3D

DMX Demonstration in Dunkirk

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Executive summary

This report will be used as basis for the design and cost estimation of the CO_2 transport part of the value chain. It presents a study of potential storage sites, with a recommendation of the most promising options, as well as the design basis with the technical boundary conditions. This information will be used to frame the transport studies and provide the basis for the recommended technical solutions and cost estimates for CO_2 transport that will be reported in the final transport study report (D 6.2).

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1 Introduction

The environmental ambition of the European Union is a reduction from 1.7 tons of CO_2 emitted per ton of steel to less than 1.2 in 2030, which is only reachable via CCS.

The 3D project is targeting a considerable reduction in the CO_2 emission from industries and more especially steelmaking industry to comply with EU 2030 expectations, as the project aims to prove that CO_2 capture technology DMX™ can be operated successfully in connection with a blast furnace gas from a steel plant. The 3D project objective is threefold:

1. Demonstrate the effectiveness of the DMX™ process on a pilot industrial scale.
2. Prepare the implementation of a first industrial unit at the ArcelorMittal site in Dunkirk, which could capture more than 1 million metric tons of CO_2 per year and be operational starting after 2025.
3. Design the future European Dunkirk North Sea cluster for handling 10 million metric tons of CO_2 per year, and be operational by year 2035.

As part of objective number 2 a preliminary design and costing (CAPEX + OPEX) will be established for:

- a full-scale CO_2 capture plant from the HF4 Blast Furnace gas in Dunkirk based on results of DMX ™ process
- demonstration at pilot scale (0.5 tCO_2/hr) which will include also heat recovery study in the ArcelorMittal steel mill to produce steam needed for DMX ™ solvent regeneration
- CO_2 conditioning unit (compression and liquefaction)
- CO_2 transport from Dunkirk to a storage site in the North Sea

This report will be used as basis for the design and cost estimation of the CO_2 transport part of the value chain. It presents a study of potential storage sites, with a recommendation of the most promising options, as well as the design basis with the technical boundary conditions. This information will be used to frame the transport studies and provide the basis for the recommended technical solutions and cost estimates for CO_2 transport that will be reported in the final transport study report (D 6.2).

2 Description of the activity

This report consists of two main parts:

- Study of potential storage
- Design Basis

The aim of the study of potential storage has been to identify the promising and potential options for storage in the North Sea for CO_2 captured in Dunkirk. This includes ongoing projects that are being matured by the industry as well as depleted fields from open literature with potential for CO_2 storage. The study has identified three promising concepts. The most mature of these three concepts is the Northern Lights project, which will consequently be used as the base case, while the two other options represents possibilities closer to Dunkirk.

The storage concepts that have been identified will provide technical information, such as CO_2 specification, pressure, temperature, that is used to frame the transport study such that the technical solutions for transport can be obtained. It is not part of the scope in WP6 to establish cost estimates for the different storage options, but required input for conducting such cost estimation, such as number of wells, reservoir depth, site location, water depth etc., will be provided for Concept no 1, the standalone option. For Concepts no 2 and 3, which are based on plug in to existing projects, WP6 will not make any assumptions or estimations of what tariffs these projects may charge.

The design basis describes the technical framing in both ends of the transport chain and lists the boundary conditions that will be used to develop the technical solutions for both ship and pipeline transport. Ship transport will be the base case transport mode, given that this is the only option that is possible for phase 1 of Northern Lights. Pipeline transport will be included as a possible solution for the two other storage concepts.

The value chain option that will be used as the base case in the transport study, also illustrated in Figure 1, consequently becomes the following:

- 1 Mt CO_2/year captured in Dunkirk to be stored in the Northern Lights reservoir
- Ship transport from Dunkirk to Northern Lights terminal
- Ship transport conditions compatible to Northern Lights Phase 1
- CO_2 purity according to the Northern Lights specification

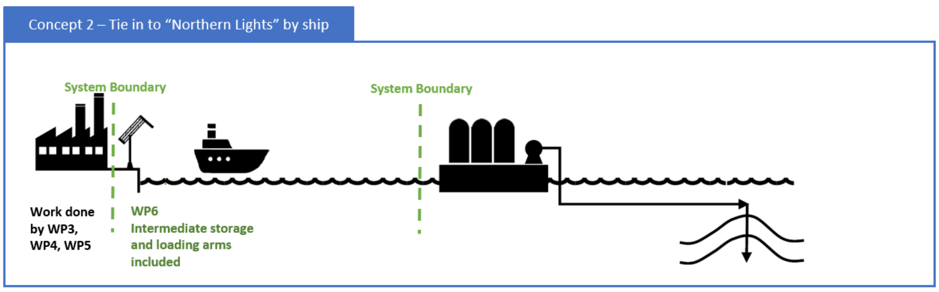

Figure 1 – Conceptual figure of the base case transport scenario

3 Potential Storage and concept definition

3.1 Task definition

Task 6.1: Identification of potential storage in the North Sea and its associated costs [M4-10] (Leader: TOTAL)

To define the appropriate transport hypothesis, various storage alternatives will be screened. Based on former storage potential identification in the North Sea, a storage solution will be proposed including:

• Delivery point localization

• Delivery conditions (pressure/temperature)

• Injectivity and number of wells

The use case defined in the scope of work is aiming for injecting 1.5 Mt/y of CO_2 for in between 10 to 15 years, corresponding to a storage capacity of 15-20 Mt starting in 2025. This use case was changed to 1 Mt/y in a board meeting held on the 7th of February 2020. The change was made due to lower heat requirement for the capture system, and thus a more simplified heat recovery process. It will also increase the possibility for injecting the CO_2 as a part of Northern lights Phase 1.

On-going CCS projects in various countries (Norway, UK, Netherlands) will also be contacted to look at the feasibility of an integration of CO_2 from Dunkirk in their capacities.

The work done within this task will not be sufficient to fully validate a storage solution, but it will identify, based on existing data and knowledge, the most realistic storage scenario necessary for a pertinent transport study done in tasks T6.2 to T6.4 and provide the necessary information for cost estimation of the injection wells.

In order to assess the potential of different storage sites and the most appropriated transport value chain associated, 3 concepts have been identified. Each of the concepts addresses different combinations of distances, transport options, storage unloading localization with associated costs. Creating such a panel of concepts will help consolidating a data base for storage options and drive T6.1 towards a promising range of transport and storage options.

3.2 Screening for CO_2 storage localisation

A literature study was performed by TOTAL E&P CCUS storage team and summarises the offshore geological storage possibilities around Dunkirk. The main conclusions of this study are:

- There is no CO_2 geological storage potential identified in the vicinity of the Dunkirk area until at least a radius of 200km.
- The closest (200 km from Dunkirk) important CO_2 geological storage resources are either depleted fields in the south of the Netherlands offshore (close to Porthos depleted field), or a depleted field located onshore/offshore south of the UK called "Wytch Farm".
- Further, at 250-350 km from the Dunkirk area, numerous depleted fields in the north of the Netherlands offshore (in the vicinity of Aramis fields) and in the south of East UK offshore (in the vicinity of the Net Zero Teesside project), will reach their end of license in coming years and could be potentially available for CO_2 storage.

- At ~600 km from Dunkirk area, in the middle of the North Sea, the Danish offshore depleted hydrocarbon fields could be studied but, in a first approach, their chalky rocks make their CO_2 geological storage potential questionable. It has to be noticed that today, the most relevant identified CO_2 geological resources in Denmark are onshore in the Aalborg and Copenhagen area, located at 700-800 km from Dunkirk.

