Accelerated deployment of integrated CCUS chains based on solvent capture technology

Deliverable Deliverable D5.1 – Methodology for full chain CCUS assessment and cluster development

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Nature of the Deliverable		
R	Document, report (excluding the periodic and final reports)	X
DEM	Demonstrator, pilot, prototype, plan designs	
DEC	Websites, patents filing, press & media actions, videos, etc.	
OTHER	Software, technical diagram, etc.	

Dissemination Level		
PU	Public, fully open, e.g. web	X
CO	Confidential, only for members of the consortium (including the Commission Services)	

Quality procedure			
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Project Summary

Rapid up-scaling and deployment of more cost-efficient and sustainable carbon capture solutions is needed to reduce the emissions of CO_2-intensive industries. Solvent-based carbon capture is an important technology that can be readily adopted to many emission sources. Such technology can achieve high capture rates and deliver CO_2 at high purity with a relatively low energy demand. In AURORA the open and non-proprietary CESAR1 solvent technology will be optimised and qualified for commercial deployment. The technology will be demonstrated at TRL7-8 for three CO_2 intensive industries: refining, cement, and materials recycling, for which there are few other options to achieve climate neutrality. The partners will demonstrate negligible environmental impact (emissions being a potential issue for solvent technology), capture rates at 98%, and capture costs reduced by at least 47% compared to a benchmark process with the MEA solvent.

This will be achieved due to the following innovations: 1) Holistic optimisation of solvent composition, process design, emission monitoring and control, and solvent management, 2) Validated models for use in commercial process simulators 3) enhanced waste heat integration with carbon capture for reduced external heat demand and operational costs 4) Improved and integrated advanced control system for reduced OPEX and optimised performances.

These innovations will be integrated in four optimised capture processes and various aspects will be demonstrated in pilots of various size and complexity. The partners will ensure transferability of results to other CO_2 intensive industries thanks to the large variations in CO_2 source and developed clusters addressed in the project and a strong stakeholder participation. The project will also do full CCUS chain assessments for its end-users. It is noteworthy that the end-users are situated in two different regions of Europe offering different conditions for the implementation of CCUS value chains.

More information on the project can be found at https://aurora-heu.eu/.

Document Objective and Executive Summary

The objective of Deliverable D5.1 is to describe the methodology and the guidelines which will be used for assessing the different scenarios of full CCUS chains proposed for the 4 emitters of AURORA project: UMICORE material recycling plant and TOTALENERGIES Refinery in Belgium, HERACLES cement plant and MOTOR OIL refinery in Greece. It is worth noting that in other work packages, emitters are referred as "end-users" since they are potential user of the post combustion capture technology using CESAR1 solvent. In WP5 related to the assessment of the full CCUS chain, we use the term "emitter" to avoid confusion by considering the end-user as the last link of the CCUS chain.

For each emitter, the best available options will be evaluated to identify the most promising CCUS chains in each region. The building of the CCUS chain scenario will depend on opportunities in each region: the location, nature and longevity of CO_2 sources and sinks, the clustering options for capture and/or conditioning and/or transport, the available options and routes for transport by ship or pipeline at national and trans-national levels, storage sites options depending on their technical appraisal, their capacity and their maturity. Each scenario will be evaluated through a techno-economic analysis, a life cycle assessment and a social, political and commercial readiness analysis. The overall methodology for full-chain CCUS is currently foreseen to contain the following elements:

- Scenario definition
  - Description and selection of sources and sinks
  - Reference case
  - Alternate scenarios
- Regulation and policies: Regional, National and European
- Iteration on
  - Flowsheet design of each chain element
  - Cost estimation
  - Life cycle assessment
  - Assessment of social and political readiness

After a brief presentation of each emitter plant in §1, we present the whole methodology in §3. Location of CO_2 sources and potential sinks introduce the chapter §4 dedicated to the scenarios definition. The reference scenario is described along with the alternative scenarios in which CO_2 utilization for methanol production or mineralization in basalt will be considered. In §5, each block of the CCUS is detailed: capture, conditioning, transport, storage through permanent storage or mineralization, conversion. The methodology for evaluating the technical aspects, capacity and maturity of potential storage site is also presented in this chapter. Chapters §6 and §7 are devoted to CO_2 specifications, regulations and policies. The methodology adopted for the techno-economic assessment and the life cyle analysis are developed in §8 and §9. At last, KPI resulting from these evaluations are presented in §10. They cover most of the aspects of the CCUS chain since they cover the efficiency, the energy, the econcomics, the environmental along with societal, political and regulatory aspects.

List Of Partners

N°	Participant organisation name	Acronym	Country
1	SINTEF AS	SINTEF	NO
2	Norwegian University of Science and Technology	NTNU	NO
3	University of Cambridge	UCAM	UK
4	Technology Centre Mongstad	TCM	NO
5	Sapienza Università di Roma	UNIROMA1	IT
6	TotalEnergies OneTech	TOTAL	FR
8	Aker Carbon Capture AS	ACC	NO
9	MOTOR OIL	MOH	GR
10	Heracles Group	HERACLES	GR
11	UMICORE	UMICORE	BE
12	Cybernetica	CYB	NO
13	Euroquality SAS	EQY	FR

Contents

1 Introduction

1.1 The full CCUS chain assessment

The objective of Deliverable D5.1 is to describe the methodology and the guidelines which will be used for assessing the different scenario of full CCUS chains proposed for the 4 emitters of AURORA project: UMICORE material recycling plant and TOTALENERGIES Refinery in Belgium, HERACLES cement plant and MOTOR OIL refinery in Greece. This methodology must be replicable and transferable for the assessment of any other CCUS full-chain.

For each emitter, the best available options will be evaluated to identify the most promising CCUS value chains in each region. The building of the CCUS chain scenarios will depend on opportunities in each region:

- Clustering options for capture and/or conditioning and/or transport will depend on the location of emitters at the local, regional and national levels, the nature and the longevity of the emission sources.
- Available options and routes for transport by ship or pipeline, national and transnational regulations, incentives.
- Storage sites options will depend on their location (onshore vs offshore), their geological and technical aspects, their estimated storage capacity and the maturity of the infrastructure development.
- The possibility to shorten the distance for CO_2 export through utilization or mineralization of the captured CO_2 close to the capture point.
- The commercial, social and political readiness conditions in which each company, region or country deploy CCUS.

When existing, on-going or planned CCUS projects will be considered as reference scenario.

Each scenario will be evaluated through a techno-economical analysis, a life cycle assessment and a social, political and commercial readiness analysis.

1.2 Emitter plants

The aim of AURORA project is to assess the suitability and efficiency of CESAR1 solvent for capturing CO_2 on flue gas sources presenting large variation in composition. The 4 industrial partners of the consortium proposed a plant referred as “emitter plant” representative of their industry and relevant for their decarbonation strategy. The plants are (1) the Heracles cement plant in Volos, Greece, (2) the Motor Oil refinery near Corinth, Greece, (3) the refinery in Antwerp, Belgium, and (4) the Umicore material recycling plant in Antwerp, Belgium.

In all the other work package of the project, emitters are referred as “end-users” since they are potential user of the post combustion capture technology using CESAR1 solvent. In WP5 related to the assessment of the full CCUS chain, we use the term “emitter” to avoid confusion by considering the end-user as the last link of the CCUS chain.

1.1.1 UMICORE – Material Recycling plant, Hoboken, Belgium

UMICORE is a global leader in clean mobility materials and recycling. UMICORE precious metals refining plant (PMR) is one of the largest plant of that kind in the world. UMICORE is also the market leader in recycling complex wastes containing precious and other non-ferrous metals. The unique flowsheet can process over 200 residue streams and recover 17 metals at the highest yield. Industrial residues from the smelting industry, recyclables such as end-of-life electronic scrap (printed circuit boards and mobile phones) along with spent industrial and automotive catalysts can all be treated in the Precious Metals Refining (PMR) process. UMICORE recovers and refines precious metals, minor metals, and base metals. These can then be put back into the cycle for various technology applications. The PMR process incorporates a copper smelter whose average emissions are between 80 and 120 kt_{CO2}/y. This stack will be the application case of AURORA project. This Smelter is located in Hoboken, a suburb of Antwerp in the North of Belgium and is situated on the Scheldt River which connects the plant to the Port of Antwerp.

1.1.2 TOTALENERGIES – Refinery, Antwerp, Belgium

With the number of 338,000 barrels of oil per day and a facility that produces polymers with capacity of 1.1 million tons per year, TotalEnergies Antwerp refinery constitutes the third-largest refinery in Europe. With the transition of the European oil market, TotalEnergies has invested since 2013 more than €1 billion to extensively upgrade the Antwerp complex in order to improve its feedstock flexibility and meet the strictest environmental standards. In 2021, the global CO_2 emissions were 3.79 Mt_{CO2}/y.

1.1.3 HERACLES Group – Cement plant, Volos, Greece

In the Greek context, where the Volos plant is located, HOLCIM Ltd is represented by its group company HERACLES-HOLCIM, funded in 1911. HERACLES-HOLCIM is the largest producer of building materials in Greece, with approximately 50% of the annual cement capacity in Greece and more than 100 years of presence in the market. The Volos cement plant of the HERACLES Group is situated in Volos, Greece with a privately owned port. It is the largest cement production unit of HERACLES Group with cement production capacity around 2,4 Mt and it is one of the most important of HOLCIM company.

1.1.4 MOTOR OIL – Refinery, Agioi Theodoroi, Greece

Motor Oil owns a refinery near Corinth, processing approximately 185,000 barrels of crude oil per day and being one of the most advanced and modern in Europe (Nelson’s Complexity Index 12.61). It produces all types of refined fuels (gasoline, automotive diesel, jet), from various types of crude oil in accordance with the EU specifications and a number of Quality and HSE ISO standards. Motor Oil is both a domestic supplier and an exporter of fuel products. In 2022, the global CO_2 emissions were 16.8 kt_{CO2eq} for electricity and 2.28 Mt_{CO2eq} for liquid, gases and other fuels production in the whole refinery. The hydro-purification unit (HPU) averages emissions of 474.2 kt_{CO2eq}/y and is the focus of the AURORA study. The annual energy consumption for the Refinery is 30,131 TJ/y, while for the HPU is 2,198 TJ/y.

2 Terminology and definitions

- **CCUS** stands for Carbon Capture Utilisation and Storage. When the CO_2 captured is stored permanently, it refers to a CCS chain. When captured CO_2 is used either directly (i.e. not chemically altered) or indirectly (i.e. transformed) in various products, it refers to a CCU chain [1].

Three “scopes” are defined for greenhouse gas emission accounting and reporting [2].

