



## Accelerated deployment of integrated CCUS chains based on solvent capture technology

<https://aurora-heu.eu/>



### Deliverable D4.1– Methodology for large-scale assessment and benchmarking

WORK PACKAGE N°4 – Technology qualification and benchmark establishment

TASK 4.1: Methodology for large-scale capture plant assessment and technology qualification



Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.



	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

**Start date of project:** 01/01/2023  
**Duration of project:** 42 months  
**Deliverable n° & name:** D4.1 – Methodology for large-scale assessment and benchmarking  
**Version** 1  
**Partner responsible:** ACC  
**Written by:** Ricardo Wanderley (ACC), Kjetil Berget (ACC), Hanne Kvamsdal (SINTEF), Vanja Buvik (SINTEF), Hanna Knuutila (NTNU), Fredrik Gjertsen (CYB), Koteswara Rao Putta (TCM), Stephane Jouenne (TOTAL)

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			
	Name	Partner	Date
Checked by	Karl Anders Hoff	SINTEF	30.01.2024
Checked by WP-leader	Ricardo Wanderley	ACC	30.01.2024
Approved by Coordinator	Hanne M. Kvamsdal	SINTEF	30.01.2024

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

Issue date		30.01.2024
------------	--	------------

## Acknowledgments

This report is one of the 25 deliverables of the project "AURORA" which has received funding from the European Union's HORIZON EUROPE research and innovation programme under Grant Agreement n° 101096521.

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	



## Project Summary

Rapid up-scaling and deployment of more cost-efficient and sustainable carbon capture solutions is needed to reduce the emissions of CO<sub>2</sub>-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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> intensive industries thanks to the large variations in CO<sub>2</sub> sources and developed clusters addressed in the project and a strong stakeholder participation. The project will also perform 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:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

## Document Objective and Executive Summary



The goal of this document is to propose a structured methodology for technology qualification and benchmarking in order to (1) allow for a fair comparison between the CESAR1 solvent-based technology and the current benchmark, which relies on 30 wt% aqueous monoethanolamine (MEA) as its chemical scrubbing agent, and (2) mitigate risks in the deployment of large-scale carbon capture projects with the CESAR1 solvent applied to different scenarios and end-users.

This document serves as guidelines for the work in AURORA leading to the technology qualification of the CESAR1 technology and establishment of this technology as the new benchmark. The document is split in two for which PART A covers all the various elements that are needed for the techno-economic analysis (TEA) and benchmarking while PART B covers the overall qualification program. It should be noted that the some of the specifications given in this document may change depending on results from the pilot testing as well as results from other projects (e.g., the SCOPE project ([www.scope-act.org](http://www.scope-act.org)), which will end in September 2024).

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	



## 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	Total Energies 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

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	



# Contents

Acknowledgments .....	2
Project Summary .....	3
Document Objective and Executive Summary .....	4
List Of Partners.....	5
1 Introduction to Techno-Economic Analysis .....	1
1.1 Methodology.....	1
1.2 Summary of work done in the European Benchmarking Task Force (EBTF) .....	2
1.3 Summary of the work done in the OCTAVIUS project.....	3
1.4 Summary of the work done in the ALIGN-CCUS.....	3
1.5 Summary of the work done in HiPerCap .....	3
2 General CCP Information .....	4
2.1 End-user cases .....	4
2.1.1 The plants in Antwerp .....	4
2.1.2 The Heracles cement plant in Volos .....	4
2.1.3 The Motor Oil's refinery plant near Athens .....	4
2.1.4 Establishment of the end-user cases based on the four plants.....	5
2.2 General Technical Framework.....	5
2.3 Assessment and benchmarking criteria.....	6
2.4 Solvent system properties.....	7
2.5 External interfaces/battery limits .....	8
2.6 Process configuration .....	9
2.6.1 Carbon capture plant .....	9
2.6.2 Compression / liquefaction plant.....	10
3 Basis for Heat & Mass Balance Calculations .....	13
3.1 Overall specifications .....	13
3.2 Flue gas conditioning (SCOPE 2).....	14
3.3 Cost input data .....	14
3.3.1 Equipment cost input data .....	14
3.3.2 Operating cost input data.....	15
3.4 Specifications and assumptions for unit operations in the capture plant (SCOPE 1).....	15
3.4.1 Columns .....	15



	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

3.4.2	Heat exchangers / coolers .....	17
3.4.3	Blower/Fan.....	20
3.4.4	Pumps .....	20
3.4.5	Reclaiming .....	21
3.5	Water-balance control .....	21
3.6	Utilities.....	22
3.6.1	Cooling water .....	22
3.6.2	Steam.....	22
3.7	Assessment of alternative heat sources and process modifications .....	23
3.7.1	Assessment of waste-heat sources and use of heat-pumps .....	23
3.7.2	Assessment of absorber inter-cooling and emission mitigation technologies .....	24
3.7.3	Assessment of renewable energy alternatives .....	25
3.8	Simulation tools and solvent models .....	25
3.8.1	Simulation tools.....	25
3.8.2	Solvent modelling.....	26
4	Basis for cost calculations .....	28
4.1	Methodology.....	28
4.2	CAPEX.....	28
4.2.1	Total Equipment Cost (TEC).....	28
4.2.2	Total Direct Plant Cost (TDPC).....	29
4.2.3	Total Indirect Plant Cost (TIPC).....	29
4.2.4	Fixed Capital Investment (FCI) .....	29
4.2.5	Total Capital Investment (TCI).....	29
4.3	OPEX .....	30
4.3.1	Direct Production Costs .....	30
4.4	Assumptions.....	31
5	Benchmarking and Assessment Criteria .....	32
5.1	Benchmarking .....	32
5.2	Assessment criteria.....	32
5.2.1	Energy requirement .....	32
5.2.2	Emission of amines and degradation products to air.....	33
5.2.3	Solvent management (including solvent consumption) .....	34
5.2.4	Effect of heat integration .....	34
5.2.5	Flexible operation of the capture plant.....	34
5.2.6	Dynamics and control .....	35
6	Summary for Techno-Economic Analysis .....	36
7	Introduction to Technology Qualification .....	38



	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	



7.1	The goals of technology qualification .....	38
7.2	An overview of the technology qualification methodology .....	38
7.2.1	Qualification Basis .....	39
7.2.2	Technical Assessment .....	40
7.2.3	Risk Categorization .....	41
7.2.4	Qualification Plan .....	41
7.2.5	Qualification Execution .....	42
7.2.6	Performance Assessment .....	42
7.3	AURORA end-users and case-studies .....	42
8	Basis for Qualification .....	43
8.1	Selection of general technical parameters .....	43
8.2	Selection of functional requirements .....	43
8.3	Selection of energy requirements .....	44
8.4	Selection of environmental requirements .....	44
8.5	Breaking down the technological elements .....	45
8.5.1	Direct contact cooler .....	46
8.5.2	Other pre-treatment alternatives .....	47
8.5.3	Flue gas fan .....	47
8.5.4	Absorber column .....	47
8.5.5	Desorber column .....	49
8.5.6	Emission control .....	49
8.5.7	Reboiler .....	50
8.5.8	Energy savings alternatives .....	51
8.5.9	Reclaimer .....	51
8.5.10	Solvent health .....	52
8.5.11	Other items .....	53
8.6	Risk categorization .....	53
9	Technology Qualification Activities .....	54
10	Summary for Technology Qualification .....	59
11	References .....	60
12	.....	60
13	.....	60

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

# PART A

## TECHNO-ECONOMIC ANALYSIS

## AND BENCHMARKING

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

# 1 Introduction to Techno-Economic Analysis



## 1.1 Methodology

To see the potential of new technologies, we need to assess and compare it to more state-of-the-art technologies. But how do we do the assessment and which criteria to be used? Which reference state-of-the-art technology shall we choose, especially since post-combustion CO<sub>2</sub> capture applications are still very limited? What should be the source(s) of the flue-gas to be treated? And how can we avoid conducting an unfair "apples to oranges" comparison? During the last 20-30 years of CO<sub>2</sub> capture technology development, there has been a lot of effort put into the development of guidelines for how this should be done in a proper way. Common amongst these guidelines is an overall methodology structure containing the following aspects:

- Definition of case(s)
  - Should it be a real or generic case?
  - Site (or area) location (important for, e.g., feed stream conditions, ambient temperature, cooling water conditions, costs) or typical values
- Should it be assessed wrt. both ship and pipe transportation, as this will affect the impurity requirement and also the heat integration options?
- Definition of criteria for comparison like energy use, costs, and operational issues
- Definition of a common basis for comparison (like configuration and system boundaries, assumptions, tools etc.)
- Overall comparison especially on how to use the results obtained for each comparison criterium

In the CAESAR, CESAR and DECARBIT projects which were conducted around 2010, a joint effort named European Benchmarking Taskforce (EBTF) was put into systemizing this methodology for CO<sub>2</sub> capture technologies in a guideline document (e.g., Booth et al. (2011)<sup>1</sup>). A summary of the work done in the EBTF study is given in the next sub-section.

Although the EBTF document has been widely used since it was completed, it has some clear limitations. Firstly, the cases listed are focused on power plants only while the focus has been shifted towards other industrial sources of CO<sub>2</sub>. Furthermore, the benchmark technology addressed in the EBTF document and still used actively since then is a post-combustion type of capture based on amine absorption with the simplest amine MEA (monoethanolamine) and a conventional absorber/stripper process. As there are several improvements in solvent-based technologies, this should also be reflected in the use of benchmark technology as recognized in the HiPerCap project (2014-2017, see Section 1.5), in which the CESAR1 solvent was used as the benchmark solvent. The challenge is that the feature and performance of the benchmark technology should be well-known and though it has been studied (e.g., in the OCTAVIUS project 2012-2016 and the ALIGN-CCUS project 2017-2020) since the development in the CESAR project (2008-2011) and even

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

suggested as the new benchmark, it has not been qualified in the same manner as MEA. However, this is something we will ensure through the qualification procedure as described in Part B and we will also benchmark it towards the present used benchmark MEA using other criteria in addition to the energy requirement and cost criteria as used in the EBFT.



It should be noted that the TEA and benchmarking to be conducted in AURORA are more a concept study than detail engineering work. This is reflected in the level of details in the simulations as well as the cost estimates. E.g., unless it is deemed necessary, there will be no contact with equipment suppliers. All data needed are based on partner experiences, availability in literature and information in the simulation and cost estimation tools that will be used in the study. Nevertheless, some optimization will be done to determine the most proper solution for each case. Since there are quite many degrees of freedom, there will be a need for specifying certain parameters while a sensitivity analysis will to a certain extent be performed for others. Details about this are given in Section 3.4.

## 1.2 Summary of work done in the European Benchmarking Task Force (EBTF)

The European Benchmarking Task Force (EBTF) guidelines identify and define parameters, methods, and best practices for three different 7<sup>th</sup> Framework Programme (FP7) EU funded carbon capture projects. The outcomes of the three projects were intended to be used for future research and development of European carbon capture projects to ensure that technical and economic comparison of novel power cycles involving capture technologies follows sound Techno-Economic Assessment (TEA) methods based on parameters that have been reviewed by a group of experts from academia and industry. While the other two project focused on other capture technologies, the CESAR project focused only on absorption-based capture based on amines. The objective of the project was to design an optimized post-combustion capture process integrated with power plants. The project covered coal and natural gas (NG) based power plants.

Each project covered the reference power plant description and comparison of CO<sub>2</sub> capture technologies integrated in each plant. All three projects were based on similar size and type base case studies and using the same approach in evaluating plant performance after the integration of the CO<sub>2</sub> capture system. The following parameters were common for all projects:

- Ambient conditions
- System unit description: (gas turbine, steam turbine, heat exchangers, boiler, pressure drops)
- Fuel composition and characteristics
- Operating and cost parameters of standard components
- All plants are operating on identical yearly load (base load)
- The CO<sub>2</sub> capture solutions are investigated for newly built plants (*Green field*)

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

- 2008 was the reference year of costing

The evaluating approach covers plant efficiency, power penalties, breakeven cost of electricity and cost of CO<sub>2</sub> avoided calculation.

The EBTF work covered also a sensitivity analysis for several economical parameters.

### 1.3 Summary of the work done in the OCTAVIUS project



As indicated previously, the CESAR1 solvent systems were compared to the 30 %wt. MEA in the OCTAVIUS project. As in the EBTF work, the focus was integration with power plants (specifically an 800 MW bituminous coal case and a 430 MWe NGCC case from the EBTF guideline document). Furthermore, effects of process modifications like absorber intercooler and lean vapor recompression (LVR) were studied for the two solvent systems and the two power plant cases. The main KPIs used in the assessment were energy usage and cost of CO<sub>2</sub> capture. It was concluded that the CESAR1 solvent system in a conventional absorber/stripper scheme is less costly (almost 17% lower capture cost) than the MEA solvent system in a process with LVR for the coal case, while it is very similar for the NGCC case (Kvamsdal et al. 2016)<sup>2</sup>. However, the costs associated with emission and any countermeasures and solvent management were only roughly dealt with. Only base load operation with fixed 90% capture was considered.