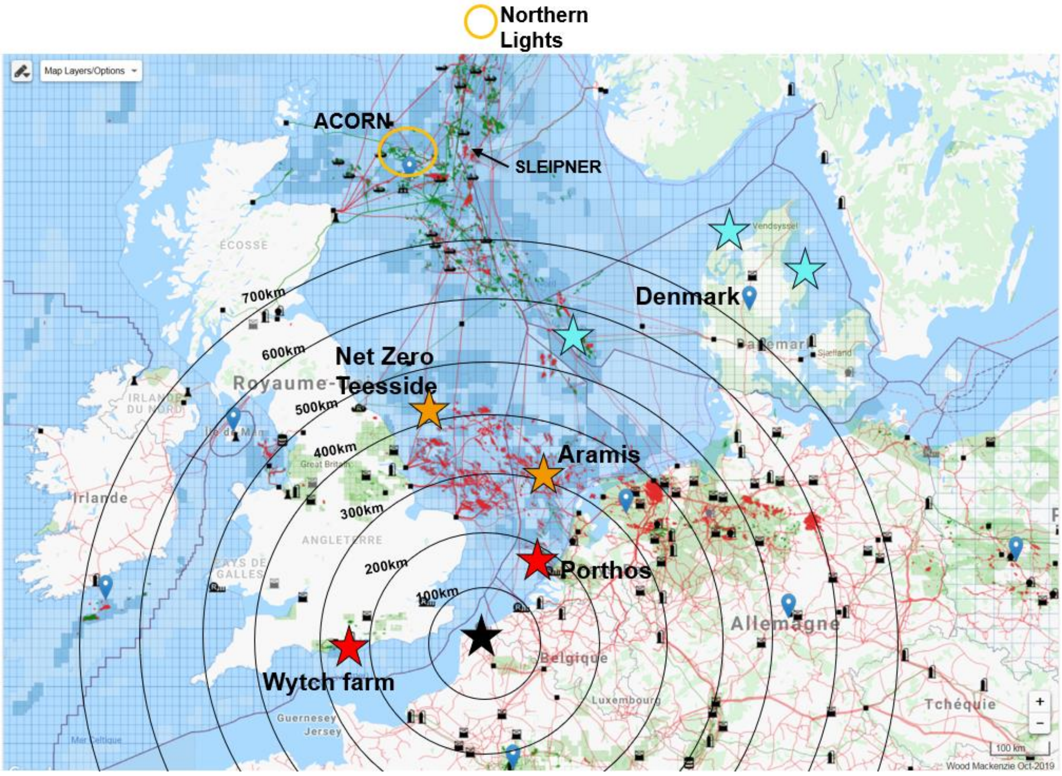

Figure 2 – Map of potential CO_2 storage locations around Dunkirk

It is to be noticed that the work done to identify CO_2 geological storage resources will not be enough to validate these storage solutions. Indeed, the identification will be based on existing data and knowledge. The data that are used in this document are from publicly available resources and are not validated by Total.

3.3 Concepts definition

3.3.1 Concept n°1: "Stand alone"

The "stand alone" concept will give us an independent case study, to be compared with concepts n°2 and n°3, which are project dependent.

In concept 2 and 3, the CO_2 is transported (by ship or pipeline) from Dunkirk to an onshore terminal (Norway or Netherlands) before reinjection via an offshore pipeline. Hence for those two concepts, the availability of storage for the CO_2 coming from Dunkirk relies on the completion of 3^{rd} party projects. To provide a solution in case none of those 3^{rd} party projects would be executed and also to study and compare different modes of CO_2 transportation and offloading philosophies, the choice of location for concept 1 has been done to differentiate from the other concepts. For that matter, a direct connection from source to injection site without the requirement of an onshore terminal has been considered.

The storage/injection site should be located at a certain distance from the coast (more than 80 - 100km) such that this direct injection concept would make sense economically compared to other alternative i.e. boat to onshore terminal and then offshore pipeline option.

Table 1 – Storage localisation and distance from Dunkirk and shore

Storage localization	Distance from Dunkirk	Distance from onshore	Candidate for direct offloading
South UK (Wytch Farm)	250 km	0 – 10 km	✗
South Netherland (Porthos area)	250 km	10 km	✗
North Netherland (Aramis area)	350 km	150 km	✓
East UK (Net Zero Teesside area)	300 km	50 – 200 km	✓
West Denmark offshore	550 km	200 km	✓
Onshore Denmark (Copenhagen, Aalborg areas)	800 km	0 km	✗

In order to differentiate from Concept 3 (plug in to a Dutch project), the North Netherlands option was discarded.

Out of the remaining options, the **East UK is the selected one** because of two main reasons:

- The offshore Denmark fields are producing from chalky reservoirs which is not the most favorable rock for CO_2 geological storage;
- Metocean conditions as well as water depth criteria favor the UK option compared to the Danish one.

The relatively short distance from Dunkirk to this area allows two options for transport: Concept 1a considers transport by pipeline and Concept 1b by ship with direct offloading.

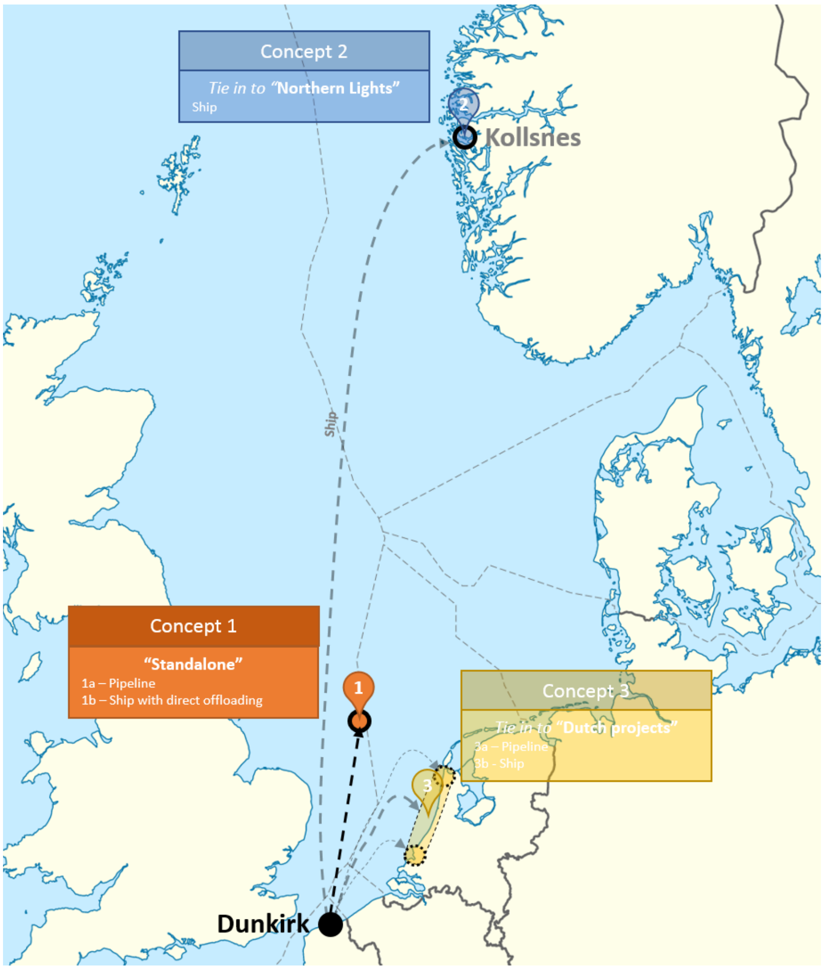

Figure 3 – Concept 1 – Standalone transport to UK offshore field

Numerous depleted (or soon to be) hydrocarbons fields are located in that East UK offshore area and a publicly available database was used to further screen the characteristics of these potential storages.