- **Scope 1 emissions** are direct GHG (greenhouse gas) emissions which occur from sources that are owned or controlled by the company. They result principally from the following types of activities:
    - Generation of electricity, heat, or steam. These emissions result from combustion of fuels in stationary sources, e.g., boilers, furnaces, turbines.
    - Physical or chemical processing. Most of these emissions result from manufacture or processing of chemicals and materials, e.g., cement, aluminum, adipic acid, ammonia manufacture, and waste processing.
    - Transportation of materials, products, waste, and employees. These emissions result from the combustion of fuels in company owned/controlled mobile combustion sources (e.g., trucks, trains, ships, airplanes, buses, and cars).
    - Fugitive emissions. These emissions result from intentional or unintentional releases, e.g., equipment leaks from joints, seals, packing, and gaskets; methane emissions from coal mines and venting; hydrofluorocarbon (HFC) emissions during the use of refrigeration and air conditioning equipment; and methane leakages from gas transport.

Direct CO_2 emissions from the combustion of biomass shall not be included in scope 1 but reported separately. GHG emissions not covered by the Kyoto Protocol, e.g. CFCs, NOx, etc. shall not be included in scope 1 but may be reported separately.

- **Scope 2 emissions** account for GHG emissions from the generation of purchased electricity consumed by the company. Purchased electricity is defined as electricity that is purchased or otherwise brought into the organizational boundary of the company. Scope 2 emissions physically occur at the facility where electricity is generated.

- **Scope 3 emissions** is an optional reporting category that allows for the treatment of all other indirect emissions. Scope 3 emissions are a consequence of the activities of the company, but occur from sources not owned or controlled by the company. Some examples of scope 3 activities are extraction and production of purchased materials; transportation of purchased fuels; and use of sold products and services

- **CO_2 captured / CO_2 avoided:** The amount of CO_2 avoided is the difference between the emissions of the reference plant and the emissions of the plant with carbon capture. Because additional energy is required for capture, it results in additional CO_2 emissions (SCOPE 2 emissions) which can be captured or not. Consequently, the net amount of CO_2 avoided is always smaller than the CO_2 captured. In case where a full CCUS chain is considered, the additional CO_2 results from the additional energy required for capture, conditioning, transport and storage, and any leakage during the transport [3].

3 Methodology for full CCUS chain assessment

The overall goal of the work done in regard to full-chain CCUS in AURORA is to develop a replicable and transferable full-chain methodology. The overall methodology for full-chain CCUS is currently foreseen to contain the following elements:

- Scenario definition
  - Description and selection of sources and sinks
  - Reference case
  - Alternate scenarios
- Regulation and policies: Regional, National and European
- Iteration on
  - Flowsheet design of each chain element
  - Cost estimation
  - Life cycle assessment
  - Assessment of social and political readiness
- KPIs for evaluating the chains

All these items are interlinked together according to the schematic of Figure 1.

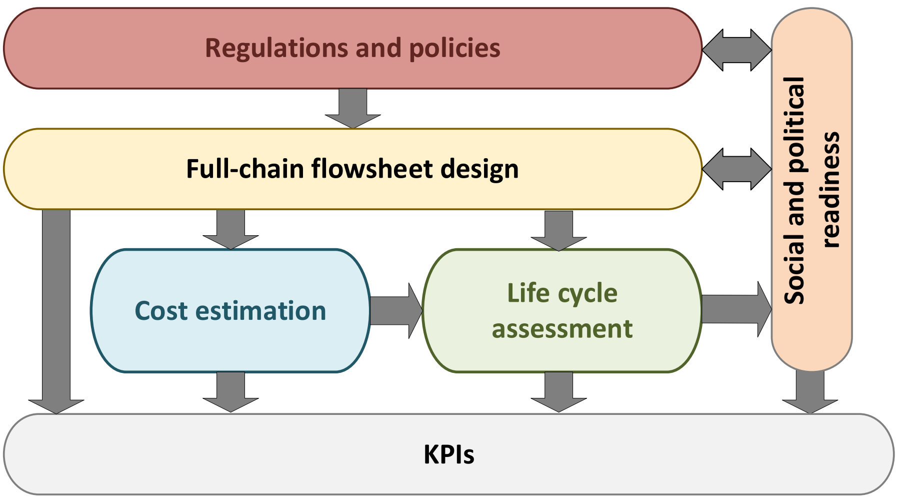

Figure 1: The overall full-chain CCUS methodology.

4 Scenarios definition

4.1 Sources

There are a total of four emitters in the project, two in Belgium and two in Greece. The locations of the emitters are shown in Figure 2 along with potential mode of transport towards storage sites. More information about the emitters is provided in §1.2.

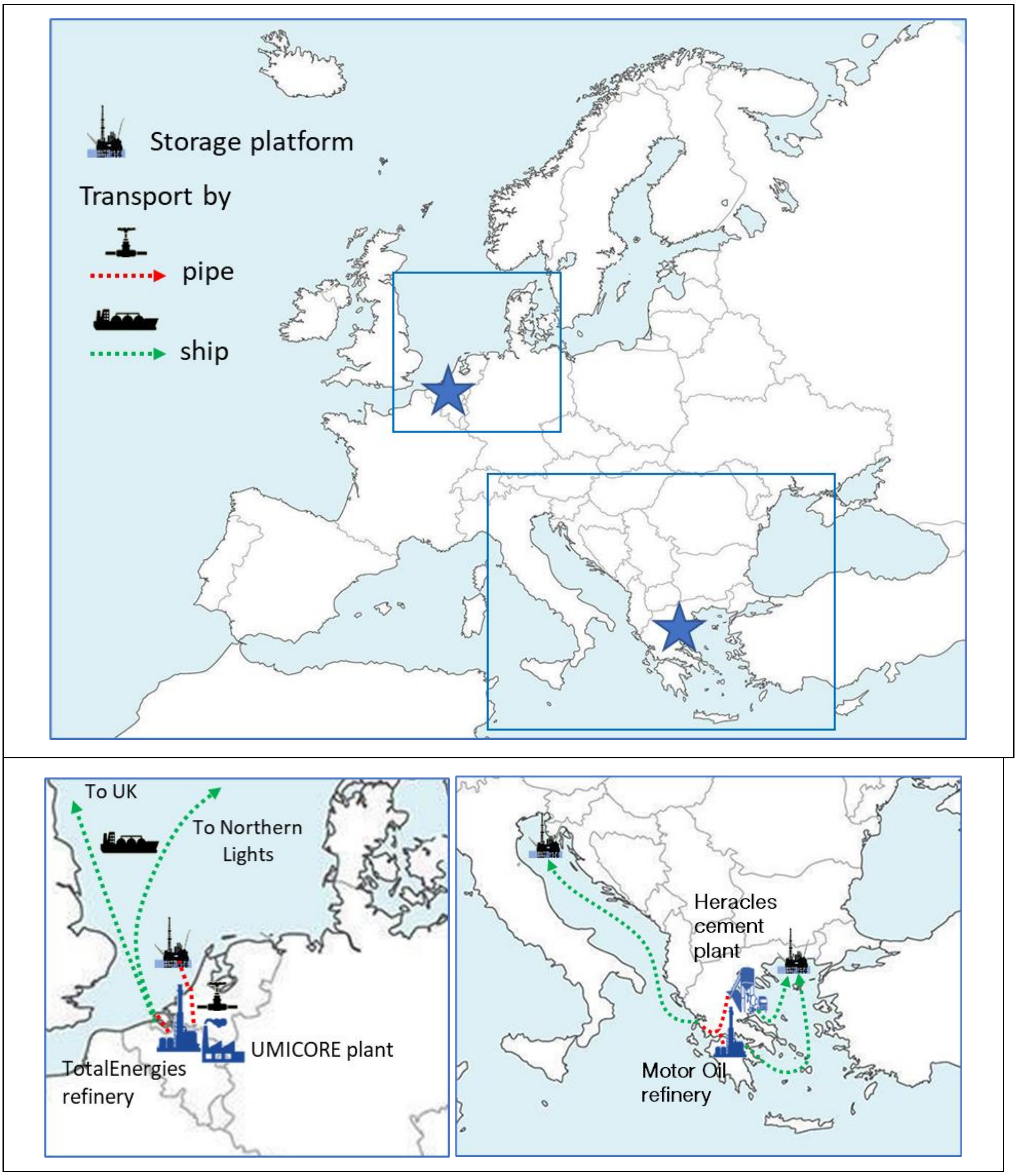

Figure 2: Location of the 4 emitters of AURORA project.

4.2 Sinks

4.2.1 Potential areas for storage in AURORA project

The Adriatic Sea region

The Adriatic Sea geological province spans from the coast of Venice in the north to the Gulf of Taranto in the south. From a geological perspective it represents the foreland/foredeep domain of three distinct fold and thrust belts, the Southern Alps in the north, the Apennines to the west and the Dinarides in the east [4][5][6]. The three orogens, associated with different subduction zones, formed in the broad and articulated framework of the N–S convergence between the European and the Adriatic plates [7]. The Adriatic Sea geological province is one of the most important regions of natural gas and oil production in the entire Mediterranean area. Indeed, starting from the early 1950's, about one hundred small gas fields have been discovered in the Italian part of the basin, mainly within Pliocene clastic sequences; a similar situation exists on the Croatia site [8][9].

Recently, the Adriatic Sea has attracted much attention also for the geological storage of CO_2, due to the occurrence of well-known physical traps (confirmed by the now mostly exploited hydrocarbon reserves) and deep saline aquifers within both the carbonate and siliciclastic sequences [5][6][10][11]. These geological attributes combined with the presence of different industrial centres along the coasts (representing a relatively close source of CO_2) and with the already existing infrastructure for the management and distribution of natural gas (gather centre, pipelines), make the Adriatic Sea geological province a promising area for CO_2 storage.

During the last fifteen years, several European projects have focused on the evaluation of the potential of CO_2 storage and on the storage capacity calculation of the European territory. The projects have been based on common shared criteria and both the theoretical and effective storage capacities were calculated [12][13][14]. According to these studies [10][19][15][16][17][18], the Adriatic Sea province represents a valid potential storage province. In the Geocapacity project [20], appraisal of storage potential was focused on saline aquifers, both in the siliciclastic and in the carbonate portion of the stratigraphic succession; more recently, the potential of depleted gas reservoirs has also been evaluated [18] (Figure 3).

The onshore southern Balkan area

Results from the Geocapacity and CO2stop projects make other areas of potential interest for the AURORA project: in particular, the onshore Balkan area, which includes the orogenic system of the Balkan chain (the so called "mobile Europe"), formed and largely influenced by the Alpine orogeny. For the AURORA project, we will include potential areas belonging to onshore northern Greece, Croatia and Romania [21][22][23]. The total CO_2 storage capacity of these countries was already evaluated in several EU projects (CASTOR, CCUSTRATEGY). The most outstanding features in "mobile" Europe are the high mountain chains of the Carpathians and Dinarides that surround the southern Pannonian Basin, where the main storage target is represented by Miocene deposits that host the most important aquifers and hydrocarbon reservoirs (Focsani basin).

The Ionian Sea and Eastern Greece

Greece offers opportunities for CO_2 geological storage such as deep saline aquifers in the Greek Mesohellenic basin and existing depleted hydrocarbon fields in the Tertiary sedimentary basin of Prinos. The Mesohellenic basin and its Grevena sub-basin area offer CO_2 storage for the Western Macedonia industrial cluster due to its 50 km proximity and the occurrence of deep saline aquifers [21]. It is partly located in Northern Greece and partly in Albania and was formed from Middle Eocene to Upper Miocene. Koukouzas et al. [24] estimated the theoretical CO_2 storage capacity for the Mesohellenic basin in the Grevena area to be about 700 gigaton.