### 1.4 Summary of the work done in the ALIGN-CCUS

Also in the ALIGN-CCUS project the CESAR1 solvent was compared with MEA. Though one case was a lignite fired power station based on EBTF, there were also considered one waste-to-energy and one cement case. The aim was to use the following key performance indicators (KPIs) for the assessment and benchmarking: specific primary energy consumption for CO<sub>2</sub> avoided (SPECCA), cost (different for the three cases), emission, solvent management, plant flexibility, dynamics and control, but it turned out that the last 5 was only briefly used in the assessment. The result of the benchmarking can be found in Garcia et al. (2021)<sup>3</sup>.

### 1.5 Summary of the work done in HiPerCap

The HiPerCap project was quite different from the OCTAVIUS and ALIGN-CCUS projects as new and emerging technologies for post-combustion capture were developed (solvent, membranes, and sorbents). However, the methodology from OCTAVIUS for technology assessment and benchmarking was adopted and as indicated previously the CESAR1 solvent system was actually used as the benchmark solvent. The same 800 MW bituminous coal case as in OCTAVIUS was used for the integration. In addition to the two main KPIs, cost and energy requirement, several others were used in the assessment. While a more quantitative approach was used for the two main criteria, a traffic light assessment was used to support the overall assessment. Though, a much simpler cost estimation method was used due to the low TRL, it can be mentioned that the CESAR1 solvent performed better than any of the technologies considered (9 others), even though some of the solvent-based systems showed improvements energy-wise. The conclusions might

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

not have been the same if other sources of CO<sub>2</sub> had been used in the analysis. However, the results clearly show that it is important to use as benchmark a system that also reflects the improvements in solvent-based technology developed during the last 20 years. This will help further development of various technologies and facilitates progress towards less costly technologies.

## 2 General CCP Information

### 2.1 End-user cases

The aim of the AURORA project is to assess the CESAR1 solvent for a large variation in flue gas sources. By having four plant owners as partners in the consortium the idea is to choose cases (hereafter referred to as the end-user cases) relevant for their plants. The plants are (1) the Heracles cement plant in Volos, Greece, (2) the Motor Oil refinery near Athens, Greece, (3) the Total Energies refinery in Antwerp, Belgium, and (4) the Umicore material recycling plant in Antwerp, Belgium. Further details about the plants are given in the following subsections.



#### 2.1.1 The plants in Antwerp

The Total Energies refinery and petrochemicals complex in Antwerp is their largest in Europe. 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, Total Energies constitutes the third-largest refinery in Europe. Also, with the transition of the European oil market, since 2013 Total Energies has invested more than €1 billion to extensively upgrade the Antwerp complex to improve its feedstock flexibility and meet the strictest environmental standards.

UMICORE is a global leader in clean mobility materials and recycling. UMICORE precious metals refining (PMR) is one of the largest precious metals recycling operations in the world. It 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 PMR process. UMICORE recovers and refines the precious metals, minor metals, and base metals. These can then be put back into the cycle for various technology applications.

#### 2.1.2 The Heracles cement plant in Volos

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.

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

### 2.1.3 The Motor Oil’s refinery plant near Athens

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.

### 2.1.4 Establishment of the end-user cases based on the four plants



The four end-users represent three quite distinct carbon emitting industries, and though there are two refineries, both have different emitting sources representing a large variety in terms of flue gas flowrates and composition as shown in the typical flue gas characterization given for each of the end user cases. At least four different end-user cases will be established as an initial part of the TEA based on the information in Table 2-1 and the following information for each plant:

- Plant products
- Annual production rates (e.g.: tons of H<sub>2</sub>/clinker)
- Annual CO<sub>2</sub> emissions (total and to be captured) – absolute (Mt CO<sub>2</sub>) and specific (e.g., kg CO<sub>2</sub>/t H<sub>2</sub>)
- Waste heat availability (LP steam and or as source for heat integration/heat pump)
- Steam generation, this is case-dependent (see Section 3.7 for alternative solutions)
- Cooling water options (seawater/cooling water tower, need for extra capacity)
- Availability of land area for the capture plant (will influence the design)

*Table 2-1: End-user cases flue gas characteristics. Note that the refineries have several sources, but here only the range is indicated for those sources that will be considered to establish the end-user cases.*

Parameter	P	T	O <sub>2</sub>	CO <sub>2</sub>	H <sub>2</sub> O	SO <sub>2</sub>	NO <sub>x</sub>	NH <sub>3</sub>	CO	Particles
Partner	bara	°C	%mol			mg/Nm <sup>3</sup>				
TOTAL	1.07	61-270	2-3.4	8-14.5	16.3-18	25-160	212-510			
MOH (Hydro Purification Unit)	0.97	201	6.31	15.3		0.00326	0.0441		0.00318	
HERACLES	1	100-115	10.5-14.5	12-19	10	1-2	350-700	0.5-1	350-700	3-5
UMICORE	1	10-40	1-2	5-20	1-2	60	50		20	0.02

The remainder of the flue gas composition is N<sub>2</sub> + Ar (approx. 0.7 %mol).

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

## 2.2 General Technical Framework

In this section some basic definitions are made. Basically, the SI unit system is to be used.

In the previously mentioned studies, the ISO standard conditions for ambient air were used. These are applicable for the Antwerp cases, but for Greece the conditions imply some deviations and in Table 2-2, the conditions to be used for the end-user cases are indicated as ranges. Ultimately, when the TEA calculations begin, each end-user will have their site-specific design bases.

*Table 2-2: Ambient design reference conditions*

	Unit	Value
Air pressure	(MPa)	0.101325
Air temperature	(°C)	15-35
Relative humidity	(%)	40-60
Gas constant	(J/mol K)	8.314
Molecular mass air	(kg/kmol)	28.854
Cooling water temperature	(°C)	18-22



In case steam is provided from a natural gas and/or refinery gas, the air- and fuel composition and calorific values will be needed. The air composition is given in Table 2-3. The calorific values for natural gas and specific CO<sub>2</sub> emission are (from ETBF):

- Higher Heating Values (HHV): 51.473 MJ/kg
- Lower Heating Values (LHV): 46.502 MJ/kg
- Specific CO<sub>2</sub> emission: 208 g/kWh LHV
- Site elevation
  - For the TEA, the specificities of the site-preparation work will be lumped in with the EBTF methodology, hence the site elevation data will not be used directly in the calculations.

*Table 2-3: Air composition*

Component	Volume fraction dry (%)	Volume fraction wet at 60% rel. humidity (%)
N <sub>2</sub>	78.09	77.3
O <sub>2</sub>	20.95	20.74
H <sub>2</sub> O		1.01
Ar	0.932	0.923



	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

CO <sub>2</sub>	0.03	0.03
-----------------	------	------

## 2.3 Assessment and benchmarking criteria

Both the MEA solvent system and the CESAR1 solvent system will be assessed based on the following Key Performance Indicators (KPI):

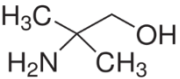
- Specific Primary Energy Consumption for CO<sub>2</sub> Avoided (SPECCA)
- Cost of CO<sub>2</sub> capture
- Cost of CO<sub>2</sub> avoided
- Electrical power consumption
- Emission of amines and degradation products to air
- Solvent management (including solvent consumption)
- Effect of heat integration
- Flexible operation of the capture plant (including capture efficiency)
- Dynamics and control



Description of the KPI's and how they are used as criteria in an overall assessment and benchmarking procedure are further detailed in Section 5.2.


## 2.4 Solvent system properties



The CESAR 1 solvent system consists of 3M 2-amino-2-methylpropanol (AMP) and 1.5M Piperazine (PZ) corresponding to 27 wt% AMP, 13wt% PZ and 60 wt% water. Information for the two components can be found in Table 2-4.

*Table 2-4: Information (name, Chemical Abstracts Agency (CAS) number, structure formula, Molecular weight, and melting point) about the two components (AMP and PZ) in the CESAR1 solvent system.*

Solvent component	CAS number	Structure	MW	MP, °C	Comment
2-amino-2-methyl-1-propanol (AMP)	124-68-5		89.14	24	Base component ("carbon-sink").

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

Piperazine (PZ)	110-85-0		86.14	106	Promotor component ("activator").
--------------------	----------	---	-------	-----	-----------------------------------

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

## 2.5 External interfaces/battery limits

The total process with its interface or battery limits for the various focus areas (scope) are shown schematically in Figure 2-1. The core part is the capture process (Scope 1). Then any Pre-treatment like de-NOX, de-SOX, and particulate removal constitutes Scope 2, Scope 3 is the source plant, while Scope 4 is the CO<sub>2</sub> compression and conditioning part prior to transportation. Scope 5 is the combination of Scope 1 and 2, which is the main target for the TEA in the present report. However, heat integration between the process of Scope 1 and the process of Scope 4 is an important part of the TEA and as such Scope 6 is also a focus area in this report.

The intention of the TEA is to encompass Scope 5 (i.e., Scope 1 + Scope 2). However, the limited amount of information available for carrying out a proper TEA of Scope 2 might render that as a simplified TEA case, with input from the industrial partners in AURORA.

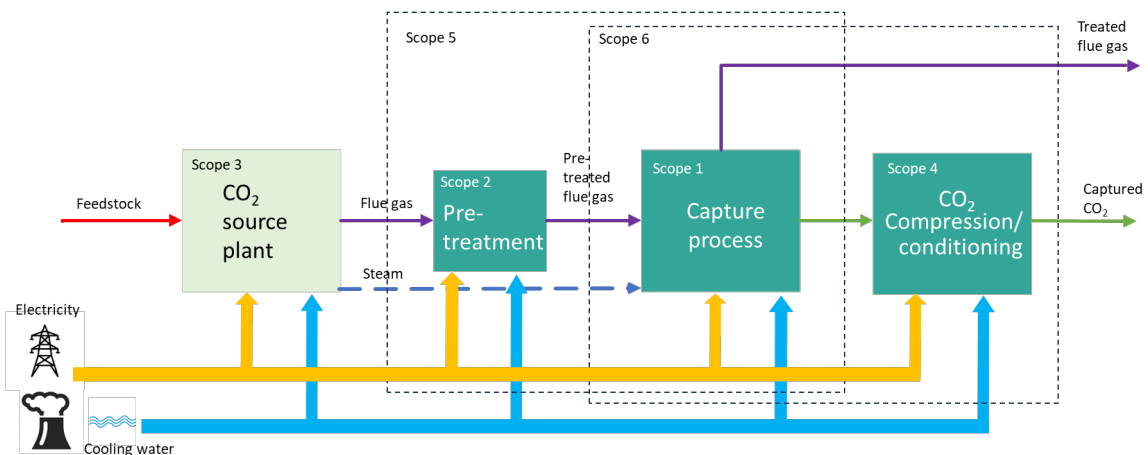




Figure 2-1: Schematic process with interface/battery limits and major flows including electricity and cooling-water

Also in Figure 7-1, the major flows including electricity and cooling water crossing the interfaces are indicated. However, there are also other important flows in and out of Scope 5 and 6 which are important for the TEA. Examples are:

- Wastewater management
  - Excess condensate/process water from the DCC
  - Process water from acid wash
  - Condensate/process water from CO<sub>2</sub> compression
- Consumables
  - Caustic soda
  - Sulfuric acid
  - Demin water
  - Potable water

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	



- Anti-foam
- Wastes
  - Condensate from acid wash
  - Reclaimer waste

## 2.6 Process configuration

### 2.6.1 Carbon capture plant

The CO<sub>2</sub> capture process is based on a conventional absorber-stripper system and a schematic flow diagram for the capture plant is as shown in Figure 2-2. It shows the main equipment and the main streams in such plants.

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 cooler. The water circulation stream is cooled by means of a cooling medium dependent on the end-user case. The 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<sub>2</sub>. 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 the emission of solvent and degradation products. The solvent, which is “rich” in CO<sub>2</sub>, is pumped to the top of the desorber via a cross-heat exchanger. The solvent is regenerated in the desorber at higher pressure (around 1.7–2 bara) 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<sub>2</sub> from the solvent. The stripping steam associated with the CO<sub>2</sub> product leaving the stripper is recovered by means of a condenser and fed back to the stripper. The CO<sub>2</sub> product thus leaving the condenser is relatively pure, with water vapour being the only other major component. In addition to the condenser which also will wash out and condense some of the entrained contaminants (basically solvent and degradation products as well any soluble compounds from the flue gas), an additional water-wash system should be considered in the top of the desorber. The lean solvent with residual amounts of CO<sub>2</sub> 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. Emission mitigation options in both the absorber and desorber, location of the blower, solvent management/reclaiming, and means of heat integration will be part of the optimization process of the TEA (see Chapter 3 for further details).