The CO_2 Storage Evaluation Database, or CO_2 Stored, originally developed in the UK Storage Appraisal Project (UK SAP, 2010), was commissioned and funded by the Energy Technologies Institute (ETI) and then The Crown Estate to provide a comprehensive, auditable and defensible estimate of UK CO_2 storage capacity. It was executed by a consortium of academic, public and private sector organizations comprising the British Geological Survey and provides an overview of CO_2 storage data for over 500 potential CO_2 storage sites around offshore UK. This includes depleted oil and gas reservoirs and saline aquifers for which important parameters are recorded: location, storage type, lithology, water depth, porosity, permeability, formation thickness, formation depth, formation pressure.

The East UK area of interest for Concept 1 is identified as the Southern North Sea area in the CO_2 Stored database (Figure Figure 4 – Offshore UK fields areas – The Southern North Sea is the area of interest in our study – Source CO2stored4) where 100 depleted gas fields are recorded.

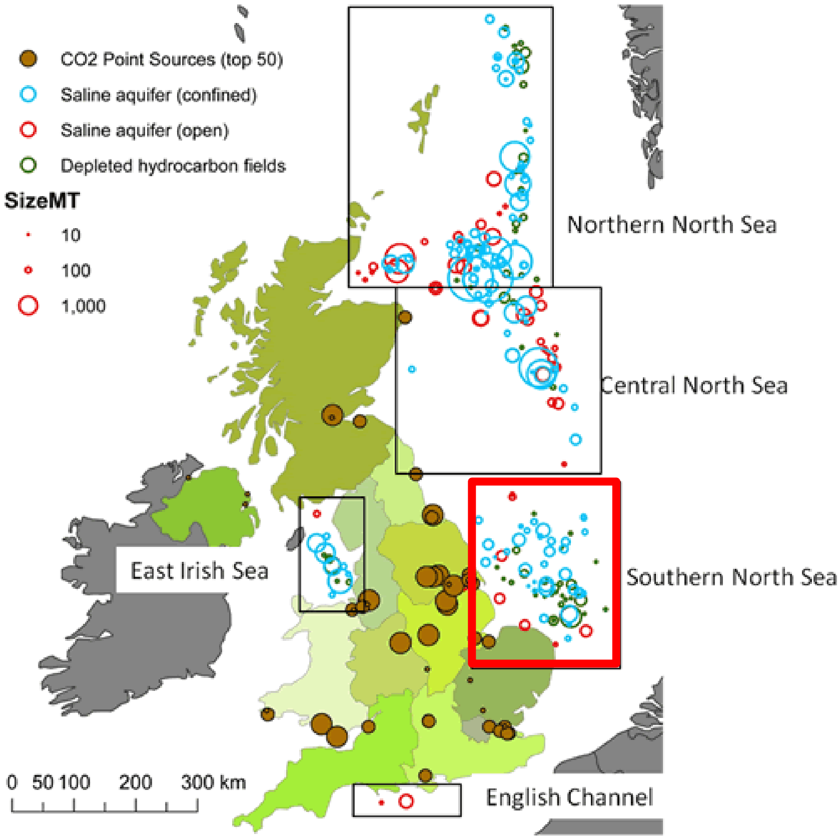

Figure 4 – Offshore UK fields areas – The Southern North Sea is the area of interest in our study – Source CO2stored

In order to identify potential candidates for storage, two filter criteria were applied on these fields:

- Theoretical storage capacity should be greater than 20 Mt CO_2 (P90);
- The end of production / closure date should be before 2025.

Around 30 gas fields fulfill these criteria (Table 3). The assumption is that the selected storage location for Concept 1 will be one of these fields with the following characteristics:

Table 2 – Concept 1 storage characteristics

Field location	Southern North Sea
Distance from Dunkirk	300 km[1]
Water depth	30 m[2]
Reservoir depth	2,500 mTVD[3]

[1] Average distance between Dunkirk and the localization of the depleted fields in this area

[2] Average maximum water depth of depleted gas fields in this area

[3] Average value of reservoir depth of depleted gas fields in this area

Table 3 – Depleted gas fields with potential CO_2 static storage capacity greater than 20Mt and end of license before 2025 - Source CO2stored

Field	End of prod/closure	Reservoir age	Formation	Water depth (m)	Reservoir depth (mTVD)	Cum gas prod 10e9m3	Theoretical CO2 storage capacity Mt		
							max	med	min
Amethyst East	2018	Rotliegend	Leman sandstones	30	2664	17	55	50	50
Anglia	2018	Rotliegend	Leman	25	2650	6,9	24	21	21,4
Audrey	2020	Rotliegend	Leman sandstones	25	2840	20	69	63	56
Camelot C S	2011	Rotliegend	Leman sandstones	30	1844	6	24	22	20
Cleeton	2000	Rotliegend	Leman sandstones	25	2770	10	34	31	31
Excalibur	2024	Rotliegend	Leman sandstones	20	2650	7	25	23	23
Ganymede	2019	Rotliegend	Leman sandstones	30	2500	8	28	25	22
Indefatigable	2016	Rotliegend	Leman sandstones	30	2590	158	436	397	397
Lancelot	2012	Rotliegend	Leman sandstones	20	2600	8	29	26	26
Markham	2023	Rotliegend	Leman	40	3477	8,4	24	22	21,7
Murdoch	2018	Carboniferous	Westcoe coal	35	3566	14	40	36	36
Neptune	2017	Rotliegend	Leman sandstones	45	2698	12	38	34	34
North Valiant	2019	Rotliegend	Leman	15	2105	6,2	23	20	20,3
Orwell	2009	Trias	Bunter sandstones	33	1612	9	42	38	38
Ravenspurn	2024	Rotliegend	Leman sandstones	45	3085	41	131	117	117
Rough	2021	Rotliegend	Leman sandstones	35	2738	14	31	29	29
Schooner	2022	Carboniferous	Schooner sandstones	70	3597	9	26	24	22
Skiff	2018	Rotliegend	Leman sandstones	25	2542	8	29	26	26
Thames	2011	Rotliegend	Leman	30	2377	6,9	24	22	21,5
Valiant south	2012	Rotliegend	Leman sandstones	25	2522	9	33	30	30
Victor	2015	Rotliegend	Leman sandstones	25	2700	30	93	85	85
Viking S	2015	Rotliegend	Leman sandstones	25	2764	91	299	268	268
Vulcan	2022	Rotliegend	Leman sandstones	20	2377	19	71	63	63
West sole	2021	Rotliegend	Leman sandstones	25	2743	58	192	173	173

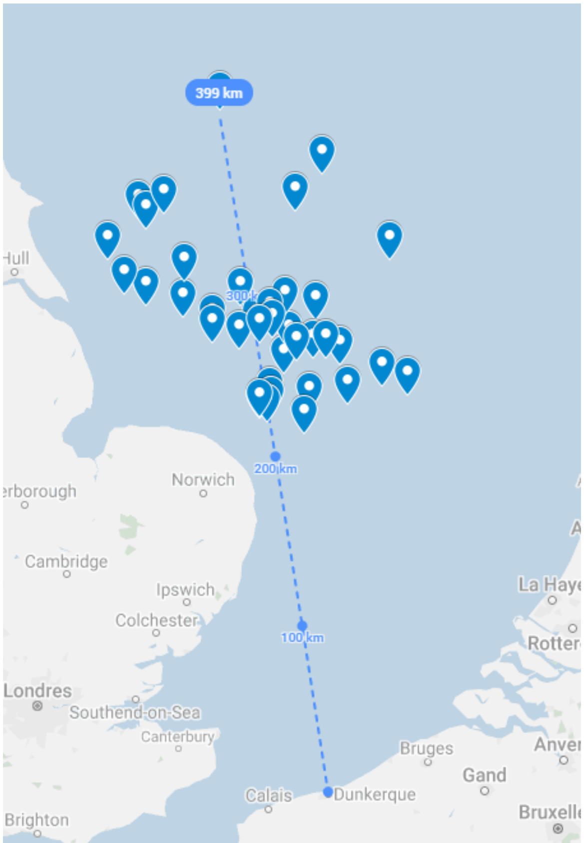

Figure 5 – Depleted gas fields in Southern North Sea area with distance from Dunkirk – Source CO2stored

Number of wells and injection rate

The CO2stored database also provides some parameters regarding injection such as:

- Estimated injectivity per well (in Mt/yr)
- Virgin reservoir pressure (MPa)
- Bottom hole injection pressure (MPa)

The well injectivity is estimated from production history data and the distribution for these fields is in a range between 0.1 to 0.5MT/yr (Figure 6). Since this property will dictate the number of required wells for injection, the choice of the field will be strongly influenced by this parameter. The assumption is that the selected field will be in the high end of the injectivity property range i.e. 0.4-0.5MT/yr.