Along the eastern coast, the Geocapacity project assessment of CO_2 storage capacity in deep saline aquifers in Greece also includes the Tertiary sedimentary basin of Prinos [25]. The potential storage site is the partially depleted Prinos oil reservoir. The Prinos basin is formed at the southern end of the Rhodope Massif, between Thassos island and the mainland; the main axis is oriented NE-SW, and the basin covers an area of about 800 km2.

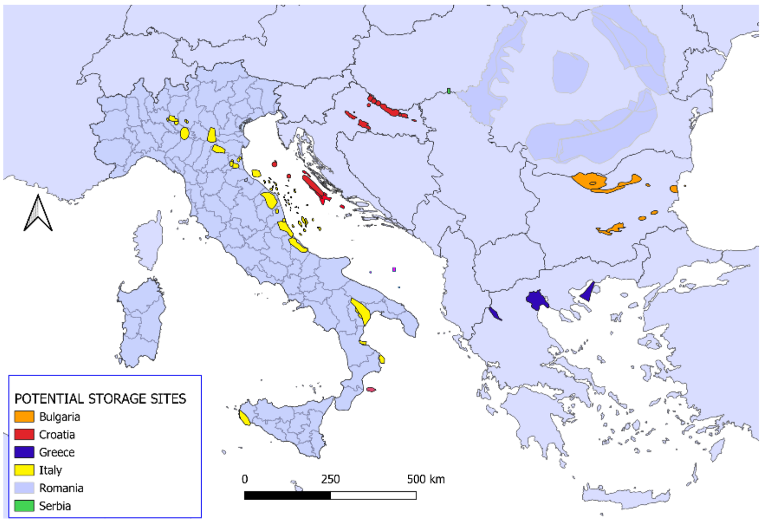

Figure 3: Location of potentially suitable for CO_2 geological storage in southern – central Europe (data from [5][6][18][25].

4.2.2 Basaltic area for Mineralization

Recently, the potential for CO_2 storage in basalts has been demonstrated by CARBFIX project [26][27]. Basaltic area prone for CO_2 storage are based on the surface of basaltic rocks area (volcanic and plutonic) on the continents, on the ocean floor including both Europe and United States of America. Recently KouKouzas et al. [28] proposed some exploratory studies on basaltic rocks outcropping in central Greece near Volos (close to HERACLES cement plant) to evaluate potential CO_2 storage, largely cropping out in the area. The potentiality of mineralization processes as storage option will be evaluated in AURORA project.

4.3 The CCUS chain overview

The overall CCUS chain consists of the consecutive blocks of CO_2 capture, CO_2 conditioning, CO_2 transport, permanent storage and/or utilisation. A generic chain with typical elements is shown in Figure 4.

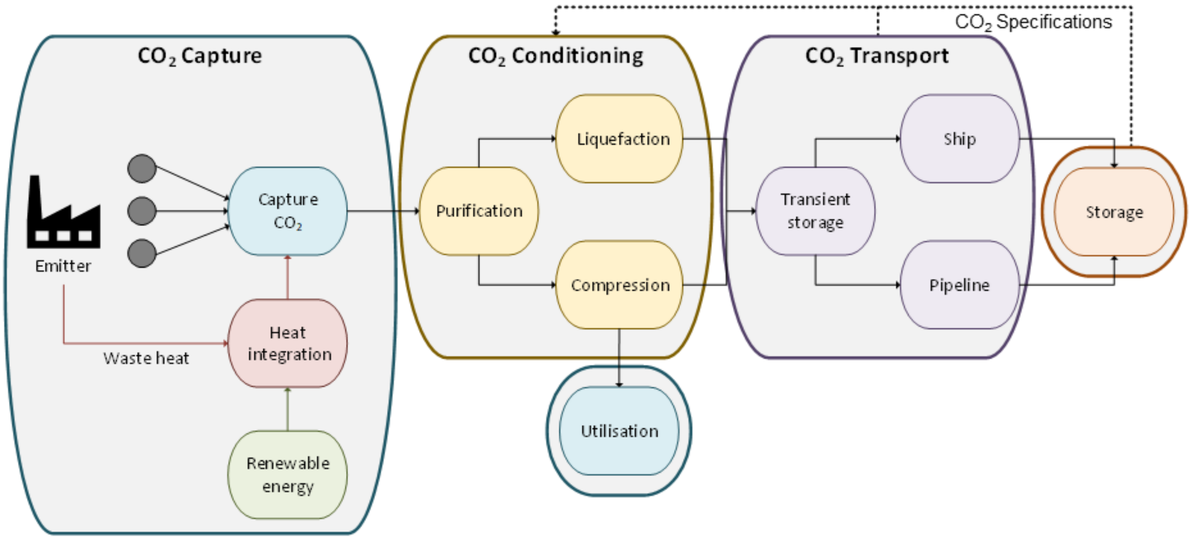

Figure 4: Schematics of the links between the different blocks of a full CCUS chain.

The chain design will vary from case to case and will depend on:

- The location of the CO_2 source(s) – more than one? Single or cluster approach?
- The CO_2 stream purity and temperature and pressure (T/P) from CO_2 capture plants.
- The type and location of the CO_2 sink.
    - Storage – reservoir characteristics, impurity limitations, T/P, onshore/offshore
    - Utilisation – CO_2 specification
- Regulatory limitations.
    - E.g., onshore pipeline transport pressure restrictions
- The type of transport – ship, pipeline, trucks, barge, rail.
    - Transport T/P and CO_2 purity limitations
- The number of transport stages.
    - Need for hubs and reconditioning of the CO_2

The first stage in developing the CCUS chains is the source/emitter and sink mapping so as to identify where the CO_2 is emitted and where it will be stored and/or utilised. In the AURORA project, the sources are well defined and have already been described in §1.2. The sinks, permanent storage and utilisation alternatives, will be further developed as part of the project.

4.4 The reference scenario without CCUS

For each emitter, the reference scenario without implementation of CCUS is business as usual. The economics will be based on the annual CO_2 emissions, the annual energy consumption and the cost of ETS. A carbon footprint of the sold product can be calculated and may become incompatible with specifications for the future.

4.5 The reference scenario with CCS

Depending on clustering, transport, regulation and storage options, different scenarios will be developed and assessed. In Europe, CCS infrastructures are at very early stage and there is no pipeline network to transport the captured CO_2. In the ACCSESS project, which aims at improving and developing CCUS chains across Europe, Baltic area and North sea, transport options have been considered as ready-to-use when they were at high technology readiness level and available for rent or purchase on the market. Pioneered CCUS chains were established based on the currently available technology from the point source capture until the storage site [29]. Such chains can be regarded as a way to accelerate CCS deployment while avoiding CO_2 emissions until infrastructures with lower carbon footprint such as pipeline network are available.

In AURORA, one reference scenario will be built for each emitter. Each scenario will rely upon the actual and/or planned commercial CCS projects in each region. In Belgium, the commercial project Antwerp@C [30] will be the reference. For Greek emitters, the Energean CO_2 storage project in Prinos and Eni CO_2 storage in Ravena, both identified as projects of common interest for European union, will be considered. For each scenario, the overall CO_2 reduction potential will be evaluated by taking into account the CO_2 emissions all along the chain mainly due to the steam, the electricity and the fuel consumed.

4.6 Alternative scenarios

4.6.1 CCS clustering opportunities

The clustering opportunities around each plant will be assessed mainly for the purpose of sharing CO_2 conditioning and/or transport infrastructures. The first step in assessing clustering opportunities is to map local, regional, and national emitters in Belgium and Greece from the perspective of the emitters taking part of the AURORA project. The second step is to identify realistic clustering opportunities for each plant for shared CO_2 conditioning and/or transport infrastructure. Here the CaptureMap tool developed by Endrava will be used.

There are a few CO_2 infrastructure initiatives already ongoing in Europe. In addition to Northern Lights in Norway and the Porthos project in the Netherlands, there is also the Antwerp@C project in Belgium. This project, currently at the feasibility stage, investigates the possibility to construct a backbone pipeline through the industrial zone along the river Scheldt.

4.6.2 Alternative CCS scenarios

Alternative scenario will depend on the clustering options and the evaluation of other storage locations maybe less commercially mature. Such scenario could have lower cost concerning transport and/or storage and a lower global warming impact.

4.6.3 Mineralization as an alternative to storage

For the HERACLES cement plant in Volos, a recent publication [28] indicates that basaltic rocks from the region of Volos have the appropriate physicochemical properties for the implementation of a financially feasible mineral carbonatation in subsurface. The development of a chain with CO_2 capture, conditioning and injection for in-situ mineralisation will be evaluated.

4.6.4 Carbon utilisation as an alternative to storage

Complimentary to permanently storing CO_2 underground, the CO_2 captured can be used to generate valuable products. Carbon Capture and Utilization (CCU) strives to address climate change by not only curbing CO_2 emissions but also by creating economic opportunities through the conversion of CO_2 into useful products. CCU holds the potential to contribute to a circular economy and decrease reliance on fossil fuels.

However, there are significant challenges associated with CCU. The first challenge is the substantial energy requirement for both the CO2 capture and conversion processes. The second challenge is the relatively brief storage time or sink factor, referring to the duration for which CO_2 is removed from the atmosphere.

The utilisation pathway considered in AURORA will likely be methanol production. Methanol is an attractive chemical and could potentially have a future role as carbon neutral fuel and hydrogen carrier. Its carbon neutrality will depend on the production pathway. Currently, the predominant method for methanol production is through reformating of natural gas. Alternatively, captured CO_2 and hydrogen produced through water electrolysis based on renewable electricity can produce methanol through the CO_2 hydrogenation process.

The evolution of the Renewable Energy Directive III will be followed as it may influence the scenario. Indeed, some restrictions about the origin of the captured CO_2 can affect the possible uses of e-methanol.

5 Description of each block of the CCUS chain

5.1 CO_2 capture

The CO_2 capture process in AURORA is based on a conventional absorber-stripper system with CESAR1 as the solvent. A schematic flow diagram of such capture plant is shown in Figure 5. It indictes the main equipment and the main streams in such plants.