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

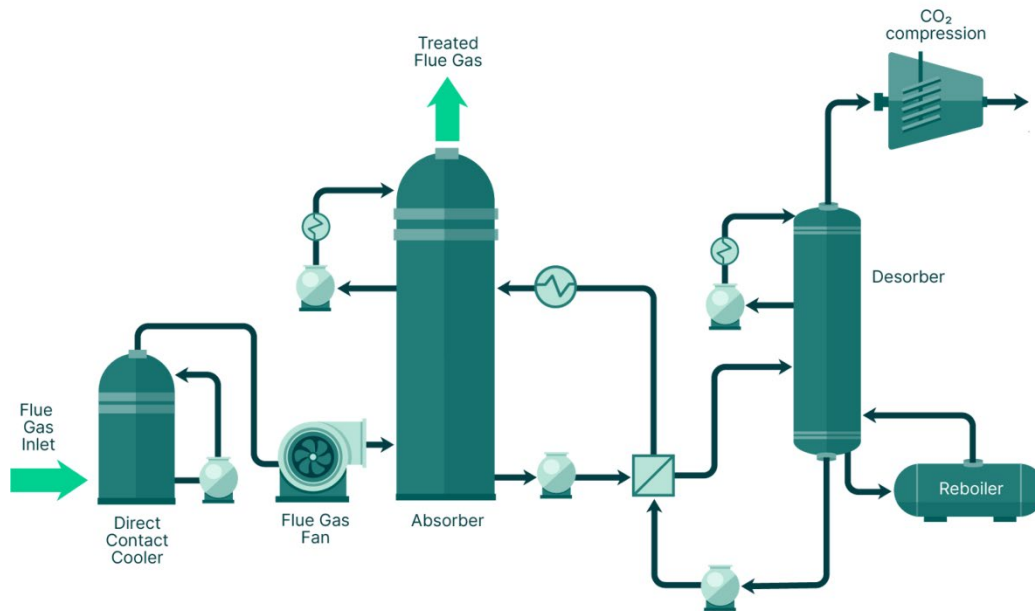




Figure 2-2: Sketch of a conventional absorber/desorber process flowsheet

## 2.6.2 Compression / liquefaction plant

In AURORA, two alternative means of transportation will be considered, transportation by pipelines or transportation by ships. The pre-condition prior to these two transportation modes is different as described in the following:

### Pipeline transportation

A schematic process flow diagram for a compression train is shown in Figure 2-3 . It consists of a four-stage compressor with intercooling, a dehydration system, and a final pump. As indicated the CO<sub>2</sub> stream leaving the condenser of the stripper is a CO<sub>2</sub> rich stream (> 97.7% vol), with the rest being mostly water vapour and traces of other contaminants. It is believed that the contaminants are removed in the two first two compression stages, but this will be confirmed as part of the pilot testing in AURORA. The water vapour is progressively removed in the compressor interstage knock-out drums (due to intercooling). However, the specified maximum content of water in the CO<sub>2</sub> stream after the compression will not be achieved without an extra purification or drying step. For example, with inter-cooling to 30°C the final water content after compression is around 1400-1500 ppmv. Further drying can be achieved by adding an absorption (glycols) or adsorption (molecular sieves) step after the compression train (P>73 bar) at which CO<sub>2</sub> is supercritical and thus in the dense phase. The latter means that the physical properties are closer to a compressible liquid and as such 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. The location of the dehydration step and the number of necessary compressor stages will be part of the optimisation process of the TEA.

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

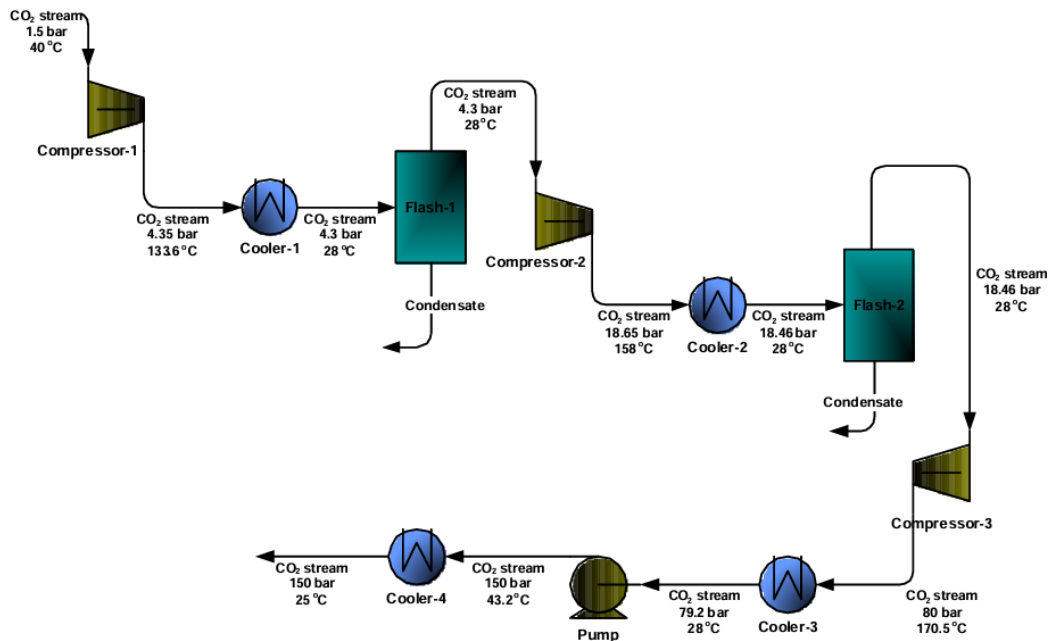




Figure 2-3. Schematic flow diagram for a compression train prior to pipeline transportation, according to CAESAR guidelines. Source: “D4.9 European best practice guidelines for assessment of CO<sub>2</sub> capture technologies”.

### Ship transportation

Prior to ship transportation, the CO<sub>2</sub> needs to be conditioned. The reference ship transport chain here is the one under development in the Longship/Northern Lights project. Here, the CO<sub>2</sub> is transported as a liquid at 13 - 15 barg and -30.5 - -26.5 °C. The CO<sub>2</sub> specification is currently under revision and an updated specification is reported to be ready in Q1 2024<sup>4</sup>. There are two main approaches for liquefaction, internal (ICL) and external cooling loop (ECL). In the internal cooling loop process it is the CO<sub>2</sub> itself that is the working medium. To liquefy, the CO<sub>2</sub> is compressed to above 70 bar and then expanded to the transport pressure. Approximately 60% of the CO<sub>2</sub> is liquefied through this expansion, while the other 40 % remains in gaseous phase (the ratio between liquid and gaseous CO<sub>2</sub> depends on  $\Delta P$ , the pressure before and after the expansion and the temperature at which the expansion takes place). The liquefied CO<sub>2</sub> is then sent to an intermediate storage tank, while the gaseous CO<sub>2</sub> is returned to the appropriate compression stage for recompression. (The boil-off gas from the storage tanks and return gas from the ship/truck also needs to be recompressed/reliquefied.) In the external cooling loop, the CO<sub>2</sub> is compressed to transport pressure and then cooled with the aid of a cooling medium (e.g., NH<sub>3</sub>). The two methods both have advantages and disadvantages. The ICL only requires compression, no cooling medium is needed, however 40 % of the CO<sub>2</sub> remains in a gaseous state and must be recompressed, increasing the compression power needed.

It is the ICL approach that is employed in the liquefaction process to be installed at Heidelberg Materials in the Longship project. The process is schematically shown in Figure 2-4. The CO<sub>2</sub>

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

enters a 4-stage compressor (or more) with intercooling and knock-out drums. Before the CO<sub>2</sub> 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 adsorbs CO<sub>2</sub> while the other is regenerated. The bed is regenerated by heated dry CO<sub>2</sub>. Additional purification might be done through the inclusion of distillation column. Finally, the dry and pure CO<sub>2</sub> is then sent to the last compression stage, after which it is expanded to transport pressure. As not all of the CO<sub>2</sub> becomes liquid through the expansion, the part that remains gaseous is sent back to the appropriate compressor stage. The liquid CO<sub>2</sub> is sent to an intermediate storage tank.

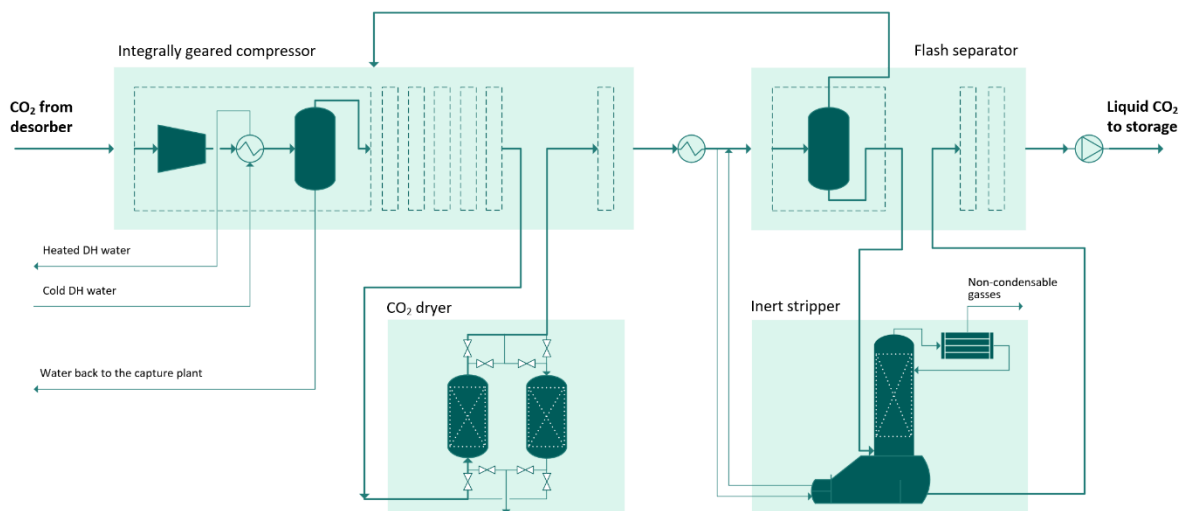




Figure 2-4: Schematic flow diagram for a liquefaction train prior to ship transportation.

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

## 3 Basis for Heat & Mass Balance Calculations

This Chapter will provide:

- Instructions for process modelling of the large-scale end-user cases
- Description of computational assumptions for the capture plant
- Specifications that influence CAPEX and OPEX

As indicated earlier, there is a need to reduce the number of degrees of freedom and as such certain parameters are specified, while others will be part of the optimisation process of the TEA.



### 3.1 Overall specifications

Specifications for some of the main parameters, which influence on the capital costs (CAPEX) and operating costs (OPEX) are listed in Table 3-1. It should be noted that the pressure of the desorber will be part of the optimization process of the TEA though this is limited by thermal degradation of the solvent.

*Table 3-1: Overall pre-fixed specifications for the AURORA large-scale CO<sub>2</sub> capture plants*

Parameter	Fixed values	Comments
Flue gas CO <sub>2</sub> content	Case dependent	At least four different values 1) Refinery case (Total Energies) 2) Refinery (Motor Oil) 3) Cement case (Heracles), and 4) materials recycling (Umicore)
Flue gas flowrate	Case dependent	At least four different values 1) Refinery case (Total Energies) 2) Refinery (Motor Oil) 3) Cement case (Heracles), and 4) materials recycling (Umicore)
H <sub>2</sub> O in flue gas prior direct contact cooler (DCC)	Case dependent	At least four different values 1) Refinery case (Total Energies) 2) Refinery (Motor Oil) 3) Cement case (Heracles), and 4) materials recycling (Umicore)
Flue gas temperature after direct contact cooler (DCC)	35°C	Absorber inlet gas is saturated. The value is reasonable at least if the blower is located downstream the DCC but should be verified by the test campaigns in AURORA.
Capture rate	95 % of inlet content	Average on the flue gas treated
Solvent	30 wt% MEA + CESAR1 (3M AMP+ 1.5M Piperazine)	MEA is the reference.



	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

Packing material in columns (included water-wash sections)	Sulzer Mellapak 2X	May change to Sulzer CC if enough data available. Might also updated choice of packing based on feedback from industrial partners.
Condenser temperature*	40°C	Saturated with water
Amine/Ammonia content in flue gas leaving the absorber	<0.2 ppmv / 0.5 ppmv**	Will influence the choice of water-wash and or other emission mitigation options.
Yearly average nitrosamines and nitramines in the nature	<0.3 ng/m <sup>3</sup> in air and <4 ng/L in drinking water	Based on permit limits at TCM. Will influence the choice of emission mitigation options.

