection of materials should adhere to requirements outlined in ISO 3183 [23] or other applicable standards and be compatible with all phases of the CO_2 stream [24]. Material selection for the pipelines will assume that the Northern Lights specification is met.

Referring Equinor's FEED study for Northern Lights [25], carbon steel is considered a feasible choice.

Carbon steel is considered feasible for pipelines where the free water content of the CO_2 is controlled to avoid formation of free water in the pipeline, hence avoiding the corrosion mechanism [20]. It is therefore critical that the operational conditions are monitored, and water dew point kept below the service temperature. Operating under these conditions, very limited internal corrosion can be expected, and the corrosion allowance is therefore set to zero.

Pipelines containing hydrogen sulphide (H_2S) shall be qualified for sour service according to ISO 15156 [26]. Since the CO_2 is assumed to meet Equinor's Northern Lights specification, the content of H_2S is very low and would most likely fall in region 0 of [26] where no immediate action is required. None the less, since there is a risk that the H_2S limitation of region 0 could be exceeded, it would be prudent to specify the material for sour service according to [26].

Furthermore, candidate materials need to be qualified for the potential low temperature conditions that could occur during pipeline system commissioning, operation, decommissioning or recommissioning. This is however not critical, as carbon steel line pipes typically show good ductility and toughness values down to temperatures well below 0°C (noting that for CO_2 pipelines the requirements to Charpy test values will be stricter than commonly specified in codes for pipelines carrying other fluids).

The steel strength grade X65 is selected for this feasibility study due to its' relatively high mechanical strength, good cost efficiency and good track record. X65 is a very common choice for pipeline projects not involving highly corrosive or severe sour service. The only material grades allowed, considering the performed full scale tests [20] are X60 and X65. X60 could be used as alternative resulting in slightly higher wall thicknesses in some cases.

It must be noted that the technical feasibility of carbon steel for a CO_2 pipeline depends on the contents of the transported CO_2. The Northern Lights specification is quite pure, which allows for the selection of carbon steel. In case transport of less pure CO_2 be required, cross chemical reactions and corrosion mechanisms must be assessed.

The choice of a carbon steel as pipeline material hence requires the CO_2 quality to be of high purity, which may be a cost driver for the capturing facility. Alternatively, allowing for a lesser quality CO_2, leading to a nobler material choice for the pipeline, could have detrimental effect on the project feasibility.

Material selection for components, seals etc. is beyond the scope of this feasibility study.

5.11.1 Running Ductile Fracture

Pipelines carrying expansive media such as gasses or multi-phase fluids have the risk of running ductile fracture, since these media maintain the internal pressure acting on the pipeline, longer than liquids do, in case a rupture occurs. When expanding, dense phase CO_2 maintains its' saturation pressure longer than natural gas does and requires greater care when designing against running ductile fracture. The worst-case threat is that the pipeline is split along its' axis from the fracture initiation point till the end.

A split pipeline is a catastrophic scenario since it involves both a loss of the entire pipeline asset, and a large risk of harm to people or livestock, since the entire CO_2 inventory of the fractured pipeline will escape instantaneously, evenly distributed along the whole fractured section of the pipeline. Hence pipelines must be designed to avoid running ductile fracture.

Running ductile fracture is avoided by limiting the stresses in the pipeline, and by specifying sufficient base material toughness, as to arrest an initiated fracture. The pipeline design codes have criteria established for this. Alternatively crack arrestors may be applied, limiting running fracture to a limited section of the pipeline. This feasibility study takes point in arresting the fracture in the line pipe by specifying sufficient ductility.

According to [20], table 5-5, full scale testing for arrest of running ductile fracture has only been performed on thermo-mechanical controlled process pipes (TMCP) which were welded by submerged arc welding (SAWL), and on pipes with diameter between 16” and 36”. Therefore, the line pipe for this feasibility study is chosen to be TMCP SAWL, for pipes of 16” diameter and above.

Pipes with diameter below 16” can normally not be procured as TMCP SAWL. For this feasibility study, pipes below 16” diameter are therefore selected as seamless pipes, grade X65 QE according to ISO 3183 [23], under the assumption that seamless pipes can also be qualified to fall within the limitations of validity. Quoting DNV-RP-F104, table 5-5 [20], this should be a reasonable assumption:

“The differences in alloying philosophy and microstructure for QT or seamless pipes renders the applicability of the defined criteria uncertain for these pipes. However, it is likely that acceptable solutions can be demonstrated by special considerations for high quality QT or seamless pipes.”

It is assumed that pipes below 16” can also be qualified to fall within the validity range.

One design arrives at a wall thickness slightly below the 10 mm specified as the minimum of the validity range. For this case, 12.7 mm is selected as the design wall thickness to avoid the limitation.

DNV is currently hosting a Joint Industry Project, in an attempt to widen these ranges of applicability.

5.12 Wall thickness design

A set of preliminary wall thickness designs have been performed in accordance with ISO 27913 [24], DNV-RP-F104 [20] and ISO 13623 [27]. [24] addresses design aspects specific to CO_2 pipeline, hereunder design against running ductile fracture, whereas [27] concerns wall thickness design for internal pressure and applies to pipelines in general. [20] defines the limit for applicable pipes for which the current approach for design against running ductile fracture is applicable without additional testing.

The wall thickness designs cover two design load cases, i.e., normal operation and pressure testing in connection with commissioning (hydrotest with water). As per ISO 13623 [27] the pressure testing pressure required depends on the location class, and fluid category of the pipeline service medium. CO_2 is regarded as fluid category “E”.

Two location classes have formed the basis for the design. Location class 2 for rural areas with scarce population, and class 5 for areas with dense population. Location class 5 is the strictest class according to the ISO 13623 [27] classification, and it has been conservatively selected to cover the areas where the pipelines will cross urban territory.

The design pressure and MAOP have conservatively been assumed to be 150 bara and 145 bara, to account for possible geographical topology along the pipeline routes. The wall thickness design must account for possible pressure surges, e.g., in connection with closure of valves. Based on brief calculations with the Joukowski Model, it is safely assumed that pressure surges remain within the 10% exceedance of MAOP allowed by [24] section 7.3.4.

The strength of steel is a governing parameter when designing the wall thickness of a pipeline. A maximum design temperature of 35°C does not lead to a reduction in strength, i.e., $f_t = 1.0$.

Cf. [24] Section 7.3.3, determining of wall thickness based on internal pressure alone shall be based on existing pipeline standards, e.g., ISO 13623 [27]. Applying [27] for the design, a design factor, f_h of 0.77 is required for the hydrotest case, with water being a category A fluid. This case is governing for location classes with low population and is therefore included in the analysis.

The applied inputs are listed in Table 5-8.

Table 5-8: Basic inputs for wall thickness design

Location class	2 (rural)	5 (urban)
Design pressure [bara]	150	150
MAOP [bara]	145	145
SMYS [MPa]	450	450
SMTS [MPa]	535	535
Specified toughness [J] Tested at min. design temperature	250 @ -29°C	250 @ -29°C
Strength de-rating factor	f_t = 1.0	f_t = 1.0
Pipe grade ≥ 16”	ISO 3183 X65 ME (Welded)	ISO 3183 X65 ME (Welded)
Pipe grade < 16”	ISO 3183 X65 QE (Seamless)	ISO 3183 X65 QE (Seamless)
Fluid category [-]	E	E
Hydrotest factor, f_h [-]	1.25	1.40
Hoop stress factor, f_h [-]	0.77	0.45
Design temperature	-29°C to +35°C	-29°C to +35°C
Wall thick. Tolerance ≥ 16”	5%	5%
Wall thick. Tolerance < 16”	12.5%	12.5%

5.12.1 Fracture Control

ISO 27913 appendix D [24] proposes an approach (the standard Battelle Two-Curve method) for design the wall thickness against running ductile fracture. The calculation provides the Charpy V notch energy required from the line pipe material, to arrest a propagating fracture. The main inputs for the assessment are, pipe dimensions, the flow stress and the saturation pressure of the CO_2 inventory.

[24] suggests the use of SMYS + 68.9 MPa or the average of yield stress and tensile stress in transverse direction for the flow stress. Conservatively the designs are based upon average of SMYS and SMTS.

Fracture control is governed by the saturation pressure of the CO_2, which in turn is influenced by the composition elements of the CO_2 stream. Since the Northern Lights CO_2 specification arrives well above 99 % CO_2, it is assumed that the saturation pressure equals that of pure CO_2, as given in Table 5-9.

Table 5-9: Inputs for wall thickness design against running ductile fracture

Location class	2 (rural area)	5 (urban area)
Saturation Pressure – Pure CO_2 [MPag]	7.28	7.28
Flow stress [MPa]	492.5	492.5

Running ductile fracture in pipelines is an ongoing research topic, which is costly since it requires destructive full-scale testing of segments of pipeline. Quoting ISO 27913 section 7.3.5 [24]:

"Where the combination of pipeline materials and CO_2 *stream to be transported lies outside the range of available full scale test data, a full-scale test should be conducted to provide confidence that the pipeline has adequate resistance to ductile fracture."*

Hence, in addition, and to avoid full scale tests, the designs have aimed to towards staying within the boundaries of given in DNV-RP-F104, table 5-5 [20], though one of the selected wall thicknesses are slightly outside the validity range. The specified material toughness must exceed 250J to fall within the range of full-scale tests where fracture arrest was observed, c.f. [20] table 5-5.

5.12.2 Results

In the following tables the resulting wall thicknesses are presented, as well as the utilization ratios. It should be noted that for some cases the utilization ratios in Table 5-10 to Table 5-14 appear to be not optimized, but this is because running ductile fracture is governing for those cases.

Table 5-10: Resulting wall thicknesses, Kalundborg to Stenlille – Location Class 5

Parameter	Kalundborg to Stenlille – 10" pipe	Stenlille to Kalundborg – 14" pipe
Outer Diameter (mm)	273.1	355.6
Design wall thickness (mm)	12.7	15.9
Material grade	ISO 3183 X65 QE (Seamless)	ISO 3183 X65 QE (Seamless)
UR – Hydrotest (-)	0.69	0.72
UR – Operation (-)	0.87	0.91
ISO minimum toughness (J) (running ductile facture)	25 @ -29°C	35 @ -29°C
Recommended minimum toughness (J) (running ductile facture)	250 @ -29°C	250 @ -29°C

Table 5-11: Resulting wall thicknesses, Kalundborg to Stenlille – Location Class 2

Parameter	Kalundborg to Stenlille – 10" pipe	Stenlille to Kalundborg – 14" pipe
Outer Diameter (mm)	273.1	355.6
Design wall thickness (mm)	12.7 to comply with full scale tests	12.7
Material grade	ISO 3183 X65 QE (Seamless)	ISO 3183 X65 QE (Seamless)
UR – Hydrotest (-)	0.62	0.81
UR – Operation (-)	0.51	0.67
ISO minimum toughness (J) (running ductile facture)	25 @ -29°C	79 @ -29°C
Recommended minimum toughness (J) (running ductile facture)	250 @ -29°C	250 @ -29°C

Table 5-12: Resulting wall thicknesses, Kalundborg to Havnsø, – Location Class 5

Parameter	Low Case – 14" pipe	Medium Case – 16" Pipe	High Case – 18" pipe
Outer Diameter (mm)	355.6	406.4	457.2
Design wall thickness (mm)	15.9	15.9	19.1
Material grade	ISO 3183 X65 QE (Seamless)	ISO 3183 X65 ME (Welded)	ISO 3183 X65 ME (Welded)
UR – Hydrotest (-)	0.72	0.76	0.71
UR – Operation (-)	0.91	0.96	0.90
ISO minimum toughness (J) (running ductile facture)	35 @ -29°C	46 @ -29°C	43 @ -29°C
Recommended minimum toughness (J) (running ductile facture)	250 @ -29°C	250 @ -29°C	250 @ -29°C

Table 5-13: Resulting wall thicknesses, Kalundborg to Havnsø, – Location Class 2

Parameter	Low Case – 14" pipe	Medium Case – 16" Pipe	High Case – 18" pipe
Outer Diameter (mm)	355.6	406.4	457.2
Design wall thickness (mm)	12.7	14.3	15.9
Material grade	ISO 3183 X65 QE (Seamless)	ISO 3183 X65 ME (Welded)	ISO 3183 X65 ME (Welded)
UR – Hydrotest (-)	0.81	0.76	0.77
UR – Operation (-)	0.67	0.63	0.63
ISO minimum toughness (J) (running ductile facture)	79 @ -29°C	64 @ -29°C	76 @ -29°C
Recommended minimum toughness (J) (running ductile facture)	250 @ -29°C	250 @ -29°C	250 @ -29°C

Table 5-14: Resulting wall thicknesses, Stenlille to Havnsø, – Location Class 2 and 5

Parameter	Stenlille to Havnsø – 14" pipe	Stenlille to Havnsø – 14" pipe
Location Class	2	5
Outer Diameter (mm)	355.6	355.6
Design wall thickness (mm)	12.7	15.9
Material grade	ISO 3183 X65 QE (Seamless)	ISO 3183 X65 QE (Seamless)
UR – Hydrotest (-)	0.81	0.72
UR – Operation (-)	0.67	0.91
ISO minimum toughness (J) (running ductile facture)	79 @ -29°C	35 @ -29°C
Recommended minimum toughness (J) (running ductile facture)	250 @ -29°C	250 @ -29°C

5.12.3 Results of fracture control assessment

In Table 5-10 to Table 5-14, is given the Charpy V notch toughness required avoid running ductile fracture. This toughness is based on the model proposed by ISO 27913 appendix D [24]. In addition to this, running ductile fracture has been assessed based on DNV-RP-F104 [20], assuming a line pipe Charpy V notch toughness of 250J. The presented designs have been plotted into DNV-FP-F104 Figure 5-3 [20], which is presented in Figure 5-12, and it follows that all the selected wall thicknesses fall in the category that qualifies by small scale testing only:

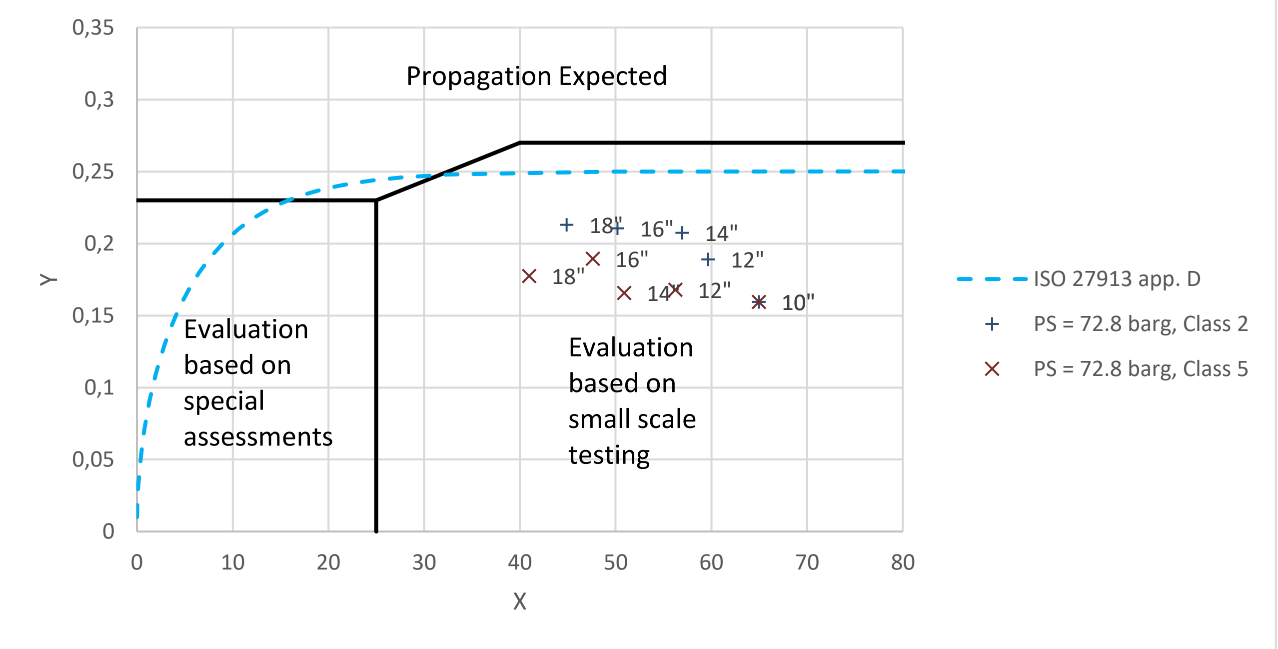


Figure 5-12: Wall thickness designs and ISO 27913 appendix D curve plotted into DNV-RP-F104 fig. 5-3

5.12.4 Wall thickness conclusion

As can be seen from the results, the wall thicknesses and toughness values arrived at result in D/t ratios ranging from 24 to 29, and a recommended toughness requirement of 250 J. These can be considered normal and technically feasible values, and pipeline carbon steels can normally be supplied with a Charpy V notch toughness in the range of 150 J to 250 J at -29°C without imposing additional material cost.

5.13 Pipeline routing

The envisioned route corridor for the Kalundborg-Stenlille pipeline, the Stenlille-Havnsø pipeline and the Kalundborg - Havnsø pipeline have been assessed in section 5.13.1.1, 5.13.1.2 and 5.13.1.3 respectively. The gas phase gathering network in the Kalundborg Hub has been assessed in section 5.13.2. Existing pipelines [18] and nature protected areas [28] [29] are included in Figure 5-13 to Figure 5-18. It shall be acknowledged that this is considered a high-level assessment of the routing, hence a detailed route assessment is considered outside the scope of this feasibility study.

5.13.1 Dense phase Backbone pipeline

The envisioned route corridor for the dense phase Kalundborg-Stenlille pipeline, the Stenlille-Havnsø pipeline and the Kalundborg-Havnsø pipeline have been assessed with consideration to cities/populated areas, protected nature areas and crossings. Further, the existing pipeline corridors and potential power lines have been considered. Crossings of roads and railways are considered included in the normal project costs, where the larger crossings of protected areas are expected to have higher impact of the final costs and are therefore addressed in further detail.

5.13.1.1 Kalundborg Hub to Stenlille storage

The envisioned pipeline route from Kalundborg Hub to the Stenlille storage site is shown in Figure 5-13. The first part from Kalundborg Hub towards east runs parallel to an existing pipeline which also includes crossing of a Natura2000 area. This crossing is expected to require a Horizontal Directional Drilling (HDD) section of 1 km as shown in Figure 5-14. The second part of the route from the HDD crossing to the Stenlille storage site is here suggested not to follow the existing pipeline route, but a corridor routed north of the cities Ruds Vedby, Skellebjerg, Dianalund and Stenlille is suggested here.

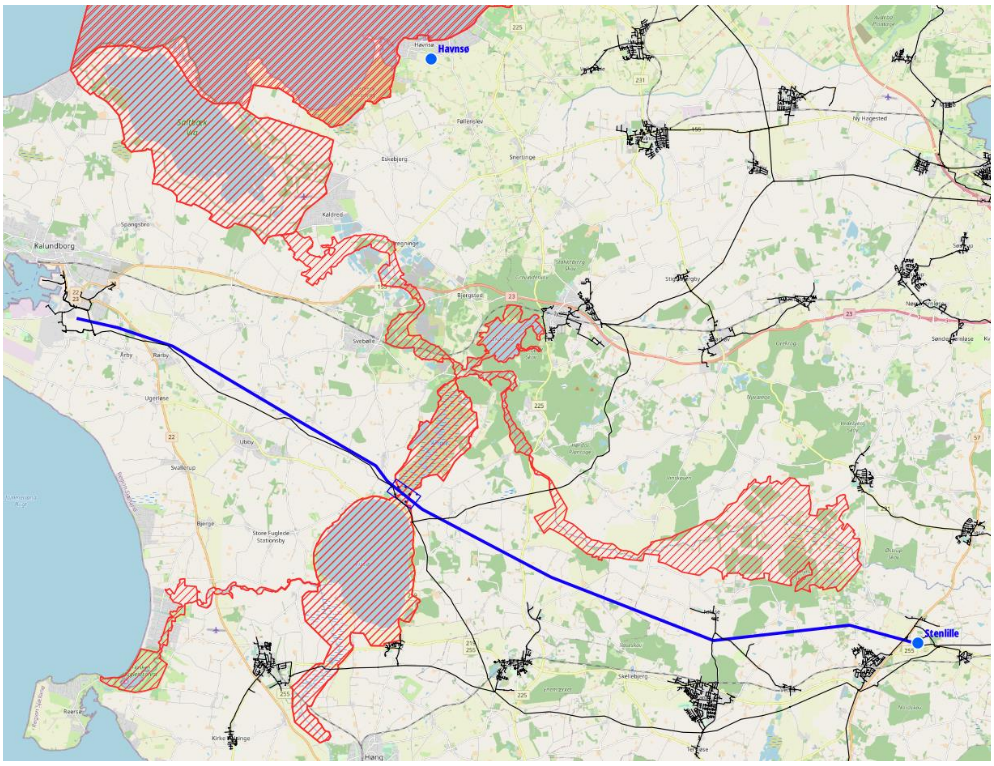


Figure 5-13: Pipeline route connecting Kalundborg HUB and Stenlille storage (modelled in QGIS). Blue line: the envisioned pipeline route. Blue dots: Storage locations. Red scattered areas: protected nature areas. Black line: Existing natural gas pipelines.

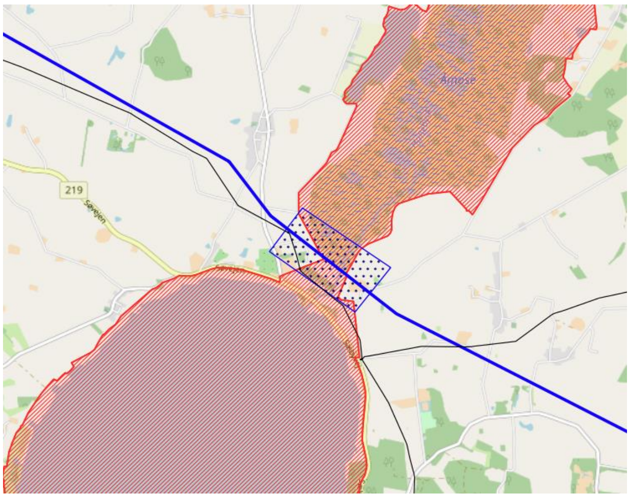


Figure 5-14: Expected 1 km HDD section for crossing of protected on the Kalundborg Hub – Stenlille storage pipeline (modelled in QGIS).