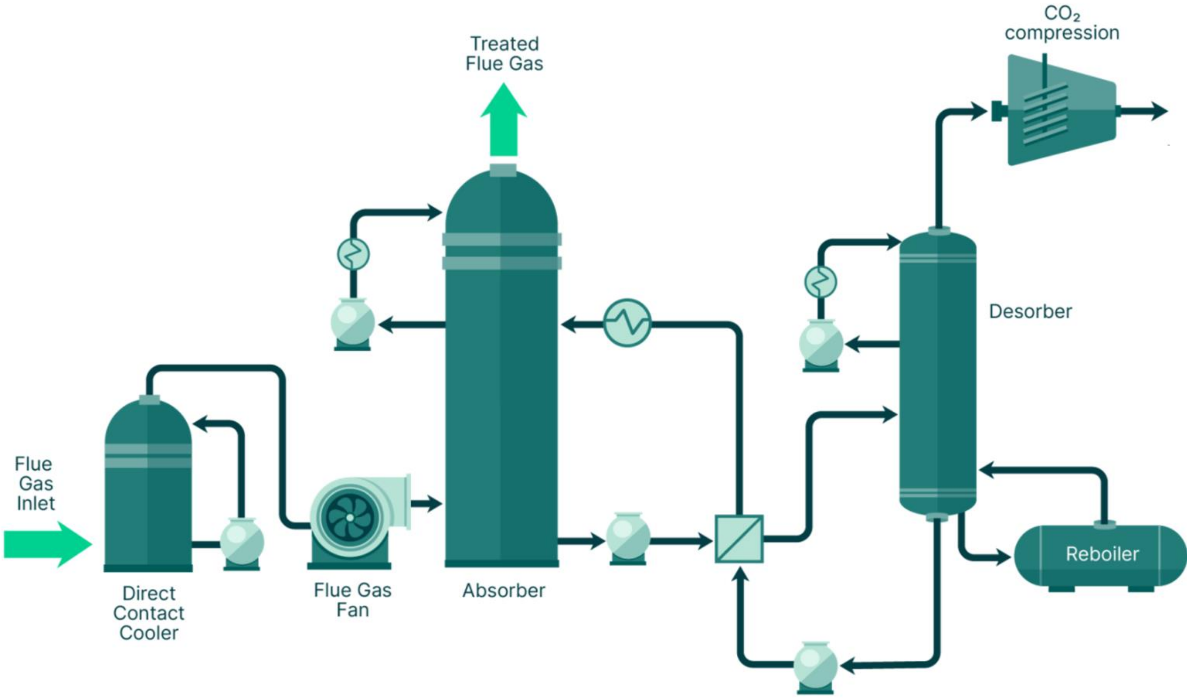

Figure 5: Main streams and equipments of a amine-based post-combustion CO_2 capture plant.

The flue gas is first cooled to a specified temperature in a direct contact cooler (DCC). The DCC consists of a column with a packed section and a water pump-around, which includes a pump and a separate cooler. The water circulation stream is cooled by means of a cooling medium dependent on the end-user case. The water saturated flue gas out of the DCC then passes through a blower to overcome the pressure drop in the DCC and the absorber column. In the absorber section, the flue gas encounters the solvent, which chemically binds the CO_2. The treated flue gas, before being emitted to the atmosphere, passes through a water wash system to balance the water in the system and to avoid emission of solvent and any degradation products. The solvent, which is "rich" in CO_2, is pumped to the top of the desorber via a cross heat exchanger. The solvent is regenerated in the desorber at higher pressure (around 1.8-2 bar absolute) and temperature (120-125°C). The stripper is heated by means of a steam reboiler to maintain regeneration conditions. The heat in the stripper is necessary to further heat the solvent, generate stripping vapour and desorb the chemically bound CO_2 from the solvent. The stripping steam associated with the CO_2 product leaving the stripper is recovered by means of a condenser and fed back to the stripper. The CO_2 product thus leaving the condenser is relatively pure, with water vapour being the only other major component. In addition to the condenser which contributes to wash out some of the entrained contaminants (basically solvent and degradation products as well any soluble compounds from the flue gas), an additional water-wash system is placed on top of the desorber. The lean solvent with residual amounts of CO_2 from the desorber is pumped back to the absorber via the cross-heat exchanger and a cooler to lower the temperature of the lean solvent stream entering the absorber.

In each full CCUS chain scenario, the capture block will correspond to the optimized capture solution for each emitter.

5.2 CO_2 conditioning

After the CO_2 is captured, it needs to be conditioned, see Figure 4. The type of conditioning will depend on how the CO_2 is transported in the next chain segment. The two most common ways of transporting CO_2 in a large-scale CCS chain are either by pipeline, ship, or a combination of the two. For pipeline transport, both onshore and offshore transport is possible. In some cases, rail, truck, and barge transport might also need to be considered. CO_2 is normally either transported in dense phase or as a liquid to increase transport efficiency. CO_2 is rarely transported in gaseous state due to the low gas density.

It is foreseen that the CO_2, when transported from the end-user plant to the permanent storage or the conversion plant, will undergo several transport stages and consequently, conditioning stages.

In AURORA, two alternative means of transportation are foreseen, transportation by pipelines and/or transportation by ships. In the sub-chapters below, the general CO_2 conditioning approach for the two alternatives is presented. It should however be kept in mind that the transport and conditioning will depend on the full-chain scenarios to be investigated.

5.2.1 Pipeline transport

Transport of CO_2 in a pipeline normally takes place at high pressures, often between 40 – 150 bar, in what is called a dense phase. The transport pressure is reached by compressing the CO_2 in a multi-stage compression train with intercooling and knock-out drums for water removal. At P>73 bar, CO_2 is supercritical and thus in the dense phase. The latter means that the physical properties are closer to a compressible liquid and as such a further increase in pressure can be achieved by using a pump followed by a final cooling step to meet the specification which depends on the specific case. Further drying can be achieved by adding an absorption (glycols) or adsorption (molecular sieves) step after the compression train.

5.2.2 Ship transport

The reference ship transport chain here is the one under development in the Longship/Northern Lights project. Here, the CO_2 is transported in a liquid state at 13 - 15 barg and -30.5 - -26.5 °C. The CO_2 specification is currently under revision and an updated specification is reported to be ready in Q1 2024. There are two main approaches for liquefaction, internal (ICL) and external cooling loop (ECL). In the internal cooling loop process, it is the CO_2 itself that is the working medium. Liquefaction is performed by compressing CO_2 to P =74 bar and then expanding to the transport pressure. Approximately 60 % of the CO_2 is liquefied through this expansion, while the other 40 % remains in gaseous phase (the ratio between liquid and gaseous CO_2 depends on ΔP, the pressure before and after the expansion and the temperature at which the expansion takes place). The liquefied CO_2 is then sent to an intermediate storage tank, while the gaseous CO_2 is returned to the appropriate compression stage for recompression. In the external cooling loop, the CO_2 is compressed to the transport pressure and then cooled with the aid of a cooling medium (e.g., NH_3).

It is the ICL approach that is believed to be the liquefaction process to be installed at Heidelberg Materials in the Longship project. The CO_2 enters a 4-stage compressor with intercooling and knock-out drums. Before the CO_2 enters the last compression stage, it passes through a dryer to remove water down to the specifications provided by the operator, i.e., 30 ppmv for Northern Lights. The dryer consists of two beds containing a solid desiccant, where one bed absorbs CO_2 while the other is regenerated. The bed is regenerated by heated dry CO_2. Additional purification might be done through the inclusion of distillation column. Finally, the dry and pure CO_2 is then sent to the last compression stage, after which it is expanded to transport pressure. As not all the CO_2 becomes liquid through the expansion, the part that remains gaseous is sent back to the appropriate compressor stage. The liquid CO_2 is sent to an intermediate storage tank.

5.3 CO_2 transport

5.3.1 Pipeline

In a CCS chain pipeline transport can take place both onshore and offshore. The operating pressure and temperature will depend on several factors like distance, velocity, end specifications (delivered at a certain pressure), and pressure restrictions due to local/national/international regulations. Onshore pipeline transport of CO_2 is currently being done at large-scale in the US, with more than 8 000 km of pipelines transporting around 70 Mt CO_2 per year [31]. Since 2008, CO_2 captured through natural gas sweetening has been injected into the Snøhvit field in Norther-Norway. Here, the CO_2 is transported to the offshore injection site through a 153 km long pipeline [32]. In the Northern Lights project the CO_2 received at Øygarden will be transported through a 110 km pipeline to the offshore injection site [33]. The pipeline was reported to be under construction in 2022 and ready for installation in 2023 [33].

It is expected that for the full-chain case scenarios to be studied in the AURORA project that both onshore and offshore pipelines will be considered. Their operating conditions will depend on the purpose of the specific transport step and any regulatory constraints.

Typical transport pressures today are:

- Onshore
  - CO_2 pipelines in the US normally operates at pressures between 80 – 150 bar, with some as high as 170 – 190 bar [34]
  - Onshore gas pipelines in the UK – operate at between 70 – 100 bar [35]
  - CalCC project (France) – 50 km pipeline transporting CO_2 in dense phase is planned [36]
- Offshore
  - Snøhvit (in operation) – 150 km pipeline (uninsulated) compressed CO_2 in liquid phase [37]

- Porthos project (planned) – onshore and offshore pipeline pressure 35 barg and 130 barg, respectively [38]
- Northern Lights (under construction) – offshore pipeline design pressure reported to be 290 bar [39]

Booster stations can be included, especially for onshore applications, to boost the pressure along the route.

5.3.2 Ship transport

In December 2022, Northern Lights and Kawasaki Kisen Kaisha, Ltd. ("K" LINE) formalized an agreement to operate the first two CO_2 cargo ships, each with a cargo carrying capacity of 7 500 m^3 [40]. Further cargo ship specifications are given in Table 1.

	Unit	Value
Ship size*	m^3	7 500
Net CO_2 carrying capacity	m^3	5 400
Operating pressure	barg	15
Operating temperature	°C	-27
Ship length*	m	130
Molded width*	m	21.2
Structural draft*	m	8
Primary fuel*		LNG

Table 1: The Northern Lights CO_2 cargo ship specifications [41].

In September and again in December of 2023, Northern Lights announced that that agreements have been signed for two additional CO_2 cargo ships with the same specifications as provided in Table 1 [42].

It is foreseen that any ship transport in the full-chain cases in the AURORA project will adopt the CO_2 cargo ship specifications of Northern Lights.

In the case of estuary and inland water way transport (which could be relevant for emitters in Belgium), barge transport will be considered. It is currently assumed to have the same operating specifications, however the vessel specifications will need to be assessed based on any physical constrains, e.g., width, length, draft [43] if such information is known.

Alternative CO_2 cargo ship designs are being developed, both taking place at higher pressures (34 barg) [44], and lower pressures (6 - 10 barg) [43].

5.4 CO_2 Storage

The last step of the CCUS full chain is represented by geological storage, when the CO_2 is injected, via injection wells, into the deep sub-surface at a carefully selected site (such as a saline aquifer or a depleted oil/gas field). The selection of suitable storage sites will be based on a comprehensive set of criteria that has been extensively described in numerous publications, tested in various projects, and also adopted by the CO_2 storage atlas of several European countries (as Norway and UK) [45][46][47].

This section reviews the main strategies that have been adopted for site selection and evaluation by previous projects, describes the geological areas suitable for storage for the AURORA project and their potential, and summarizes the methodology that will be used for evaluation (ranking criteria). Considering that storage will not be included in the Life Cycle Analysis provided by WP5, an evaluation of the commercial maturity of the sites will be included in the adopted methodology.