\* In case of the “Once-trough heat pump” (OTHP), this temperature will be higher

\*\* Maybe to be updated after the SCOPE project is finished in September 2024

## 3.2 Flue gas conditioning (SCOPE 2)

As indicated in Section 2.1.4, the cases will be established initially as part of the TEA. However, it might be that the flue gas contains flue gas contaminants (SO<sub>x</sub>, NO<sub>x</sub>, NH<sub>3</sub>, CO, dust, etc.) that will need pre-treatment prior to the DCC. Such pre-treatment will be taken into consideration in the overall assessment, but not simulated. Refer to Section 2.5.

## 3.3 Cost input data



The input data needed for the cost analysis of the TEA is retrieved from the simulation results and some post-treatment of these data. This concerns data for determining the cost of equipment and some operational cost parameters as indicated in the following sections.

### 3.3.1 Equipment cost input data

The unit for the dimensioning value used for the cost estimation for the various types of equipment is given in Table 3-2.

Table 3-2: Equipment cost input data

Unit	Physical entity	Unit of measure
Empty columns and storage/buffer tanks	Volume	m <sup>3</sup>
Packed sections	Volume	m <sup>3</sup>
Pumps	Power	kW
	Liquid flow	l/s
Blower/compressor	Power	kW

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

	Actual gas flowrate	m <sup>3</sup> /h
Heat exchangers	Surface area	m <sup>2</sup>
	Type	(-)
First fill of solvent (also part of CAPEX)	Mass	tonne

It should be noted that the water-wash (WW) sections are treated separately from the absorber part, though it is most likely to be designed within the same column (see Sub-section 3.4.1 for further details). Furthermore, also note that parallel units are accounted for in case this is needed. For example, if the required heat exchanger area turns out to be larger than the maximum heat-exchanger area for the specific heat-exchanger type, the required area will be divided by the maximum area to find the necessary number.

### 3.3.2 Operating cost input data

The amount of CO<sub>2</sub> captured (tonne/h), the lean solvent flowrate (tonne/h), the reboiler duty (MW<sub>th</sub>), the total cooling duty (MW) and amount of cooling water (m<sup>3</sup>/h), and the total power consumptions in the pumps, the blower, and the compressors (MW<sub>el</sub>) are data needed for the operational cost estimation and these data are also provided based on the simulations.

## 3.4 Specifications and assumptions for unit operations in the capture plant (SCOPE 1)



The specifications for the process unit operations given here are those which are necessary for simulation of the capture processes and for calculation of the utility requirement (heat/steam, electricity, cooling water, process water).

Some specifications for all process unit operations are summarized in the following tables. It should be noted that the output pressure of the blower depends on the pressure drop in the absorber column, which again depends on the total height of packing (including the water wash section(s)).

How the heat requirement in the reboiler is provided is case dependent (see the utilities sub-section)

The water used for the DCC unit as well as the absorber and desorber water-wash sections will depend on the quality of the process water available at each plant sites, but it will be demineralized if needed. The latter will be considered in the cost analysis. See the utilities sub-section for further details about the process water as well as the cooling water.

### 3.4.1 Columns

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

## Absorber

The amount of gas to be treated in large scale absorbers is considerable and may imply that actually more than one absorber column is needed. This may further imply separate process trains.

The number of column(s) depends on several factors like type of column, packing material, flooding velocity, and practical construction limitations. As in similar earlier studies, we only consider cylinder stainless steel type of columns is considered though concrete rectangular columns have been used and considered in many larger applications as e.g., Boundary Dam, Test Center Mongstad and Kingsnorth. The column diameter shall be determined by a specification of operation below 70% of the flooding velocity (chosen for conservative reasons, might be re-adjusted after talks with vendors or fluid mechanic analyses). The practical maximum diameter of a column to be used in AURORA is 16 m. Thus, the number of trains needed must be determined based on this maximum diameter and the amount of gas to be treated.

The actual height of the column depends mainly on the required packing height (which is determined as part of the TEA optimization) and the height of the washing section, but also other internals as the liquid sump, the inlet gas duct, the gas- and liquid distribution plates and any redistribution plates will contribute to the overall height. The number of necessary packed sections depends further on the type of packing and recommendation from the packing supplier. In AURORA it is decided to use a maximum bed height of 7m (Kohl and Nielsen 1997)<sup>5</sup>. According to Sulzer it is good practice to have a liquid collector at the bottom of each packed section.



The required means for amine emission mitigation will depend on several factors and the specific emission permit. It is the aim of Aurora to develop an adequate model so that various options for emission mitigation can be assessed and thus the best solution for the specific case can be determined. This could be options like water-wash, dry bed, acid wash combined with temperature control.

In any case one water-wash section shall be included to control the water-balance of the PCC plant (see Section 3.5 or further details about the water-balance control).

The actual height of the absorber will be determined based on information given in Kvamsdal et al. 2010<sup>6</sup>. Thus, the typical height for all internals except for the packed sections, which are determined by simulation and optimization, is as shown in *Table 3-3*.

*Table 3-3: Pre-defined dimensions absorber column. The numbers are based Kvamsdal et al. 2010<sup>6</sup> with some modifications*

Height mist collector + gas outlet section	m	2.5
Height between absorber and water-wash sections and between packed sections	m	2.5
Height required for flue gas inlet and distributor (between sump and first packed section)	m	2+0.5D

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

Sump	m	Must be determined assuming 6 minutes of residence time*
------	---	--

\*Based on requirement for the rich solvent pump

### Desorber

As for the absorber the diameter of the desorber column is determined by the vapour flow specification of 70% of flooding velocity. According to Table 3-1, the structured packing Mellapak 2X will be considered also for the desorber. As in the absorber, the packing internals such as the gas and liquid distributor, redistribution plates, etc. will influence the height of the column (see Table 3-3). The liquid sump height depends on the type of reboiler and the design of it (initially kettle-type reboilers will be favoured, though this can be further explored in value improvement activities).

In the desorber tower, one wash section is present in the top of the column to avoid solvent carryover. The wash section design will be a once-through with water from the condenser reflux.

The number of stripper columns is more limited by the number of reboilers than the number of absorbers (see sub-section about the reboiler).

### Direct Contact Cooler



The purpose of the DCC is to cool down the flue gas prior to absorption so that the flue gas is saturated at a given temperature (must then be at or below the dew-point). For the DCC an arrangement as shown in Figure 2-2 can be used with counter-current flow of water (process water) in direct contact with the flue-gas. The internal should be a packed section (Mellapak 2X) with distribution plates similar to an absorber wash section. At the Tiller plant, at which the packing type is also Mellapak 2X, the height of packing is 2.5 m. The DCC packing height and packing type will be optimised in a case-specific basis and the results will be used for the TEA.

### Other columns

Buffer tanks, amine make-up tanks, amine storage tank (maintenance), and other process related tanks are dimensioned in accordance with the calculated capacity. Buffer tanks as needed for variations in solvent flow-rate and other changes in operating conditions and should be designed based on the possible operating window. Also, the column sumps can be considered as part of the total buffer-capacity. The amine make-up tanks are dimensioned according to the expected make-up rate per day and the number of days between each provision of fresh solvent. The purpose of the amine storage tank is as a holding tank for solvent during maintenance. This tank should be dimensioned based on the first fill volume of amine/solvent. The required size could also be scaled from similar studies. For instance, at Boundary Dam, the amine tank is 1758 m<sup>3</sup> in volume (18.5 m height and diameter 11m). The capture plant serves a 150 MW power station and thus the required size should be adjusted for the cases addressed in AURORA.<sup>7</sup>

## 3.4.2 Heat exchangers / coolers

Firstly, in this sub-section some general specifications are given then some further information about the type of equipment is given.

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

### Specifications



The specifications related to temperature and pressure drop for the heat exchangers for the process side is given in Table 3-4. It should be noted that the lean cooler specification may depend on the recommended emission mitigation measures and as such this will be addressed as part of the TEA.

*Table 3-4: Specifications for all heat-exchangers (process side)*

Parameter / heat exchanger	Temperature out, °C	Pressure drop, mbar, kPa	Temperature approach, °C	Comment
<b>DCC cooler</b>	35	-	See utility sub-section as an approach on the cold side is given	Water content, outlet: saturated Pressure drop neglected, but covered by the upstream pump
<b>Cooler in the water-wash recirculation loop in the top of the absorber*</b>	35	-	See utility sub-section as an approach on the cold side is given	Water content, outlet: saturated Pressure drop neglected, but covered by the pump
<b>Lean-rich heat exchanger</b>	-	-	5 °C (cold in – hot out)	Pressure drop neglected, but covered by the pump
<b>Overhead condenser</b>	40	3%		Temperature dependent on desorber pressure and use of OTHP
<b>Reboiler</b>	120			Operating temperature dependent on desorber pressure and use of OTHP

Based on the specification as listed in Table 3-4, the heat exchanger duty is determined based on simulations. As seen from Table 3-2, the needed cost input data for the heat exchangers depends on both the heat exchanger area and type of heat exchanger. The area can be calculated from the simulations, while the type of heat exchanger must be specified. The latter influence on the maximum heat exchanger area per unit and thus the number of units required. In Table 3-5 the overall heat transfer coefficient to be used for determining the size of the chosen heat exchanger types and the max heat exchanger area is shown. Subsequently a short description for each heat exchanger is given.

*Table 3-5: Overall heat transfer coefficient and maximum area for heat exchangers design*

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

Heat exchanger	U (W/m <sup>2</sup> K)	Maximum HX area (m <sup>2</sup> )
Reboiler: Compabloc HX from Alpha Laval	3200	845
Cross HX (plate HX <sup>*</sup> )	3000	1280 <sup>**</sup>
Lean cooler (plate HX <sup>*</sup> )	3000	1280 <sup>**</sup>
Plate HX Condenser	2000 <sup>***</sup>	1280 <sup>**</sup>
Water-wash cooler (plate HX)	2000 <sup>****</sup>	1280 <sup>**</sup>

\* Gasket and brazed plate heat exchangers.

\*\* Based on TL35 Model from Alfa Laval

\*\*\* In the condenser basically three phenomena will take place (i.e., cooling of the steam, condensing of steam and cooling of water). This means that the overall heat transfer coefficient will change throughout the heat exchanger and for simplicity here, an average value is used considering a plate heat exchanger.

\*\*\*\* This number is based on pure liquid-liquid heat exchanger

There is some contention regarding the values shown in Table 3-5. Our approach shall be to use said values for the TEA calculations, but comparing the results against past data obtained from real projects and communication with vendors.

### Reboiler

The reboiler maintains the solvent temperature at the specified temperature (Table 3-4). The reboiler must be steam operated using saturated steam.



There is a Technology Qualification Activity (see Section 8.5.7) related to evaluating different reboiler types. Initially we propose the utilization of kettle type reboilers for the process. However, previous industrial projects (e.g., Cansolv at the Boundary Dam facility) have employed Compabloc type heat exchangers. The advantages and disadvantages of these different reboiler types, and others, shall be discussed further on in the TQAs.

### Cross heat exchanger

The cross-heat exchanger (lean-rich heat exchanger) shall be designed in such a way that the heat from the hot lean solvent is efficiently transferred to the rich solvent. The type of heat exchanger to be used is a plate and frame heat exchanger, thus the temperature approach (i.e. cold in – hot out) can be 5°C (as indicated in Table 3-4).

### Coolers

Traditionally, a lean cooler (trim cooler) is included to further cool down the lean stream before entering the absorber. However, this might impact on aerosol-based emission of the solvent and

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

as such the specifications for this cooler will be part of the optimisation for the emission mitigation strategy.

The water wash section maintains the water balance in the system and prevents solvent carry-over as described previously for the absorber. Thus, the flow of the water wash liquid is kept constant while the temperature is controlled by means of the water-wash cooler. A plate heat exchanger will be considered here. The overall heat transfer coefficient is mentioned in Table 3-4 together with the maximum allowed area per unit. The LMTD is determined by simulation and cooling-water requirement as the described for the utilities (Section 3.6). Thus, the number of required units can be determined. The same concerns the cooler located in the water circulation loop of the DCC and the desorber condenser cooler.

### 3.4.3 Blower/Fan

To compensate the pressure drop of the flue gas in the PCC plant (DCC + absorber), a blower or fan is needed in the flue gas stream as indicated in Figure 2-2. The pressure drop in these units shall be determined as follows (adopted from work in the OCTAVIUS project)<sup>8</sup>:

Pressure drop DCC:  $\Delta P_{DCC} = 6$  mbar for the column head + 3 mbar for the liquid distributor + 50 mbar for the gas distributor and 1.5 mbar per meter of packing section



Pressure drop absorber:  $\Delta P_{ABS} = 6$  mbar for the column head + 3 mbar per demister + 3 mbar for the liquid distributor + 50 mbar for the gas distributor and 1.5 mbar per meter of packing section

Since the required increase in pressure is relatively small, an axial blower is used similar to the induced draught. An isentropic efficiency of 75% and a driver efficiency of 95% to determine the power duty of this unit (based on the work in the OCTAVIUS project).