5.13.1.2 Kalundborg Hub to Havnsø storage

The envisioned pipeline route from Kalundborg Hub to the Havnsø gas storage site is shown in Figure 5-15. The pipeline route will have to cross a band of Natura2000 protected area, which also include wet areas and gravel pits. The crossing is expected to require a HDD section of 2 km as shown in Figure 5-16.

It is noted that this route is not running parallel with an existing infrastructure or power line, hence it is suggested that dialog is initiated on an early stage regarding environmental permitting for crossing this area.

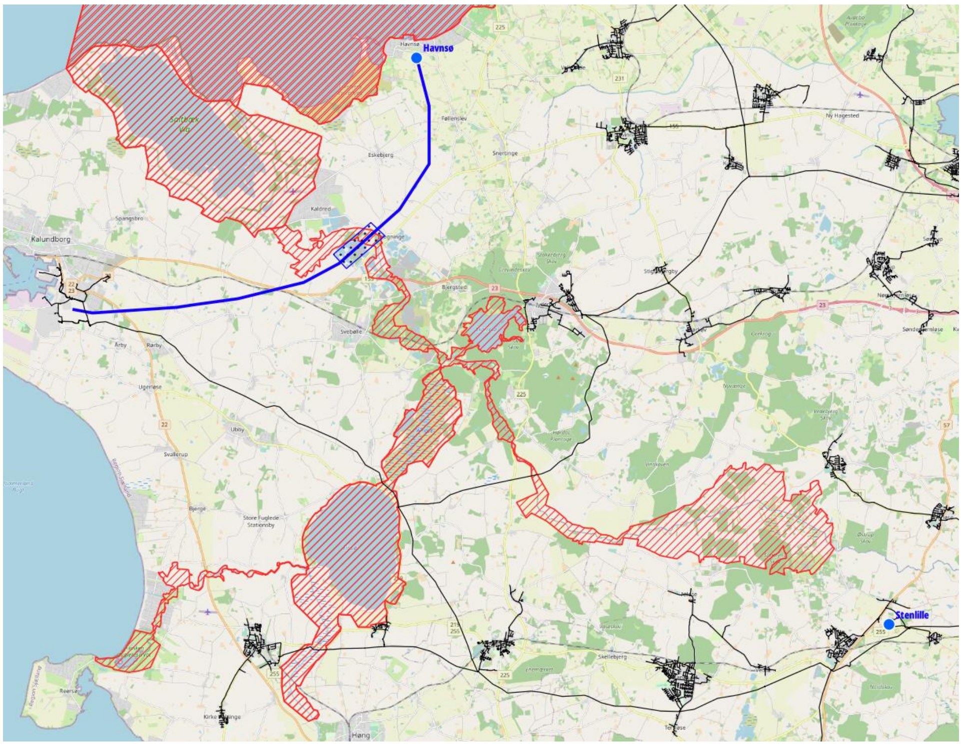


Figure 5-15: Pipeline route connecting Kalundborg HUB to Havnsø storage modelled in QGIS. Blue line: the envisioned pipeline route. Blue dots: Storage locations. Red scattered areas: protected nature areas. Black line: Existing natural gas pipelines.

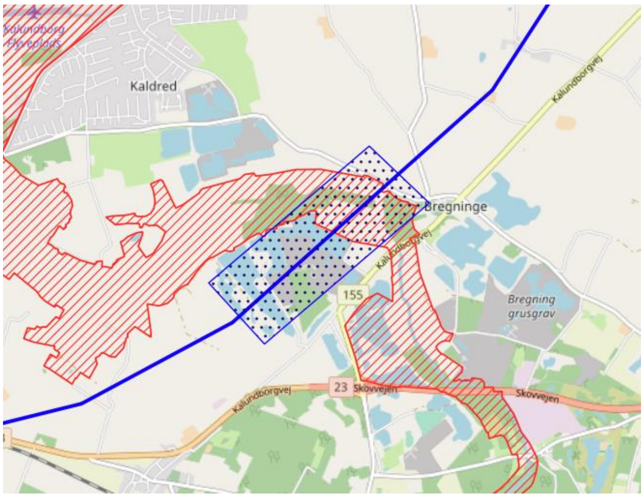


Figure 5-16 Expected 2 km HDD section for crossing of protected on the Kalundborg Hub – Havnsø storage pipeline (modelled in QGIS).

5.13.1.3 Stenlille storage to Havnsø storage

The envisioned pipeline route from the Stenlille storage site to the Havnsø gas storage site is shown in Figure 5-17. Focus have been to avoid nature protected areas and city areas (with due considerations to potential city expansions).

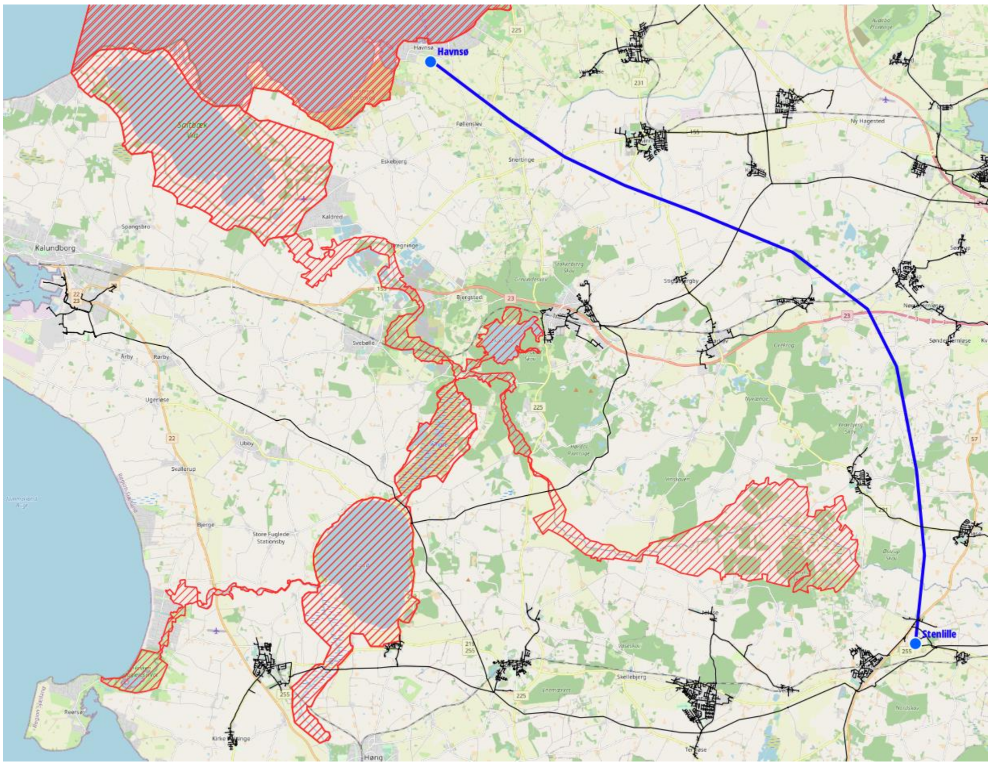


Figure 5-17: Pipeline route connecting Stenlille storage and Havnsø storage modelled in QGIS. Blue line: the envisioned pipeline route. Blue dots: Storage locations. Red scattered areas: protected nature areas. Black line: Existing natural gas pipelines.

5.13.2 Gas phase gathering network

A gas phase gathering network are envisioned for CO_2 transport from potential capture facilities at the Kalundborg Hub identified emitters to liquification and shipping or to compression and transport via dense phase backbone for the Stenlille storage site / Havnsø storage site.

A detailed assessment of the routing network is not performed in this feasibility study, as the gathering grid is expected to be a small network inside the industrial area of Kalundborg, which required detailed assessment of location of capture plants, optimal location of intermediate storage, liquefication facilities and compressor facilities.

There are existing infrastructures that can be relevant to consider when routing inside this dense build area. As indicated in Figure 5-18, there are existing gas pipelines connecting Kalundborg Bioenergy and Kalundborg Refinery, which also are in close vicinity to Gyproc. Further there are above ground steam pipelines from Asnæsværket to Novozymes (not shown on figure).

It is not considered feasible to install pipelines from Novozymes and Gyproc towards the Asnæsværket-Kalundborg Bioenergy-Kalundborg Refinery cluster, as the emissions potentials at these are considered too low. If capture facilities are installed at Gyproc and Novozymes, it is considered/judged more feasible to utilize CO_2 trucks for the CO_2 transport.

The gathering network is for this feasibility study estimated to be a 2 km network for connection Asnæsværket, Kalundborg Bioenergy, Kalundborg Refinery, the liquification station and the compressor station.

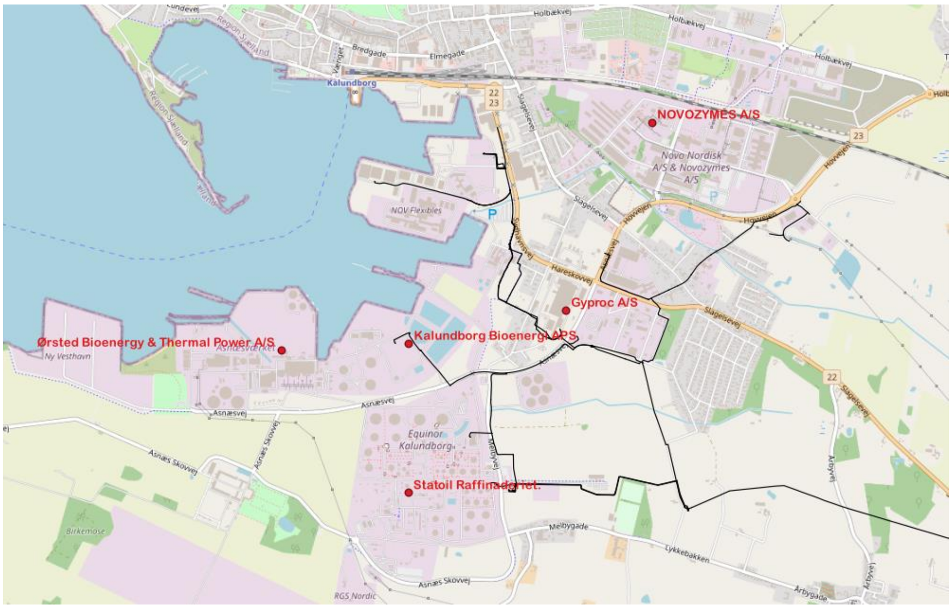


Figure 5-18 CO_2 emitters located in Kalundborg.

5.14 Risk and safety perspectives

Carbon dioxide is normally present in the atmosphere at about 400 ppm (at present), and harmless for life at those levels. At concentrations above a few percent by volume however, it distorts respiration, causes nausea and leads to loss of consciousness and finally to coma and death for concentrations above 10% as shown in Figure 5-19. Further, CO_2 vapour is invisible making a release more dangerous.

CO_2 concentration in air (% v/v)	*Exposure*	*Effects on humans*
17 – 30	Within 1 minute	Loss of controlled and purposeful activity, unconsciousness, convulsions, coma, death.
>10 – 15	1 minute to several minutes	Dizziness, drowsiness, severe muscle twitching, unconsciousness.
7 – 10	Few minutes	Unconsciousness, near unconsciousness.
	1.5 minutes to 1 hour	Headache, increased heart rate, shortness of breath, dizziness, sweating, rapid breathing.
6	1 – 2 minutes ≤ 16 minutes Several hours	Hearing and visual disturbances. Headache, difficult breathing (dyspnoea). Tremors.
4 – 5	Within a few minutes	Headache, dizziness, increased blood pressure, uncomfortable breathing (equivalent to concentrations expired by humans).
3	1 hour	Mild headache, sweating, and difficult breathing at rest.
2	Several hours	Headache, difficult breathing upon mild exertion.

Figure 5-19 Acute health effects of high concentrations of inhaled CO_2 [20]

The consequence of a release of CO_2 can be severe and due consideration have to be taken to assure a safe design and mitigating measures have to be assessed.

The pipelines shall be designed for the standard pipeline threats but also the CO_2 specific threats as:

- Material incompatibility (pipeline material and components).
- Internal corrosion due to water and impurities in the CO_2 stream.
- Overpressure due to thermal expansion.
- Low temperature embrittlement.
- Escalating events as propagating pipeline cracks (as designed for in section 5).

These threats have to be taken into consideration in the design of the systems e.g. material of pipeline and components, CO_2 quality control, pressure control systems, valve sectioning, leak detection, inline inspections and routing.

Furthermore, the intermediate storage and the process facilities of the system (compressors, liquefaction station, etc) have to be assessed with regard to safe operation.

For this feasibility study it is assumed that a dense phase pipeline can reach Kalundborg port to a distance within 2-3 km, considering potential concerns with dense phase pipelines in populated areas. This premise is also applicable to ship import and location of transition between LCO_2 (ship condition) and dense phase pipeline transport.

It is recommended to perform risk & safety assessments of the concept solution e.g., HAZID studies, consequence analyses, identify required distance to nearby population for the envisioned CO_2 infrastructure, early in the maturation of these concepts.

5.15 Legislation and permitting

The legislative requirements for CO_2 pipeline infrastructure and the according permitting requirements are important to identify when designing and constructing the pipeline infrastructure in Denmark.

CO_2 pipeline infrastructures in Denmark are legally mandated to adhere to "Undergrundsloven" (The Underground Act), Executive Law no. 1533 of 16/12/2019, "Bekendtgørelse af lov om anvendelse af Danmarks undergrund".

This executive law lies with the Danish Ministry of Climate, Energy and Utilities, and are ministered by the Danish Energy Agency.

Geological storage of CO_2 is further mentioned in "CCS Bekendtgørelsen" Executive Order No. 1425 of 30/11/2016. The executive order presents the requirements for application for permission to storage and requirements to operation, surveillance, status reporting, inspections and closing of storage.

Key points are outlined for relevance to current project:

- Permission for geological storage and pipeline transport of CO_2 must be given by the Danish Ministry of Climate, Energy and Utilities, where details on routing, dimensions, owner and tariff costs are defined. Reference is made to paragraph §23U in Executive Law no. 1533 of 16/12/2019.
- Approval of the organization, operation and a plan for mitigating measures must be given by the Danish Ministry of Climate, Energy and Utilities. Reference is made to §23D, subsection 2, in Executive Law no. 1533 of 16/12/2019.
- The operator of the CCS infrastructure is to be appointed by the Danish Ministry of Climate, Energy and Utilities as per §24 in Executive Law no. 1533 of 16/12/2019. Only operators who are assessed to possess the necessary technical and financial capacity can be appointed as operators. The Minister for Climate, Energy and Supply consults the supervisory authority in accordance with the Offshore Safety Act (Executive Law no. 125 of 06/02/2018) before an operator is appointed.
- The CO_2 flow must by far predominantly consist of pure CO_2. Danish Ministry of Climate, Energy and Utilities can define criteria and procedures for composition of CO_2 flow. Further reference is made to §23g. This is further outlined in Executive order no. 1425 of 30/11/2016 §6 and §7 (CCS bekendtgørelsen).
- The expropriation approvals must be given by the Danish Ministry of Climate, Energy and Utilities. Reference is made to paragraph §36.
- The Danish Energy Agency expects a fair and open access to a CO_2 infrastructure grid and storage facilities to the extent possible with regards to capacities, technical specifications etc. This is further outlined in Executive order no. 1425 of 30/11/2016 §22 (CCS bekendtgørelsen).

Based on the "Undergrundsloven", Executive Law no. 1533 of 16/12/2019, the permission and project approval will be given by Danish Ministry of Climate, Energy and Utilities, and therefore the Danish Energy Agency. It is recommended to enter a dialogue with the Danish Energy Agency about the application process in a very early stage of a potential project. With regards to guidance on safety technical aspects for the CO_2 infrastructure it is expected that the Danish Energy Agency will require the use of international recognized standards. In addition, it has been noted on other projects where the authority has been the Danish Energy Agency that independent verification towards international recognized standards of all project phases will be a requirement.

CO_2 pipeline infrastructure are further subject to the "Miljøvurderingsloven" (Environmental Assessment Act), Executive Law no. 4 of 03/01/2023, "Bekendtgørelse af lov om miljøvurdering af planer og programmer og af konkrete projekter (VVM)".

5.16 Planning and scheduling

In the assessment of the planning and scheduling of the envisaged CO_2 pipeline infrastructure, various aspects that will affect the timeline are discussed. In general, gas transmission system construction is common practice and pipeline operators, and contractors are familiar with the design and construction of such systems. Usually, new stretches of gas pipelines can be designed and constructed in a matter of a few years, but there are some circumstances that make CO_2 pipelines more complicated to be established. Some of these are:

- **Physical properties of** CO_2, making it a potentially hazardous substance in case of gas releases into the atmosphere, and possible phase shifts occurring within the pressure and temperature ranges that are normally applied in pipeline transmission systems;
- **Limited financial-economic drive**; unlike fuels for example, CO_2 represents less added economic value. Removing CO_2 will add to the cost of living for most people and therefore costs must be kept as low as possible, causing commercial margins of CCS projects to be stretched rather thin in order to remain socially acceptable;
- **Public acceptance** of pipelines containing a hazardous substance running in close vicinity of inhabited areas or the use of underground storage reservoirs may be difficult to achieve; in contrast to e.g. natural gas pipelines CO_2 transmission systems bring not much immediate advantages to the public.

Regarding the physical properties of CO_2 it is important to note that it may take a while before permits are being issued, since the risk profiles associated with the handling and (onshore) storage of CO_2 need to be thoroughly studied and possibly additional safety measures may need to be taken. This may cause unforeseen delays in project development.

Aspects as technology readiness level of the CO_2-emitters and storage facilities involved and land procurement disputes can further cause delay or increased investment.

Safety concerns will also play an important role in the public acceptance of CCS projects, which can delay or even risk cancellation of CCS projects.

The conclusion of this all is that the time required for implementing CCS projects is very hard to predict. Although construction and commissioning of newly built pipelines may take a relatively short time, typically one to two years, the preparatory phase will present the most uncertainties timewise.

5.16.1 Scheduling approach

In general in pipeline design and construction projects, four phases can be distinguished, being:

1. preparatory phase
2. planning & design phase
3. engineering, procurement & construction (EPC) phase
4. commissioning phase.

The four phases can be broken down into various activities which will be discussed in more detail in the next sections.

Low and high-risk scenario:

Regarding the foreseen timeline, two scenarios will be discussed, named the 'low risk' and 'high risk' scenario. The low-risk scenario applies to the situation where a longer lead time of the project is considered acceptable; in the high-risk scenario more (financial) risks are taken in (pre-) ordering goods and services whilst previous activities have not yet led to a conclusive decision whether or how to proceed. An example of such is land procurement without all permits having been obtained yet; by procuring land in advance, matters can be speeded up, but on the other hand a risk remains that essential permits will not be granted after all.

5.16.1.1 Preparatory phase

The preparatory phase starts with developing the first ideas on business development /expansion, and ends with the final approval of conceptual designs, financing arrangements and the signing of Letters of Intent and more definite contracts. The preparatory phase can be considered to include all activities leading to the final investment decision.

Typical activities to be taken up in the preparatory phase are (pre)feasibility and FEED studies, and fund raising. In Figure 5-20 the various steps in this phase are shown. It is to be noted that the shown sub-activities on the right-hand side of the table may be done in parallel within one of the five main activities. In general these five main activities are to be done in sequential order. During the preparatory phase a number of go / no-go decisions can be made in order to avoid further development costs in case the project does not appear to be viable after all. Information obtained during this phase should suffice to base an investment decision on.

Stage		Phase	Activity
1	**Preparatory work**	1.1	Idea conception & development
		1.1.1	Devloping ideas
		1.1.2	Go/no go decision
		1.2	(Pre-)feasibility
		1.2.1	Market assessment
		1.2.2	Playing field analysis
		1.2.3	Stakeholder analysis
		1.2.4	Supply / demand analysis
		1.2.5	Technical research
		1.2.6	1st conceptual design
		1.2.7	Fin. Econ. Analysis
		1.2.8	Regulatory analysis
		1.2.9	Stakeholder meetings / interviews
		1.2.10	Tasks / responsibilities assessment
		1.2.11	Go / no go decision
		1.3	FEED
		1.3.1	Technical design & modelling
		1.3.2	Cost / benefit analysis
		1.3.3	Financial modelling
		1.3.4	Go / no go decision
		1.4	Pre-contracting
		1.4.1	Public relations campaign
		1.4.1	LOI / commitment statements
		1.4.2	Financing surveys
		1.4.3	Draft intake / delivery contracts
		1.5	Investment decision
		1.5.1	Investment decision

Figure 5-20 Activities associated with the preparatory phase

5.16.1.2 Planning & design phase

Once an investment decision has been made in favour of continuation of the project, a more detailed design can be made, and further planning can be done. The first steps in this phase are to make a list of functional specifications and other requirements, usually bundled in a Basis of Design document. After that the conceptual design, risk assessments, procedure preparation and the permitting activities can be commenced. An overview of the involved main and sub activities is presented in Figure 5-21.