5.4.1 Feasibility study experiences from other projects

The methodology adopted to complete the full chain evaluation within the AURORA project will be based on the experience gained during previous EU projects and existing CCS cluster projects in Northern Europe. In fact, there is growing interest in the evaluation of the full chain of CCUS, since this approach can better define potential issues and total costs. Among these projects, the recent Strategy CCUS [48] project developed a complete methodology that was applied to eight potential onshore storage sites in Europe, based on an approach for new ICCS clusters (also known as industrial hubs). This project reviewed existing methodologies from a storage point of view, proposing a synthesis and several recommendations. The recommended approach was based on several documents, including: the Norwegian Storage Atlas, the UK CO_2 Stored database, the Society of Petroleum Engineers - Storage Resource Management System or “SPE-SRMS” [49] and, for storage capacity calculation, the American analytical equations for capacity (from CO_2 Storage Atlas of USA) [50].

The CCUS Strategy approach is a common storage methodology which was applied to the promising regions of the project. It combines a qualitative suitability appraisal and a capacity estimate. Suitability covers all technical aspects of storage, from reservoir capacity and quality to seals, faults, and wells. The Boston square score was adopted for the CCUS Strategy appraisal. Particular attention was dedicated to the capacity estimation, based on the approach of the quantitative resource pyramid [51]. Four ranking degrees were defined that represent the increasing maturity of data and understanding of the potential storage capacity, along with a progressive reduction of the scale that ranges from a regional approach to the targeted storage site candidates. These four levels are comparable with existing evaluation schemes such as SPE-SRMS and CSLF TERR [49][52], which means that the results and overall evaluation can be compared with those from other projects.

There are other comprehensive global evaluations available, such as the CO_2 Storage Resource Catalogue [53] that includes a global view of the commercial readiness of CO_2 storage resources in key markets. Even in this case, this database classifies the resource maturity of published storage sites based on evaluations using the SPE-SRMS approach. The common use of the SPE-SRMS reduces the subjective nature of resource assessment and helps in the comparison of resource potential and maturity. The CO_2 Storage Resource Catalogue and Storage Resources Management System includes CO_2 storage in saline aquifers and in depleted or partially depleted oil and gas fields but excludes CO2-Enhanced Oil Recovery (CO2-EOR) and other storage options such as unmineable coal, mineralisation, and organic-rich shales. Moreover, it does not provide information for the areas of interest of the AURORA project.

5.4.2 Adopted methodology

Site selection in the described areas will be performed in the AURORA project by adopting the procedure already proposed in the Strategy CCUS project. This choice will favour standardization of the adopted criteria for site selection in European countries that still do not have a comprehensive storage atlas; on the other side, as this methodology includes some economical/commercial aspects, it will provide a more complete full chain analysis.

Consequently, the proposed methodology described in this section represents a synthesis of the main methods adopted in the past by previous projects. For this reason, it can be considered a practical and comprehensive approach to the problem.

From the storage side, the method provides a double approach. On one side it evaluates the site from a geological point of view (considering some geological aspects as a function of data quality). On the other, it evaluates the state of development of the site from a technical-economic point of view, including the capacity estimation (introducing the concept of SPE-SRMS).

In this way the method provides two scores, based on two evaluation procedures:

- for geological aspects the Boston square analysis approach is used
- the economical evaluation is based on the SPE SRMS, which includes and evaluates commercial potential. In this way it includes some technical aspects, such as the occurrence of infrastructure, the distance from the CO_2 source, etc.

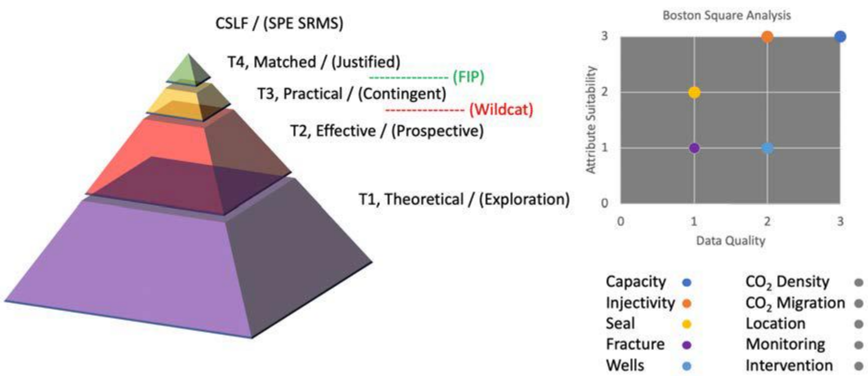

Figure 6: (Left) Four-tier capacity pyramid with CSLF and SRMS terminology, (Right) Boston square analysis (from [54])

5.4.2.1 Evaluation of the geological aspects (Boston square score)

This appraisal consists of a Boston square score for both attribute suitability (y-axis) and data quality (x-axis). Each attribute, whose list is presented in Table 2, is plotted to provide an overview of the site and data gaps that may need addressing (Figure 6). The criteria used in the Boston analysis are summarized in the following table:

Attribute	Criteria	Score	Comments
Storage suitability	Capacity	3	Large volume, dominant high scores in the checklist
		2	Medium – low volume, low score in some factors
		1	Dominant low values or score cose to unacceptable
	Injectivity	3	High value for permeability * thickness (k*h)
		2	Medium (k*h)
		1	Low (k*h)
Seal suitability	Seal	3	Good sealing shale, halite (high score in the checklist)
		2	At least one sealing layer wit acceptable properties
		1	Seal with uncertain properties, low score in the checklist
	Fracture	3	Dominant high score in the list
		2	Insignificant fractures, either natural or wells
		1	Low score in the checklist
	Wells	3	No previous drilling in the reservoir, safe plugging of wells
		2	Wells penetrating seal, no leakage documented
		1	Possible leaking wells, need for evaluation
Data quality	All criteria	3	High quality data with good coverage and density
		2	Adequate data with some gaps in coverage
		1	Low quality and/or sparse data with known gaps
Other Suitable Attributes	CO_2Density	1,2,3	Supercritical, high denser gas or low-density gas
	CO2 Migration	1,2,3	Low migration risks, moderate and low risks
	Location	1,2,3	Location suitability relative to other sinks and sources
	Monitoring	1,2,3	Suitability of site for performance monitoring
	Interventions	1,2,3	Suitability of site for remedial interventions
	Upside	1,2,3	Suitability of site for growth as a storage hub

Table 2: Technical attributes for evaluating a storage site through Boston square analysis.

5.4.2.2 Evaluation of the storage capacity (SPE-SRMS)

For capacity evaluation the AURORA project has adopted the four-tiered pyramid based on the pioneering North American CSLF approach [12][52], with levels mapped to CSLF and SRMS terminology [49]. This capacity evaluation is then included in the Boston square analysis for each site.

The capacity quantification will be based on available data, integrated, where possible, by new data and calculations. The calculations will be expressed, when possible, using the common P90-P50-P10 probabilistic estimation approach and will be based on available databases (Geocapacity, CO2Stored) and other more recent published data. The capacity values will be evaluated using the quantitative resource pyramid approach consisting of four tiers. Each level represents the increasing maturity of data and understanding about the potential storage capacity, from regional first approximations to targeted storage site candidates. The described tiers are compatible with existing schemes [49][52], allowing outcomes to be transferred to equivalent classifications:

• Tier 1 - Regional assessment; the lowest tier, equivalent to Exploration (Theoretical), with generic global or regional SEFs (Storage Efficiency Factor). Formation and storage unit estimates. First approximation. Low data burden and global SEF values if data is poor and boundary conditions poorly constrained.

• Tier 2 - Discovery assessment; equivalent to Prospective (Effective), with tailored SEFs. Daughter unit estimates, second approximation. Moderate data burden and lithology-specific storage efficiency.

Distinction between DSA (deep saline aquifer), DHF (depleted hydrocarbon field), and UCB (Unmineable coal beds (UCB)). Boundary conditions established.

• Tier 3 - Prospect assessment; equivalent to Contingent and pending/on hold (Practical), detailed data, prospective candidates. Third approximation with a more taxing data burden, including sub-attributes of the main factors used to estimate capacity and lithology-specific local storage efficiency factors. Each candidate prospect requires either existing or targeted data acquisition sufficient to build a simple geomodel for simulation and proposed injection well location.

• Tier 4 - Site assessment; equivalent to Justified/Approved/On Injection (Matched), site project. The final approximation prior to operation. This has the highest data burden and requires a detailed geomodel for reservoir simulation. Simulations test the accuracy of storage efficiency factors and provide well placement/scheduling scenarios to maximise capacity.

Suitability is scored by expert judgement. High values indicate good attributes such as high capacity, high reservoir porosity and permeability, an effective seal, an absence of problematic faulting, fracturing or well issues; low scores flag a prospect for review. Data quality indicates strengths and gaps in the evidence base.

5.4.2.3 Integration in the full chain

The evaluation of the potential storage sites should consider the possibility to create an integrated capture, transport, and storage chain. Considering this, the Boston square analysis will be integrated with the evaluation of the hub and CO_2 transport assessment. Capacity and injectivity are two main aspects that need to be evaluated. For this reason, it is important to consider the rate at which CO_2 can be injected into a reservoir (which in turn depends on the injectivity, on the number of injection wells used, and on pressure constraints). While it may be possible to use more wells or to manage pressure in the reservoir to increase the total injection rate, this increases the costs of developing a storage site. The total achievable rate of injection needs to be matched with the total rate of capture for the single or multiple carbon sources. The potential for variation in CO_2 flow, including temporary stoppage, also needs to be considered. CO_2 storage location has a direct effect on the costs of CO_2 transport, and so on the total cost of a CCS operation (although the effect is relatively greater for pipeline transport than for transport by ship).

5.5 CO_2 mineralization

In-situ mineralisation is a process of permanently converting carbon dioxide into stable carbonate materials such as calcite, dolomite, magnesite, and siderite. This is typically performed by injecting CO_2 underground to undergo an exothermic reaction with the host alkaline rock to form carbonate minerals. This process can remove large amounts of CO_2 from the atmosphere and permanently store it underground.

Basaltic rocks exhibit appropriate physicochemical properties for the implementation of carbonate mineral precipitation, through interaction of the Ca-Mg-Fe rich minerals with carbonic acid, derived from the dissolution of the injected CO_2 in water.

According to literature [28], basalts from the region of Volos (close to emitters in Greece) have the necessary appropriate physicochemical features to be considered as potential sites for implementing carbon capture and storage technologies.

It is foreseen that CO_2 mineralisation in Volos region will be included in AURORA project as a CO_2 storage scenario for emitters from Greece. Operations of such storage will result in CO_2 emissions which will be taken in account when assessing the overall CO_2 reduction potential of the scenario.

5.6 CO_2 Utilization

Methanol (MeOH) is a versatile chemical compound that not only serves as a fuel, and hydrogen energy carrier, but it also a base chemical for the chemical and petrochemical industry.

Commercial MeOH is catalytically synthesised mostly from natural gas via an intermediary synthesis gas (syngas), a mixture of CO, H2 and some CO_2. MeOH synthesis from syngas follows Equations 1-3. There is no consensus amongst researchers whether CO or CO_2 is the source of carbon in the synthesis, and the kinetics describing MeOH formation is still under discussion.