### 3.4.4 Pumps

For the real necessary work of the pumps, the static pressure head and pressure drop must be determined. By assuming all pumps to be located on the same and lowest level, the static pressure head for the rich and lean pumps is determined roughly based on the height of packing times two to account for the real height. For the water-recirculation pump of the DCC and the water-wash pumps the static pressure is the real height for the pump-around and it is determined as the packed section times two. Roughly the static pressure is 0.1 bar/m times the pressure head (static pressure of water). Additionally, the pressure discharge must also account for pressure loss in the pipelines as well as in the heat-exchangers. It is assumed 20% increase of the static pressure to account for the pressure loss in the pipelines and 1 bar increase for each heat-exchanger. For the condenser pump there is no net static head, but some pressure drop in the pipe-lines. The pressure head and pressure drop are summarized for all recirculation pumps in Table 3-6.



	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

*Table 3-6: Assumed pressure head and pressure drop for the major liquid pumps in the PCC plant for determining the discharge pressure of the pumps*

	<b>Rich solvent pump</b>	<b>Lean solvent pump</b>	<b>DCC water circulation pump</b>	<b>Absorber water-wash pump</b>	<b>Stripper condenser pump</b>
Pressure head (m)	2*packing height of the desorber	2*packing height of the absorber	2*Height of packing in the DCC	2*Height of packing in the water-wash	
Pressure drop	1 bar in the cross HX	20% in piping + 1 bar for the cross HX and 1 bar for the lean cooler	20% in piping + 1 bar for the sea-water cooler	20% in piping + 1 bar for the sea-water cooler	1 bar for the cooler + 20% in piping

Centrifugal pumps are assumed. Furthermore, a hydraulic efficiency of 80% and a driver efficiency of 95% will be used to determine the power duty of these units (based on the work in the OCTAVIUS project).

### 3.4.5 Reclaiming

To avoid accumulation of solvent contaminants, a reclaimer must be applied to separate degradation products and other contaminants from usable amines in the process. Optimization of the reclaimer process is important in order to minimize the amine consumption, but also because of regulations for handling of the reclaimer bottom products.



As the degradation of the CESAR1 solvent is a slow process, any reclaiming will be done batchwise. Though some work was done at the RWE pilot plant related to reclaiming as part of the ALIGN-CCUS project, there are still uncertainties related to the type of reclaiming and the frequency. This will be studied as part of AURORA and thus the choice will be established as part of the TEA optimisation process.

## 3.5 Water-balance control

Depending on process conditions, the capture plant may accumulate water or lose water. Balancing this is very important as accumulating water will require large buffer tanks combined with the need for waste-water treatment, while losing water will require supply of fresh water. The latter could be important in case supply of process water is limited and/or demineralised water is needed.

To implement an efficient water-balance control it is important to note the major sources and sinks of water in the system. In addition to water being part of the solvent, there is water in the flue-gas and in the circulation streams of the DCC and the water-wash sections both in the absorber and in the desorber. The net process water requirement will become zero if the amount of water supplied by the flue gas equals the amount of water contained by the cleaned gas and the compressed CO<sub>2</sub> stream. In a scenario of complete water balance, no bleed or make-up would be required. However,



	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

it is not straightforward to fulfil the ideal scenario as several inter-related factors affect the water-balance as described in more details by Kvamsdal et al. (2010)<sup>6</sup>.

A proper control philosophy would be to reduce the temperature of the flue gas in the DCC to slightly below dew point and the same amount as the condensed water is bled from the DCC water recycling loop as indicated in Figure 2-2. Depending on the flue-gas purity and process water quality, this water can act as the “fresh water” make-up and thus routed to a water buffer tank or directly drained depending on the level of water in the buffer-tank. The flue-gas leaving the DCC is saturated at the operating temperature (controlled by the temperature of the DCC water circulating stream) as specified in Table 3-1. At the Tiller pilot the temperature in the gas leaving the water-wash is controlled with a set-point equal to the temperature out of the DCC with an additional adjustment through level control of the buffer-tanks since the pressure and composition in the flue gas differs slightly. However, there are also other possibilities for controlling the water-balance and in AURORA the possible control philosophies will be studied to determine the best solution.

Also, the excess water from the desorber condenser and from the knock-out drums of the CO<sub>2</sub> compressor train can be recycled to the solvent buffer-tank or just drained. However, in case of the latter it should be noted that as the buffer-tank will contain some amine impurities from the recycling of water from the condenser and compression train, the buffer-tank cannot be drained without special waste-water treatment. In case the DCC needs make-up which happens if the dew-point of the flue-gas is lower than the operating temperature, this might require addition of fresh demineralised water. Nevertheless, the best solution is case-dependent and will be part of the TEA optimisation process.



## 3.6 Utilities

### 3.6.1 Cooling water

Depending on location of the CO<sub>2</sub> host plant, the cooling-water could be provided by means of sea-water, from cooling-water towers, or local water reservoirs. The temperature of the cooling water depends further on this and local conditions, but at least a yearly average will be assumed and the specification on the cooling water return temperature will be 10°C higher unless local conditions require a different value. It should also be noted that if the cooling-water requirement for the PCC plant turns out to exceed the existing capacity of the CO<sub>2</sub> source plant, we need to include CAPEX associated with an additional supply. This will be considered in each case.

### 3.6.2 Steam

Steam for the reboilers is the largest contributors to the energy requirement of a PCC plant and should be reduced as much as possible. Nevertheless, steam may not be available at the host CO<sub>2</sub> plant (as typically in cement plants) and even if it is available like in the refineries maybe the capacity is limited so additional capacities must be established. In AURORA we will aim at choosing solutions for the steam that will not decrease the amount of CO<sub>2</sub> avoided due to the steam supply. In fact, it should be noted that ideally the amount of CO<sub>2</sub> avoided should be equal to the amount

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

captured in the PCC plant, but most likely the electricity from the grid is based on non-renewable or a mix of non-renewable and renewable so the CO<sub>2</sub> avoided will be less than the capture rate. Both means of energy reduction and solutions for renewable based electricity will be studied in more detail in Task 4.3 of AURORA.

Nevertheless, based on the steam specification, the following procedure for the choice of solution for each of the end-user cases will be:

1. If steam is available as for the refineries, the following needs to be considered:
  - In case the boilers consume natural gas and thus generate CO<sub>2</sub>, can we employ CO<sub>2</sub> capture of said gas?
  - Will the PCC need to be oversized to deal with extra amount of CO<sub>2</sub> if it is possible to capture it?
  - If not possible to capture CO<sub>2</sub> from boilers, then other low-emission alternatives will be assessed (like use of biofuel instead of natural gas, heat integration, use of heat-pumps, even electric boiler as well as combinations of the alternatives as addressed in Section 3.7)
2. If steam is not available other alternatives will be assessed (addressed in Section 3.7). At least establishment of new natural gas fired boilers will not be the first choice.



The temperature requirement for the steam supply should be as follows:

- Supply
  - $T_{\text{steam}} = T_{\text{process}} + 10^{\circ}\text{C}$  (at dew point)
  - $p_{\text{steam}} = p_{\text{sat}}(T_{\text{process}} + \text{Reboiler Delta}_T_{\text{min}}) + p_{\text{loss}}$
- Return
  - $T_{\text{condensate}} = T_{\text{process}} + 10^{\circ}\text{C}$  (at boiling point)
  - $p_{\text{condensate}}$
- Reboiler Delta<sub>T</sub><sub>min</sub>: 10°C

### 3.7 Assessment of alternative heat sources and process modifications

As mentioned previously, energy reduction and assessment of alternative heat sources will be assessed both with the aim of reducing energy requirement, but also to maximise the amount of CO<sub>2</sub> actually avoided by employing CCUS solutions for the end-user cases. Furthermore, this work will be combined with the assessment of various options for mitigating emission. In the following some information will be given about the work and the various options for energy reduction, energy supply while maximising the amount of CO<sub>2</sub> avoided.

#### 3.7.1 Assessment of waste-heat sources and use of heat-pumps

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

For each of the end-user cases, we will quantify and assess possible exploitation of all waste-heat sources in the CO<sub>2</sub> host plants. Additionally, this will be done for possible heat-sources within the capture plant (like the desorber condenser and the inter-cooler). Since many of these heat sources will be available at a temperature that is too low for direct integration with the reboiler, the use of a heat-pump will be considered. A heat pump is defined as a device that uses work to transfer heat from a lower-temperature reservoir to a higher-temperature reservoir by transferring thermal energy using a vapour-compression cycle.

The amount of work required to drive an amount of heat  $Q$  from a lower-temperature reservoir to a higher-temperature reservoir is:

$$W = \frac{Q}{COP} \quad 8-1$$

Where



- $W$  is the work performed on the working fluid by the heat pump's compressor.
- $Q$  is the heat transferred from the lower-temperature reservoir to the higher-temperature reservoir.
- $COP$  is the instantaneous coefficient of performance for the heat pump at the temperatures prevailing in the reservoirs at one instant.

The coefficient of performance of a heat pump is greater than unity so the work required is less than the heat transferred, making a heat pump a more efficient form of heating than electrical resistance heating like electric reboilers. However, it should be noted that relevant heat-pumps are still limited for the use in the process industry and the specific temperature range. Furthermore, as far as known it has never been thoroughly assessed how such unit can be integrated with a reboiler. E.g., is it possible to replace directly the reboiler with the condenser of the heat-pump or should there be a separate cycle (steam) to provide the necessary heat to the reboiler. The latter will of course reduce the efficiency. In AURORA these issues will be further assessed.

Other options that can be considered as heat-pumps that will be assessed in AURORA is lean vapour recompression (LVR) and once-through heat pump (OTHP) as described in the following paragraphs.

#### **Lean Vapour Recompression (LVR)**

In an LVR cycle the hot regenerated solvent from the stripper bottom is flashed at reduced pressure in a flash vessel to generate vapour (mostly steam). The vapour from the flash is recompressed by the means of a mechanical compressor and injected in the desorber just below the bottom of the packing. The pressure in the flash is controlled by the compressor. The liquid phase from the flash (lean solvent) is returned to the cross-heat exchanger and enters the normal lean solvent loop. Both in the CESAR and the OCTAVIUS projects this option was studied. In the CESAR project the LVR was tested at the Esbjerg pilot plant, and it was found that both the reboiler duty was reduced by up to 20% for MEA and 15% for CESAR1<sup>9</sup>. However, the electric power will increase due to the

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

compressor and the CAPEX might increase due to the extra equipment. The latter is somewhat counteracted by less heat exchanger area in the reboiler and obviously the benefit of the LVR option requires a more thorough cost-estimation. This was addressed in the OCTAVIUS project in which it was concluded that MEA had a more pronounced effect of using LVR than CESAR1<sup>Error! Bookmark not defined.</sup>. However, in that study the PCC was integrated with power plants and as such the effect of using LVR will still be considered for the four end-users in AURORA.

### Once-Through Heat Pump (OTHP)

A once-through heat pump system (OTHP) utilises the CO<sub>2</sub> compression train to provide usable heat for the reboiler by increasing the electric load of the compressors to upgrade the condenser duty and compression heat. Of course, the electric duty of the compression train will increase, but less primary energy is used for the steam generation. It must also be noted that heat integration in general requires extra equipment and thus increased CAPEX. It will also make the process more complex, which may influence operational aspects as flexibility, operability, and availability.

## 3.7.2 Assessment of absorber inter-cooling and emission mitigation technologies

Absorber intercooling was also assessed in the CESAR and OCTAVIUS projects with the main emphasize to study the effect on the heat requirement. In both studies it was concluded that there is a positive effect on reboiler duty for CESAR1, but not so pronounced for MEA. In AURORA we will additionally check if this process modification has any positive effect on emission.



## 3.7.3 Assessment of renewable energy alternatives

As mentioned previously, to increase the amount of CO<sub>2</sub> avoided, the energy used in the capture plant should ideally been based on renewable sources. In case of a steam boiler, biofuel could be an alternative to natural gas. The benefit by using biomass as fuel is that burning of biomass only release biogenic CO<sub>2</sub> and that biomass is a renewable energy source. A downside effect is that biomass is a lower calorific fuel, requires drying and is more labour intensive.