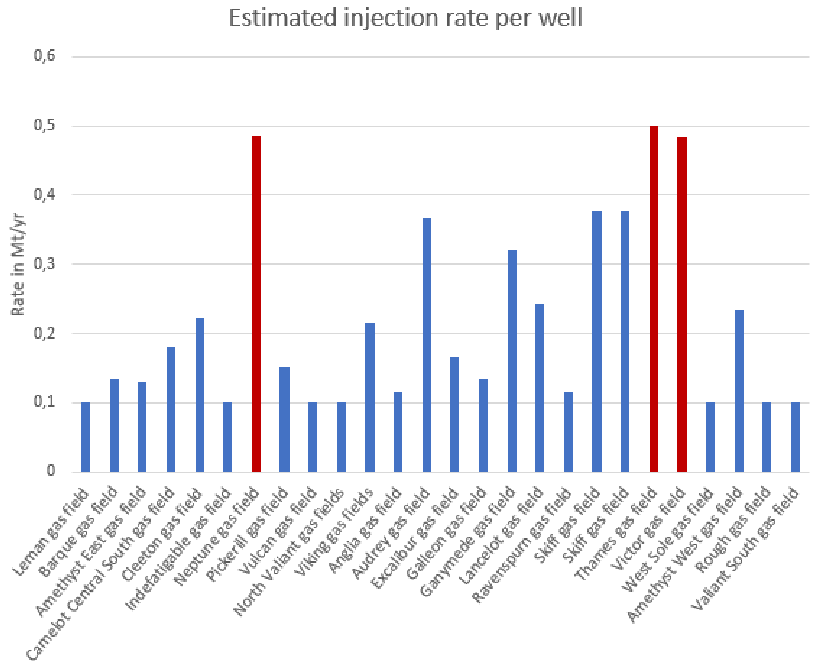

Figure 6 – Depleted gas fields injection parameters. Highlighted in red are the top 3 (top 10%) fields in terms of injectivity property – Source CO2stored

The number of wells required to store 1 Mt CO_2/yr for 15 years is then calculated:

[Total injection rate (1 Mt CO_2/yr)] / [Injection rate per well] = 2 to 2.5 wells

It would then require a maximum of **3 injection wells**. This would allow to inject 3 x 0.4 = 1.2 Mt CO_2/yr which provides 20% margin in case of operational unavailability.

Injection pressure and temperature

The injection temperature is dictated by two criteria:

- Bottom hole temperature should be above a minimum value in order to avoid hydrate or clathrate formation when CO_2 is mixed with the pore water;
- Another consideration on the temperature is that it should be above freezing temperature at injection in order to avoid ice formation around the subsea injection line.

It is difficult to evaluate hydrate formation risks at this stage without a proper study and additional data (well architecture, water characterisation, reservoir characteristics etc.). As an assumption, we can state that an **injection temperature above freezing condition i.e. 2°C** (with some safety margin) will be sufficient to fulfill both criteria.

The bottom hole injection pressure that is indicated in the database is quite large and corresponds to the maximum allowable pressure before expected fracture is reached (D. Gammer, S. Holloway, G. Smith, & Consortium, 2010). The virgin reservoir pressure corresponds to the initial reservoir pressure of the field before production.

The required injection wellhead pressure is calculated considering an overpressure at bottom hole over reservoir pressure minus the CO_2 column height in the tubing. It is expected that the reservoir pressure in the depleted field will be low at the beginning of the injection life and progressively increase in time. In order to design the surface facilities (injection pump duty, pipeline design pressure etc.) the maximum foreseen injection pressure needs to be estimated. During injection, the reservoir pressure will increase up to a certain maximum value that is decided by the operator. If this value exceeds the initial (pre-production or virgin) reservoir pressure, a comprehensive subsurface integrity study must be conducted to show the absence of risk. As this study is theoretical and will not target a specific field, the assumption is that the reservoir pressure will always remain under its initial value. The maximum injection pressure is therefore calculated considering an end of life pressure in the reservoir equal to the initial reservoir pressure. This value can be found for each of the selected fields in the public database CO2stored. The calculation of the surface injection pressure is simplified and considers the hydrostatic pressure the CO2 fluid column and a fixed pressure loss through the formation: .

$$WHP_{max} = P_{res\_ini} + DeltaP_{formation} - P_{CO2column}$$

Where:

P_{res_ini} = Initial reservoir pressure
$DeltaP_{formation}$ = Pressure loss in formation for injection
$P_{CO2column}$ = CO_2 column weight in tubing

The CO_2 column weight is dependent on the reservoir depth and fluid density. In the pressure and temperature conditions of the expected operational window, the fluid density can vary between 800 to 1000 kg/m^3 (Figure 7). A sensitivity calculation has been done for each gas field in the area with 3 different fluid density values: 800, 900 and 1000 kg/m^3. This gives a range for **injection pressure of 30 to 120 bar** (mean values discarding outliers) (Figure 8).