2	**Planning & design**	2.1	Basis of Design
		2.1.1	Functional specifications
		2.1.2	Project / process organisation
		2.1.3	Initial pipeline routing study
		2.1.4	Storage demand & design
		2.1.5	Location analysis / land ownership
		2.1.6	Geological survey
		2.1.7	Power supply study
		2.1.8	Materials study
		2.1.9	Permit requirement inventory
		2.1.10	Environmental impact studiy
		2.1.11	Operational aspects (flows / pressures)
		2.1.12	Dispatching assumptions
		2.1.13	Reporting
		2.1.14	Approval
		2.2	Conceptual design
		2.2.1	Final pipeline routing
		2.2.2	Pipeline operation simulations
		2.2.3	Hydraulic calculations
		2.2.4	Crossings design
		2.2.5	Pipeline dimensioning / sectioning
		2.2.6	Grid connection design
		2.2.7	Liquefaction plant design
		2.2.8	Pressure Reduction Station design
		2.2.9	Control systems design
		2.2.10	Cathodic protection system design
		2.2.11	Leak detection design
		2.2.12	Pig launcher / receiver design
		2.2.13	Dispatch centre design
		2.2.14	Gas quality management design
		2.2.15	Custody transfer equiment design
		2.2.16	Conceptual design approval
		2.3	Risk assessments
		2.3.1	Quantitative Risk Assessments
		2.3.2	HAZOPs
		2.3.3	HAZIDs
		2.4	Operational safety procedures
		2.4.1	Pipeline evacuation procedures
		2.4.2	Venting procedures
		2.4.3	Pipeline repair procedures
		2.5	Permitting
		2.5.1	Legal consultation
		2.5.2	Meetings with competent authorities
		2.5.3	Permit application submission
		2.5.4	Discussion with authorities
		2.5.5	Final permit issuing

Figure 5-21 Planning & design phase activities

Please note that the sub tasks may vary per project; some activities may be skipped, and others need to be added.

Especially in the conceptual design phase a number of iterations based on different variations of the design will be required (dark blue area). Multiple pipeline routing options will require several designs to be explored and appraised before a final decision can be made. It must be acknowledged that such iterative process may take considerable time.

Once the pipeline route has been chosen, further design activities may be started, not only associated with the pipeline itself, but also of various system facilities like compressor / pumping / liquefaction stations, pressure reduction stations and all kinds of auxiliary systems. Also in this phase, risk assessments must be done, e.g., leading to certain safety distances and risk mitigating measures to be applied.

Once the overall design of the system has been established the permitting procedure is to be started. In the preparatory phase it has already been assessed what types of permits are to be applied for, what documentation is to be provided and where to submit these applications. Especially in case of objections being raised, or critical authorities, the permitting phase may take a long time (i.e. several years).

5.16.1.3 EPC-phase

Once the main project features are specified and the required permits are provided, detail design and construction of the system can start. Again, depending on the risk level to be considered acceptable some activities from this stage may be started early.

Typically, in the EPC phase much work is outsourced to specialized contractors and usually one EPC contractor will be in the overall lead of the design and construction work, who will also be responsible for a timely and proper delivery of the project. The main contractor will also be responsible for hiring sub-contractors if and where needed. In the start-up of the EPC-phase, tenders must be published, and offers are to be appraised considering factors like costs, delivery time, experience, quality of the work and many other aspects. Contracting out the work may already be done in the Planning & Design phase, depending on the risk level being applied.

3	EPC	3.1		EPC contracting
			3.1.1	Preparing tender documents
			3.1.2	Public tender
			3.1.3	Meetings and negotiations
			3.1.4	EPC contract signing
		3.2		EPC activities
			3.2.1	Detail engineering
			3.2.2	Bill of materials
			3.2.3	Hiring sub contractors
			3.2.4	Procurement of land / materials / equipment
			3.2.5	Material / equipment testing
			3.2.6	Site preparations & prepratory work
			3.2.7	Pieline system construction
			3.2.8	Welding inspections
			3.2.9	Hydraulic pressure tests
			3.2.10	Cleansing / drying
			3.2.12	Pipeline fill

Figure 5-22 EPC-activities

Once the EPC contractors are hired, most of the hands-on work to be done can be left to them, but the overall supervision must be done by a dedicated project team of the future asset owner / operator. It must be assured that this project team is sufficiently qualified to oversee all aspects of the work done.

In the second part of the EPC phase the most tangible results will be achieved; the design will be finalized for the last time, a bill of materials will be prepared and materials and equipment will be ordered, and the actual construction of the transmission system has started.

It must be noted that the EPC-phase may also introduce delays, e.g. as a result of long delivery times of system components, wrongly manufactured parts or bad weather conditions.

A typical example of such would be rotating equipment like compressors and pumps. There is a high demand of such components and the types most suitable for the job may be supplied by only a few manufacturers globally. Although pipeline and facility construction may be taken up simultaneously and executed in parallel, the likelihood of the pipeline system being completed ahead of the facilities is very high, also because such facilities are more complicated in general. The system parts with the longest delivery time will in the end determine the pace at which the system can be completed. This has to be considered when making a detail planning of the activities.

5.16.1.4 Commissioning

In the commissioning phase the system is put into operation once the results of the final partial tests of individual system components were satisfactory. The system is filled and ready to go, but first some final holistic tests must be done to confirm that the entire system functions as desired. For this, site acceptance tests must be done for which the system is to be fully operational, including the feeding in and delivery of CO_2. Only in such real life tests the actual performance of the system can be fully tested. If necessary, in this project phase minor adaptations to the system and its controls can be made. Once the system meets its specifications the handing over to the new owner operator can be done and the system can be put in operation.

5.16.2 Low-risk schedule

Based on a number of assumptions and knowledge of the development of typical transmission systems at present and in the past, an estimate of the probable timeline in the low-risk scenario has been made. In this scenario, all steps are taken after each other so that the next phase will be started only after the previous one has been fully completed and all conditions for the execution of the next phase are set.

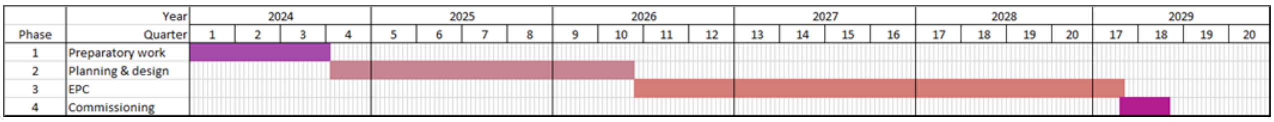


Figure 5-23 Gant chart of main project phases in the low-risk case

From the above Gant chart it may be concluded that the project will be completed by the end of Q2, 2029 in case the low-risk approach will be taken. The project will take over five years to complete if no serious setbacks are going to be met. A more detailed Gant chart, including all previously discussed sub-activities is provided in Appendix B.

5.16.3 High-risk schedule

In case more risks are taken, e.g. in case of a desire of completing the CCS collection and transmission in a shorter time, the various project phases may partly overlap in time. In that case the high-level Gant chart will look more like the one shown in Figure 5-24. A more detailed Gant chart is provided in Appendix C.

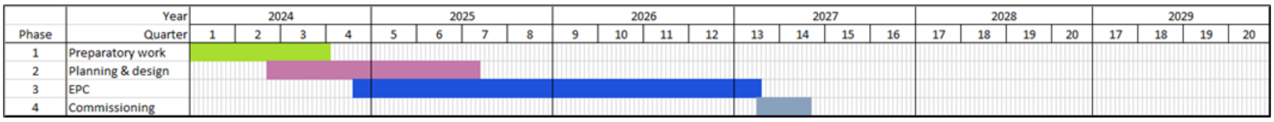


Figure 5-24 Gant chart of main project phases in the high-risk case

5.16.4 Conclusion of planning and scheduling

In both scenarios the starting date of the project is set to be Q1-2024. In case of the project starting sooner or later, the end date of the project will shift accordingly. In the low-risk scenario the overall project lead time will arrive at around 5.5 years. This is without allowing for excessive delays due to legal procedures, technical difficulties or other mishap. In case the project is to be hurried, lead time may be shortened to some 3.5 years, also under the assumptions that no extra delays will occur. Financial risks will increase significantly though. The above conclusions are without taking technology readiness at the emitters' plants and the storage facilities into account.

6 POTENTIAL FUTURE INTEGRATION WITH PTX INFRASTRUCTURE

The Danish Energy Agency define Power-to-X as “a blanket term that covers technologies that produce fuels, chemicals and materials based on green hydrogen produced through electrolysis” [30]. The main step of a PtX facility is to produce green hydrogen from water using energy from renewable sources such as solar and wind power. Next steps can be:

- to combine hydrogen with nitrogen to form green ammonia, which can be used for production of fertilizers and other chemicals or as a future maritime fuel.
- to combine hydrogen with carbon to form a variety of fuels such as diesel, aviation fuel (kerosene) and methanol.

EU define Renewable Fuels from Non-Biological Origin (RFNBO) as fuels with energy content derived from renewable sources other than biomass, i.e. renewable electricity. This means that RFNBOs can be pure hydrogen, ammonia, hydrocarbon gases or liquids. RFNBOs produced from combining renewable hydrogen from electricity with CO_2 are often called e-fuels. To decarbonize hard-to-abate sectors that are difficult to electrify, such as aviation and maritime, large volumes of e-fuels will be required.

The Danish Government has proposed that Denmark should aim to build up to 4-6 GW of electrolysis capacity by 2030 [31]. In this section the potential future integration with Power-to-X (PtX) infrastructure has been analysed. Integration possibilities include delivering CO_2 as input factor to e-fuel production and take advantage of synergies between burying CO_2 and hydrogen pipelines together. In addition to mapping announced projects in section 6.1, DNV has also analysed other optimal locations for potential future PtX plants in section 6.2. Section 6.3 describes Denmark’s infrastructure visions and possible integration and synergies.

Table 6-1 shows an overview of key numbers and assumptions for P2X facilities relevant for this chapter. These are high level estimates to be used to get a view on the approximate ratios and conversions, and to get an understanding of sizes, volumes and input requirements. Note that power requirements and losses for additional steps of e-fuel production, such as the CO_2 step, is not considered.

Table 6-1: Key numbers (approximate) and assumptions for P2X facilities

		Per kg hydrogen	For a 100 MW electrolyser
Input	Power	~50 kWh/kg hydrogen	100 MW
	Water	9 liter/kg hydrogen	20 m3/hour[3]
	Cooling water	-	40 m3/hour[4]
	CO_2 (for e-fuel production)	Kerosene: Approx. 20 kg/kg hydrogen [32] Methanol: Approx 11 kg/kg hydrogen	Kerosene: Approx 40 tons/hour Methanol: Approx 22 tons/hour
Output	Hydrogen	-	2 tonnes/hour
	Heat output	15-20 kWh/kg hydrogen	33 MW
	Oxygen	8 kg/kg hydrogen	18 tonnes/hour
	e-fuel	6,6 kg kerosene/kg hydrogen 8,0 kg methanol/kg hydrogen	13 tonnes kerosene/hour 16 tonnes methanol/hour

6.1 Announced PtX projects on Zealand

Currently there are announced projects in Greater Copenhagen, in the western part of Zealand and the southern Part of Zealand (Vordingborg) and Lolland (Nakskov). According to Brintbranchen there are 7 announced P2X projects[5] in Zealand as of June 2023. In addition, European Energy's PtX project in Freerslev Energipark in Hillerød municipality has been added. Table 6-2 lists information on the eight announced PtX projects on Zealand.

For this project, looking at synergies and integration with CO_2 pipelines, the projects requiring CO_2, i.e. e-fuels production, are the most interesting to focus on. Three of the PtX projects at Zealand have announced potential e-fuels production such as sustainable aviation fuel, methanol and diesel; Green Fuels for Denmark located in Hvidovre in outer Copenhagen, Arcadia Vordingborg, and European Energy Freerslev Energipark. The latter has announced a potential CO_2 volume, while for the two other plants DNV has made a high level estimate on CO_2 volumes required based on announced production capacity or annual production. CO_2 demand (tonnes/year) is estimated based on the projects' announced fuel volumes, chemical composition of the fuel and the molar mass of the C, H and O atoms in the process.

[3] Rule of thumb is 200 liter water per hour per MW electrolyser. Water Treatment for Green Hydrogen, whitepaper by Eurowater, Ultrapure water for hydrogen production (eurowater.com)

[4] Rule of thumb is 400 liter cooling water per hour per MW electrolyser. Water Treatment for Green Hydrogen, whitepaper by Eurowater

[5] Brintbranchen had 8 projects, but based on public information DNV assumes PtX Cluster Zealand and Dynelectro Kalundborg to be the same project.

Table 6-2: Announced PtX projects on Zealand (source: Brintbranchen, DNV, project's websites)

Project	Location	Production capacity (MW)	E-fuel production (tonnes/ year)	Startup year	Main product	Partners	Estimated CO_2 demand (tonnes/ year)
Green Fuels for Denmark	Copenhagen	1300	275 000	10 MW in 2025 Gradual increase to full capacity after 2030	Kerosene, methanol	Ørsted, Copenhagen Airports, A. P. Moller-Maersk, DSV Panalpina, DFDS, SAS, Everfuel, NEL, Molslinjen, Topsoe, COWI, Københavns Kommune, Region Hovedstaden	850 000
Arcadia eFuels Vordingborg	Vordingborg	254	80 000	2026	Kerosene	Arcadia eFuels ApS, DCC & Shell Aviation Denmark A/S, Topsoe, Sasol	250 000
European Energy Jammerland Bugt	Jammerland Bugt (Kalundborg)	240 (offshore wind power)	Unknown	Unknown	European Energy have several renewable energy and PtX.projects, but there is no specific information on PtX in this location	European Energy	N/A
European Energy Freerslev Energipark	Hillerød municipality	180 MW solar power (PtX size unknown, approx. 20 MW for 3000t H2)	16 000	2024 or 2025	Hydrogen and later potentially e-methanol	European Energy	22 500
Vordingborg Biofuel	Vordingborg	240	200 000t biomethanol 100 000t e-methanol	2025	Biomethanol and e-methanol	Vordingborg Havn, Topsoe, Rambøll, Biofuel Technology A/S, Kinetic Biofuel	0 (assume they will be covered with their own biogenicic CO_2)
Kragerup Gods PtX	Kalundborg municipality	6	0	2023/2024	H2	Siemens Gamesa Renewable Energy, Kragerup Gods	0
H2RES	Copenhagen	2	0	2022	H2	Ørsted, Everfuel, NEL Hydrogen, Green Hydrogen Systems, DSV Panalpina, Brintbranchen, Energinet	0
PtX Cluster Zealand	Kalundborg	0.1	0	2023?	H2 (with goal to "Make green fuels cheaper")	Dynelectro, Unibio, Nordphos, Algiecel, G2B, Ørsted, Evida, DTU, Gas Storage Denmark, Knowledge Hub Zealand, Energy Cluster Denmark, Erhvervshus Sjælland	0

The map in Figure 6-1 shows the locations of the PtX projects at Zealand. The bubble size indicates the size of the project. The projects with green color are the ones who have announced potential e-fuel production and hence require CO_2.

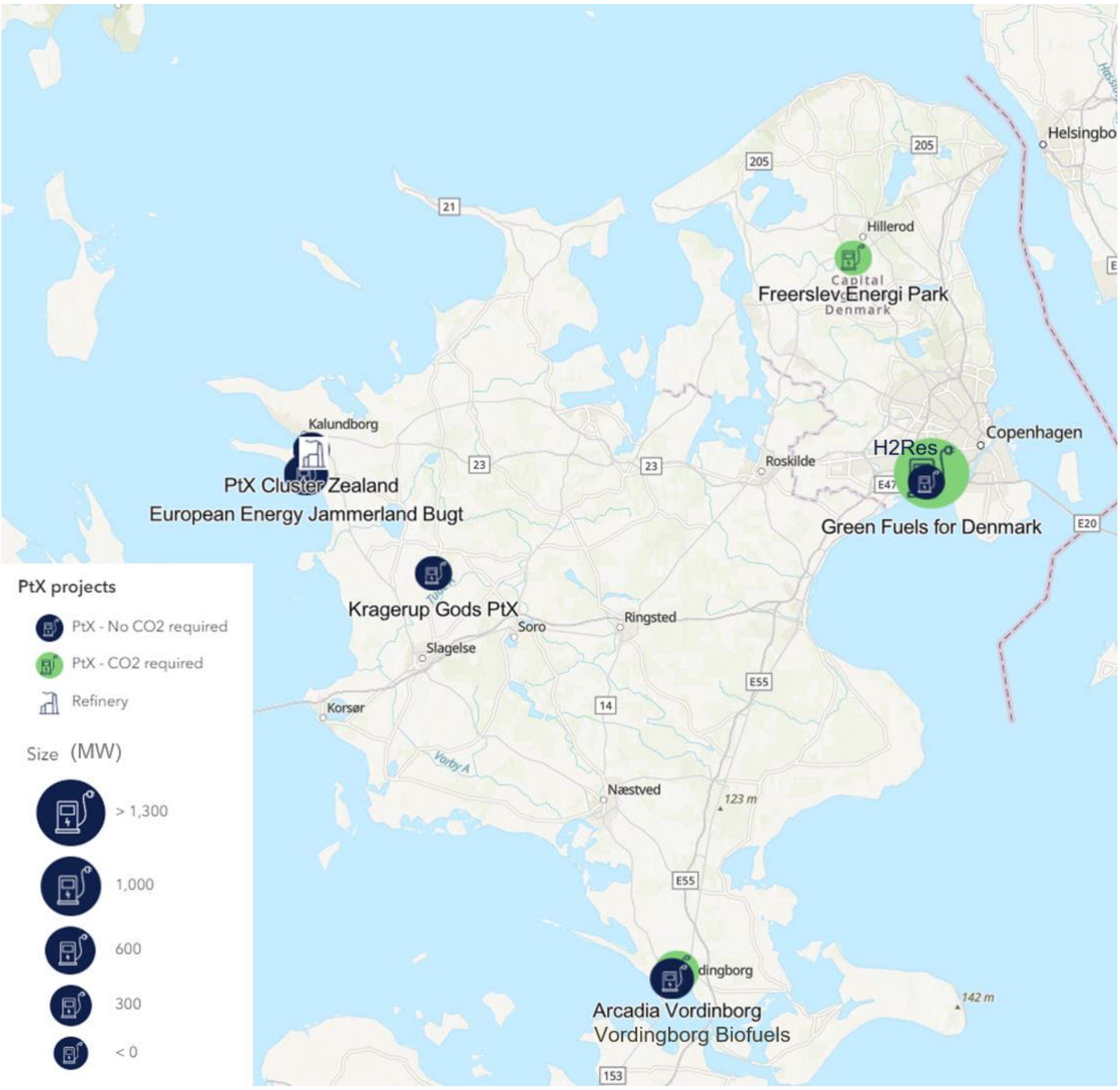


Figure 6-1: Map of PtX projects at Zealand. Green projects plan e-fuel production and require CO_2

Figure 6-2 (left) shows the total PtX capacity at Zealand, while Figure 6-2 (right) shows the estimated CO_2 demand from these projects.

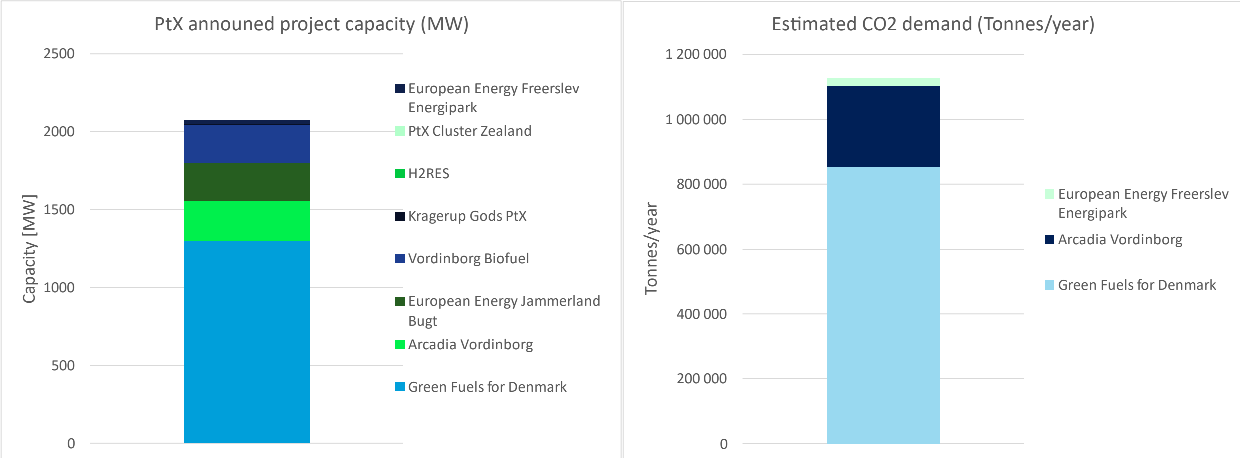


Figure 6-2: Announced PtX projects in Zealand (left) and estimated CO_2 demand (right)

Below are short descriptions of the e-fuels projects at Zealand.

6.1.1 Green Fuels for Denmark

Green Fuels for Denmark is a consortium between Ørsted, various leading companies within road transport, shipping, aviation and other relevant actors. The project was granted IPCEI (Important Project of Common European Interest) status in 2022 [33]. The project is located at Avedøre Power Station in Copenhagen. According to Ørsted [34] the project will use renewable energy from offshore wind and biogenic point-source CO_2.

The project will be constructed in three phases:

- Phase 1 (2025) 10 MW producing 1000 tonnes of renewable hydrogen for heavy road transport per year.
- Phase 2A (2027): 100 MW producing 50 000 tonnes per year of e-methanol for shipping and e-kerosene to potentially fuel Denmark's first green domestic air connection
- Phase 2B (2028/2029): 300 MW producing more than 100 000 tonnes of e-methanol and e-kerosene per year
- Phase 3 (Beyond 2030): 1300 MW producing 275 000 tonnes of e-fuels per year.

6.1.2 Arcadia eFuels Vordingborg

Arcadia are planning an e-fuel production plant in Vordingborg. The electrolyser will have a capacity of 250 MW, and the plant will produce approximately 100 million liters sustainable aviation fuels (SAF) per year (80 000 tonnes SAF and naphtha [35]). Topsoe and Sasol are selected as technology providers [36]. As of May 2023 final investment decision had not been taken, but the aim is plant startup in 2026.