For the electricity requirement, it is assumed that the same source as in the CO<sub>2</sub> host plant will be available for the PCC plant as well. This is highly case dependent, and it will be assessed in terms of the actual energy source as this will highly influence the amount of CO<sub>2</sub> actually avoided. Additionally, an assessment of alternative heat sources, specifically the use of solar for directly providing the heat/electricity input to heat-pumps and other types of equipment requiring electricity for each of the end-user plants of AURORA will be conducted. Particularly, this will be assessed with regard to capture costs, CO<sub>2</sub> avoided, and availability of the energy source based on considerations like time-dependent electricity prices, ambient temperature and solar radiation.

## 3.8 Simulation tools and solvent models

### 3.8.1 Simulation tools

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

Basically, there are two different tools that will be used in AURORA for process simulations of the PCC cases (which tool to be used for each case will be determined later). These are: 1) the in-house tool CO<sub>2</sub>SIM owned by SINTEF and 2) the commercial tool Aspen Plus. Additionally, a tool from Sulzer (Sulcol) is used to determine the column diameter of the absorber and desorber columns and the pressure drop over the packed section. These three tools are slightly summarized in the following paragraphs.

### CO<sub>2</sub>SIM

CO<sub>2</sub>SIM is an in-house software tool developed in SINTEF and basically used in connection with amine-based solvent development and preliminary design of solvent-based carbon capture plants. CO<sub>2</sub>SIM is continuously developed and updated at SINTEF. It is today an advanced platform for modelling absorption-based processes. The development started in 2002 with thorough explanations and descriptions of the tool and its developments found in previous studies<sup>10, 11, 12, 13</sup>.

The main benefit of using an in-house tool is of course access to the source code (only for SINTEF as it is not open source), which makes it easier to implement new features and improve underlying models. Furthermore, the numerical engine implemented in the CO<sub>2</sub>SIM tool ensures easy flowsheet convergence. Another feature of the CO<sub>2</sub>SIM tool is its use for efficient solvent development as further described in Section 3.8.2. The process models for selected amines, like MEA, have been extensively validated towards pilot data. However, the number of components and thus their physical property and thermodynamic relations is limited compared to a commercial tool like Aspen Plus.



### Aspen Plus

Aspen Plus (a registered trademark of Aspen Technologies Inc.) is a general-purpose process simulation software that is used extensively for process simulation of chemical processes including amine-based CO<sub>2</sub> capture processes. The main benefit is the extensive portfolio of components and underlying models. However, in case of new components (especially mixed solvents as the CESAR1) and new process units not available in the portfolio it is not so straight forward to make changes as for an in-house tool where you have full access to the code. Furthermore, flow-sheet convergence maybe a challenge.

### Sulcol™ 3.6.0

Sulcol™ V3.6.0 and KG-TOWER® V5.4 are free softwares provided by Sulzer and Koch Glitsch respectively and they will be used in AURORA to size the column diameter based on a gas flow rate which is 70% of the gas velocity at flooding conditions. The physical properties (mass flow, temperature, density, and viscosity) of the stream connected to the units will be retrieved from CO<sub>2</sub>SIM and Aspen Plus. As indicated the same software will be used to estimate the pressure drop across the structured packing.

## 3.8.2 Solvent modelling

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

### Solvent models for CO<sub>2</sub> absorption in general

Post-combustion capture with amines is a reactive absorption process, and it is a general understanding that a rate-based model best describes the separation process. To perform process simulations for CO<sub>2</sub> absorption, underlying models for each specific solvent are necessary as input to the various parameters in the mass and energy balances for the process. This concerns equilibrium, kinetics, and physical properties, e.g., density, viscosity, heat capacity, and heat of reaction. Needless to say, the establishment of such models for each solvent requires a lot of experimental effort. This was the background for the development of so-called "soft models" and implementation in CO<sub>2</sub>SIM. The use of "soft models" was an efficient way to determine energy requirement in a total process as part of solvent development in the CASTOR and the CESAR projects and has also been used extensively since then for other solvents.

#### Equilibrium modelling



The equilibrium relation for each solvent is the most important part of proper modelling of the separation. However, there exist several types of models with varying degrees of complexity. Within the CO<sub>2</sub>SIM simulator, three approaches have been implemented 1) Soft model, 2) Astarita representation and 3) electrolyte-NRTL (e-NRTL) model. While the first one has been implemented for quite many different solvents the last two have been implemented for only a limited number of solvents. In Aspen Plus there are more options available, but it seems that the e-NRTL model is mostly used for amine -based process simulations. In the following, both the soft model and the e-NRTL are briefly described:

##### *Soft model*

This type of equilibrium model is used for systems when limited data is available as well as when implementation time is an issue. The model determines the equilibrium partial pressure of CO<sub>2</sub> over a solvent system based on a fitting towards experimental data as function of liquid CO<sub>2</sub> loading and temperature. The partial pressure of CO<sub>2</sub> is defined by means of several complex functions where adaptative coefficients are regressed. By such an approach, no activity coefficients are needed (as for the e-NRTL model). The soft model approach emphasises the importance of correctly describing the partial pressure driving force ( $p_{\text{CO}_2} - p_{\text{CO}_2, \text{eq}}$ ) by an accurate and consistent fit to the experimental VLE data. This has shown to give a good agreement with the pilot plant results from Tiller.

##### *e-NRTL model*

This activity coefficient-based model gives a detailed description of amines using a general framework and also gives the activity coefficient for all the species in the solution. In this way, better knowledge of the details of the absorption system will be obtained and thus can be used whenever this is required. However, electrolyte-NRTL development is more time demanding as it requires more experimental data, and it makes the convergence of the flowsheet more difficult and tedious, while the soft model approach ensures numerical stability and fast convergence. Despite giving the full speciation of the liquid phase, the more elaborate models may often struggle with the accurate description of driving forces ( $p_{\text{CO}_2} - p_{\text{CO}_2, \text{eq}}$ ), since the equilibrium  $p_{\text{CO}_2}$  is not always accurately



	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

described in the low loading range. The activity-based models may allow extrapolation and a more detailed description of liquid phase variations within the different streams of the process, but only if a significant amount of consistent experimental data is also available for the individual components and the binary and ternary sub-systems (PZ-water, AMP-water, CO<sub>2</sub>-PZ-water, CO<sub>2</sub>-AMP-water etc.). This makes VLE model development very time and cost intensive.

### Modelling of the CESAR1 solvent

The CESAR1 solvent is an aqueous mixture of 2-amino-2-methyl-1-propanol (AMP) and piperazine (PZ). Having two amines in the blend makes it very difficult to model since they have different properties, there are more reactions, and there might be some other interactions than in a single amine system<sup>14</sup>. This was recognized in the CESAR project, and a thorough experimental work was initiated as a basis for the CO<sub>2</sub>SIM implementation of the CESAR1 solvent<sup>15</sup>. Since CO<sub>2</sub>SIM is an in-house tool owned by SINTEF, there have been some efforts since the CESAR project to develop appropriate models for the CESAR1 solvent within commercial simulation tools like Aspen Plus and ProTreat. While all these models show adequate results related to energy requirement in the process, it was seen in the ALIGN-CCUS project that these models were inappropriate for lower concentrations of the species. That is important for determining solvent emission and thus designing proper emission mitigation options like the water-wash section. Thus, within the SCOPE project there has been an effort to improve the models for both Aspen Plus and ProTreat. Based on this, further improvements are planned for the AURORA project including improved models for the kinetics and the physical properties both in CO<sub>2</sub>SIM and in Aspen Plus.



	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

## 4 Basis for cost calculations

### 4.1 Methodology

The cost estimation methodology for benchmarking in AURORA will be based on the EBTF work.

The economic performance for each end-user will be evaluated with CO<sub>2</sub> capture both for the MEA case and for the CESAR1 case. The governing criterium for assessing the economic viability of each case will be the cost of CO<sub>2</sub> avoidance versus the ETS prices.

### 4.2 CAPEX

#### 4.2.1 Total Equipment Cost (TEC)

The mass and energy balances prepared for the MEA and CESAR1 cases will define the sizing of the main equipment for the CO<sub>2</sub> capture processes. The main equipment are those discussed in Section 3.4.

The requirement or not of additional equipment to provide utilities, e.g., cooling water and steam, will be defined by the capabilities of each end-user site. As an example, in cases where no steam is available to provide solvent regeneration, alternatives for heat recovery (e.g., heat pumps and/or external integration with the end-user process) will become a requirement, and thus the equipment necessary to provide said heat recovery must be considered in the benchmarking.



The costs of the main equipment will be determined based on public data and vendor information. Extrapolation of said public data will be carried out using power law cost correlations in order to correct the equipment cost from the tabled base-case capacity to the relevant capacity given by heat and mass balance calculations. Additionally, when public data for equipment costs are available for years previous to when the benchmarking is carried out, the Chemical Engineering Plant Cost Index (CEPCI) will be used for adjustment to the current date.

Furthermore, it should be pointed out that the industrial partners in AURORA have had previous contact with equipment vendors and are thus able to pull data from commercial suppliers in order to provide a sanity check of the costs obtained through the methodology outlined above. Whenever significant discrepancies appear, vendor data will be used to recalibrate the cost estimates. Hence, we expect the costs to be used in the benchmarking process to be more trustworthy than what is conventionally obtained by conventional literature research and CEPCI adjustment.

The sum of all equipment costs for each carbon capture plant will constitute the Total Equipment Cost (TEC). The TEC is used to estimate the cost of construction of the carbon capture plant, as shown below.

Beyond the heat integration aspect, the costs for connecting the emitter source to the carbon capture plant will not be in the scope of this benchmarking work. Though this is certainly an



	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

oversight, it must be highlighted that the end goal of this work is to compare the economics of an MEA-based plant to those of a CESAR1-based plant, and the solvent employed for the CO<sub>2</sub> capture plant will have no impact on the costs of tie-in.

#### 4.2.2 Total Direct Plant Cost (TDPC)

Once the TEC has been calculated, the Direct Construction Costs can be estimated via the fixed percentages outlined below:

Instrumentation and control	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
<b>Sum</b>	<b>101% of TEC</b>

The sum of Total Equipment Cost and Direct Construction Costs is the Total Direct Plant Cost (TDPC). Therefore, following the assumptions presented here, **TDPC = 2.01·TEC**.

Internal feedback from ACC is that the civil costs are typically a percentage of the whole project and not just of the direct plant cost. In effect, in ACC's experience, civil costs can reach 18-25% of the total project cost. In the current calculation methodology, civil costs are 11% of TEC, i.e., 4.8% of the Fixed Capital Investment (see below). This means that we might be underestimating the civil costs in more than four-fold. This needs to be highlighted and further evaluated during the TEA analyses effective.

#### 4.2.3 Total Indirect Plant Cost (TIPC)

As above as below, the Indirect Construction Costs can be calculated as fixed percentages of the TDPC:



Yard improvements	1.5% of TDPC
Service facilities	2.0% of TDPC
Engineering, supervision and construction	6.5% of TDPC
Buildings (including services)	4.0% of TDPC
<b>Sum</b>	<b>14.0% of TDPC = 28.14% of TEC</b>

The Total Indirect Plant Cost (TIPC) is thus 28.14% of the TEC or 14% of the TDPC.

#### 4.2.4 Fixed Capital Investment (FCI)

Adding up the TDPC and TIPC, one ends up with the Fixed Capital Investment (FCI). Hence, it can be seen that **FCI = TIPC + TDPC = 1.14·TDPC**.

#### 4.2.5 Total Capital Investment (TCI)

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

The Total Capital Investment is compounded by the Fixed Capital Investment plus additional costs. These are:

Startup costs	Solvent inventory (first fill)
Contingencies	25% of TCI
Capital fee	2% of TCI
Working capital	3% of TCI

Therefore,  $TCI = FCI + \text{additional costs} = FCI + 0.3 \cdot TCI + \text{solvent inventory}$ . Rearranging that,  **$TCI = (FCI + \text{solvent inventory})/0.7$** . The cost of the solvent inventory for first fill will be discussed in the next section.

The Total Capital Investment (TCI) is simply another name for the CAPEX. Hence, all of the calculations outlined above will result in the CAPEX estimate.

## 4.3 OPEX

The OPEX is the sum of the Direct Production Costs and Fixed Charges.

### 4.3.1 Direct Production Costs

The Direct Production Costs are given by adding up variable and fixed production costs. Variable costs account for raw materials and utilities, and for each end-user case they scale-up accordingly with how much capacity is designed for the carbon capture plant (i.e., how much CO<sub>2</sub> is captured). Meanwhile, the fixed costs address the cost of maintenance and labour and are only indirectly correlated to the design capacity of the carbon capture plant.



Variable costs are:

- Raw materials
- Utilities

Fixed costs are:

- Maintenance & repairs
- Operating labour
- Operating supervision
- Operating supplies
- Laboratory charges

In the context of the carbon capture plant, raw material costs will account for (1) amine make-up to replenish the solvent and account for degradation / emissions (in the case of AURORA, these are the costs of MEA, PZ and AMP), (2) sodium hydroxide make-up, which is consumed in the Direct Contact Cooler, (3) sulphuric acid make-up, which is consumed in the acid wash. Utilities are costs for cooling water, process water, and electricity.