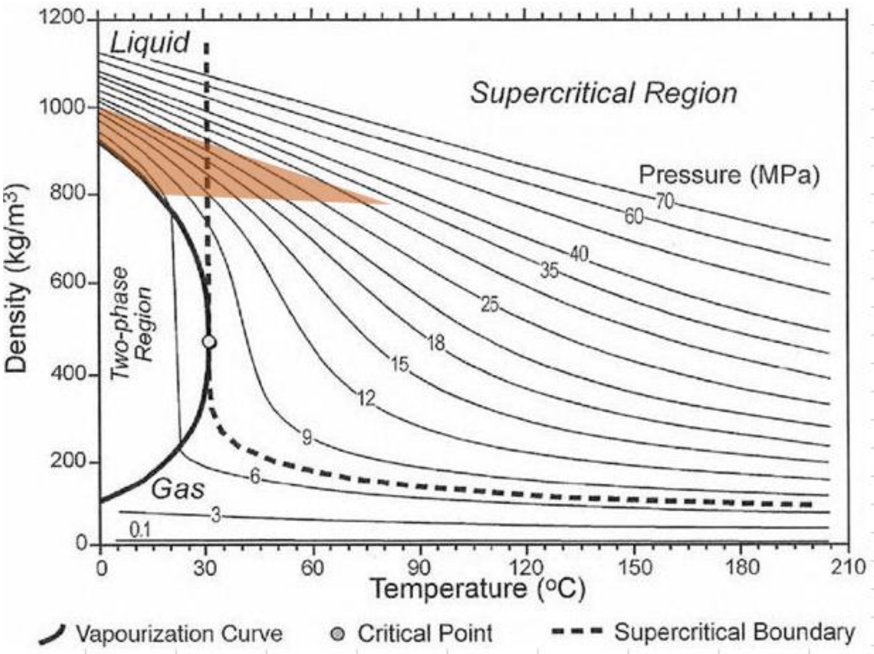

Figure 7 – CO_2 density chart – Expected operational window in shaded area

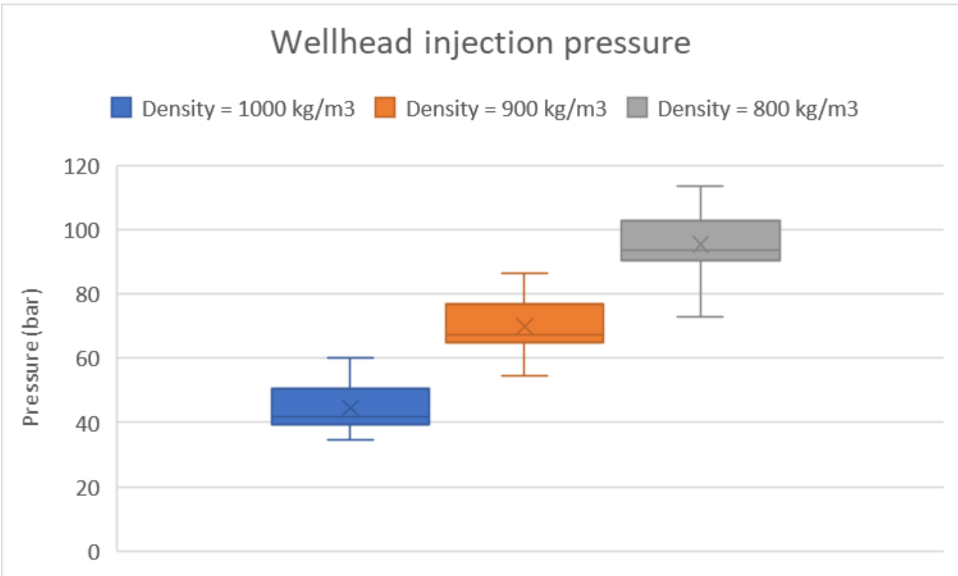

Figure 8 – Wellhead injection pressure (bar chart showing minimum, 1st quartile, median, mean, 3rd quartile and maximum values) calculated for the 30 depleted gas fields in Southern North Sea area

3.3.2 Concept n°2: Plug-in on Northern Lights, Norway

Following the first concept exploring the possibilities of transporting and storing 1 million ton of CO_2 per year, for 10 to 15 years, in reservoirs around Dunkirk area, an option of joining a mature project in the North Sea has been considered. Known today as one of the most advanced CCUS project in the world and part of the Full-Scale CCS project in Norway, the Northern Lights project is an initiative supported by the Norwegian government aiming to transport by ship liquid CO_2 captured from two industrial sources in the Oslofjord region to an onshore terminal located on the Norwegian west coast. The liquefied CO2 will then be transported by pipeline to an offshore storage site subsea in the North Sea for permanent storage.

The Norwegian government, through the Full-Scale CCS project, is aiming to develop a full-scale CCS value chain in Norway by 2024. The pre-project (concept and FEED studies) is governed by a study agreement between Gassnova and Equinor. A collaboration agreement between Equinor, Shell and Total governs the study work and the preparations for establishing a Joint Venture Agreement at the time of a positive investment decision by the partners. Equinor is operator of the project. Norske Shell and Total E&P Norge are equal partners.

The Northern Lights project takes in charge the transport and storage scope of the Norwegian Full-Scale CCS Project (Figure 9). Pressurized liquefied CO_2 will be loaded on dedicated CO_2 carriers in Oslo area, which will navigate along the Norwegian coasts and unload onto onshore intermediate storage tanks. This configuration of buffering the CO_2 in an onshore intermediate storage facility enables CO_2 transport by pipeline to the offshore subsea location for a continuous injection into a subsurface geological storage location.

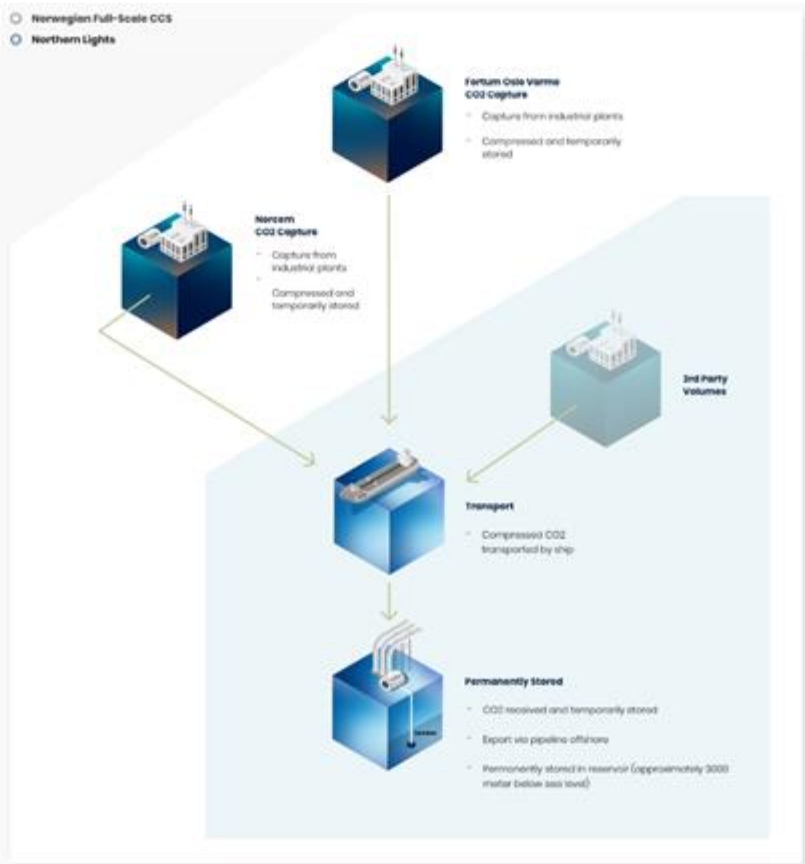

Figure 9 – The Full-Scale CCS project – http://northernlightsccs.com/en/about

Two phases of the project are considered: Phase 1 corresponds to the concept capacity to transport, inject and store up to 1,5 million tons of CO_2 per annum. Phase 2 increases the capacity to receive, inject and store an additional 3,5 million tons of CO_2 per annum, adding up to a total of 5 million tons of CO_2 per annum. Fortum Oslo Varme and Norcem, the Norwegian CCS Full-Scale Project capture sources, account for 800 000 tons per annum of CO_2. Phase 1 and 2 will offer some spare capacity to receive extra volumes from other European CO_2 sources.

In this concept 2, it is considered to transport the liquid CO_2 via ship, from Dunkirk to Kollsnes. It has been selected as the base case because of the unique maturity and high probability of success of Northern Lights project to store CO_2 in the North Continental Shelf. Kollsnes, on the west coast of Norway, is the location where the onshore receiving facilities will be built. The terminal will be designed and equipped to host CO_2 carriers with an import jetty, intermediate storage tanks, conditioning and export facility, administration and visitor center. Two semi-pressurized and refrigerated CO_2 carriers have been defined for the Northern Lights project with a capacity of 7500m3 at medium pressure (15barg, -30°C) and transporting a volume of 400 000 tonnes/y of CO_2 each.

The distance between Dunkirk and Naturgassparken, the Norwegian industrial area where the terminal is located, is approximately 1100 km. This option will allow exploring some aspects of long-distance CO_2 shipping with low volumes. It will serve as a base case for technical feasibility (port technology, CO_2 specification, frequency of delivery…) and for cost assessment.