Figure 6-3: Arcadia eFuels Vordingborg [37]

6.1.3 European Energy Freerslev Energipark

European Energy currently have several wind, solar and PtX projects in development in Denmark, with focus on producing hydrogen, e-methanol and e-SAF **[38]**. Two of their projects are located on Zealand – in Hillerød Municipality (Freerslev Energipark) and Jammerland Bugt cluse to Kalundborg. In Freerslev Energy Park in Hillerød Municipality European Energy are planning a 180 MW solar power park. In connection to this plant they are planning a hydrogen facility and potential e-methanol production. Based on available public information, the project in Jammerland Bugt is offshore wind, with no specific PtX plans announced.

European Energy is also developing a concept for a PtX plant at Kassø, Aabenraa, illustrated in Figure 6-4. The numbers are equivalent to the project in Hillerød. They plan to produce 3000 tons of hydrogen and potentially add biogenic CO_2 to produce e-methanol for the transport and plastics sector [39]. As shown in the figure, they plan a combination of direct connection to the solar power plant and grid connection.

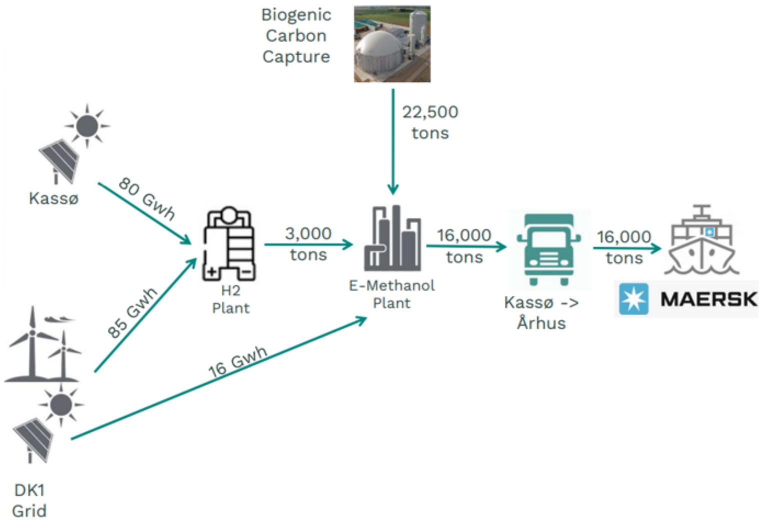


Figure 6-4: European Energy's hydrogen and potential e-methanol plans

6.1.4 PtX Cluster Zealand

PtX Cluster Zealand currently don't have a specific plan for e-fuels production (only hydrogen production), but their goal is to make green fuels cheaper. PtX Cluster Zealand is a consortium consisting of five tech companies at Zealand (Dynelectro, Unibio, Nordphos, Algiecel and G2B) as well as several utilities and other central actors such as Knowledge

Hub Zealand, Energy Cluster Denmark and Erhvervshus Sjælland [40]. The companies collaborate on technology development that can help reduce the cost of PtX by up to 20 percent.

PtX Cluster plan construction of a container-based prototype electrolysis plant of 100 kW at Kalundborg utility, which is planned to be a 12 month project. Part of the project is to investigate coupling of new PtX technology to the existing industry symbiosis in Kalundborg, where companies have collaborated and shared resources for many years. According to Brintbranchen data there is, in addition to the PtX Cluster Zealand project, a small PtX project (30kW) planned by Dynelectro and Rambøll, but DNV expects this to be part of the PtX cluster Zealand project.

6.2 Potential locations for future PtX projects

DNV has also analysed other optimal locations for establishing new PtX plants, i.e. where companies might establish PtX facilities in the future. This is to understand where there can be synergies between different opportunities in the future – such as where there will be CO_2 demand for e-fuel production.

DNV has analysed and mapped several parameters that are relevant to consider when searching for the optimal location for PtX on Zealand – some parameters more important than others. The mapped data is listed in Table 6-3.

Table 6-3: Data mapped for screening of potential PtX locations

Category	Data mapped	Comment
PtX projects	Announced PtX projects on Zealand	Competitors or collaboration/synergies
Power and grid	Transmission grid	Locations with strong grid
	Production surplus/consumption coverage areas (2035)	Areas with future potential available power and grid. Consumption coverage areas are calculated as annual electricity production divided by annual electricity consumption per municipality. Higher consumption coverage = higher production surplus
	Offshore wind plans	Future available power and strong transmission grid
Transportation and local offtake possibilities	Deep sea ports	Local offtake and transportation possibilities
	Maritime activity	Local offtake possibilities
	Airports	Local offtake possibilities
	Refineries	Local offtake possibilities.
Bi-product offtake	District heating network	Waste heat offtake (the plant can sell waste heat to district heating networks).
Other input access	Access to CO_2/ CO_2 emitters	Important for e-fuel production. For H2 production this can be potential industrial hydrogen offtakers.
	Access to water	A PtX facility require large amounts of water, both purified water for the electrolysis and cooling water.

6.2.1 Power and grid

Access to input is the most important criteria when establishing a PtX facility. To produce hydrogen through electrolysis you need power and water. While access to water can be a challenge for some locations, the key input that must be secured is access to power.

PtX plants can either be directly connected to a renewable power plant or connected to the grid, or a combination of the two by getting power from the grid in hours when there is no wind/solar generation.

EU regulation determines requirements on renewable electricity to produce RFNBO's so they can count as fully renewable. Key requirements are listed below [41]:

- Hydrogen produced from directly-connected renewables: The renewable installation needs to be commissioned no earlier than 36 months before the electrolyser
- Hydrogen produced from the grid:
    - If the electrolyser is in a bidding zone where the renewable share exceeds 90%, the hydrogen counts as fully renewable
    - For bidding zones with less than 90% renewables the plant can fulfil the requirements of electricity sourcing through a power purchase agreement (PPA), given that conditions related to additionality, temporal correlation and geographical correlation are met.

As the grid situation is constantly changing with new consumption, production and grid projects, it is challenging to know where there will be available capacity to connect a planned PtX facility. To get a view on favorable areas from a power and grid perspective, DNV has looked at:

- Where the transmission grid is
- Consumption coverage and production surplus per municipality
- Offshore wind plans

6.2.1.1 Transmission grid

Locating a PtX facility close to the transmission grid and transmission grid substations is favorable as there is generally higher probability of getting access to enough grid capacity here, and you avoid having to build long connection lines. Figure 6-5 shows the electricity transmission system at Zealand.

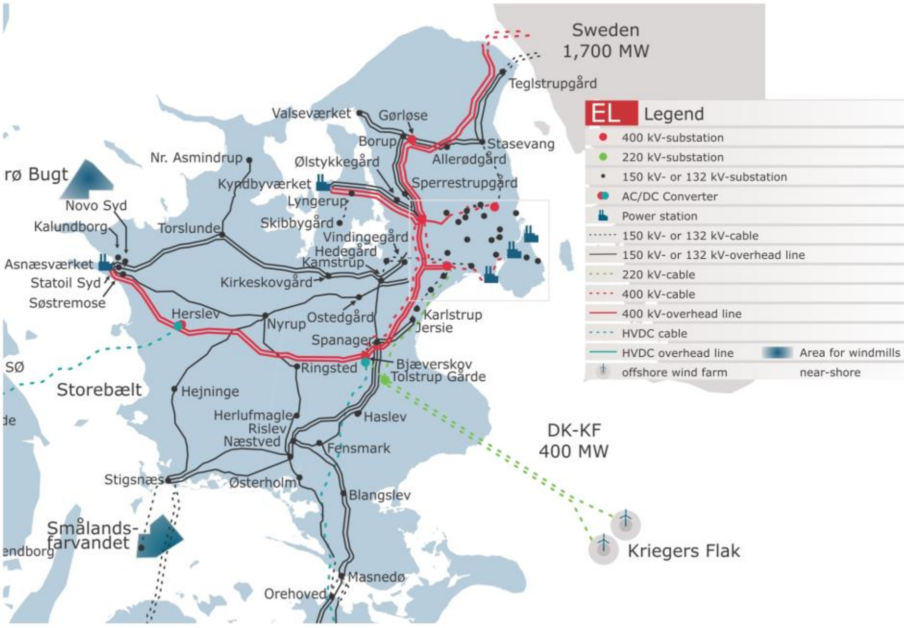


Figure 6-5: Zealand electricity transmission system, 2020, Energinet [42]

6.2.1.2 Consumption coverage and production surplus

Figure 6-6 shows how the Danish electricity grid is expected to look in 2030. Zealand is in general a consumption dominated area, especially around the Copenhagen area, but south Zealand (and some parts of North Zealand) is expected to be production-dominated in 2030.

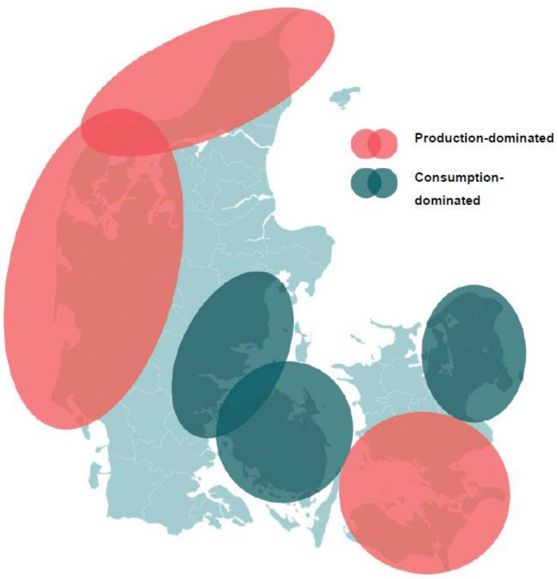


Figure 6-6: Capacity map of the Danish electricity grid (2030 expectation). Source: Energinet/PtX strategy

Energinet publishes interactive capacity maps on their web site [43] – Both *production maps* showing available capacity for connecting new production to distribution and transmission grid, and *energy maps* showing geographical distribution of production and consumption in the transmission through *consumption coverage*, *production surplus* and *technology distribution*.

There are no maps showing available capacity per substation for connecting new consumption, so consumption coverage has been used to indicate where there can be available capacity to connect new consumption such as a PtX facility. The consumption coverage is obtained by dividing the annual electricity production by the annual electricity consumption. These calculations incorporate aggregated values for stations situated within the same county. If the consumption coverage exceeds one, it indicates a production surplus, implying that the area collectively generates more electricity than it consumes throughout the year. However, it does not provide insights into the specific production and consumption profile. Figure 6-7 shows expected consumption coverage by municipality at Zealand in 2035. The CO_2 pipeline concept from chapter 5 is included in the map for reference.

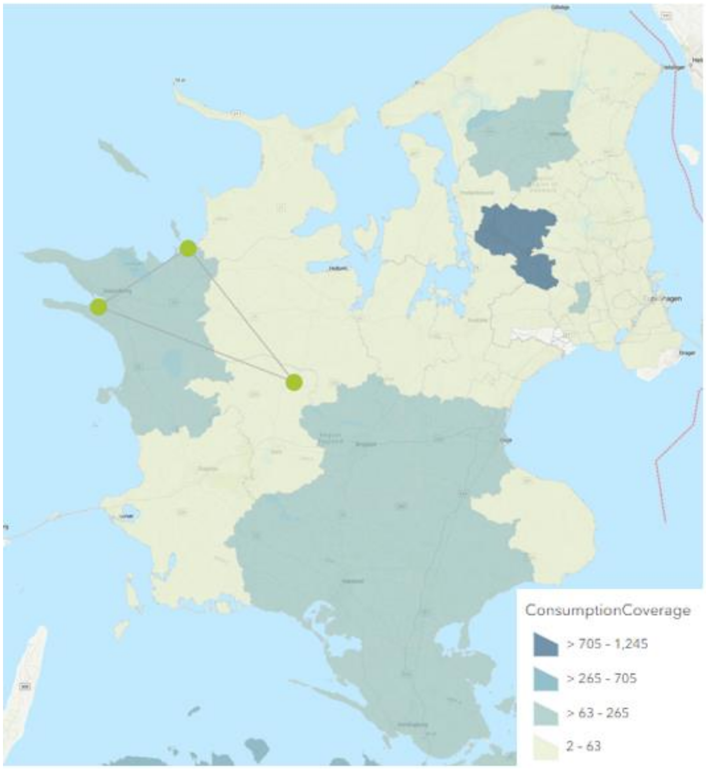


Figure 6-7: Consumption coverage (2035) The consumption coverage is obtained by dividing the annual electricity production by the annual electricity consumption. Source: Energinet [44]

6.2.1.3 Offshore wind plans

Figure 6-8 shows operational and planned offshore wind farms around Zealand. The locations of the planned offshore wind farms link well with the municipalities expecting production surplus (high consumption coverage) mentioned in the previous section (Figure 6-7).

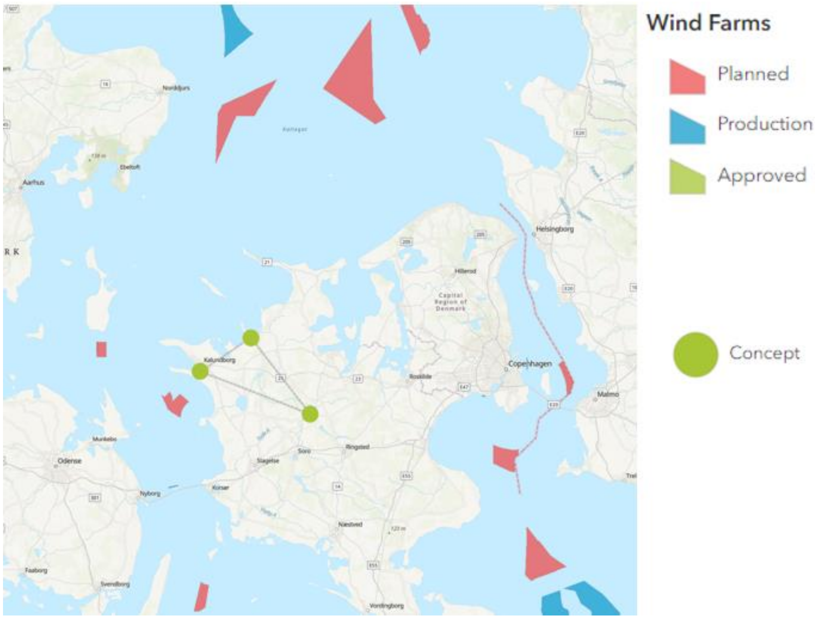


Figure 6-8: Offshore wind plans around Zealand. Source: EMODnet [45]

6.2.2 Transportation and local offtake possibilities

When planning a PtX facility logistics around transporting the end product ("X") to offtake locations is important. The most suitable transportation method depends on volumes, location and type of end product, but ship is seen as a transport solution suitable for most end products. Some also look at train or road transport by trucks. Hydrogen and ammonia can also be transported by pipelines, which makes locations close to proposed or planned hydrogen pipelines attractive. Hydrogen pipelines have not been a part of this mapping as the focus is on screening locations for PtX with CO_2 demand.

For large-scale PtX facilities possibilities for transporting the product to different offtake locations (here mainly further south to Europe) will often be more important than looking for local offtakers. But local offtakers can be an important first step to get a project up and running. PtX fuels are expected to play an important role in "hard-to-electrify" sectors such as shipping and aviation, and locating a facility close to ports or airports can be an advantage.

6.2.2.1 Maritime deep-sea ports and maritime fuel consumption

Proximity to a deep sea port (i.e. a port suitable for goods traffic) will be important to transport the end product to offtake locations by ship. In addition to being transport terminals, ports give potential local product offtake from the maritime sector. (e-)methanol and (e-)ammonia are seen as promising fuels for decarbonizing the maritime sector, and potentially also e-diesel/MGO as a drop-in fuel in existing engines. The ports visualized in the figure below are collected from the European Marine Observation and Data Network (EMODnet)), showing all main ports for goods traffic.

The blue circles show the estimated annual fuel demand at each port, based on AIS data for 2022 and DNVs tool for fuel consumption estimation. In this map the fuel demand for each voyage is assigned to the start port, so this does not represent where ships bunker today, but is an indication on where there can be demand for renewable and low-carbon fuels in the future.

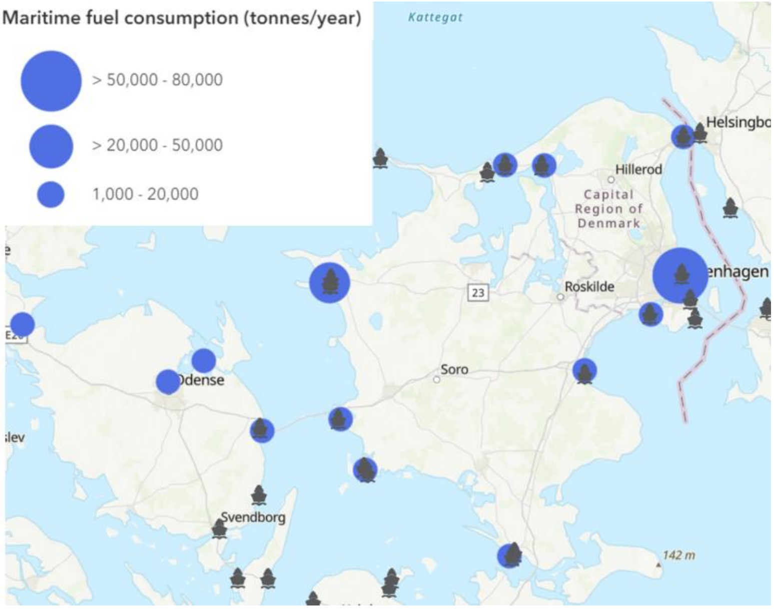


Figure 6-9: Estimated maritime fuel consumption per port (source: DNV)

6.2.2.2 Airports

Like maritime, aviation is a “hard-to abate” sector. The shortest flights can be electrified, medium-haul flights can potentially use hydrogen in the future, while to decarbonize the long-haul flights (which consume most of the fuel and emits most of the CO_2 from the sector) sustainable aviation fuels (SAF) are needed. SAF are “drop-in fuels” that have the same properties as fossil aviation fuel but is produced artificially. SAF can either be based on biomass (biofuel), fossil waste (Recycled Carbon Fuel, RCF), or electricity (Renewable Fuel of Non-Biological Origin, RFNBO or low-carbon e-fuel).

ReFuelEU Aviation is the EU’s first regulation mandating sustainable aviation fuel blending at European airports. April 2023 there was a political agreement on binding volumetric SAF mandates from 2025 with synthetic aviation fuel (RFNBO) sub mandates from 2030 [46]:

- The overall SAF mandate starts at 2% in 2025 and gradually increases to 70% in 2050.
- The synthetic fuel sub mandate starts at 1.2% in 2030 and gradually increase to 35% in 2050.

These blending mandates gives large demands for SAF, including e-SAF, in the EU from 2025. Hence, if planning a PtX facility, the aviation sector will be a potential offtaker, and locating the facility close to airports or other aviation fuel infrastructure will be beneficial (if the “X” is SAF).

In addition to the EU blending mandates, the Danish Government has announced a goal to make all domestic flights fossil fuel free by 2030 [47].

Today there are two larger airports at Zealand; Copenhagen and Roskilde, with domestic flights to other destinations in Denmark.

6.2.2.3 Refineries

Locating an e-fuel production facility close to a refinery is beneficial for:

– Using existing refinery to upgrade e-crude to final fuel (don't need to build an additional refining step at the e-fuel facility)

– Can utilize existing logistics and infrastructure.

There is only one refinery at Zealand; Kalundborg Refinery (mapped in Figure 6-1).

6.2.3 Bi-product offtake (district heating network)

A significant amount of the electricity input to a PtX facility goes to waste heat. An electrolyser typically has an efficiency of 60-70% -i.e. 30-40% of the energy input goes to heat, and even more when adding additional steps to the process. An opportunity to reduce waste of energy and create an additional income stream for the PtX facility is to sell this heat to a district heating grid. Locations close to a district heating network can hence be favorable for improving the business case of a PtX plant. Figure 6-10 shows district heating networks areas in Zealand.

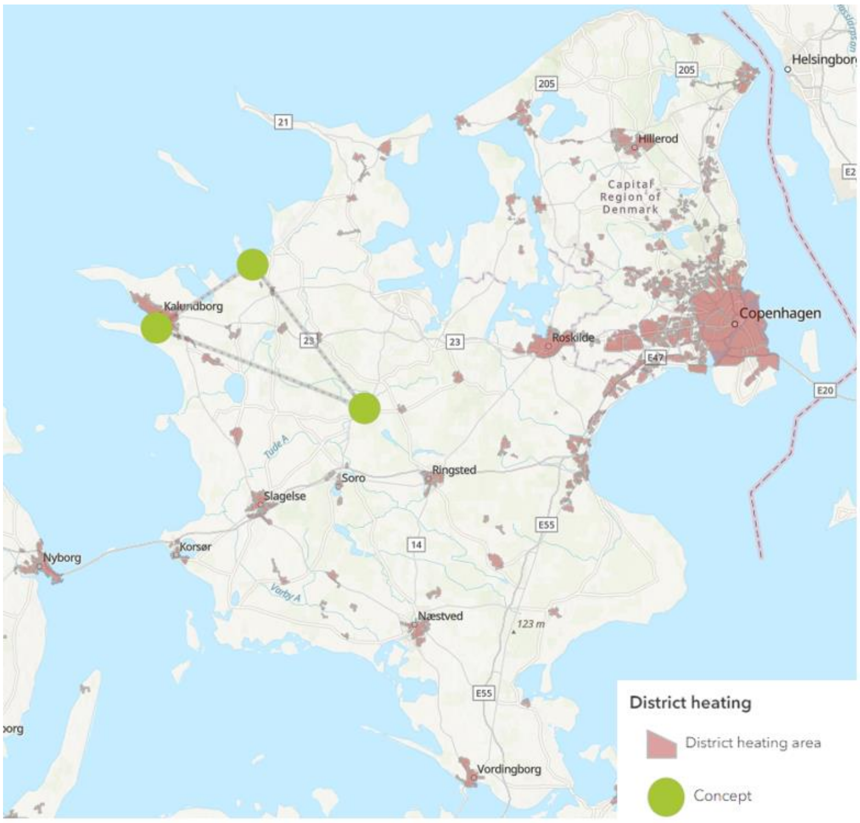


Figure 6-10: District heating networks at Zealand

Another bi-product from PtX facilities is oxygen. Approximately 8 kg of oxygen is produced per kg of hydrogen. There can be significant revenue potential from selling oxygen to a nearby oxygen consumer, such as food industry, hospitals or high temperature industries using oxyfuel burners. Oxygen can also be used in water-purification plants, where the oxygen is forced through water to increase the production of bacteria that metabolize wate products in the water [48], [49].