Equation 1 $$CO + 2H_2 \leftrightarrow CH_3OH$$

Equation 2 $$CO_2 + H_2 \leftrightarrow CO + H_2O$$

Equation 3 $$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O$$

Alternatively, captured CO_2 and hydrogen produced through water electrolysis based on renewable electricity can produce methanol through the CO_2 hydrogenation process (Equation 3).

It is foreseen that CO_2 utilisation to produce methanol through hydrogenation with H2 will be included in AURORA project as a CCU scenario. Both North Sea and Mediterranean Sea would be studied to focus on the emitter's locations.

For both areas, H_2 needed for the hydrogenation process would be produced locally through water electrolysis based on renewable electricity. However, green H2 production will be kept out of AURORA scope. It is here assumed that sufficient green H2 would be available in both areas.

A generic methanol plant from literature will be used as reference to model MeOH production [55].

6 Specifications on CO_2

Today, there is no standardization of the CO_2 specification for transport and storage. It is up to the operators of the transport and storage network to define the specification the CO_2 needs to adhere to when entering the network. However, it is expected that a common standard will be established as the market develops. The current framework at the EU level is under development.

The specifications adopted in AURORA will be aligned with the specifications provided by ARAMIS and Northern Lights commercial projects. These specifications are continuously evolving, and the project will adopt the specifications that are valid at the time of execution.

Design of conditioning process is not however expected to address all specifications. The focus will be on oxygen and water content as this can be addressed in the simulation for the design of the conditioning process. Other trace elements will not be considered despite that some components could be critical for the operation of transport and storage networks. Such components will be discussed and measurements suggested. Experimental studies in which CO_2 composition is measured after the conditioning step are necessary to validate the efficiency of the conditioning process.

7 Regulations and policies

The integration of policy and regulatory aspects is critical to properly define the main strategic KPIs linked to a full life-cycle assessment of CCUS, given that the existence of a well-defined set of rules builds a favourable environment for investors and overall CCUS development.

This can be described at the European and national levels.

At the European level, the *Directive on the geological storage of CO_2* (Directive 2009/31/EC) establishes the legal framework for the development of geological storage of CO_2 as a measure to mitigate the effects of climate change. It covers all CO_2 storage in geological formations in the EU over the entire lifetime of the storage sites, including guidance to ensure that they are environmentally safe.

This Directive also contains indications about capture and transport, the other two components of CCS. These activities are already covered by other existing EU environmental legislation (such as the Environmental Impact Assessment and Industrial Emissions Directives), however amendments introduced by the CCS Directive add some specific aspects. Capture and transport are described in several articles in the CCS Directive, mainly related to environmental safety, transnational transport, and the main characteristics of CO_2 streams for the purpose of storage. The amendments (Chapter 7) to the other Directives deal mainly with technical aspects of pipelines (Directive 85/337/EEC), licence management (Directive 2001/80/EC), and CO_2 streams composition (Directive 2008/1/EC).

The *Environmental Impact Assessment (EIA) Directive* (2011/92/EU as amended by 2014/52/EU) covers capture and transport of CO_2, considering that development projects in the EU must first be assessed for their impact on the environment before they can start.

The *Industrial Emissions Directive* (IED) aims to achieve a high level of protection of human health and the environment by reducing harmful industrial emissions across the EU. It is based on several pillars, including the need to have a permit for all kinds of industrial plants and the definition of the Best Available Techniques (BAT) to define emission limit values. The IED allows competent authorities some flexibility to set less strict emission limit values for specific cases but contains mandatory requirements on environmental inspections. Member States must set up a system of environmental inspections and draw up inspection plans accordingly.

The same regulation introduces the right of the public to participate in the decision-making process, and to be informed of its consequences, by having access to permit applications, permits and monitoring results. Emission data reported by Member States are made publically accessible via the European Pollutant Release and Transfer Register (E-PRTR), which provides environmental information on all major industrial activities.

In 2022, the Commission adopted proposals to revise the IED and the E-PRTR. The proposals aim to improve the Directive by increasing the focus on energy, water, and material efficiency and reuse, thus providing a framework for the operation of EU industrial installations that is in line with the European Green Deal and the Zero-pollution action plan.

At the national level, the situation varies amongst the European countries. It should be noted, however, that a recent update of the state of national implementation of the CCS Directive, published in October 2023, shows that all European countries have transposed the Directive into national laws.

The report also indicates that: "since the third implementation report in 2019, considerable progress has been reported regarding the deployment of CO_2 storage sites notably but not only in the North Sea region in the form of awarded (or soon to be awarded) exploration permits, which are an important step towards a storage permit. EU Member States and Norway continue to support in the future, through their national programmes or funds, research and demonstration activities on CCS. Furthermore, many countries are involved in several European research and collaborative projects. The European Commission supports capture and storage of carbon dioxide with the ETS Innovation Fund, including full value chain projects combining capture, transport, and storage".

Based on past experience in other industries, it is clear that the existence of a strong regulatory framework can play an important role in the creation of a favourable environment for industrial CCS development. The proposed method for AURORA can be based on the identification of these issues, also taking into consideration similar evaluations that have already been carried out (as, for example, in the CCUS Strategy project).

As such, a list of issues that contribute to the creation of a favourable environment, and thus represent KPI's, could include:

- CCUS integrated into national Carbon Neutrality strategies
- Permitting and liabilities are clearly addressed in national legislation
- Sufficient incentives for CO_2 capture, whether subsequently stored or used
- Policies allowing trans-European CO_2 transport, use and storage.
- Legal framework for CCUS infrastructure projects
- Well-established and fast permitting process at national and local level for transport and storage infrastructures
- CCUS integrated into Territory Special Planning tools (mapping several infrastructure options to support convincing deep decarbonisation solutions)
- Existence of national strategy and a legal framework for hydrogen
- Existence of a negative CO_2 emissions accounting framework (e.g., BECCS, DAC)
- Incentives in the form of co-financing

8 Techno-economic analysis

Among the objectives of AURORA is to evaluate the economic viability of the CCS value chains for the sources and proposed storage sites in the project, with the option to additionally evaluate utilization if the need arises. Since techno-economic analysis (TEA) will be done first at the component level within each of the relevant work packages, then at the value-chain level after the component models are available, it is important to develop a single methodology to ensure consistency at every level.

Investment costs are evaluated using a bottom-up approach for the CO_2 capture, storage, and (if needed) utilization phases. Transport and other costs not linked to a fixed component will be added during the analysis of the full value chain. Operation and maintenance costs are estimated based on material replacement and industry-specific factors, while variable operating costs are based on material, fuel, and energy consumption.

The project will use the cost estimation methodology established by the European Benchmarking Task Force (EBTF) [56]. This methodology was previously used for the CESAR project.

8.1 Economic assumptions

To ensure consistency in economic evaluations across the project, this section fixes common base economic data for the project. The main assumptions are summarized in Table 3. Construction start time will set at the level of the subproject, since different elements of the value chain may require different amounts of time to build.

Parameter	Value	Unit
Cost base year	2022	year
Currency	Euro	€
Project life	25	year
Real discount rate	10	%
Inflation rate	2	%

Table 3: Base economic assumptions

All techno-economic evaluations will be reported in euros on a 2022 basis. When capital costs are not available for 2022, they will be adjusted using the Chemical Engineering Plant Cost Index (CEPCI). If necessary, the European Central Bank (ECB) reference rate [57] on the last business day of 2022 will be used to convert costs to euros, as shown in Table 4.

Currency	1 Euro (EUR)
British pound (GBP)	0.88693
Norwegian kroner (NOK)	10.5138
US dollar (USD)	1.0666

Table 4: ECB reference exchange rates on December 30, 2022.

8.2 CAPEX

The total capital requirement of the CO_2 capture, storage, and utilization phases is estimated using a bottom-up approach as outlined by the EBTF methodology. In this approach, the total equipment cost (TEC) is first calculated by summing the costs of the base process equipment required in each facility. From this, the total direct construction costs are estimated using the cost factors [56] shown in Table 5.

Cost factor	Calculation
Instrumentation and controls	9% of TEC
Piping	20% of TEC
Electrical equipment and materials	12% of TEC
Civil works	11% of TEC
Erection, steel structures, and painting	49% of TEC
Total	**101% of TEC**

Table 5: Cost factors for calculation of Direct Construction Costs (DCC) from Total Equipment Cost (TEC).

The Total Direct Plant Cost (TDPC) is the sum of the TEC and the DCC: $\mathrm{TDPC} = \mathrm{TEC} + \mathrm{DCC}$

Total Indirect Plant Cost (TIPC) can then be estimated from the TDPC by applying the cost factors shown in Table 6.

Cost factor	Calculation
Yard improvements	1.5% of TDPC
Service facilities	2% of TDPC
Engineering, supervision, and construction	6.5% of TDPC
Buildings (including services)	4% of TDPC
Sum	**14% of TDPC**

Table 6: Cost factors for calculation of Total Indirect Plant Cost (TIPC) from Total Direct Plant Cost (TDPC).

The Engineering, Procurement, and Construction (EPC) cost is then the sum of the total direct costs (TDPC) and total indirect costs (TIPC): $\mathrm{EPC} = \mathrm{TDPC} + \mathrm{TIPC}$

The Total Capital Investment (TCI) required is equal to the EPC cost plus additional cost factors, shown in Table 7.

Cost factor	Calculation
Startup costs	Facility-specific
Interest during construction	Calculated during construction time
Contingencies	25% of TCI
Capital fee	2% of TCI
Working capital	3% of TCI

Table 7: Cost factors for calculation of Total Capital Investment (TCI) from Engineering, Procurement, and Construction (EPC) cost.

Startup costs are unique to each facility and will be determined on a case-by-case basis. Interest accrued during construction will be calculated from interest rates and the estimated construction schedule.

In the bottom-up approach, the direct costs of each process component are estimated first. These are summed to yield the total direct cost (TDC) without contingencies. Process and system contingencies are added to yield the full TDC. Next, indirect costs are estimated and added to the TDC to yield the total engineering, procurement, and construction costs (EPC). The addition of project contingencies yields the total plant costs (TPC). Finally, owner costs and costs for spare parts, modifications, start-up, and interest accumulated during construction yield the total capital requirement (TCR). This approach is illustrated in Figure 7.

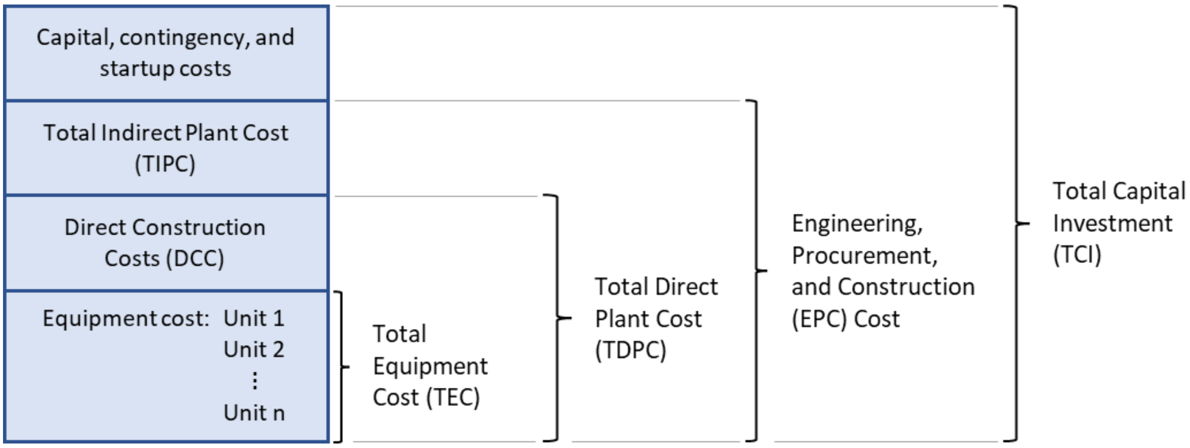

Figure 7: Methodology for bottom-up cost estimation.