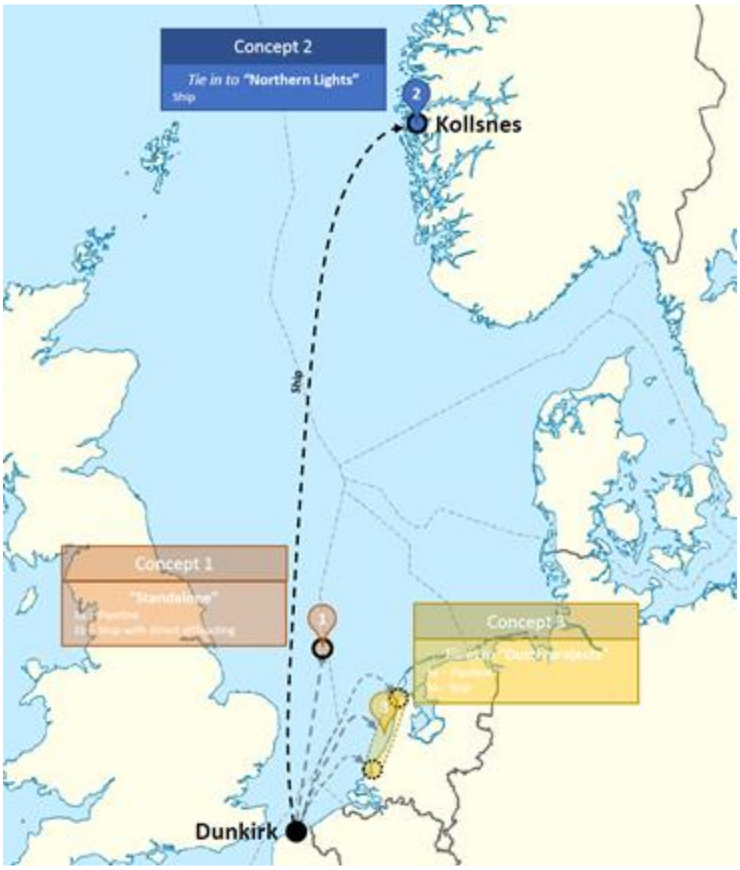

Figure 10 – Concept 2 – Plug-in to the Northern Lights project

3.3.3 Concept n°3 : Plug-in on a Dutch project (closer to Dunkirk)

Netherlands is the third region targeted as a potential receiving area for CO_2 captured and transported from Dunkirk. This region is hosting various CCUS projects under different levels of development. It is most probable that dedicated infrastructures for receiving, handling and exporting CO_2 will be developed in this area. No specific project is targeted but the Amsterdam to Rotterdam area is foreseen as the region where the potential hub infrastructure will be built.

The Netherland's projects, concept 3, has been identified as an interesting case due to the proximity to Dunkirk and the numerous options of CCS projects under development hosted in its coastal areas. In this concept, connection to an existing CO2 handling terminal on the Dutch coast is considered. Although the location of the terminal is not defined here (between 150 km and 250 km from Dunkirk whether it is close to Rotterdam or Amsterdam), a mean distance of 200 km from Dunkirk will be taken as an assumption. This relatively short distance gives room for 2 potential transport options:

- Concept 3a: Pipeline from Dunkirk to the Netherlands
- Concept 3b: Ship from Dunkirk to the Netherlands

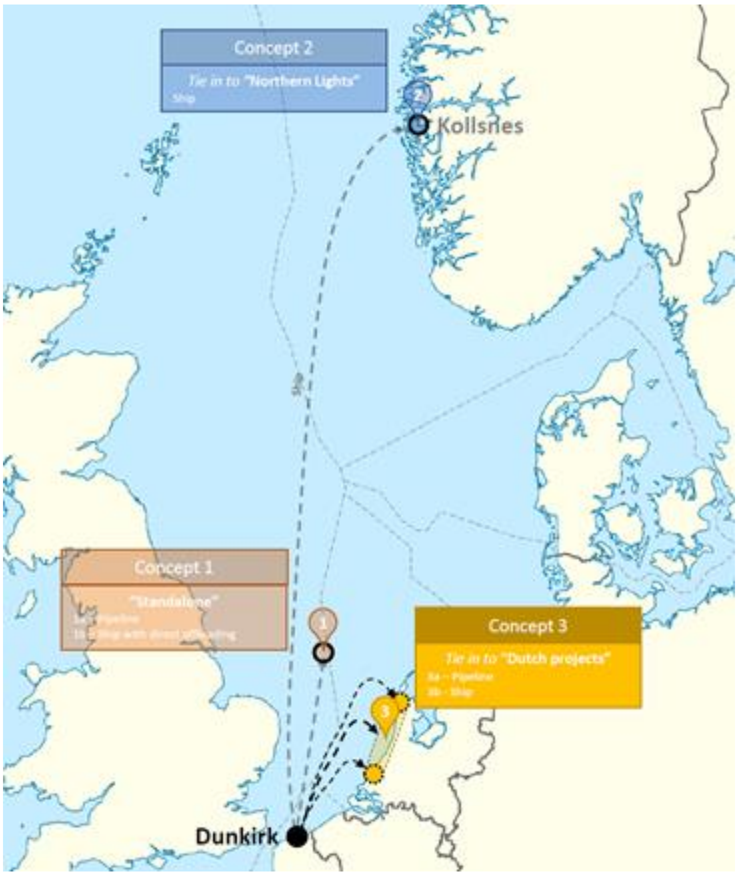

Figure 11 – Concept 3 – Plug in to Dutch project

4 Design basis

4.1 Battery limits

A general illustration of the battery limits for the value chain is shown in Figure 12. More detailed descriptions are given for the different concepts further down. The building blocks shown within capture, conditioning and storage are not part of the scope for Work Package 6.