6.2.4 CO_2-emitters and CO_2 infrastructure

Access to CO_2 is important for e-fuel production. CO_2 can be biogenic or fossil from industrial facilities or power plants, or it can be captured directly from air (Direct Air Capture, DAC).

A criteria for a fuel to qualify as RFNBO is at least 70% GHG emission reduction compared to a fossil comparator. The Delegated Act on Article 28 in REDII sets the requirements to the methodology to assess greenhouse gas emission savings from RFNBO (and recycled carbon fuels). Key formulations to understand are what types of emissions can be considered as “avoided”, i.e. what CO_2 sources does not have to be included in the emission calculations and can be used to produce an RFNBO. A key takeaway from the Delegated Act is that fossil CO_2 sources can be considered as “avoided” before 2041 (as long as they are from an activity included in EU ETS or similar carbon pricing scheme), while from 2041 the CO_2 must be biogenic or from DAC to be counted as “avoided”[6]

The emitter map from section 4.1 is useful to include when screening locations, as well as any planned CO_2 transport infrastructure.

6.2.5 Water supply

Green hydrogen production is based on water, and production of 1 kg hydrogen takes approximately 9 liters of water, or approximately 200 L water/hour per MW electrolysis capacity [50]. In addition, water is needed for cooling however the exact quantity depends more on-site specific circumstances. The most common water sources for hydrogen production are surface water, seawater, groundwater, or wastewater.

As water is a scarce resource the production of green hydrogen calls for sustainable water management, Therefore, reuse of water such as wastewater for onshore hydrogen production can be considered as sustainable alternative. To support the development of sustainable water management practices, the EU has developed the European Water Re-use Regulation, for safe and sustainable use of treated wastewater [51].

The water for electrolysis must be ultra clean to avoid corrosion and to maximize the performance of the electrolysis. As water needs to be ultra clean then water treatment (such as purification, desalination etc.) is necessary. In addition, the quality of the water will have to meet certain standards depending on which type of technology (PEM, SOEC or PMEC) used for the hydrogen production.

The supply of water and wastewater treatment is estimated to be 1 percent of total capex for a hydrogen plant. In the identified locations for PtX-production the amount of wastewater is estimated to be sufficient for the production of the planned hydrogen amounts. However, in terms of regulation there is a challenge with permitting in the Danish Environmental Protection Act using wastewater in Denmark [52].

For some H2 plants seawater can be used, but while the demand of energy for purifying 1 m3 of water is estimated to be 2.2 kWh for wastewater, 6-7 kWh is estimated to be used to purify 1m3 of seawater [50].

[6] To be considered as ”avoiding emissions”, the CO_2 must come from a) An activity listed under Annex I of Directive 2003/87/EC (covered by EU ETS) and has been taken into account upstream in an effective carbon pricing scheme, This is only valid until 01.01.2041 (01.01.2036 for CO_2 from electricity generation) b) Direct Air Capture (DAC), c) Production of biofuels of combustion of biofuels, RFNBOs or RCFs, d) A geological source and the CO 2 was previously released naturally.

6.2.6 Summary map, key takeaways and potential locations

Figure 6-11 shows a summary map of Zealand containing all the data layers described in the previous sections.

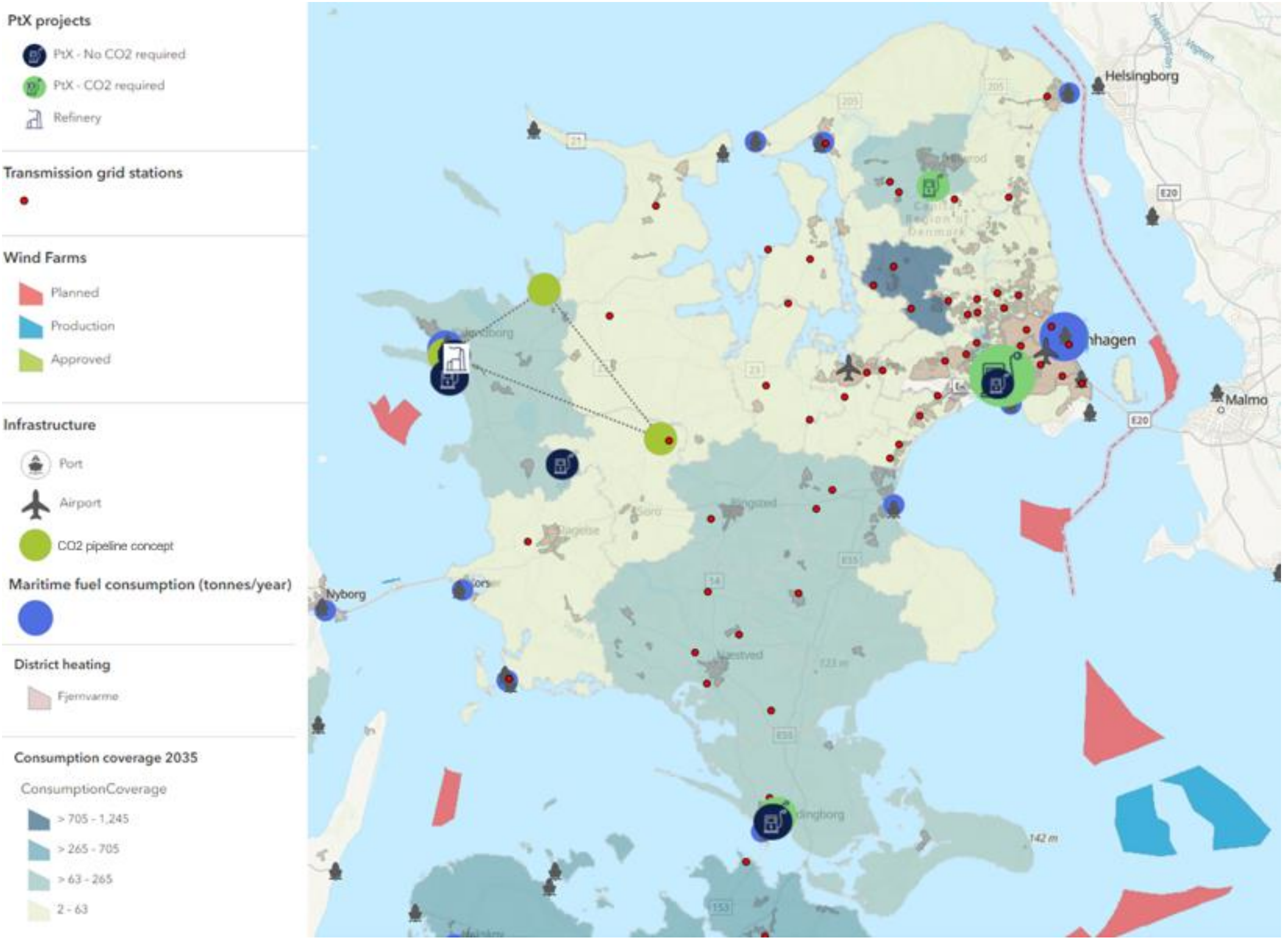
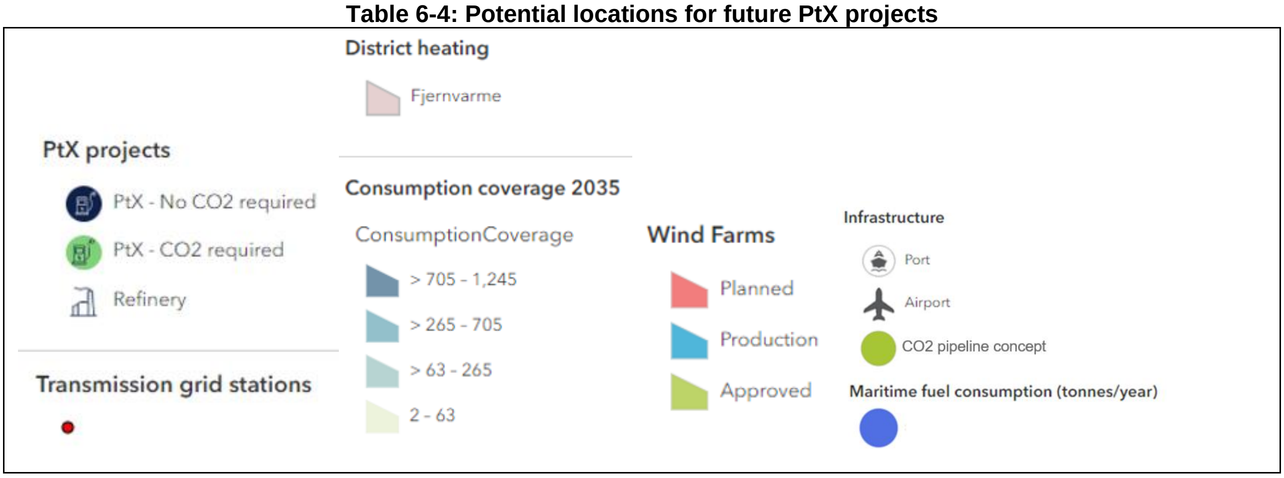
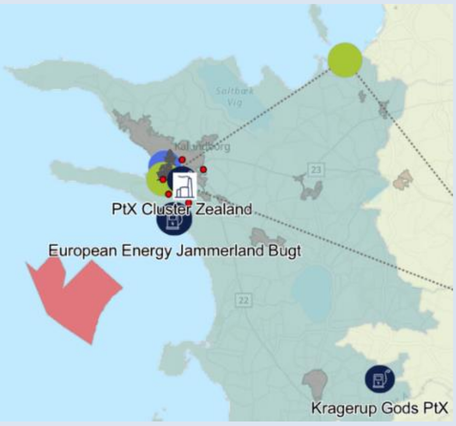
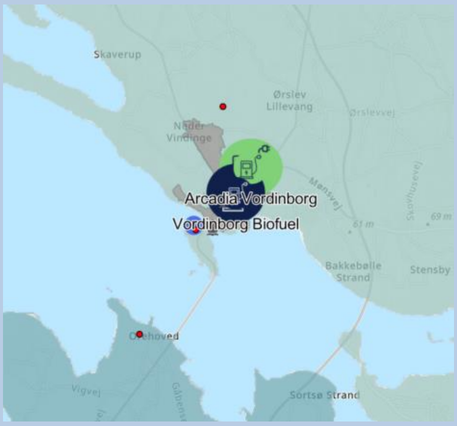
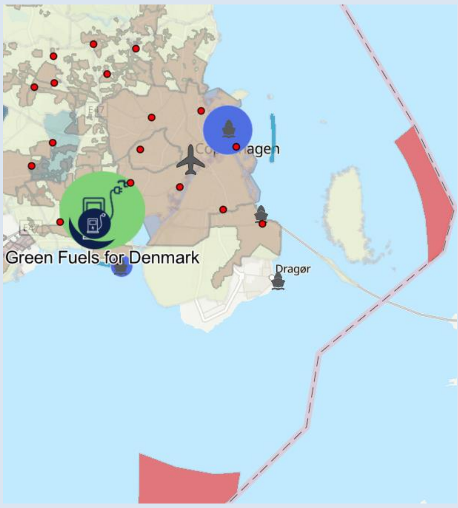


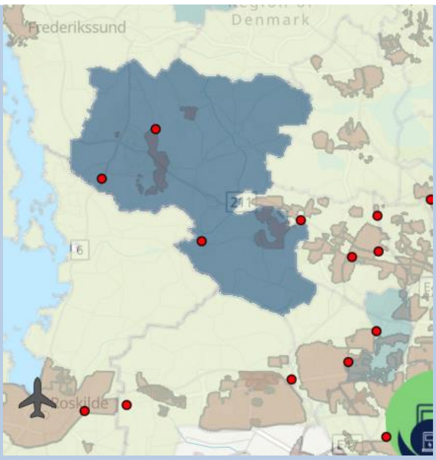
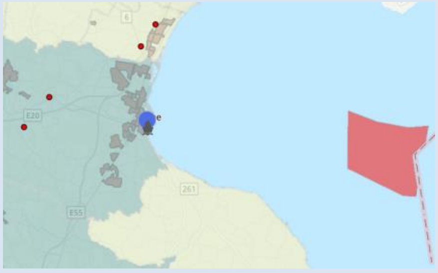
Figure 6-11: Summary map of infrastructure for potential PtX locations

The most “optimal“ locations for a company to establishing PtX projects depends on the purpose of the company – what the end product is, whether local offtake is important, or the aim is export, the size of the project etc. The areas that already have announced PtX projects score high in this screening exercise:

Table 6-4: Potential locations for future PtX projects



Location	Pro's	Con's
Kalundborg 	- Power surplus - Offshore wind planned nearby - High maritime activity and deep sea port - Refinery - 400 kV + 132 kV grid and several high voltage transformer stations - District heating network - Available CO_2	- Several ongoing PtX projects (not necessarily negative)
Vordingborg 	- Power surplus - Deep sea port with development plans and strong green profile [53] - District heating network	- Several ongoing PtX projects (not necessarily negative) - A lack of CO_2 sources nearby
Copenhagen area 	- High maritime activity and deep sea ports - Nearby airports (fuel offtake) - Several high voltage transformer stations - Proximity to offshore wind plans	- Area is consumption dominated, so access to power and grid can be a challenge - Several ongoing PtX projects (not necessarily negative)
Egedal municipality	- Large future production surplus expected	

	- 400 kV transmission grid and several high voltage transformer stations - Proximity to two airports and large offtake potential around Copenhagen area	
Køge 	- Future production surplus expected - Proximity to offshore wind plans - Maritime offtake potential and deep sea port	

6.3 Infrastructure visions and possible integration

At present there are several infrastructure visions with potential implications for the planned activities to develop hydrogen production and capture and storage of CO_2 on Zealand. Production of e-fuels for aviation, shipping or e-methanol for other industry purposes is highly dependent on a well-developed and integrated infrastructure to get the full benefit of synergies between different infrastructure branches such as CO_2, hydrogen, electricity, water, district heating and ports as described in section 6.2.

6.3.1 Potential CO_2 infrastructure

Denmark has favorable conditions for storing CO_2 in the underground. The Geological Survey of Denmark and Greenland has estimated that the Danish Underground can contain up to 22 billion tons of CO_2 on a Danish strategy for CCS [54]. A broad majority of the Danish parliament has agreed on a vision to develop Denmark as a European hub for storage of CO_2. This vision relies on extensive development of CO_2 capture plants on major point sources in Europe especially in Denmark's neighbouring countries and an infrastructure that facilitates the most cost-effective transportation of CO_2 from the point source to storage onshore or offshore.

The North Sea Basin Task Force [55] consist of public authorities and private entities from countries around the North Sea with the purpose to develop transport, injection and storage of CO_2 in the North Sea Area. At present the countries behind NSBTF consist of Denmark, Flanders, France, Germany, The Netherlands, Norway, and the UK. The countries behind NSBTF have developed a strategic regional plan for cross-border CO_2-transport and storage infrastructure with the main objective to develop a CO_2 transport and storage network in the North Sea.

The Trans-European Network for Energy (TEN-E) regulates CO_2 infrastructure among European countries – not only for pipelines but also shipping, rail and truck transport. A range of large-scale CCS-projects are under development in

European Countries and the projects listed as Projects of Common Interest (PCI) involves connecting at least two EU-member countries.

Import of CO_2 to Zealand or other places in Denmark could potentially be supported by CO_2 pipelines from Zealand to Germany and Sweden. Pipelines to neighboring European countries would contribute to the development of Denmark as European Hub for storage of CO_2.

EVIDA has published results from the market dialogue for CO_2-infrastructure in Denmark [56]. According to the results from the dialogue there a feasibility study of Danish point sources will shed light on the need for a CO_2-infrastructure in Denmark. A feasibility study will create an overview of where there could be potential to build a CO_2 pipeline grid. This will also create more transparency for the companies in the market when it comes to where a CO_2-pipeline grid could be expected to support their business. Furthermore, the report concludes that there is a demand in the market for an analysis of the market potential in a cross-border CO_2 infrastructure.

6.3.2 Potential Hydrogen infrastructure

Multiple actors have done feasibility studies for a hydrogen infrastructure in Denmark

Together with German Gas TSO, Gasunie, Energinet has published an assessment of the hydrogen market and proposed a network coupling the western part of Denmark with Germany. A hydrogen network between Denmark and Germany will increase market opportunities for hydrogen developers in Denmark planning to produce hydrogen either onshore or offshore as there is a huge industrial demand for hydrogen in Germany. The market assessment estimates that Germany will become a net importer of green hydrogen, with demand for green hydrogen forecasted to be 93 TWh in 2030 increasing to more than 500 TWh in 2050.

Figure 6-12: H2 Network between Denmark and Germany, Energinet and Gasunie

The European Hydrogen Backbone [57] is an initiative that consists of specific TSO's and other infrastructure operators across Europe. The European Hydrogen Backbone has mapped a potential grid made of existing and new hydrogen pipelines. The purpose is to develop a more liquid, pan-European, competitive hydrogen market that can contribute to the decarbonization of industry in Europe. The European Hydrogen Backbone, which is a vision for 2040, connects continental Europe with the Northern part of Europe with hydrogen pipelines onshore and offshore via Denmark and Zealand. Offshore wind from Denmark could be used for hydrogen production and hydrogen pipeline grid connecting Denmark to Sweden, Norway, Finland and the Baltics will allow green hydrogen to be transported to industry in Northern Europe demanding green hydrogen. A well-integrated hydrogen infrastructure will benefit industry and companies working with both CCUS and hydrogen.

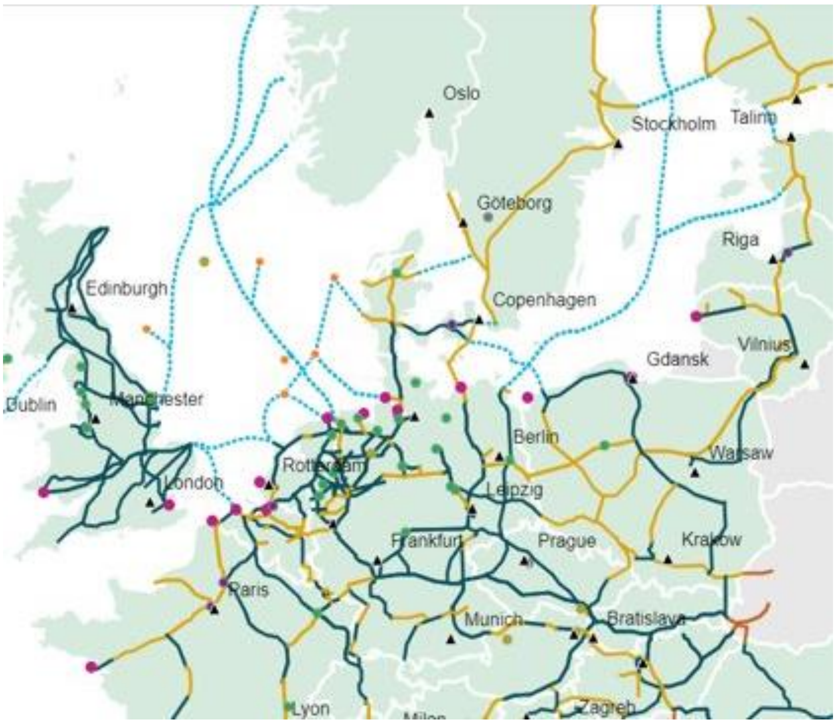


Figure 6-13: European Hydrogen Backbone map

The Ostend declaration, the Esbjerg declaration and the Marienborg declaration calls for huge built out of offshore wind.[7] This will have implications for the development of hydrogen grid onshore and offshore in Northern Europe as well as a stronger electricity grid, and more interconnectors to handle the increasing amount of power generated from offshore wind.

6.3.3 Integration and synergies

There are likely positive benefits related to burying CO_2 pipelines and hydrogen pipelines together. However, further analysis of safety issues with two pipelines in the same pipeline trace will have to be done. There might be safety issues related to the characteristics of materials used for the two pipelines. A thorough risk assessment of the materials of each pipeline used for hydrogen and CO_2, and the risk of burying the two pipelines in the same trace will have to be studied in greater detail. Collocation of the pipelines will rely on whether there is consumption or production of both hydrogen and CO_2 at the same time. The market dialogue on CO_2 infrastructure also calls for CO_2 pipelines and hydrogen pipelines to be collocated and synergies with other infrastructure such as district heating have to be thoroughly analyzed.

The collocation of pipelines will also foster the development of new industrial PtX-CCUS clusters and create benefits for the companies working in an industrial symbiosis as in Kalundborg.

[7] Ostend declaration (2022), Esbjerg declaration (2022), Marienborg declaration (2022).

7 PERSPECTIVES AND REALIZATION OF THE POTENTIALS IN THE AREA

7.1 Introduction

In 2021 Denmark's CO_2 emission were according to Energistyrelsen 43.9 million tons CO_2-equivalents [58]. Denmark's climate targets are to achieve a 70 % reduction in carbon emissions by 2030 and to achieve full climate neutrality by 2050 [59]. To follow up on these targets the Danish Government has launched an ambitious CCUS strategy to reduce CO_2-emissions especially in hard to abate sectors such as industries and waste management [60].

In relation to this strategy, Ørsted has received roughly 8 billion DKK in funding to capture CO_2-emissions at Asnæsværket (ASV) and Avedøreværket (AVV) power plants in Zealand which makes up 430 000 MTPA of CO_2. The captured CO_2 then needs to be transported in a cost-efficient way to either storage facilities or facilities for further processing.