Finally, geographical location may have an impact on material and labor costs during plant construction due to differences in material costs, labor costs, and labor productivity in different countries. Geographic factors will be used to adjust base material costs, labor costs, and labor productivity according to geographic location.

8.3 OPEX

Operating expenses consist of the fixed and variable costs incurred to operate a facility on an annual basis. Variable costs depend on plant operating status and output and consist of raw material and utility costs. The operating status over the course of a year is represented by the capacity factor, defined in §8.3.1. Fixed costs are those that are incurred regardless of the operating status of the plant, including direct and indirect labor, maintenance, operating supplies, laboratory charges, insurance, property taxes, and plant overhead.

8.3.1 Capacity Factor

The capacity factor represents the actual productivity achieved by the plant over the course of a year in comparison to the productivity it would have achieved if operated at its nominal capacity with zero downtime. It is computed as a ratio and expressed as a percentage:

$$\text{Capacity factor (CF)} = \frac{\text{Actual annual production}}{\text{Nominal annual capacity}}$$

While the analysis will assume that the CCS chain operates at a normal capacity for most of its expected service life, the first two years of operation will be assumed to operate at reduced levels to account for ramping up and resolving technical issues. In keeping with the EBTF methodology employed in the CESAR1 study, it will be assumed that during the first and second years of operation, capacity factors at the capture sites will be 40% and 65%, respectively. After this initial startup period, a stable capacity factor of at least 85% will be assumed. Finally, it will be assumed that the capture sites will be the bottleneck in terms of capacity, and that the transport systems, storage, and utilization sites can accommodate all the captured CO_2.

8.3.2 Variable Operating Costs

Variable operating costs include material and utility consumption such as electricity, natural gas, process water, and chemicals. These costs will be evaluated based on the specific process energy and mass balance at each stage of the value chain, with material and utility costs to be determined based on the source, quantity, and geographic location of the process. When data are not available for a specific site, prices will be based on national or European averages.

In cases where utilities such as electricity or cooling water are produced by facilities on the project's own industrial site, the cost of these utilities will be accounted for through the associated CAPEX and OPEX, rather than through a purchase price.

Material and utility consumption rates will generally be proportional to the capacity factor of the facility. If specific cases are identified where this is not true, adjustments will be made on a case-by-case basis. An example of such a case might be a piece of equipment that must continue consuming significant quantities of heat or electricity during down periods to avoid further delays due to long startup times.

8.3.3 Fixed Operating Costs

Fixed operating costs consist of direct and indirect labor, maintenance, operating supplies, laboratory charges, insurance, and property taxes.

The direct operating labor cost will be estimated based on the number of employees and a fully burdened cost of labor, accounting for geographic location and assuming a five-shift schedule. Labor costs will be based on the Labor Cost Survey performed by Eurostat, shown in Table 8. If information is not available, 60k€/year will be assumed for each employee.

Country	**Hourly direct labor costs (€)**
Euro area (19 countries)	34.3
Belgium	43.5
Greece	14.5
Norway	55.6
United Kingdom	To be defined – index no longer included since UK Brexit

Table 8: Average hourly labor cost by country, 2022 [58].

The remaining fixed operating costs will be estimated from other CAPEX and OPEX estimates using the cost factors shown in Table 9.

Cost factor	Calculation
Indirect labor	30% of direct operating labor
Insurance and local property taxes	2% of EPC
Maintenance	2.5% of EPC
Operating supplies	15% of maintenance
Laboratory charges	10% of total labor costs
Plant overhead costs	60% of (maintenance + total labor)

Table 9: Cost factors for calculating fixed operating costs (except direct labor).

8.4 CO_2 capture and conditioning

The technical basis will be provided through the work done in WP4 and delivered in the form of a sized equipment list that also includes utility consumption.

The CO_2 capture and conditioning cost estimation will follow the bottom-up approach described in §8.2 for estimating the CAPEX. OPEX cost elements, in addition to the ones listed in §8.3 are make-up of Cesar1, waste handling (reclaimer waste), electricity consumption, and chemical consumption other than amine (if relevant). The remaining utilities, cooling water and steam supply systems is currently expected to be established within the boundary limit of the CO_2 capture and conditioning plant.

Alternatively, cooling water supply could be an OPEX in the form of a tariff if there is remaining capacity in the plant's existing supply system. However, this needs to be confirmed.

8.5 CO_2 transport

8.5.1 Pipelines

Any pipeline segments in the transport network will be sized and cost estimated separately and, depending on where in the transport network the segment is, additional conditioning might also be needed. In such a case, the conditioning will be assigned to the segment block. The pipeline length will be calculated based on aerial distance (e.g., Google Maps) + a topography factor (20% and 15% is suggested for onshore and offshore, respectively). The pipeline dimensions will be calculated based on CO_2 volume flow and velocity for the specific segment and then roundup to the nearest API (American Petroleum Institute) 5L pipe dimension. The conditioning step before pipeline transport is determined by three factors; the pressure of the CO_2 from the previous block, the pressure specifications out of the block, the pressure loss (mainly friction loss) over the pipeline length, and potential external pressure constrains. From literature it seems that the recommended pipeline material is carbon-manganese steel. Material choice and the need for insulation will be assessed when the technical basis is prepared.

Also here, the bottom-up approach is adopted. The CAPEX will be based on pipeline material cost. Pipeline OPEX is likely also to include a unit cost for operation and inspection per meter pipeline.

Conditioning cost will be calculated as described in §8.4.

8.5.2 Shipping

The current assumption is that the ships are similar to the CO_2 cargo ships under construction in the Northern Lights project, see Table 5 for details. The ship size specifications in the table, the CO_2 volume, and the ship's route (CO_2 export and import location) will form the basis when designing the system. The key cost driver is the number of ships needed for efficient operation and will be subjected to optimisation. As for the previous chain blocks, the bottom-up approach will be adopted. CAPEX will include

- CO_2 cargo ship cost (light ship cost, cargo tank cost, loading/unloading pump cost, and loading arm cost
- CO_2 conditioning cost as previously described in §8.4
- Intermediate storage cost (on both the CO_2 export and import terminal there is need for intermediate storage)

OPEX cost elements for the land-based units associated with CO_2 shipping is electricity consumption. Calculating OPEX cost for the ship operation itself will include the following cost elements; fuel consumption (likely LNG), crew (personnel), port charges and pilot fees, and other cost (insurance, maintenance, management etc.).

8.6 CO_2 storage

The costs to geologically store CO_2 are dependent on a list of factors that will be used in AURORA project during the site section illustrated in §5.4.2. At the end of this selection process, geological sites with the best evaluation will correspond to the ones requiring minimum costs (both OPEX and COPEX). For example, considering the type of field (oil and gas depleted field versus saline aquifers), depleted fields generally require lower cost if the field contains legacy wells that can be re-used. Re-use is cheaper than building new wells, even with costs associated with closing unusable wells and mitigating the risk of CO_2 leaking from old wells. Other constraints (listed in §5.4.2) are the geological characteristics of the field (e.g. determining the average CO_2 injection rate per well), the field depth, its location (on- or offshore) which are included. All these aspects contribute to determine CAPEX cost, mainly on the drilling phase, that can include drilling of new wells or the re-use of older ones or both, in the case of the need of more than one injection well (low permeability and low infectivity of the reservoir).

During the operational time of the field, main costs are represented by injection activity and monitoring. Injection cost considers mainly the management of the wells (pressure management, wells manutention and efficiency), whereas monitoring costs include activities to measure, monitor and verify stored CO_2 for safety and regulatory purposes.

The operational lifetime of the storage site is generally considered of 20 years; after that, fields and wells are closed and handed over to the regulators. The storage costs also include the costs of monitoring and verification of the field for a period of 20 years after its economic lifetime has passed. Storage costs also include other liability fund, to cover potential uncertainties during operational phase.

8.7 CO_2 mineralization

Estimating the cost of a new plant for CO_2 mineralization in the Volos region should include an extensive study of feasibility according to the same approach of other storage site. This should describe potential capacity of the area and define the main impact factors. This kind of evaluation also represents a preliminary cost for this technology. Once the feasibility is assessed, CO_2 mineralization costs mainly can be distinguished in CO_2/water treatment; build infrastructures, monitoring operation. CO_2/water treatment includes CO_2 purification processes as well as desalination of seawater (if applicable). Infrastructures imply the drilling injection wells (and monitoring wells) and porosity/permeability management (hydraulic stimulation of target rocks, pumping pre-heating fluid to heat the rock). Dissolution of CO_2 into water prior or during injection ensures that chemical reactions between the host rock and injected fluid take place immediately after injection. The injected carbonated water is denser than the surrounding water in the geological formation and therefore has the tendency to sink after it has been injected: so, in theory, potential leakage of gaseous CO_2 can be avoided. In any case, monitoring activities costs, that has the main purpose to measure, monitor and verify that there isn't any leakage and quantify the amount of stored CO_2 cost is the important aspect during operational phase.

8.8 CO_2 utilization

The current assumptions to be taken in account for CO_2 utilisation as methanol techno-economic analysis are:

- A generic MeOH plant production from literature [33]
- Selling price of MeOH
- Cost of CO_2 as the cost of CO_2 allowance in the EU
- Cost of H2 as a typical industrial-scale electrolyser operating full-time.

The key cost drivers are the available quantity of CO_2 and H2 for MeOH production to determine the size of the MeOH plant to be considered. They will be subject to optimization.

Renewable electricity production and electrolyser are out of scope of the AURORA project.

9 LIFE-CYCLE ANALYSIS

Life cycle analysis will follow ISO14040. The usual four stages will be carried out:

1 Goal and scope definition

2 Inventory analysis,

3 Impact assessment and

4 Interpretation/Evaluation.

As recommended in the ILCD [59] handbook, this will be done iteratively, with a first pass through steps 1-4, before further iterations to identify weaknesses in data or assumptions.

The analysis will be attributional, i.e. with static background processes, using average data from the specific location of each of the case studies. The ILCD recommendations [59] will be used to critique this assumption. Commercially available software and databases (Simapro + Ecoinvent) will be used to provide the background data, and perform the inventory calculations and impact assessment.