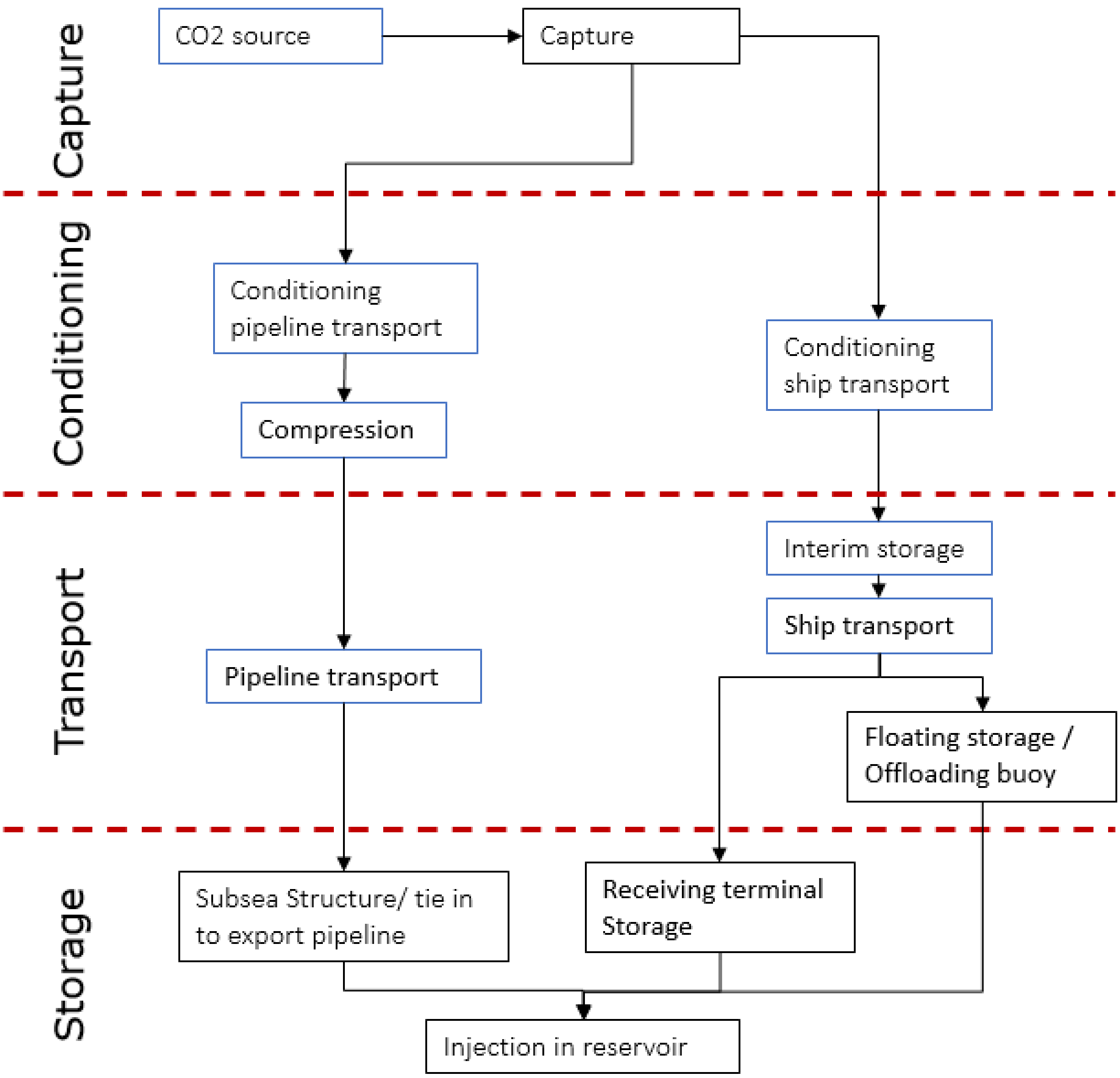

Figure 12 – Battery limits in the value chain – WP6 is responsible for the transport part only

Concept 1 – Stand alone

In this concept, the battery limit starts at the outlet of the conditioning process in Dunkirk (WP5) and ends at the connection with the offshore injection facilities.

For concept 1a, this is from downstream of the compression facility, to the connection point between the offshore pipeline and the injection facility.

For concept 1b, where ship is the mode of transport, the intermediate storage and loading arms in Dunkirk area are considered part of the scope of work, as well as the ship and floating intermediate storage up to the connection to the injection facility.

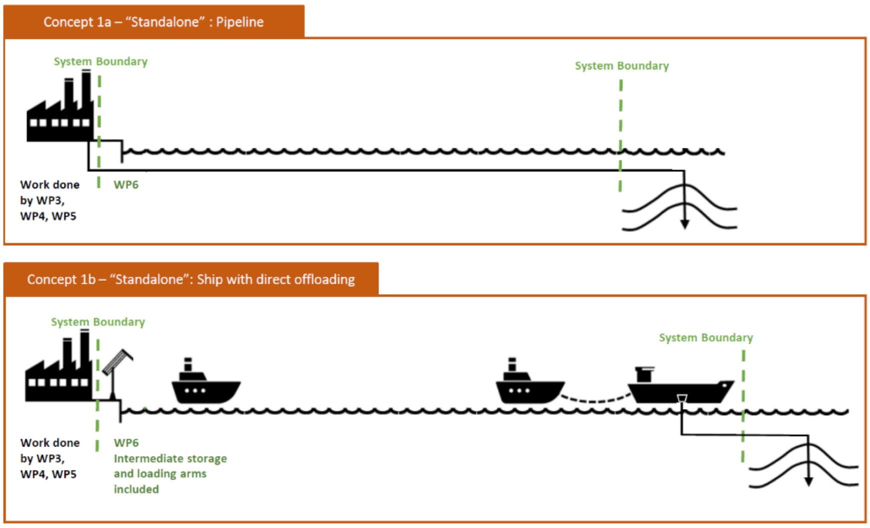

Figure 13 – Concept 1 battery limits

Concept 2 – Plug-in to the Northern Lights project

The battery limits of the system are the outlet of the conditioning process in Dunkirk (WP5) to the import jetty in Kollsnes. This includes the intermediate storage and loading arms technologies onshore in Dunkirk area, as well as the ship and technologies to transport the CO_2. The battery limit ends upstream the onshore receiving terminal.

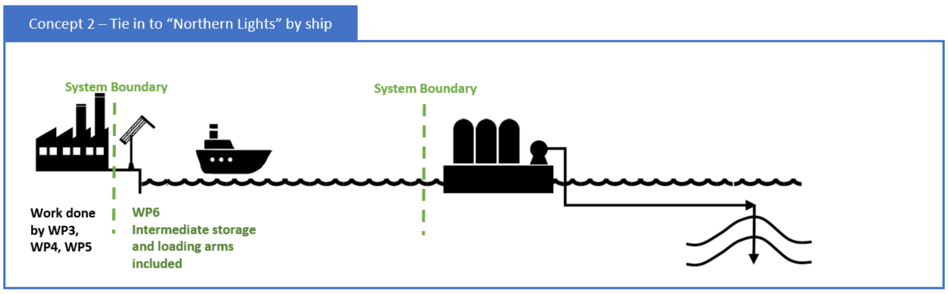

Figure 14 – Concept 2 battery limits

Concept 3 – Plug-in to Dutch projects

In concept 3a, offshore pipeline has been preferred to onshore pipeline, due to the intrinsic complexity of the latter (land access, right of way, social acceptance). In concept 3b, a ship would leave Dunkirk to a Dutch harbor with CO_2 receiving facilities.

For concept 3a, where pipeline transports the liquid CO_2 coming from Dunkirk, the battery limit starts downstream of the conditioning onshore units (WP5) and ends at the connection point to the export pipeline from the onshore export facility in Netherlands to the offshore injection facility.

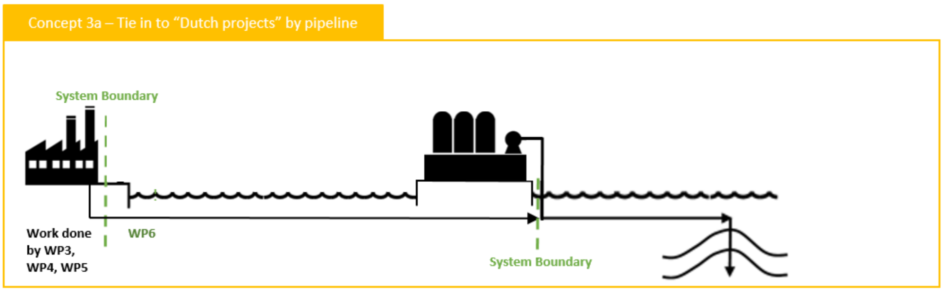

Figure 15 – Concept 3a battery limits

For concept 3b, the intermediate storage and loading arms in Dunkirk area are considered part of the scope of work, as well as the ship, up to the connection to the onshore export facility in the Netherlands.