This chapter aims to show how a CO_2 pipeline infrastructure in (North-western) Zealand can facilitate the efficient transport of CO_2 , as well as benefit and create value for a range of CO_2 emitters and industries in Zealand that use CO_2 in their production processes. To show this, a high level qualitative socio-economic cost-benefit analysis, based on the findings in previous chapters will be performed.

7.2 Scope and limitations of the analysis

Ørsted will install CO_2 capture technology at Asnæsværket and Avedøreværket with government support. The starting point for the analysis is therefore a hypothetical situation where CO_2 capture at Asnæsværket has already been built. There is currently no CO_2 pipeline to onshore storage sites in Denmark. Hence, as a minimum, some investments to facilitate transport of the CO_2 by ship for offshore storage have to be made. This is called the Business-as-Usual Concept (BaU).

In practice this means that the climate-effect for Asnæsværket of building a pipeline infrastructure compared to shipping the CO_2 to an offshore site is zero[8]. However, building a CO_2 pipeline can facilitate the cost-efficient transportation of CO_2 from other capture sites to storage and CO_2-processing sites. A pipeline can thus reduce costs and improve the business case both for CO_2 capture, use and storage at other sites in Zealand. This includes PtX initiatives.

The main focus of this analysis is thus to identify what added value a centralised CO_2 pipeline infrastructure in Zealand can give compared to a BaU- concept for all users of such a pipeline. Costs associated with storage is outside the scope of the analysis. This means that tariffs for transport and storage are not included. We do however assume that storage capacity is available once the infrastructure is ready to be commissioned.

A rough division between biogenic and fossil CO_2 will be made, and some assumptions will be included concerning the value of biogenic emissions.

The analysis will build upon the pipeline concepts described in section 5 of the report. Sensitivities with different volumes of CO_2 in MTPA will also be taken into account. A range of costs and benefits will be assessed in the analysis. As a general rule, only the direct effects are included. This means that indirect and ripple effects are not included in the assessment, but they may be explained where relevant.

The BaU concept is included as a separate concept. The other concepts will implicitly be compared to the BaU, meaning that the costs and benefits related to the BaU will be taken into account when assessing the cost and benefit effects for the other concepts and sensitivities. For example, when assessing the CAPEX of a concept, the cost of the BaU will be subtracted from the analysis. When assessing the climate effects, the CO_2 savings from the BaU are included in the other scenarios as well.

[8] For the sake of simplicity, we here disregard the potential differences in emissions from the construction and operation of ships vs. pipeline

7.3 Methodology

In the analysis all costs and benefits will be evaluated qualitatively in line with the table below. Where quantitative numbers of relevance exist, these are included.

The framework below is a useful tool when performing high level socio-economic analyses or when effects are difficult to give a monetary value. Each effect will be evaluated in terms of importance for society (Small-Medium-Large) and impact on society (Large/medium/small negative – No effect – Large/medium/small positive).

To carry out the evaluation, three questions are asked:

1. How many people are affected by each effect?
2. How large is the impact of each effect on the people affected?
3. What value are those effects given in a societal perspective?

When assessing *importance for society* one considers how important the effect is for the group of people affected by the effects of the measure (i.e. CO_2 pipelines). For this particular analysis, one would then consider both the businesses that could potentially connect to the CO_2 pipeline as well as how it would affect the Danish population in general in terms of how the pipeline can contribute to Denmark reaching their climate targets.

When assessing *impact on society* one considers how extensive the effect of the measure is compared to the BaU for the groups that will be affected.

Based on this evaluation, a qualitative value is given that ranges between plus 5 (+++++) and minus 5 (-----). It is important to note that the evaluation is high level, meaning that the *"plusses"* and *"minuses"* are scores and not quantitative values. The score of each effect is thus only comparable to a certain point within each effect and especially between effects.

A summary of the overall effects is nevertheless given in the "Summary of the analysis" section where the overall outcomes are commented on and compared.

		Importance for society		
		Small	Medium	Large
Impact on society	Large positive	+++	++++	+++++
	Medium positive	++	+++	++++
	Small positive	+	++	+++
	No effect	0	0	0
	Small negative	0/-	-	--
	Medium negative	--	---	----
	Large negative	---	----	-----

Table 7.1 Methodology and scoring of effects in the high level socioeconomic analysis

7.4 Concepts and sensitivities

There is a range of different concepts that can be realized and analysed, as shown in chapter 5. For this analysis we have limited the number of concepts to three which include different volumes of CO_2. The Charts below give a short summary of the concepts and CO_2 volumes analysed. Table 7-1 gives a summary.

Table 7-1 Summary of concepts analysed

Concepts	CO_2 volumes to consider:	Amount from each source:	Total:
1A Business as Usual	CO_2 transport from Kalundborg Hub to export via shipping.	0.5 MTPA from Kalundborg HUB	0.5 MTPA
3A No imports	Kalundborg Hub to Havnsø storage. Copenhagen HUB to Havnsø storage via Kalundborg	1 MTPA from Kalundborg HUB 4 MTPA from Copenhagen HUB	5 MTPA
3C With imports	Kalundborg Hub to Havnsø storage. Copenhagen HUB to Havnsø storage via Kalundborg Shipping imported to Havnsø storage.	1 MTPA from Kalundborg HUB 4 MTPA from Copenhagen HUB 7 MTPA from Shipping	12 MTPA

7.4.1 Concept 1A: Business-as-Usual

In the business-as-usual concept, no new CO_2 pipelines are built except from Asnæsværket to Kalundborg port. This concept includes liquification equipment and a storage tank for the liquid CO_2 so that the CO_2 can be liquified, and temporarily stored before it's moved to a ship and transported to an offshore storage site.

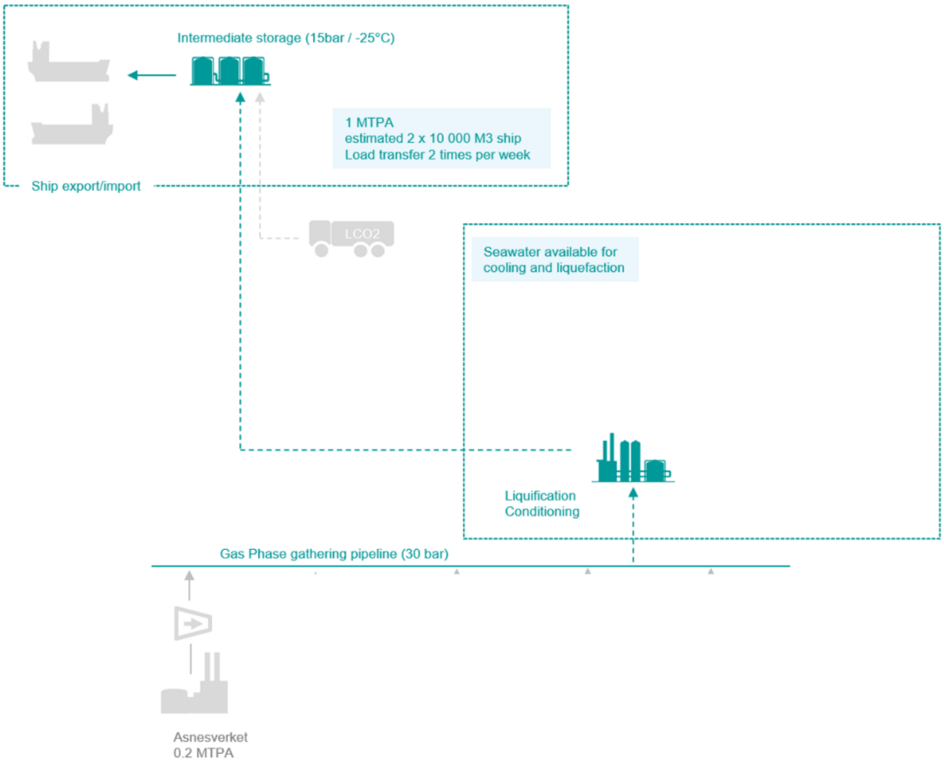


Figure 7-1 Design in the Concept 1A – Business-as-usual

7.4.2 Concept 3A: Kalundborg - CPH-Havnsø without imports

In Concept 3A, a CO_2 pipeline is built between Kalundborg where Asnæsværket is situated and Stenlille where a CO_2 storage testing site is planned, and the pipeline can connect to a CO_2 pipeline running from the Copenhagen area. From the Kalundborg hub a pipeline also runs to the Havnsø storage site. See figure 7.2 below for an illustration. The CO_2 volumes includes 1 MTPA from the Kalundborg region and 4 MTPA from the Copenhagen region giving a total CO_2 amount of 5 MTPA.

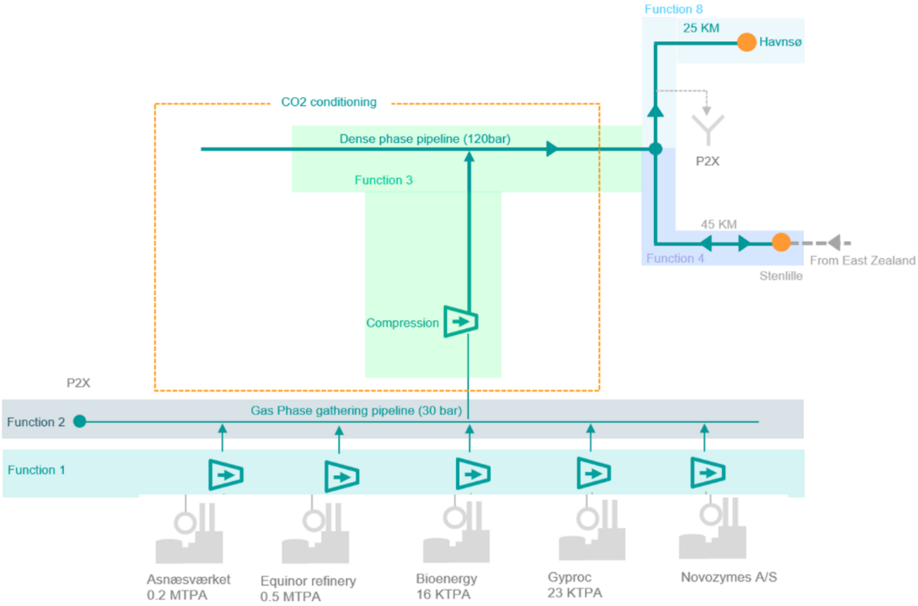


Figure 7.2 Design of Concept 3A – No imports

7.4.3 Concept 3C: Kalundborg - CPH-Havnsø with imports

In Concept 3C, the CO_2 network is identical to Concept 3A, except that there is also infrastructure to receive CO_2 imports in Kalundborg port. A CO_2 pipeline is built between Kalundborg where Asnæsværket is situated and Stenlille where a CO_2 storage testing site is planned, and the pipeline can connect to a CO_2 pipeline running from the Copenhagen area. From the Kalundborg hub a pipeline also runs to the Havnsø storage site. The dimensions of this pipeline is larger than in concept 3A to accommodate the larger volumes of CO_2. See figure 7.3 below for an illustration.

The CO_2 volumes includes 1 MTPA from the Kalundborg region, 4 MTPA from the Copenhagen region in addition to 7 MTPA from imports giving a total CO_2 amount of 12 MTPA.

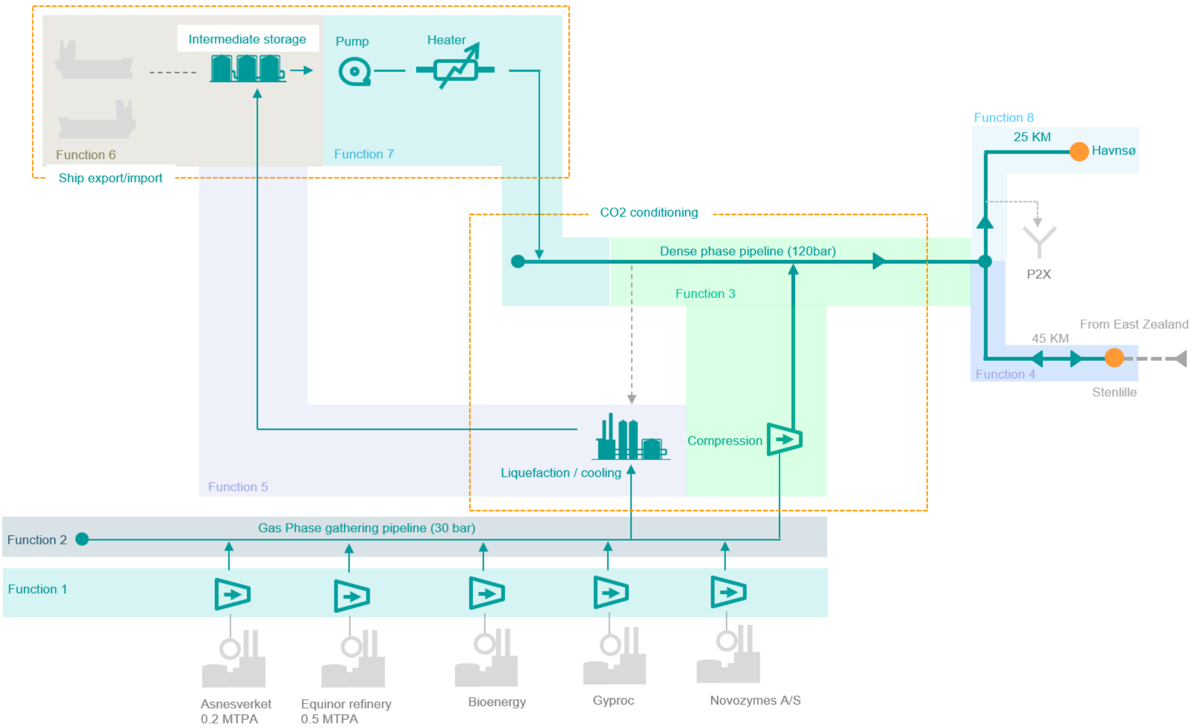


Figure 7.3 Design of Concept 3C – With Imports

7.5 Analysed cost effects

In this chapter of the report, all of the cost elements of the concepts are analysed. These include investment costs, operating costs and environmental costs.

Benefits, and a summary of the net value for society of realising the concepts is analysed and described in chapter 7.6 and 7.7 respectively.

7.5.1 Investment costs

Investment costs reflects the initial investment that have to be made to realise the different concepts. Important components include the pipes, regulators, meters, compressors etc. Costs related to planning, licencing and construction are also included in this category. The investment costs will increase with more extensive topologies. They can also vary considerably depending on market prices and demand for similar technological components globally and regionally.

7.5.1.1 Business-as-Usual (BaU)

The investment costs in the BaU will include planning, engineering and construction of liquification equipment and a storage tank for the liquid CO_2 from where it will be loaded on ships and transported to an offshore storage site for CO_2. In chapter 5.6 this has an estimated CAPEX of 47 MEUR. **The importance for society** is assessed to be small as although the investments will be covered through existing government grants paid financed by Danish tax payers, the sum is not large. **The impact on society** is set to small negative as the investment costs are small and will have little impact on the cost side of ASV's business case. Overall this gives a negative rating of (-) for the investment costs in the BaU concept.

7.5.1.2 Concept 3A – No imports

The investment costs in concept 3A – no imports- includes planning, engineering and construction of compression equipment and a gas gathering pipeline in Kalundborg. Furthermore, it includes pipelines running from Kalundborg to Stenlille where there is a connection to the Copenhagen pipeline. It also includes a pipeline running from Kalundborg to the Havnsø storage site. In chapter 5.6 this has an estimated CAPEX of 112 MEUR.

Overall, the rating of investment costs for concept 3A – no imports – is (--). **The importance for society** is assessed to be small as the investments will be carried through private funding and through existing government grants financed by Danish tax payers. However, with some private funding, the broader impact is not large. The overall sum is still larger than in the BaU and **the impact on society** is therefore set to medium negative.

7.5.1.3 Concept 3C – with imports

The investment costs in concept 3C – with imports will include planning, engineering and construction of compression equipment and a gas gathering pipeline in Kalundborg. Pipelines run from Kalundborg to Stenlille where there is a connection to the Copenhagen pipeline. It also includes a pipeline running from Kalundborg to the Havnsø storage site. Pumps, heaters and storage to facilitate imports are also included. In chapter 5.6 this has an estimated CAPEX of 229 MEUR.

The importance for society is assessed to be medium as the investments will partially be carried by private investors and partially through existing government grants hhe sum is also significantly larger than in Concept3A. **The impact on society** is set to medium negative. Overall this gives a negative (---) rating of the investment costs in concept 3C – with imports.

Concepts	1A- BaU	3A - No imports	3C – with imports
Investment costs	-	--	---

Table 7.3 Qualitative scoring of investment costs. The table summarises the negative impact of investment costs on total socio-economic impact on the project for the three scenarios 1A, 3A and 3C.

7.5.2 Operating costs

The operating costs related to CO_2 pipelines are assumed to be similar to that of gas networks. These costs are overall assumed to be low. The main drivers of operating costs are compression costs related to transport loss, the energy costs of operating compressors, as well as some potential costs related to inspections and leakages. The operational costs will increase with higher pipeline utilization rates, meaning higher volumes of CO_2 compared to the dimensions of the pipelines.

Operating networks closer to maximum capacity ratings will significantly increase overall compressor fuel requirements and maintenance costs.

7.5.2.1 Concept 1A - Business as usual

The operating costs in the BaU concept will include costs associated with operating and managing the liquification, storage and loading facilities in Kalundborg port.

The tariffs associated with offshore storage are not included, as these are not known and are outside of the scope of the analysis. Costs of offshore storage with onshore storage will therefore have to be compared separately. If the tariffs cover more than operating costs for the transport and storage facilities, Denmark will in practice also be paying for a share of the investment costs in the storage project without reaping the benefits of these investments. Depending on the size of the expected investments and benefits, It should be assessed from a Danish point of view whether the best use of tax money is through offshore transport and storage or building and operating transport and storage facilities themselves.

In chapter 5.6, the OPEX for this concept is estimated to 12 MEUR per year.

Overall the rating of the operating costs in the BaU concept is set to (-) with **The importance for society** assessed to be small and **The impact on society** is set to small negative. The reasoning is that the costs are relatively small and will therefore have both limited impact and importance for society.

7.5.2.2 Concept 3A – no imports

The operating costs in Concept 3C – no imports - is in chapter 5.6 estimated to 21.5 MEUR per year. This includes operation and maintenance of compression facilities and pipelines running from Kalundborg to Havnsø and Stenlille.

The OPEX is almost twice as high as in the BaU concept, and although the annual operating costs may seem limited, they add up to a significant sum over a 20-year lifetime. The rating of the operating costs in concept 3A – no imports is therefore set to (--) with a **small importance for society** and **medium negative impact on society**.

7.5.2.3 Concept 3C – with imports

The operating costs in Concept 3C – with no imports - is in chapter 5.6 estimated to 34.4 MEUR per year. This includes operation and maintenance of compression facilities and pipelines running from Kalundborg to Havnsø and Stenlille, as well as facilities for heating and pumping CO_2 from ships into the CO_2 pipeline infrastructure.

The rating of the operating costs in concept 3C – with imports is therefore set to (---) with a **medium importance for society** and **medium negative impact on society** as the costs are higher than in previous concepts and add up over the lifetime of the project.

Concepts	1A- BaU	3A - No imports	3C – with imports
Operating costs	-	--	---

Table 7.4 Qualitative scoring of operating costs. The table summarises the negative impact of operating costs on total socio-economic impact on the project for the three scenarios 1A, 3A and 3C.

7.5.3 Environmental costs

Environmental costs reflect the negative impact that is inflicted upon natural values from the construction of the pipeline networks. The natural values can for example include short- and long-term consequences for wildlife and ecosystems on land and at sea, as well as for clean air and water. Physical disturbance of popular outdoor areas should also be taken into account.

Environmental costs will vary most with the length of network, but different dimensions of the pipelines can also have an influence. The costs will also vary with geography and planning of the network, in the sense that if the pipes are planned to run through particularly vulnerable areas on land or at sea, or near where endangered species have their local habitats, the environmental costs will increase. Another important aspect is how much supporting and temporary infrastructure has to be built to realise the project. The routing and environmental consequences of the pipeline concepts in this analysis is covered in more detail in chapter 5.14.

7.5.3.1 Business as usual

In the business-as-usual concept the environmental costs will be minimal, as no harmful measures will be performed, especially in untouched areas. The connection from Asnæsværket to the port, liquification and storage facilities will be built in the industrial area surrounding ASV.

Importance for society is analysed to be small as the area that will be affected is already an industrial area with little environmental value. **Impact on society** is set to no effect as the environmental impact is minimal. Overall this gives a (0) rating of the environmental costs in the BaU concept.

7.5.3.2 Concept 3A – no imports

In Concept 3A pipeline will run from Kalundborg to Stenlille and Havnsø, which includes pipelines through two natural protected areas. For both these areas, it is possible to build the pipelines alongside existing infrastructure, and also use a method called Horizontal Directional Drilling (HDD) to reduce the surface impact of the installation of the pipeline.

In total this means that mitigation measures can help considerably with the environmental impact. **Importance for society** is therefore set to small and **impact on society** is assessed to be small negative. This gives a rating of (-).

7.5.3.3 Concept 3C – with imports

The topology in concept 3C is the same as in concept 3A, but the dimensions of the pipelines are larger for the Kalundborg-Havnsø route as there is more CO_2 to be transported. There is also some more construction work needed in Kalundborg Port to facilitate the onshoring of the CO_2 from ships.

Overall, the environmental costs are assessed to be very similar to that of concept 3A. The assessment is therefore the same, with an overall rating of (-). **Importance for society** is set to small and **impact on society** is assessed to be small negative.

Concepts	1A- BaU	3A - No imports	3C – with imports
Environmental costs	**0**	**-**	**-**

Table 7.5 Qualitative scoring of environmental costs. The table summarises the negative impact of environmental costs on total socio-economic impact on the project for the three scenarios 1A, 3A and 3C.