The foreground system will consist of the carbon capture unit, downstream gas processing and compression, transport and storage, compatible with the scenarios in §4. Data from the TEA will provide many of the inputs of material and energy flows, supplemented with additional models as needed. The no-capture plant scenario will serve as a reference case and baseline. Scenarios for transport and storage are well defined, with the TEA able to provide good-quality data and models that can feed into the LCA. For CCUS, CO_2 to methanol is the chosen process route for utilization. Displacement of methanol in the current market will serve as the reference for comparison. CCU is not included in the TEA carried out elsewhere in the project, so the LCA will have to construct Its own models of processes based on literature data, or may require some additional process modelling. The modelling of this will necessarily be of a lower fidelity than that carried out in the detailed TEA elsewhere in this project.

One challenge to be addressed is the allocation of environmental burden when the CO_2 from the single capture plant is feed into a hub for CCS. A cradle-to- hub analysis rather than cradle-to-grave (storage) is straightforward but gives a lower bound estimate of the burden. Here, if a scenario feeds CO_2 into a hub, various methods of calculating the burden will be attempted to produce a plausible range of answers and examine the sensitivity to assumptions, e.g. lower bound cut-off (i.e. burden only to hub connection), dedicated pipeline to storage site (upper bound), marginal physical apportionment of burden for compression, and apportionment based on flows if data for hub and network exists.

10 KPI on the whole CCUS chain

10.1 Efficiency of the capture plant block

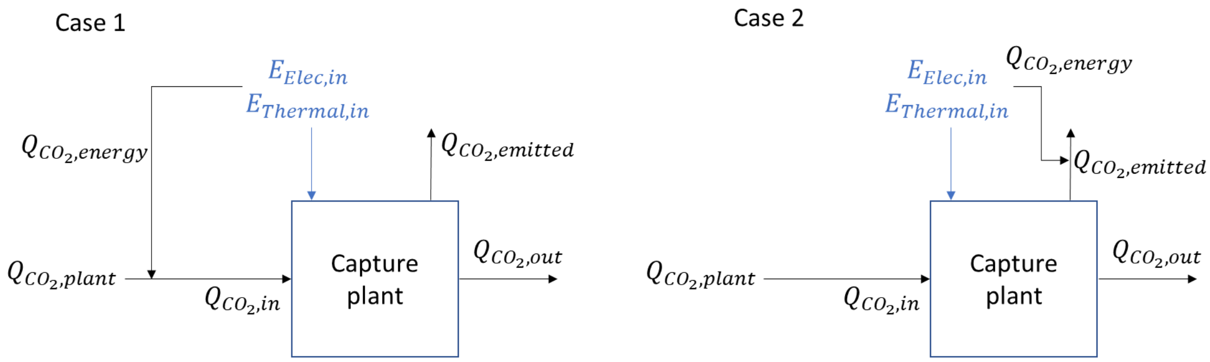

Figure 8: Schematic of the CO_2 fluxes and energy inputs in the CO_2 capture unit

Concerning the CO_2 emissions related to the energy supply of the capture plant, two extreme cases can be considered as illustrated in Figure 8. In both cases, the stream of CO_2 captured by the plant is $Q_{CO_2,out}$. On the left, the CO_2 emitted for producing the energy of the capture plant ($Q_{CO_2,energy}$) is sent to the inlet of the capture plant and is part of the inlet stream of CO_2 to be captured ($Q_{CO_2,in}$). Such a case would correspond to the steam generation by a fossil fuel-fired auxiliary boiler. On the right, the CO_2 from the energy supply is emitted to the atmosphere with the depleted flue gas of the capture unit ($Q_{CO_2,emitted}$). It would correspond to a steam generation with an electrical boiler. In general, the CO_2 from the energy supply (SCOPE 1 and 2) will be partially captured and partially emitted. Captured ($Q_{CO_2,captured}$) and avoided CO_2 ($Q_{CO_2,avoided}$) streams are defined as follow:

- $Q_{CO_2,avoided}$ = $Q_{CO_2,plant}$ - $Q_{CO_2,emitted}$
- $Q_{CO_2,captured}$ = $Q_{CO_2,out}$

Several KPI can be defined:

- The capture rate of the unit: $\eta_{CO_2} = Q_{CO_2,out} /\ Q_{CO_2,in}$
- The global capture efficiency: $\eta_{EFF} = Q_{CO_2,avoided} /\ Q_{CO_2,out}$
- The global energy intensity: $I_{energy} = E_{in} \ /\ Q_{CO_2,out}$
- The electrical intensity: $I_{elec} = E_{Elec,in} \ /\ Q_{CO_2,out}$
- The thermal intensity: $I_{elec} = E_{Thermal,in} \ /\ Q_{CO_2,out}$
- The global Carbon intensity: $I_{CO2} = Q_{CO_2,emitted} /\ Q_{CO_2,out}$

10.2 Efficiency of the whole chain

The previous KPI can be calculated for each block of a CCUS chain as schematized in Figure 9.

For each block, the CO_2 avoided can be evaluated as: $Q^i_{CO_2,avoided} = Q^i_{CO_2,in} - Q^i_{CO_2,emitted}$

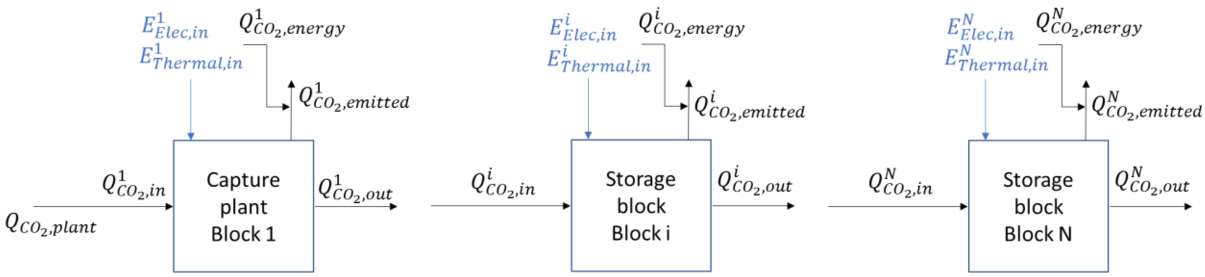

Figure 9: Schematic of a generic CCS chain with CO_2 and energy fluxes.

The KPI related to the whole chain can be expressed as:

- Chain Capture rate: $\eta_{CO_2} = Q^N_{CO_2,out} / Q^1_{CO_2,in} = \prod_1^N \eta^i_{CO_2}$
- Global capture efficiency:

  $\eta_{EFF} = (Q_{CO_2,plant} - \sum_1^N Q^i_{CO_2,emitted}) \,/\, Q^N_{CO_2,out} = (Q_{CO_2,plant} - \sum_1^N Q^i_{CO_2,emitted}) / (Q^1_{CO_2,in} \times \eta_{CO_2})$
- Energy intensity: $I_{energy} = \sum_1^N E^i_{in} / Q^N_{CO_2,out} = \sum_1^N E^i_{in} / (Q^1_{CO_2,in} \times \eta_{CO_2})$
- Carbon intensity: $I_{CO2} = \sum_1^N Q^i_{CO_2,emitted} / Q^N_{CO_2,out} = \sum_1^N Q^i_{CO_2,emitted} / (Q^1_{CO_2,in} \times \eta_{CO_2})$

10.3 Economic KPI

For each block of the CCUS chain (block i), the cost for capturing, conditioning, transporting and storing one tone of CO_2 will be calculated by:

- $Cost\ per\ tonne\ CO_2\ at\ the\ outlet\ of\ block\ i = \frac{Annualised\ CAPEX + Total\ OPEX}{Q^i_{CO_2,out}}$

The same calculation can be applied related to the avoided CO_2 of each block:

- $Cost\ per\ tonne\ CO_2 avoided\ in\ block\ i = \frac{Annualised\ CAPEX + Total\ OPEX}{Q^i_{CO_2,in} - Q^i_{CO_2,emitted}}$

The other economic indicators are:

- the cost of industrial product with CCU or CCS
- the cost of industrial product with carbon tax

10.4 Energy and Environmental KPI from the LCA

The LCA analysis will provide a full environmental profile for the 16 impact Categories recommended in the PEF method [60]. Of particular interest in this project are the indicators for: Climate Change (kg-CO_2 eq), Land use, water use (kg world eq. Deprived), Resource use- Minerals and metals (kg-Sb eq), Resource Use-energy carriers (MJ).

Energy and environmental indicators from the LCA are:

- Direct specific primary energy consumption
- Direct specific CO_2 emissions
- Specific electrical/thermal energy consumption
- Indirect specific primary energy consumption
- Indirect specific CO_2 emissions
- Specific primary energy consumption
- Specific CO_2 emissions
- CO_2 capture ratio
- Direct CO_2 avoided index
- CO_2 avoided index
- Specific primary energy consumption for direct CO_2 avoided
- Specific primary energy consumption for CO_2 avoided

The KPI related to energy and emissions are complementary to those calculated in §10.1 and 10.2 for which only Scope 1 and 2 are taken into account.

10.5 Societal, political and regulatory KPI

Designing and implementing a strong regulatory framework will play an important role in building a favourable environment for industrial CCS development. However, regulation by itself is only one element and the wider social and political will ultimately determine whether projects can obtain the necessary social license to operate and public and political support. Several issues that can help to describe the political and regulatory status are proposed in AURORA, based on similar evaluations already carried out (as, for example, in the Horizon Europe Strategy CCUS project as well as previous EC projects, which have investigated social and political aspects related to CCUS and industrial decarbonisation, including ConsenCUS, ACT, CCUS ZEN, Negem and ACCSEPT). We will be carrying out both large-scale nationally representative public surveys as well as looking into attitudes in the regions in detail and stakeholder concerns. As such, a list of issues that contribute to the creation of a favourable regulatory environment, and thus represent KPI's, could include:

- CCUS integrated into national Carbon Neutrality strategies and Nationally Determined Contributions (NDCs) submitted every five years to the UN Framework Convention on Climate Change (UNFCCC)
- Permitting and liabilities are clearly addressed in national legislation
- Proper incentives for CO_2 capture, whether subsequently stored or used
- Policies allowing trans-European CO_2 transport, use and storage.
- Legal framework for CCUS infrastructure projects
- Well-established and fast permitting process at national and local level for transport and storage infrastructures
- CCUS integrated into spatial planning tools (mapping several infrastructure options to support convincing deep decarbonisation solutions)

In addition, we will use the results of our research into public and stakeholder views to develop KPIs on specific questions such as:

- Most important issues facing the country
- Prioritise environment and climate action or economy
- Knowledge on energy and environmental issues
- Saliency and awareness of different energy and climate measures
- Prioritisation of industrial manufacturing
- Support for greening industrial clusters
- Support for different energy sources
- Awareness of CCUS technologies
- Knowledge of CCUS technologies
- Personal energy savings behaviour
- Belief in climate change

We will also explore how these key metrics vary according to demographics such as age, gender, region, urban/rural, etc. Further, we will examine relationships between some of these key variables, e.g., whether belief in climate change or knowledge of energy and environmental issues is associated with greater awareness or knowledge of CCUS technologies and ultimately support for CCUS technologies.

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