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

Since all of these costs are highly variable with time, and since this document only intends to outline the general methodology for benchmarking, no values for such costs will be given here.

The cost of operating labour is calculated from:

Parameter	Value	Unit
Working hours per person	1 752	hr/person/yr
Number of shifts	5	--
People per shift	2	person
Labour	17 520	hr/yr
Wage tariff	45	€/hr

The above is simply some standard values obtained in a previous project. Clearly, the wage per hours must be adjusted based on project location and the definition of the particular labour activities. This must be evaluated in a case-by-case basis, and will be revisited during the TEA calculations.



The remainder of the fixed production costs can be calculated with the percentages given below:

Supervision	30% of operating labour
Maintenance	2.5% of FCI
Operating supplies	15% of maintenance
Laboratory charges	10% of total labour costs
Plant overhead costs	60% of maintenance + operating labour + supervision

## 4.4 Assumptions

The methodology will follow the same lines as outlined in the EBTF work. The basis for cost in AURORA will be defined based on when the benchmarking work is performed, most likely 2025.

In general, the lifetime of a carbon capture plant is dependent on the upstream flue gas source. For AURORA, the lifetime of all capture plants will be defined as 25 years, both in order to be conservative and to extend the same estimation basis to all different end-users. Meanwhile, the number of operating hours per year will be set at 8000 hr/yr unless specified otherwise by restrictions in the end-user side.

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

## 5 Benchmarking and Assessment Criteria

### 5.1 Benchmarking

We will use several KPIs to assess the CESAR1 solvent system and benchmark against the 30wt% MEA solvent system for a conventional capture configuration. While we will compare directly the numbers for SPECCA and cost related to CO<sub>2</sub> capture for each of the cases, we will use the results from the more qualitative-based assessment (based on argumentation) for the other 4 KPIs as a support in the overall assessment and benchmarking. It is emphasized that if the CESAR1 solvent system will be classified as unfit for the environmental KPIs (emission and solvent management), we will not pursue the idea of using CESAR1 as the new benchmark solvent system for general benchmarking of other technologies.

### 5.2 Assessment criteria

#### 5.2.1 Energy requirement

##### **SPECCA**

The Specific Primary Energy Consumption for CO<sub>2</sub> Avoided (SPECCA) determines the primary energy used to avoid CO<sub>2</sub> emissions to the atmosphere. It is defined as the difference in equivalent primary energy consumption of the CO<sub>2</sub> source ( $q$ ) plant with and without CO<sub>2</sub> capture ( $ref$ ), divided by the difference in equivalent CO<sub>2</sub> emissions ( $e$ ) with and without capture ( $ref$ ):

$$SPECCA = \frac{q - q_{ref}}{e_{ref} - e} \quad 9-1$$

The label "ref" refers to reference process without CO<sub>2</sub> capture. The primary energy consumption ( $q_{clk}$ ) = [MJ/t] is the sum of direct and indirect energy consumption. CO<sub>2</sub> emitted ( $e$ ) is correspondingly defined as the sum of direct and indirect emitted CO<sub>2</sub> from the source plant.



It is expected that the raw material and the energy consumption will be the same regardless of CO<sub>2</sub> capture implementation for the source plant. Thus, the extra energy needed to operate the capture plant is considered for the capture plant.

In the next sub-sections, the energy requirement for the capture plant and how it should be determined is described.

##### **Energy requirement in the capture plant**

The major energy consumers in the capture plant are the stripper reboiler, the blower upstream the absorber column, the liquid recirculation pumps, and cooling water pumps.

##### *Reboiler*

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

The steam requirement in the reboiler is determined from the simulations. However, the energy requirement needs to be calculated in terms of electric power ( $MW_e$ ) for inclusion in the SPECCA formula. This means that the steam requirement in the reboiler must be transformed to equivalent work. How this should be done will depend on how the steam is provided.

#### *Blower*

The required electric power highly relies on the pressure drop in the absorber and the DCC unit. It is determined from the simulations and then using the process unit efficiency numbers as given in Section 3.4.3.

#### *Liquid recirculation pumps*

For the real necessary work of the pumps, the total pressure head must be determined and then using the process unit efficiency numbers as indicated in Section .

#### **Cost of CO<sub>2</sub> capture**

CAPEX and OPEX are determined as described in Chapter 4.

The cost of CO<sub>2</sub> capture is defined as follows:

$$\text{Cost per tonne CO}_2 \text{ captured} = \frac{(\text{Annualised CAPEX} + \text{Total OPEX}) * 1\,000}{\text{Tonne CO}_2 \text{ captured per year}} \quad 9-2$$

The amount of CO<sub>2</sub> captured is determined as the amount of CO<sub>2</sub> fed to the DCC minus the amount of CO<sub>2</sub> out of the desorber condenser.



#### **Cost of CO<sub>2</sub> avoided**

The CO<sub>2</sub> avoided is defined as the amount of CO<sub>2</sub> capture minus the CO<sub>2</sub> generated due to energy consumption. This the cost of CO<sub>2</sub> avoided can be determined as:

$$\text{Cost per tonne CO}_2 \text{ avoided} = \frac{(\text{Annualised CAPEX} + \text{Total OPEX}) * 1\,000}{\text{Tonne CO}_2 \text{ avoided per year}} \quad 9-3$$

## 5.2.2 Emission of amines and degradation products to air

Solvent is lost due to solvent degradation, aerosol formation and due to the solvent volatility. Aerosol formation should be avoided since this can easily have a high impact on the solvent losses. The amount of solvent losses can be controlled by proper design of emission mitigation options combined with proper temperature control. The aim of the AURORA project is to determine the best options to minimise loss of solvent for all cases. This will be included in the cost estimate and as such been taken care of by the cost criteria.

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

Nevertheless, piperazine in CESAR1 forms harmful nitrosamines that could be the potential showstopper for proposing CESAR1 as the new benchmark solvent system unless the nitrosamine emissions and exposure for the operators dealing with the liquid samples can be kept very low (below the requirements set by the authorities). As degradation of CESAR1 is a slow process, it is most likely not possible to detect the relevant values of nitrosamines formed during the pilot campaigns and thus to quantify the amount to end up in the atmosphere. However, long-term testing of the CESAR1 solvent have been conducted at the RWE pilot in both the ALIGN-CCUS and the SCOPE projects. Thus, results from these campaigns combined with degradation experiments in the lab during the AURORA project will be used to determine an estimate for the nitrosamines formed per emitted amount of piperazine. However, there is still a question of where it ends up in the environment and if it will have any effect on the environment and the human health. This will not be covered by AURORA, but these issues are part of the ongoing project SCOPE and results will be used to support in a traffic-light assessment of both CESAR1 and 30wt% MEA (based on earlier pilot plant campaigns).

The way in which the avoidance of emissions will be incorporated into the TEA is that every optimised plant considered for the TEA calculations must adhere, by its own design, to the emission limitations defined in the functional requirements and in the technology qualification activities (see Part B).



### 5.2.3 Solvent management (including solvent consumption)

The amount of solvent make-up needed is a sum of solvent loss due to volatility, aerosol formation and solvent degradation. The solvent loss due to volatility can be either measured or it can be estimated using data from laboratories, whereas solvent losses due to degradation can be estimated by monitoring the formation of degradation compounds (those detectable).

More directly, however, solvent losses can be measured in terms of how much solvent make-up must be added to the aged solvent in order to maintain its alkalinity and species distribution in their target concentrations. In other words, if one is attempting to maintain the CESAR1 solvent with 13 %wt. piperazine and 27 %wt. AMP, solvent losses can be calculated simply by how much piperazine and AMP had to be fed to the pilot plant to counter losses from degradation, emissions, etc. Regardless of the destination of these losses, therefore, the impact to the TEA will be in the cost of raw materials.

At the same time, solvent management will impact the TEA via the cost of producing and managing effluents (e.g., acid wash effluents must be treated before disposal, reclaimer waste must be destroyed at a cost to the operation of the carbon capture plant) and, of course, via the cost of consumables employed for solvent health management.

### 5.2.4 Effect of heat integration

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

Though the effect of heat integration will be included in the cost criteria, it could be useful to assess the two solvent systems wrt. the effect related to SRD, L/G, height of absorber column, CAPEX, OPEX, and CO<sub>2</sub> capture cost.

### 5.2.5 Flexible operation of the capture plant



Except for the UMICORE case, the other plants are basically operating at full load. The latter means that the capture plant is designed to operate at optimal parameters and conditions for a fixed capture efficiency (95% CO<sub>2</sub> removal in AURORA). Nevertheless, changes in plant operation will affect not only the efficiency of the capture plant, but also its environmental impacts and energy requirements. Solvent degradation, volatile and aerosol emissions, reboiler duty are affected during transient operation. Flexibility may also be required in relation to operational constraints imposed from the downstream CCUS chain elements. In any case, the ability to be operated in a flexible manner should be considered when designing the capture plant. Though it has been demonstrated for power-plants that the efficiency of the power and capture plants differs between full-load and part-load operations, it is still unknown how much changing loads will influence on degradation and emission in the capture plant and even less knowledge is available for industrial processes.

Nevertheless, both in the ALIGN-CCUS and the SCOPE projects there were tested some flexible scenarios for both the MEA and CESAR1 solvent systems at Tiller in connection with testing of the CENIT advanced control system and the influence of dynamic operation on degradation and emission at RWE for both MEA (ALIGN-CCUS) and CESAR1 (both ALIGN-CCUS and SCOPE). Even more comprehensive testing will be done in AURORA related to the tests of the CENIT control system (both at the Tiller and TCM pilots). The results will be used to make a qualitative based assessment of the MEA and CESAR1 solvent system and then use a traffic light approach for the assessment, in which we will classify based on effect on reboiler duty, absorber efficiency (how much can the flowrate be reduced without reducing the efficiency), degradation, emission, foaming, precipitation, and other operational challenges.



### 5.2.6 Dynamics and control

As indicated in the previous section, dynamic tests will be conducted to further test the CENIT advanced control system. This system, which is based on Nonlinear Predictive Control (NMPC, has been tested for both the MEA (DOCPCC project<sup>16</sup>) and CESAR1 solvent systems (ALIGN-CCUS) will be further tested for CESAR1 in the AURORA project. Since the tests performed for the two solvent systems in the three projects are not completely the same, the results will be used only for a qualitative based comparison.

It could be mentioned though that controllability is often dependent on the degree of complexity in the process. It has been shown (e.g. Kvamsdal et al. 2016<sup>2</sup>) that MEA has a positive effect of process inclusion of Lean Vapor Compression (LVR) and absorber inter-cooling, which may apply higher complexity, while this was not the case for CESAR1 solvent system. However, others have reported differently so this is the reason why the various options will be further assessed in AURORA (see Section 3.7).

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	





	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

## 6 Summary for Techno-Economic Analysis

One of the major aims of the AURORA project is to establish the CESAR1 based solvent system as a new non-proprietary benchmark capture process and establish guidelines for optimal design of integrated CO<sub>2</sub> capture plants in three industrial sectors, based on experience with demonstration and pilot projects of 1<sup>st</sup> and 2<sup>nd</sup> generation technologies.



The work is based on the European Benchmarking Task Force – EBTF within the CESAR, CAESAR, and DECARBit projects, and work connected to benchmarking in the OCTAVIUS, HiPerCap, and ALIGN-CCUS projects. However, while in most of these projects, integration with power plants was focused (the ALIGN-CCUS project considered also waste-incineration and cement), only process industry cases are considered in AURORA. Furthermore, the methodology for assessment and benchmarking developed in those previous projects has been further developed and improved in the present project.

In the present document, the basis and methodology for the assessment and benchmarking work is given. 4 different base cases (2 refinery, 1 cement, and 1 for the materials recycling) are defined and described in addition to a conventional process configuration for the absorption-based CO<sub>2</sub> capture plant. The CESAR1 solvent system will be assessed and compared to the 30wt% MEA solvent system for the same process configuration for all CO<sub>2</sub> source cases. The following key performance indicators (KPIs) are used for the assessment and benchmarking: specific primary energy consumption for CO<sub>2</sub> avoided (SPECCA), cost (capture cost and cost of CO<sub>2</sub> avoided), emission, solvent management, plant flexibility, dynamics and control. While the two first mentioned KPIs will be used in a quantitative assessment the others will be used as a qualitative based support (using the traffic light colours) in the total assessment. The assumptions made for determining the energy requirement and CO<sub>2</sub> capture cost for the CO<sub>2</sub> source cases are given in the present report. In addition, there are guidelines for large scale design of the main equipment needed in the capture plant and guidelines for how the qualitative assessment and overall assessment and benchmarking shall be done.