7.6 Analysed benefit effects

In this chapter of the report, all of the benefit elements associated with the concepts are analysed. These include climate effects, additional project income, PtX production and sector coupling as well as job creation and GDP effects.

The costs elements are analysed above in chapter 7.5, whilst a summary of the net value for society of realising the concepts is analysed in chapter 7.7.

7.6.1 Climate effects

When assessing the climate effect of a measure, one usually calculates how much CO_2 emissions are permanently removed. We assume that the relevant socioeconomic value of CO_2 in Denmark comprises the sum of the ETS price and the national Danish CO_2 tax. The value used for the ETS-price is given by The Danish Energy agency in the graph below from the AF22 publication [61].

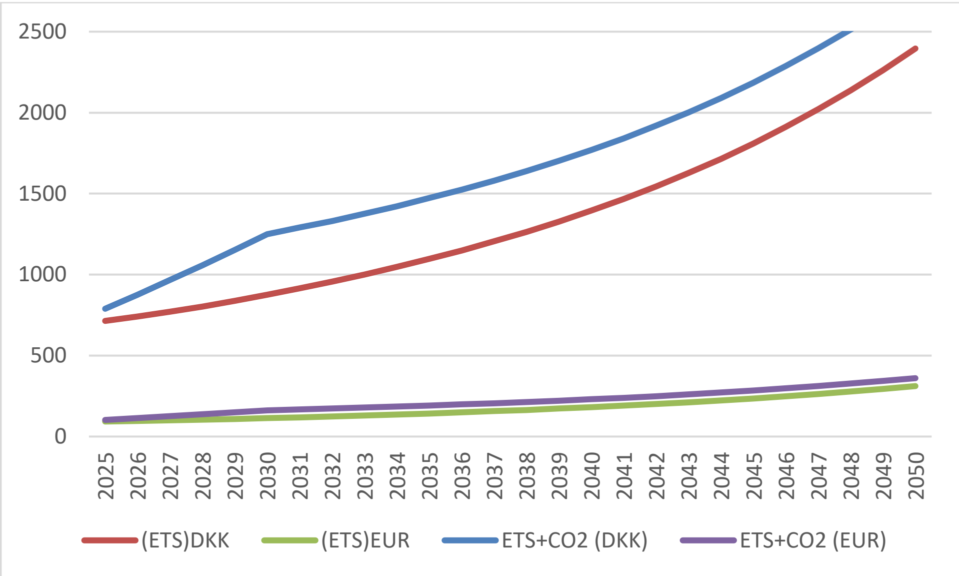


Figure 7.4. Expected ETS price and CO_2-tax development (EUR,DKK/ton, 2022-prices)[9]

The Danish CO_2-tax will be gradually introduced between 2025 and 2030, with different rates for different sectors of the economy. For the sectors that already are submitted to the ETS-regime, the CO_2-tax will reach 375 DKK/ton in 2030 [62].

When estimating the value of the avoided CO_2 emissions, it is important to bear in mind that in order to realise those values the costs of capture and storage also has to be taken into account. Although transport costs in CCUS projects vary a lot, as a rule of thumb, total transportation costs usually make up 20-30%. In this analysis we assign 25 % of the value of the avoided emissions to the transport part of the supply chain.

In this analysis there are three different categories of CO_2 emissions that contributes differently when assessing this effect.

1) Emissions from ASV

   Emissions from ASV is covered by the BaU-concept. This means that the climate effect of ASV capture will not count towards the climate effect when assessing concepts 3A and 3C.

2) Emissions from other Danish emitters connecting to the pipeline

[9] Currency rate DKK/EUR = 0,13 (2906.2023)

It is here assumed that for these CO_2 volumes, capturing the CO_2 and transporting it to storage in a different way than through a pipeline would make the business case unprofitable. These emissions therefore count towards the climate effect of the pipelines. There is however uncertainty about how much CO_2 could be expected to connect to the pipeline, although we in concepts 1 and 2 assume 1 million CO_2e in the Kalundborg hub and 4 million CO_2e from greater Copenhagen according to the findings in chapter 4.1.

3) Foreign imported CO_2 transported in the pipelines from Kalundborg Port

   Given that CO_2 is imported through the Kalundborg port, foreign CO_2 will also run through the pipeline to Danish storage sites. This CO_2 will count towards the CO_2 accounts in the originating countries. The benefit associated with these CO_2 volumes are therefore financial only.

Another important aspect to consider when addressing the climate effect is the difference between fossil and biogenic CO_2. At present, biogenic CO_2 emissions currently counts as zero towards emission accounts. Consequently, permanent storage of biogenic CO_2 does not count as emission reduction, but rather emission removal. In order to capture and store these emissions, other incentives than direct ETS fees must be applied. As storage of biogenic CO_2 thus can be regarded as “negative emissions”, one can receive compensation for it. Stored biogenic emissions is therefore included in the climate effects assessed in this chapter.

The rough calculations of the value of the project benefits include the CO_2 value from both the ETS and the Danish CO_2-tax. This applies to both fossil and biogenic emissions as we assume that stored negative emissions can receive compensation in line with the value as fossil CO_2.

7.6.1.1 Concept 1A - Business as usual

Ørsted has already agreed to ship and store 430 ktons CO_2 per year with Northern lights starting in 2026. This is the equivalent of the CO_2 emissions from ASV and AVV in the Copenhagen region which are all biogenic. (The CO_2 from AVV will be delivered by truck to Kalundborg Port) [63]. These are the volumes that are included in the BaU concept.

In 2026 the expected CO_2 ETS price is 741 DKK + and the Danish CO_2 tax is 135 DKK/ton in 2026. Multiplying these values with 430 ktpa, and assigning 25 % of it to the transport part of the CCUS chain, gives a value of 94,2 million DKK or 12,24 million EUR/year. This number is the share of the total CCUS climate effect that can be attributed to the transport part of the CCUS supply chain.

This value is only for one year. Both the ETS-price and CO_2-tax is expected to increase beyond 2026, meaning that there will also be is significant values generated over time given a over a 20 year time horizon for the project.

Importance for society is analysed to be medium as the CCUS of ASV’s emissions will contribute to Danish climate goals and indirectly impact all of the Danish population. **Impact on society** is set to medium positive as the annual value of the CO_2 stored is significant. Overall, this gives a (+++) rating of the climate effects in the BaU concept.

7.6.1.2 Concept 3A – no imports

In Concept 3A a total of 5 MTPA of CO_2 is captured and stored. As stated in chapter 5.16 the engineering and construction time of the pipeline infrastructure could take up to 5 years after all permits are in place. Assuming that concept 3A is then ready for operation in 2030, the 4,5 MTPA applies for 2030 onwards, whilst the first 0,5 MTPA is stored offshore as part of the BaU-concept.The 2030 value of 4,5 MTPA can be calculated based on an ETS-price of 875 DKK/ton + 375 DKK/ton in CO_2 tax. 25 % of the total 2030 value is then 1,4 billion DKK/year or 128 million EUR. – This is the value of the avoided fossil and biogenic CO_2 emissions that can be attributed to the transport part of the CCUS supply chain.

Importance for society is assessed to be large as the pipeline infrastructure facilitates storage of roughly 10% percent of all Danish emissions. However, the value also relies on successful implementation of capture and storage. Impact on society is set to large positive as the relevant value of the stored CO_2 is significant and more than 10 times that of the BaU concept. this gives a (+++++) rating of the climate effect in concept 3A.

7.6.1.3 Concept 3C – with imports

In Concept 3C a total of 12 MTPA of CO_2 is captured and stored, although only 5 MTPA of these are Danish emissions. As with concept 3A, EPCI could take up to 5 years after all permits are in place and we therefore assume that the concept is ready for operation in 2030. 11.5 MTPA applies for 2030 onwards, whilst the first 0.5 MTPA is stored offshore through the Northern Lights agreement.

The climate effect and 2030 value of the Danish emissions is the same as in concept 3A – 128 million EUR. The value of the imported CO_2 is covered by the effect "Additional project income", see below. This means that the assessment of the climate effect in a Danish perspective for Concept 3C is the same as in Concept 3A. This gives a (+++++) rating of the climate effects in concept 3C.

Concepts	1A- BaU	3A - No imports	3C – with imports
Climate effects	+++	+++++	+++++

Table 7.5 Qualitative scoring of Climate effects The table summarises the positive impact of climate effects on total socio-economic value of the project for the three scenarios 1A, 3A and 3C.

7.6.2 Additional project income

In addition to the value of the stored CO_2 addressed through he value of the climate effects, there are two other potential sources for project income that will benefit the project in a Danish context.

Income from imported CO_2

The value of this revenue stream is closely connected to the CO_2 price as CCUS will only be profitable for the emitter if total related costs are lower than the CO_2-price. The income per CO_2 will then likely be the equivalent of the ETS-price subtracted for the capture and transport cost to a Danish port.

Transport costs in the CCUS value chain can vary considerably, but often make up 20-30%, and are often in the higher range when ship transport is included. When taking into account the investments that have to go into infrastructure preparing the CO_2 for transport, this will reduce the percentage of the ETS-price that can go towards transport tariffs. Overall, DNV has for this analysis set the tariff rate at 10 % of the ETS price.

Subsidies may be part of the final tariff equation, but it is unsure who will carry those tariffs – Denmark or foreign countries. They are therefore kept outside of this assessment.

Additional income related to biogenic CO_2

Biogenic CO_2 can be stored and create "negative emissions". The value of these negative emissions can be sold to companies or actors that want to offset their own or upstream/downstream emissions. The value may be higher than the

CO_2-price if the “greenness” of the “negative emissions” can be used for marketing and/or reporting purposes. For the sake of simplicity these extra values have not been estimated in this analysis.

Alternatively, the biogenic CO_2 can also be sold to PtX-plants: The price obtained will most likely be set based on the price of (conventional fuel+ CO_2-price) – (production costs for PtX). This means that it will be profitable if production costs of PtX (including the price of biogenic CO_2) are lower than the cost of conventional fuel+ value of alternative use.

As this offtake option is in direct competition with the “negative emissions” value, it is assumed that these values will be approximately the same.

7.6.2.1 Concept 1A - Business as usual

In the BaU concept there is no additional income related to income from imported CO_2 or related to biogenic CO_2. The latter income stream could have been relevant, but as the biogenic CO_2 emissions from ASV are assumed to be counted in the climate effect in terms of ETS value, there is no carbon credit value in addition.

Importance for society is analysed to be small and **Impact on society** is set to no effect as there is no income to include in this effect. This gives a (0) rating of the additional project income in the BaU concept.

7.6.2.2 Concept 3A – no imports

In concept 3A, 5 MTPA CO_2 is stored and roughly 34 % of these Danish CO_2 emissions are reported to be biogenic. This is the equivalent of 1,7 MTPA of CO_2. This means that there is a large potential to sell these CO_2 volumes to PtX facilities, but at the present time there are no PtX production facilities planned in the vicinity of the pipeline, and there are no agreements made that may realise these values. We have therefore not added any extra value to the biogenic CO_2 other than that which is accounted for in the climate effects.

Importance for society is analysed to be small and **Impact on society** is set to no effect as there is no income to include in this effect. This gives a (0) rating of the additional project income in concept 3A.

7.6.2.3 Concept 3C – with imports

For concept 3C the same applies for the biogenic content as in concept 3A. However, in concept 3C, there is 7 MTPA of imported CO_2 that is received and transported from the Kalundborg Hub to Havnsø Storage. Given that the infrastructure is ready to receive the imported CO_2 in 2030, the estimated tariffs at 10% of the ETS price give an annual value of 613 million DKK or roughly 80 million EUR with a potential to be higher given that the ETS price is expected to increase.

Importance for society is analysed to be medium and **Impact on society** is set to medium positive as the income potential is substantial compared both to the climate effect and the overall investment costs. This gives a (+++) rating of the additional project income in concept 3C.

Concepts	1A- BaU	3A - No imports	3C – with imports
Additional income	**0**	**0**	**+++**

Table 7.6 Qualitative scoring of additional income. The table summarises the positive impact of additional revenue on total socio-economic value of the project for the three scenarios 1A, 3A and 3C.

7.6.3 PtX production and sector coupling effects

If the CO_2 network connection points are co-located with district heating, electricity production, hydrogen infrastructure, and waste water infrastructure, synergies can be created in the manufacturing of PtX fuels.

The more overlapping the infrastructure is, the more likely it is that PtX will be profitable. Long term, PtX will be profitable if it is cheaper to produce and sell than conventional fuel+CO_2-fees. Better access to infrastructure can both reduce costs and increase revenues. Easy access to electricity grid and surplus electricity production as well as CO_2 infrastructure would reduce investment and operating costs, whilst vicinity to large offtakers such as ports, airports and biproduct offtake can increase revenues.

At present there exists plans for PtX production facilities processing CO_2 in northern, southern and eastern Zealand, but none in the immediate vicinity of the analysed CO_2 pipeline, see chapter 6.1. The Ørsted project near Copenhagen could quite easily connect to the Copenhagen end of the CO_2 pipeline, but for the other facilities it would require significant investments to connect.

In chapter 6.2 infrastructure, that is important for PtX production, has been mapped out in order to identify possible locations for new PtX production projects. The infrastructure overview includes mapping of high voltage power grids, areas with surplus electricity production, local offtake possibilities such as ports and airports, refineries and potential for biproduct offtake such as space heating.

All of these mappings show that the Kalundborg region is excellently placed for PtX production. New projects can be set up, or the existing hydrogen production plants planned in the area can supply hydrogen to further PtX production.

The Kalundborg region is close to CO_2 pipelines in all the concepts. This means that there are small differences in the potential value sector coupling effects can contribute with between them. More CO_2 and larger pipeline dimensions create the opportunity for more PtX production, but that extra value is only realised if the CO_2 offtake opportunities are realised.

The value of the potential offtake would likely be higher than the value of storing the CO_2. The reasoning behind this is that the PtX would also reduce emissions: If we take 1 ton CO_2 away from the Kalundborg Hub, convert it to PtX fuel and avoid an emission of X in another sector, the total avoided emissions are 1+X. The value of the CO_2 sold should then be (1+X) multiplied by ETS + CO_2-tax. The alternative value of the biogenic CO_2 is linked to its value as negative emissions when it is stored. In order for it to be profitable to sell the CO_2 to PtX production, the selling price thus has to be equal or higher than this.

7.6.3.1 Concept 1A - Business as usual

In this concept the only CO_2 pipelines are those that will run from ASV to Kalundborg port, and the dimensions of the pipeline will be small. There is potential for a PtX project to use CO_2 from ASV, but it is not likely that such a project will be connected to the pipeline and infrastructure connecting ASV and Kalundborg port. This leaves little room for the CO_2 infrastructure to create benefits related to sector coupling and PtX production.

Importance for society is therefore analysed to be small and **Impact on society** is set to no effect as there are no expectations of a PtX production plant that will be built in relation to the CO_2 pipeline infrastructure. This gives a (0) rating of the sector coupling effects in the BaU concept.

7.6.3.2 Concept 3A – no imports

For concept 3A, a gathering pipeline in the Kalundborg region is built which can supply potential PtX facilities. There is in other words potential for PtX production based on 1,7 MTPA of biogenic CO_2[10], but there is at present little concrete evidence in the form of agreements, pilots or projects that points towards those values being realised.

The rating for concept 3A is therefore the same as in BaU – set to no effect.

7.6.3.3 Concept 3C – with imports

Concept 3C is similar to concept 3A , but the potential is even larger with the 50 % biogenic share of 12 MTPA of CO_2. However, as there are no concrete plans for PtX production facilities, also for this concept the rating is set to no effect.

Concepts	1A- BaU	3A - No imports	3C – with imports
Sector coupling	**0**	**0**	**0**

Table 7.7 Qualitative scoring of PtX production and sector coupling effects The table summarises the positive impact of sector coupling on total socio-economic value of the project for the three scenarios 1A, 3A and 3C.

7.6.4 Job creation and GDP

This effect reflects to what extent the different concepts and sensitivities facilitate direct and indirect job and value creation in different sectors of the Danish economy

- Direct job creation includes the jobs that result directly from the construction and maintenance of the CO_2 network
- Indirect job creation refers to the jobs that are created through the activity that the CO_2 infrastructure facilitates.

It is important to note that job creation doesn't automatically translate to higher value creation and GDP as Denmark is in a situation with near full employment. Taking workers from other sectors will only be beneficial in a GDP context if the CCUS industry has greater returns than the sector the workers came from. This is important when assessing the GDP effects. It is also important to assess the types of jobs that are created through the project. More job creation can give spillover effects and increased GDP, but fewer more specialised jobs with an optimised number of employees and competence can give more value creation and innovation per job.

For this project the types of jobs created include the following:

- In the investment phase: Planning, construction, verification and if relevant, manufacturing of local content.
- In the operation phase: maintenance and operation of the pipelines as well as for entry/exit points at emitter sites, storage sites, Kalundborg port and PtX facilities.

7.6.4.1 Concept 1A Business as usual

In the BaU-concept there will be some jobs and value creation related to the planning, engineering and construction of the infrastructure. Once the operation and maintenance stage is reached, this activity will cease, and minimal new activity will be necessary in order to operate and maintain the infrastructure. The jobs related to ship transport and storage is outside the scope of this analysis.

[10] In Concept 3A, there is 5 MTPA of Co2 that is stored. Based on received data, 34% of these volumes are biogenic, which gives roughly 1,7 MTPA of CO2 that can be sold to PtX production.

Importance for society is analysed to be small as a limited number of people will be employed. **Impact on society** is set to small positive as the value creation associated with the limited number of jobs is small. This gives a (+) rating of the job creation and GDP effect in the BaU concept.

7.6.4.2 Concept 3A – no imports

Compared to the BaU-concept there will be some more work related to the investment stage with planning, engineering and constructing pipelines and the necessary infrastructure. If there are local content requirements, some indirect jobs may also be created through the procurement of the necessary equipment, but it can result in lower value creation as the best content is then not necessarily chosen for the project.

Once the operation and maintenance phase is reached, there will be some more activity than in the BaU as there will be more feed-in points in the CO_2 network as well as extraction at Havnsø. The number of people employed and extra activity generated is still limited.

Importance for society is therefore analysed to be small. **Impact on society** is set to small positive as the value creation associated with the limited number of jobs is small. This gives a (+) rating of the job creation and GDP effect in the concept 3A.

7.6.4.3 Concept 3C – with imports

In concept 3C, the number of people employed will be similar as in concept 3A, but there would be larger CO_2 volumes handled in Kalundborg port and Havnsø handling the extra volumes of CO_2.

Importance for society is analysed to be small. **Impact on society** is set to medium positive as the value creation associated with the number of jobs is higher than in the BaU and concept 3A. This gives a (++) rating of the job creation and GDP effect in concept 3C.

Concepts	1A- BaU	3A - No imports	3C – with imports
GDP and jobs	+	+	++

Table 7.8 Qualitative scoring of PtX production and sector coupling effects. The table summarizes the positive impact of GDP and jobs effects on total socio-economic value of the project for the scenarios 1A, 3A and 3C.

7.7 Summary

The summary of the qualitative assessment of the effects are shown in table 7.9 below. It shows that all concepts can probably contribute with a positive socioeconomic value, with concept 3C giving the most positive results and concept 3A the least. The positive outcomes are especially dependent on the value of the climate effect and for concept 3C, the additional revenue related to imports. The socio-economic potential of connecting PtX producers to the pipeline can also be large if realised.

The value of these benefits nevertheless relies on some very strong assumptions. In order for them to be realised:

- the pipeline from CPH must be built and ready on time.
- Storage at Havnsø has to be built and ready on time.
- Danish emitters in the Kalundborg region have to agree on terms and be connected to the pipeline infrastructure.
- For concept 3C, agreements have to be made with emitters abroad, and shipping capacity must be available.

These assumptions must be closely followed up on to ensure that a realisation of the pipeline network does not result in stranded assets as a whole, or for a period of time. In order to maximise the value of the investment, making sure that capture, transport and storage infrastructure is ready for operation simultaneously is key. This is extra challenging as we know there are supply chain issues in the delivery of the equipment for CCUS infrastructure, see chapter 5.16.1.3.

Examining the results of the qualitative assessment, preliminary strategic assessments and work should be done to clarify if there are parties that are interested in storing their CO_2 emissions at Havnsø. It is also crucial to clarify whether the geological conditions at Havnsø are such that the relevant volumes of CO_2 can be stored there safely. If storing Danish CO_2 emissions is concluded to be a focus area, it would be beneficial to perform a socio-economic analysis that include both the pipeline networks in Western Zealand together with the pipeline network originating in the greater Copenhagen area. This will give a better overview of the costs and benefits related to a Danish/Zealand CCUS value chain. This is relevant input for both 3A and 3C concepts, if these are relevant to develop further.

Although this qualitative assessment can give a good indication of the potential socio-economic value associated with the project, further analysis is necessary to give more insight and precision to the analysis.

Concepts	1A- BaU	3A - No imports	3C – with imports
Investment costs	-	--	---
Operating costs	-	--	---
Environmental costs	0	-	-
Climate effects	+++	+++++	+++++
Additional income	0	0	+++
Sector coupling	0	0	0
GDP and jobs	+	+	++
Summary	**2**	**1**	**3**

Table 7.9 Summary of the socio-economic quantitative assessment. The table summarizes the positive and negative impact of different effects of the project on total socio-economic value for the scenarios 1A, 3A and 3C

In chapter 5.6 costs have been estimated for a whole range of different concepts. Although we have only included three concepts in this analysis, the findings can be used to make very high level assumptions for other concepts as well. For example, concept 2B will in many ways be quite similar to 3A in outcome with similar assessments for cost levels and benefits. Some differences are however apparent with a little lower costs, a little higher emissions related to offshore transport, and the GDP and jobs effect may be influenced by whether or not the offshore storage is a Danish site.

8 CONCLUSION

The technical feasibility of a CO_2 infrastructure in the Northwest Zealand area has given valuable insights into several important aspects of establishing such an infrastructure, including the potentials and prerequisites in the area, possible design concepts, PtX synergies and socio-economic value. These findings contribute to a deeper understanding of feasibility of such an infrastructure with identification of the possibilities, advantages and obstacles.