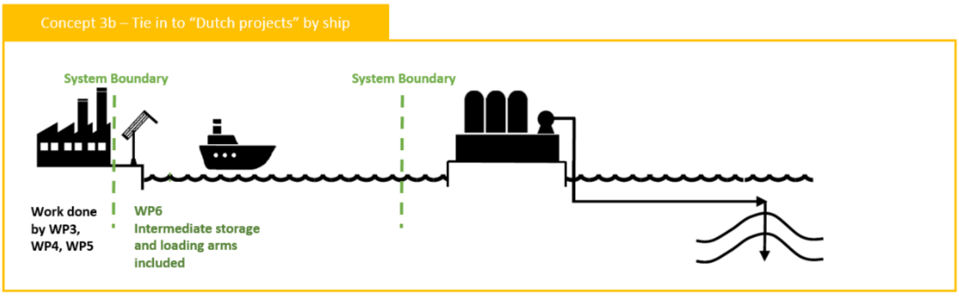

Figure 16 – Concept 3b battery limits

4.2 CO_2 specification

The CO_2 specification for the Norwegian Full Scale Project, which Northern Lights is also a part of, is shown in Table 4. This is considered to be the most mature specification that is currently available. As this storage option is also the base case for the transport study, this specification will be used as the base case for the required CO_2 quality from conditioning.

From the list impurities specified in Table 4, only water, CO and H_2S are expected to be present in the flue gas from ArcelorMittal.

Table 4 – CO_2 quality specification for the Norwegian Full Scale project, including Northern Lights

Component	Concentration (pp mol)	Remarks
Water	≤ 30	Required to avoid corrosion and hydrate creation
Oxygen	≤ 10	Required to avoid corrosion
Sulphur Oxides	≤ 10	Required to avoid corrosion
Nitric oxide/Nitrogen dioxide, NOx	≤ 10	Required to avoid corrosion
Hydrogen sulfide, H_2S	≤ 9	Toxic to personnel in case of accidental release
Carbon monoxide, CO	≤ 10	Toxic to personnel in case of accidental release
Amine	≤ 10	May react with and degrade non-metallic materials
Ammonia, NH_3	≤ 10	Flammable, mildly toxic
Hydrogen, H_2	≤ 50	May cause embrittlement of metals
Formaldehyde	≤ 20	May react with oxygen to form formic acid.
Acetaldehyde	≤ 20	May react with oxygen to form acetic acid.
Mercury, Hg	≤ 0,03	Toxic to personnel servicing the installation. May cause embrittlement of metals
Cadmium Cd Thallium, Tl	≤ 0,03	Toxic to personnel servicing the installation. May cause embrittlement of metals

Non-condensable gases are components that, when pure, will be in gaseous form at 15 barg and -26 °C. The content of non-condensable gases will be limited by the actual solubility in the liquid CO_2 within the interim storage tanks at the capture plants.

4.3 Conditions for ship transport

4.3.1 General philosophy for the ship

The ship transport GHG footprint shall be kept at a minimum. This may be achieved by utilising available technology for emission reductions, alternative fuels, operational measures such as slow speed steaming etc. Also, the cost of the ship transport should be kept as low as possible in order to accelerate the implementation of CCS.

4.3.2 Pressure and temperature

4.3.2.1 Base case medium pressure

- Operating: 13-18 barg at equilibrium
- Design pressure: 19 barg
- Design temperature: -35^{o}Ca

4.3.2.2 Low pressure sensitivity

- Operating: 6-7 barg at equilibrium
- Design pressure: 8 barg
- Design Temperature: -55^{o}C

4.3.3 Volume rate

4.3.3.1 Annual transport volume

Annual volume 1.0 Mt/y.

4.3.3.2 Offloading rate

- It is assumed deep-well cargo pumps will be used for cargo offloading.
- Pump capacity will be 600 t/h for each tank.
- It is assumed the ships will have minimum two tanks.
- Offloading rate will therefore be 1200 t/h or more for each ship, but upwards limited to 3000 t/h

4.3.3.3 Loading rate

It is assumed the same loading and offloading rate. May be increased to meet voyage planning requirements.

4.3.3.4 Offshore injection rate from FSI

- Determined of well injection rates (max, min and average)
- Continuous injection only is considered (no batch)

4.3.4 Terminal quays

Kollsnes (phase 1 quay facilities):

- Maximum ship length: 130 m
- Maximum ship draught: 8.5 m

These limits are also used for the receiving terminal in the Dutch projects.

Terminal at Dunkirk is assumed developed to fit the relevant Ship sizes. I.e. for Offshore Unloading quay facilities in Dunkirk are not considered as a limiting factor.

4.3.4.1 Intermediate storage in Dunkirk

- Base case is 1.2 times ship capacity

4.3.5 Utilities

4.3.5.1 Quay-side export harbor

The following quay-side utilities are assumed available:

- Shore power for all consumers onboard (not cargo pumps)
- Fresh water
- Bunkering services
- Garbage collection and supply services

4.3.5.2 Quay-side import harbor

The following quay-side utilities are assumed available:

- Shore power for cargo pumps and other onboard consumers
- Fresh water
- Garbage collection and supply services

4.3.6 Metocean data

4.3.6.1 Shore to Shore

Weather margin to be calculated and included in logistics calculations.

4.3.6.2 Shore to offshore

- Hook-up sea conditions limited to 4.5 Hs.
- Metocean data based on best available statistics for the offloading location.
- Weather margin to be included in logistics calculation as the shore-shore option.

4.4 Conditions for pipeline transport

4.4.1 Pressure and temperature

Inlet pressure:

The pipeline inlet pressure will be calculated based on the required outlet pressure and the diameter of the pipeline. A trade off will be made based on the cost of increasing the diameter vs the cost of increasing the inlet pressure.

Outlet pressure:

Unless otherwise is specified by the storage operator the pipeline outlet pressure will be determined by the end of life injection pressure of the CO2 reservoir, while ensuring a 5 bar margin to the CO_2 saturation line along the entire pipeline.

Temperature:

Design temperature for gas pipelines is usually between -10°C and +60°C, and the temperature of the CO_2 is expected to be within this range. The inlet temperature will be calculated by conditioning (WP5) based on the compression of the CO_2 upstream the pipeline. The outlet temperature of the CO_2 will be given by the heat exchange with the surrounding sea water along the pipeline, and will most likely be close to the sea bottom temperature.

4.4.2 Volume rate

The use case is 1 Mt CO_2/year for 10 – 15 years. Lower and higher flow rates may be explored as sensitivities.

4.4.3 Pipeline route

The pipeline routes will be based on the shortest distance from the capture site to the storage site. There will be no surveys carried out or optimization of the pipeline routing with respect to sea bottom topography, sea currents, ship traffic, environmental restrictions, regulatory requirements etc. Such detail is not considered to be necessary at the level of this study.

4.4.4 Connection to storage site

It is assumed that the pipeline is connected directly to the injection well, unless otherwise has been stated by the storage concept.

It is assumed that details downstream the connection point is handled by a storage operator, such that number of wells, well capacity etc. and cost related to this will not be calculated.

4.5 Regularity

There is no regularity requirement for the value chain. The solutions proposed will be based on good industrial standard, and the regularity will be according to this.

4.6 Assumptions for economic analyses

Input:

- Total investment cost
- Annual operating cost

Output:

- Average unit cost including total cost for the project and the on total transported mass of CO_2. An operational period of 15 years shall be included, and both the cost and the mass of CO_2 shall be discounted with 7%.

Sensitivities:

- Operational period – 10 years
- Discount rate – 5%

5 Conclusions

Based on the information presented in this report the following is chosen to be used as the base case in the transport study:

- 1 Mt CO_2/year captured in Dunkirk stored in the Northern Lights reservoir
- Ship transport from Dunkirk to Northern Lights terminal
- Ship transport conditions compatible to Northern Lights Phase 1
- CO_2 purity according to the Northern Lights specification

This represents the currently most realistic solution for transport and storage of CO_2 from Dunkirk starting in 2025.

In addition to the base case a number of sensitivities will be investigated, representing possible upsides to the base case. The sensitivities include alternative storage options, potential relaxation of the Northern Lights specification, pipeline transport, lower operating pressure during ship transport etc.

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