The studies have included dialogue with the project stakeholders, the industry and the authorities, providing valuable information into developing possible infrastructure concepts, that facilitates integration with a broader CCUS and PtX perspectives in Denmark.

The concept developments have been an iterative process with stakeholders of the project to define potential infrastructure solutions in the Northwest Zealand area resulting in multiple scenarios of CO_2 volumes and routes of CO_2 transport. It is recognized that several uncertainties revolve around these concepts. These relates to delays or cancellation of expected interfaces, hereunder the Stenlille and Havnsø storage sites, the development/reduction of identified emission volumes, the ship imported CO_2, the CO_2 from the Copenhagen area and the uncertainties with future PtX facilities. Therefore focus has been on developing a flexible study of concepts, that considers multiple infrastructure "modes", various routes and multiple capacity scenarios, that can used for further maturing of the proposed CO_2 infrastructure concepts.

Further maturation work is required for each concept in the following phases of developing a CO_2 infrastructure, with focus on safety, permitting and confirmation of premises used in this study.

Mapping of prerequisites:

Through the identification of CO_2 emitters and consumers in the Northwest Zealand area, it became clear that the significant sources relevant for a CO_2 pipeline infrastructure connecting Kalundborg, Stenlille storage and Havnsø storage are located in the Kalundborg area. The mapping concluded that no large-scale consumer of CO_2 is present in the area and with the potential volumes identified it is evaluated that infrastructure facilitating storage or export is required.

An analysis of the existing infrastructure was performed to identify potential synergies in the area for waste heat utilization from compression, harbour facilities for import and export and existing pipeline and power cable routes for utilizing existing routes around/through the multiple nature protected areas. The harbour facilities at Asnæsværket were identified as a potential export/import location, although expansions of the harbour and facilities are likely required for the higher volumes of CO_2. Furthermore, the existing pipeline infrastructure from Kalundborg to the Stenlille storage indicates a likely acceptable route, although where key aspects has to be considered, as development of populated areas and the risks associated with higher pressure CO_2 pipeline. There were not identified existing pipeline infrastructure for the Kalundborg-Havnsø and Stenlille-Havnsø route corridors, which yields higher uncertainties to the land acquisition, environmental permitting, etc.

The CO_2 quality from the emitters and the requirements for export and storage are identified as a potential risk, where development of requirements are ongoing, hence the cleaning requirements are important focus point for further studies.

CO_2 pipeline infrastructure

The study has considered 4 overall design cases:

- 1A (refence case): 0.5 MTPA export from Kalundborg
- 2A: 1 MTPA transported from Kalundborg emitters to Stenlille storage
- 2B: 4 MTPA transported from Stenlille to Kalundborg.
- 3A (low case): 5 MTPA transported from Kalundborg and Stenlille to Havnsø storage.
- 3B (medium case): 9 MTPA transported from Kalundborg and Stenlille to Havnsø storage.
- 3C (high case): 12 MTPA transported from Kalundborg and Stenlille to Havnsø storage.
- 4A: 4 MTPA transported from Stenlille directly to Havnsø.

The concept development of a CO_2 infrastructure has shown a feasible design for a dense phase CO_2 pipeline, where flow assessments have been performed for pipeline dimensioning. Further, the material selection, wall thickness, pipeline routing, risk and safety, legislation and permitting have been analyzed for maturing the concept designs.

All four design concepts resulted in achievable pipeline dimensions, with standard material choices, standard wall thicknesses and therefore considered feasible designs. It is although noted that uncertainties on routing, risk and safety aspects and the according permitting process are considered project risks that should be addressed early in the project phase.

The required facilities for gas phase gathering network, compression, liquefication, intermediate storage and pumps/ heaters have been conceptualized and analyzed for the different cases.

Finally, the CAPEX and OPEX estimations for each design case including pipelines and facilities (expect CO_2 capture facilities) for all design cases.

It is clear from CAPEX and OPEX estimations that the transport cost per ton CO_2 is highest for the low volumes of CO_2, where higher volumes reduce the transportation cost per ton CO_2. Especially, the cases of transporting captured CO_2 from the Kalundborg area for exporting via shipping or transport to Stenlille (cases 1A, 2A) yields toward significant higher transportation costs due to to low volumes compared to the remaining cases, where liquefaction and intermediate storage are the cost drivers for case 1A, and the pipeline and compression costs are the driving factors for case 2A.

The analyses of the pipeline costs for case 3A, 3B and 3C have shown minor difference in CAPEX cost for establishing a pipeline handling 5, 9 or 12 MTPA, which show the benefits of choosing a higher capacity pipeline with low financial risks associated with over-dimensioning the pipeline system.

Further, the case 4A is analyzed as an alternative case to the Kalundborg-Stenlille pipeline (case 3), which shows a viable option with comparable investment cost.

Finally, the planning and scheduling of establishing the envisioned pipeline infrastructure in the Northwest Zealand area, considering the planning & design phase, the EPC phase and the commissioning phase has been estimated. For the low risk schedule a project lead time of 5.5 years are estimated, while the high-risk schedule reduces the time period to 3.5 years.
The planning and scheduling assessment although indicates several uncertainties with establishing the CO_2 infrastructure, where limited economic drive, permitting and public acceptance are key risks to consider.

Potential future integration with PtX infrastructure:
The potential future integration with PtX infrastructure has been analysed, through identification of announced PtX project on Zealand along with the expected CO_2 demand, showing no immediate plans for large-scale PtX facilities in the area of the envisioned CO_2 pipeline infrastructure in the Northwest Zealand area.

The potential locations for future PtX projects have further been investigated by analysing the power grid, transportation and local offtake possibilities, bi-product offtake and access to CO_2 and water. These analyses have identified Kalundborg, Vordingborg and the Copenhagen area as the most favourable locations for companies to establish PtX projects, which indicates higher potential for PtX synergies with the envisioned CO_2 pipeline infrastructure of Northwest Zealand.

An outlook of the CO_2 and H2 infrastructure visions have been investigated along with discussion of possible integrations and synergies, as production of e-fuels for aviation, shipping or e-methanol for other industry purposes is highly dependent on a well-developed and integrated infrastructure to get the full benefit of synergies between different infrastructure branches such as CO_2, hydrogen, electricity, water, district heating and ports.

Several plans and outlooks are initiated for both CO_2 and H2 infrastructure nationally but also for cross-border infrastructure solutions, which are important to follow and consider for integration with the envisioned Northwest Zealand concepts.

Perspectives and realization of potentials in the area:
The perspectives and realization of the potentials in the Northwest Zealand area is analysed by assessing how the envisioned CO_2 pipeline infrastructure can facilitate the efficient transport of CO_2, as well as benefit and create value for a range of other CO_2 emitters and industries in Zealand that use CO_2 in their production processes. This analysis has

been performed with a high level qualitative socio-economic cost-benefit analysis, based on the findings of preceding work of this feasibility study,

Here the investment costs, operating costs, environmental costs, climate effect, additional income, sector coupling, GDP and jobs are quantitatively assessed for three of the design cases, where especially the climate effects and GDP and job creation shows positive impacts.

It is further identified that the high CO_2 volume case (design case 3) considering imported CO_2 have the most favourable combined score, where the additional incomes and GDP/Jobs are differentiators compared to the base case and no import concepts.

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APPENDIX A

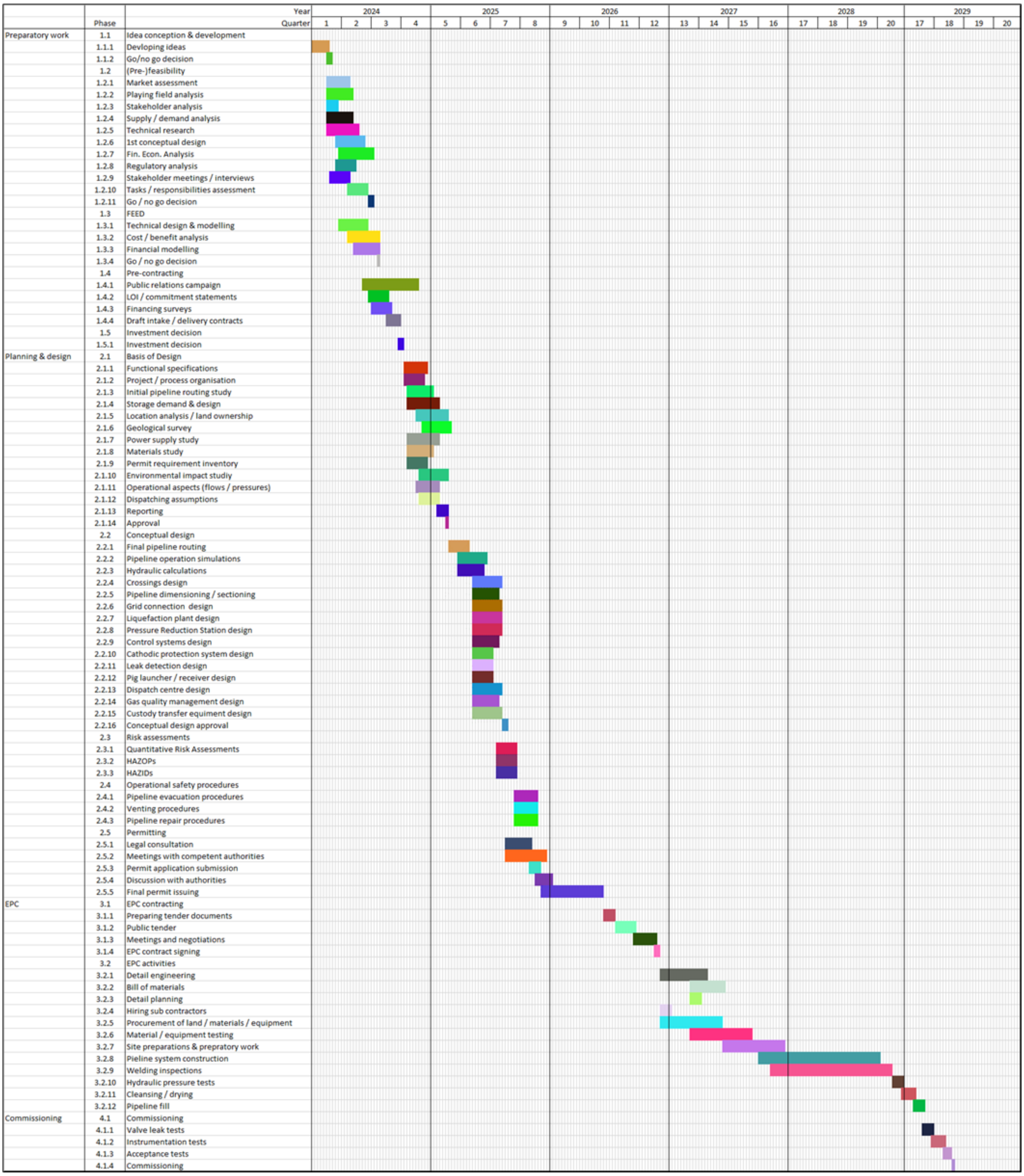
Emitters above 1.000 tons CO_2 / year and below 10.000 tons CO_2 / year

Table 9-1 Emitters above 1.000 tons CO_2 / year and below 10.000 tons CO_2 / year

ID	Facility	Postal code, City	Emission ton / year	Ref.
2191	Miljø Teknik (Novozymes A/S)	4400, Kalundborg	9757	[1], [2]
235	Hvidebæk Fjernvarmeforsyning A.m.b.a.	4490, Jerslev Sjælland	8025	[1], [2]
127	Fuglebjerg Fjernvarme	4250, Fuglebjerg	7471	[1], [2]
1176	Snertinge, Særslev, Føllenslev Energisel	4591, Føllenslev	6375	[1], [2]
484	NVE, Vedelsgade 47	4180, Sorø	6334	[1], [2]
301	Jyderup Varmeværk	4450, Jyderup	5481	[1], [2]
25	Nykøbing S. Varmeværk, Billesvej 8-10	4500, Nykøbing	5380	[1], [2]
544	St.Merløs Varmeværk	4370, Store Merløse	4428	[1], [2]
1603	Lendemarke Varmeforsyning	4780	4364	[1], [2]
504	Svebølle-Viskinge Fjernvarmeselskab	4470, Svebølle	4130	[1], [2]
413	Præstø Kraftvarmeværk	4720	3990	[1], [2]
714	Grevinge-Herrestrup Kraftvarmeværk	4571, Grevinge	3831	[1], [2]
1568	Viking Malt A/S	4760	3502	[1], [2]
326	SK-Varme A/S – Norbrinken	4220, Korsør	3454	[1], [2]
1474	Gartneriet Regnemark I/S	4140, Borup	3325	[1], [2]
429	Ringsted Fjernvarme, Nørregade 57 B	4100, Ringsted	3295	[1], [2]
268	Danish Crown Ringsted	4100, Ringsted	7634	[3]
376	Næstved Fjernvarme, Kanalvej 9	4700	3168	[1], [2]
359	Mørkøv Varmeværk Amba	4440, Mørkøv	3038	[1], [2]
1373	Sandved-Tornemark Kraftvarme	4262, Sandved	3015	[1], [2]
1073	Skuldelev Energiselskab	4050, Skibby	2627	[1], [2]
426	Ringsted Kraftvarmeværk	4100, Ringsted	2303	[1], [2]
2348	LBJBIO I/S	4250, Fuglebjerg	2302	[1], [2]

1059	Sorø Kraftvarmeanlæg	4180, Sorø	2164	[1], [2]
430	Roskilde Varme A/S, Hovedcentralen	4000, Roskilde	2090	[1], [2]
2000	Nykøbing S. Varmeværk, Fregat 4	4500, Nykøbing	2078	[1], [2]
1064	Hvalsø Kraftvarmeværk	4330, Hvalsø	1901	[1], [2]
802	Slagelse Renseanlæg	4200, Slagelse	1897	[1], [2]
297	Harboes Bryggeri A/S	4230, Skælskør	6036	[3]
1213	Benløseparken Varmecentral A.m.b.a.	4100, Ringsted	1802	[1], [2]
1441	Højby	4573, Højby	1728	[1], [2]
482	Frederiksberg Kraftvarmeanlæg	4180, Sorø	1717	[1], [2]
483	NVE, Kirkevej 41 A	4180, Sorø	1584	[1], [2]
2349	FORS Spildevand Roskilde A/S	4000, Roskilde	1148	[1], [2]
1442	Vig	4560, Vig	1054	[1], [2]

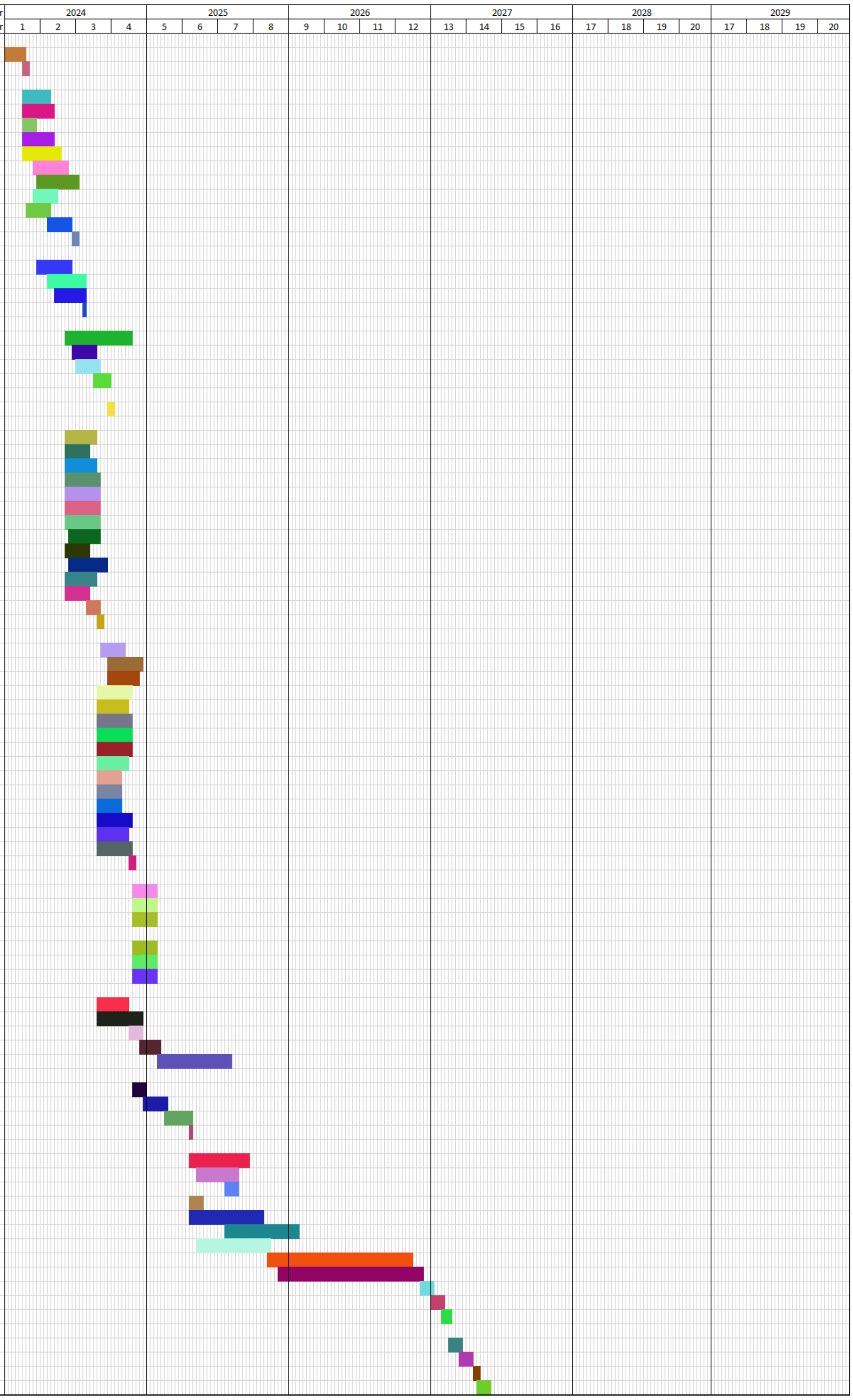
APPENDIX B
Low risk detailed Gant chart



APPENDIX C

High risk detailed Gant chart

	Phase	
Preparatory work	1.1	Idea conception & development
	1.1.1	Devloping ideas
	1.1.2	Go/no go decision
	1.2	(Pre-)feasibility
	1.2.1	Market assessment
	1.2.2	Playing field analysis
	1.2.3	Stakeholder analysis
	1.2.4	Supply / demand analysis
	1.2.5	Technical research
	1.2.6	1st conceptual design
	1.2.7	Fin. Econ. Analysis
	1.2.8	Regulatory analysis
	1.2.9	Stakeholder meetings / interviews
	1.2.10	Tasks / responsibilities assessment
	1.2.11	Go / no go decision
	1.3	FEED
	1.3.1	Technical design & modelling
	1.3.2	Cost / benefit analysis
	1.3.3	Financial modelling
	1.3.4	Go / no go decision
	1.4	Pre-contracting
	1.4.1	Public relations campaign
	1.4.2	LOI / commitment statements
	1.4.3	Financing surveys
	1.4.4	Draft intake / delivery contracts
	1.5	Investment decision
	1.5.1	Investment decision
Planning & design	2.1	Basis of Design
	2.1.1	Functional specifications
	2.1.2	Project / process organisation
	2.1.3	Initial pipeline routing study
	2.1.4	Storage demand & design
	2.1.5	Location analysis / land ownership
	2.1.6	Geological survey
	2.1.7	Power supply study
	2.1.8	Materials study
	2.1.9	Permit requirement inventory
	2.1.10	Environmental impact study
	2.1.11	Operational aspects (flows / pressures)
	2.1.12	Dispatching assumptions
	2.1.13	Reporting
	2.1.14	Approval
	2.2	Conceptual design
	2.2.1	Final pipeline routing
	2.2.2	Pipeline operation simulations
	2.2.3	Hydraulic calculations
	2.2.4	Crossings design
	2.2.5	Pipeline dimensioning / sectioning
	2.2.6	Grid connection design
	2.2.7	Liquefaction plant design
	2.2.8	Pressure Reduction Station design
	2.2.9	Control systems design
	2.2.10	Cathodic protection system design
	2.2.11	Leak detection design
	2.2.12	Pig launcher / receiver design
	2.2.13	Dispatch centre design
	2.2.14	Gas quality management design
	2.2.15	Custody transfer equiment design
	2.2.16	Conceptual design approval
	2.3	Risk assessments
	2.3.1	Quantitative Risk Assessments
	2.3.2	HAZOPs
	2.3.3	HAZIDs
	2.4	Operational safety procedures
	2.4.1	Pipeline evacuation procedures
	2.4.2	Venting procedures
	2.4.3	Pipeline repair procedures
	2.5	Permitting
	2.5.1	Legal consultation
	2.5.2	Meetings with competent authorities
	2.5.3	Permit application submission
	2.5.4	Discussion with authorities
	2.5.5	Final permit issuing
EPC	3.1	EPC contracting
	3.1.1	Preparing tender documents
	3.1.2	Public tender
	3.1.3	Meetings and negotiations
	3.1.4	EPC contract signing
	3.2	EPC activities
	3.2.1	Detail engineering
	3.2.2	Bill of materials
	3.2.3	Detail planning
	3.2.4	Hiring sub contractors
	3.2.5	Procurement of land / materials / equipment
	3.2.6	Material / equipment testing
	3.2.7	Site preparations & prepratory work
	3.2.8	Pieline system construction
	3.2.9	Welding inspections
	3.2.10	Hydraulic pressure tests
	3.2.11	Cleansing / drying
	3.2.12	Pipeline fill
Commissioning	4.1	Commissioning
	4.1.1	Valve leak tests
	4.1.2	Instrumentation tests
	4.1.3	Acceptance tests
	4.1.4	Commissioning



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