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

# PART B

## TECHNOLOGY QUALIFICATION

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

## 7 Introduction to Technology Qualification

### 7.1 The goals of technology qualification



Technology qualification is an essential tool in the de-risking of first-of-a-kind (FOAK) projects. In very general terms, a Technology Qualification Program (TQP) should start by identifying all unknowns and uncertainties in a proposed technological solution and proceed by carrying out specific Technology Qualification Activities (TQA) targeted at closing knowledge gaps whenever possible. Once these TQAs have been completed, one must identify whether they successfully demonstrated the maturity of the technical solution.

A fully mature technical solution will have little technological risks associated with its large-scale deployment. However, in the context of post-combustion carbon capture, it is expected that the proposed technical solution will not be completely mature. This is because there is very limited number of previous large-scale projects in operation which one can use as basis to justify hypotheses and assumptions. Nevertheless, it is precisely due to the moderate novelty of amine-based post-combustion carbon capture that the relevance of the TQP becomes more expressive. A technical solution can be considered ready for deployment even if it is not fully mature, as long as the TQAs identify enough evidence to minimize the risks that have been identified in the TQP. Alternatively, if the TQAs are unable to eliminate the risks associated with the proposed solution, they then must at least define contingency plans for mitigating the effects that said risks pose to the technical and critical targets.

In AURORA, there are four proposed end-users for implementing the CESAR1-based chemical scrubbing carbon capture technology. These are (1) the Heracles cement plant, (2) the Motor Oil refinery, (3) the Total Energies refinery, and (4) the Umicore material recycling plant. These four end-users represent three quite distinct carbon emitting industries, and the adequacy of the technical solution will vary with each case. More importantly, the technical and critical targets will be different depending on each end-user site, and so will the finer details of the proposed technical solution. Hence, it is impossible to delve into a proper TQP without prior definition of a case. However, this document does not intend to realize a TQP for AURORA, but simply to define a strategy which allows for future applications of the TQP methodology to different end-users and technical alternatives. To assist in this endeavour, the four aforementioned industrial cases will be used as examples to illustrate the TQP methodology, even if none of them are comprehensively examined in the present document.

### 7.2 An overview of the technology qualification methodology

The image shown in Figure 2-1 provides a schematic view of the methodology proposed for the TQP in AURORA. This methodology is based on the recommended practices by DNVGL-RP-A203 (“Technology Qualification”) and DNVGL-RP-J201 (“Qualification procedures for carbon dioxide capture technology”). Aker Carbon Capture has undergone TQPs with the assistance of DNV during the CO<sub>2</sub> Capture Mongstad (CCM) project and during the Heidelberg Materials project in the

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

past<sup>17</sup>, being more recently involved in TQPs for large UK CCUS FEED projects (Keadby 3, Net Zero Teesside). The learnings from those TQPs have been applied in the present document.

## Technology Qualification Program

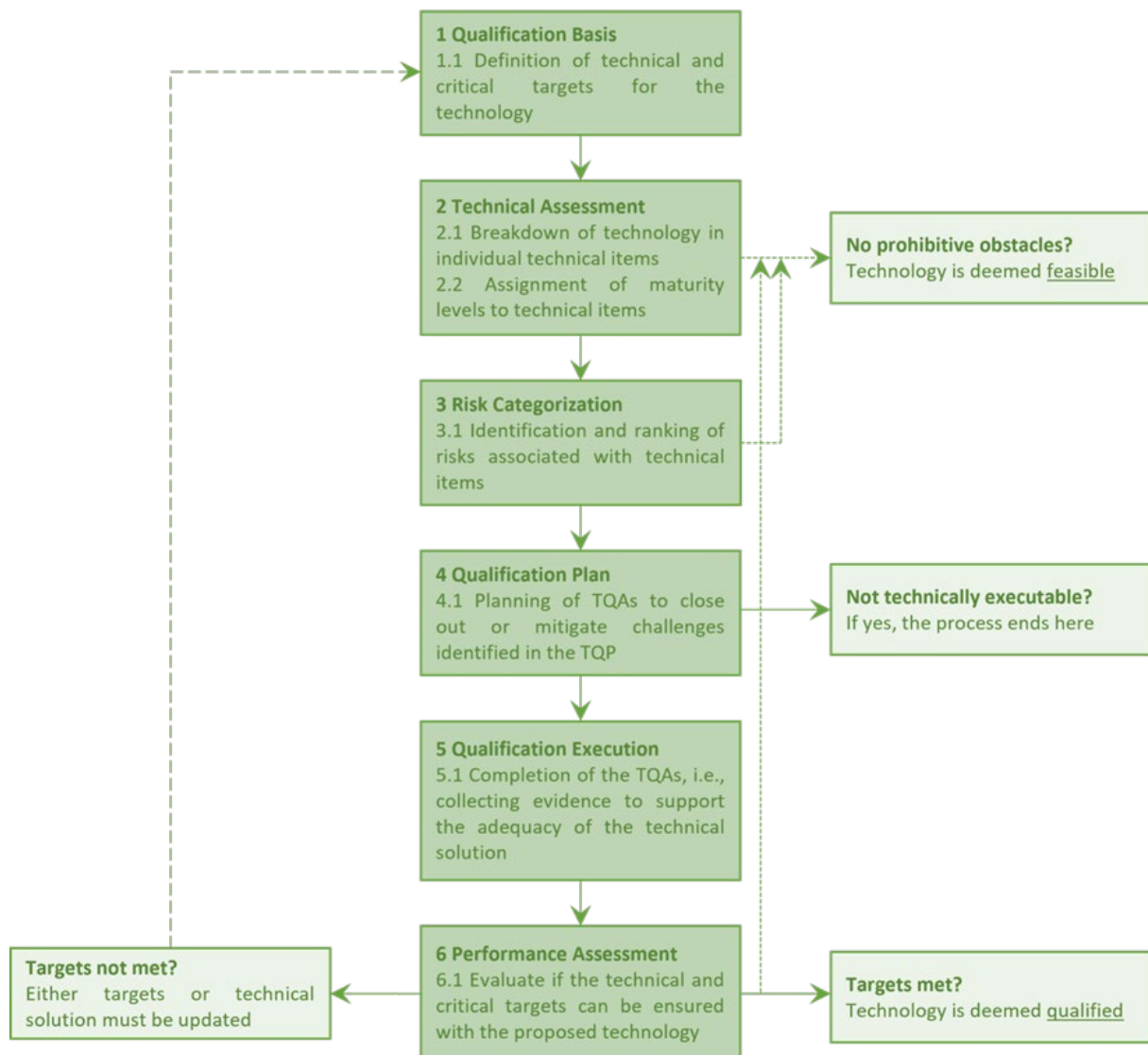




Figure 7-1: Schematics of Technology Qualification Program.

We will delve into more details regarding each one of the boxes in Figure 1 throughout PART A of the present document. For now, it is worthwhile to introduce and summarize the different aspects of the TQP in preparation for the more specific application towards the CESAR1-based CCUS technology across different industrial sectors and end-users.

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

## 7.2.1 Qualification Basis

This is where critical and technical targets for the technical solution must be defined. These targets can be *general requirements*, *functional requirements*, *energy requirements* and *environmental requirements*. General requirements are requirements such as minimizing disturbances to the end-user process upon implementation of the carbon capture solution, select equipment based on Best Available Technology (BAT) and As Low As Reasonably Practicable (ALARP) criteria, etc. Functional requirements are a selection of Key Performance Indicators (KPIs) deemed essential to the feasibility of the project, such as CO<sub>2</sub> capture capacity, availability of the carbon capture plant, and solvent consumption. Energy requirements are KPIs which have to do with the energy efficiency of the technical solution, such as cooling demands and power consumption for major equipment. Finally, environmental requirements have to do with the quality of the flue gas discharged to the atmosphere and the characteristics of the liquid effluents produced by the carbon capture plant, for example.



Having an adequately defined basis for qualification is essential when carrying out the TQP. Whatever is selected as a critical and technical target will naturally govern whether the technology is appropriate or not for the given task. For example: if 95% capture rates are defined as a functional requirement, then any unknowns that jeopardizes said capture rates (e.g., absorber hydraulics, solvent chemistry) will translate into risk for the technical solution. In commercial projects, said requirements are usually set by the needs of the client. In AURORA, the definition of technical requirements is bit looser, and will be selected so as to represent a process which is up to the expectations of most potential entrants to the CCUS market.

## 7.2.2 Technical Assessment

A Technical Assessment consists in evaluating the maturity of the technical solution for the intent of achieving the targets set in the Qualification Basis.

To simplify this task, the proposed technology is broken down into bite-sized items that can be discussed independently and assessed more easily. For example, in a carbon capture plant, these would be the Absorber, the Desorber, the Reboiler, etc. Notice that this is somewhat arbitrary: one could potentially decide to break down the Absorber into Absorber Packing, Absorber Water Wash System, and so on. However, the most important aspect is that the *whole* of the technical solution is captured by the individual technical items, regardless of how they are selected.

Another advantage of this methodology of breaking down the technical solution is allowing for a reduction in the scope of work when extending the TQP to different industrial sectors and end-users. Though the technical solution proposed for a cement plant and for a refinery might have striking differences with regards to interfaces and chemical contaminants, many technical items will remain the same across these different applications. (To some extent, that is: when discussing the Absorber, it is natural to discuss how the solvent interacts with the material of the column, which might be said to vary with the quality of the flue gas and which contaminants it possesses. These more detailed discussions will be carried out later in this document.)

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

After this division is done, one has to go over each technical item and agree upon its level of maturity. Typically, this is carried out during a brainstorming session, where inputs from different stakeholder and technical specialists can be heard. Ultimately, however, the distinction between different levels of maturity is not arbitrary, as there are guidelines for how to assign said levels which will be introduced throughout PART B of this document. We will be adopting a ranking system which goes from 1 to 4, where 1 is a fully mature technology item and 4 is an item which introduces large uncertainties for the process. Only technical items which are assigned maturity levels above 1 (i.e., items that are deemed relatively immature) will proceed to the next steps of the TQP, and items with maturity level 1 are thus assumed sufficiently qualified.



### 7.2.3 Risk Categorization

Once a technical solution is proposed and its technical items are identified, one must go over the process and identify potential risks to the attainment of its technical and critical targets. These risks are typically listed alongside the technical item where they were identified (e.g., the risk of “Corrosion in the Absorber” will naturally be attributed to the “Absorber” technical item), though there certainly is an overlap amongst certain specific threats and different item of the technical solution (e.g., the risk of “Corrosion” in general can be attributed to “Absorber”, “Desorber”, and so on). To some extent, this depends on how generally or specifically the risk is defined. Ultimately, this is not a terribly important distinction: being extremely specific will end up generating a large amount of simple TQAs, whereas being more general will produce a small amount of more complex TQAs. At the end of the day, the most important outcome is the definition of a comprehensive list of technical risks for the proposed technical solution.

Similarly, to the assignment of technical maturity levels, there are specific criteria for the assignment of risk categories that will be introduced further in this document. In general, risk categories can be defined as high, medium, and low. High level risks will immediately jeopardize the technical solution proposed for the given task and will trigger a requirement for updating the proposed technology and/or the selected technical and critical targets. On the other hand, medium and low-level risks can be potentially closed with the provision of enough evidence to mitigate the challenges and/or with the addition of contingencies to alleviate their impact.

### 7.2.4 Qualification Plan

The Qualification Plan is a list of TQAs which must be performed to address and (ideally) close out the medium and low-level risks identified in the Risk Categorization. The complexity of said TQAs will vary with the scope of the project, its intended timeline, its thoroughness, etc. Some TQAs simply entail providing proper documentation supporting that a technical item poses no threat to the process, either via evidence from the suppliers, historical documentation, or via desktop calculations. There are other TQAs that trigger extensive practical technology qualification projects, such as material testing, chemical analyses, and even pilot plant campaigns. Naturally, risks that are deemed more potentially threatening will require a larger degree of evidence in order to be closed out.

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

Additionally, a typical Qualification Plan will include, together with a list of proposed TQAs, a suggested timeline for execution and a list of acceptance criteria for each TQA. Continuing with the example of corrosion in the Absorber, acceptance criteria for closing out said risk could be (i) carrying out bench-scale material testing at representative conditions with degraded solvent, (ii) documenting practical pilot testing experience with the CESAR1 solvent at relevant conditions, (iii) showing that corrosion rates with the CESAR1 at relevant conditions are deemed acceptable for practical industrial applications. Clearly, the TQA must always be mindful of what were chosen as the initial technical and critical targets of the project. If a certain plant availability is set as a technical target and material corrosion is found to hinder said availability, then the technical solution must be revisited (e.g., by revisiting the material selection philosophy or the equipment sparing philosophy).

The Qualification Plan does not require a workshop for its elaboration but must be approved by all stakeholders before the TQAs can proceed.

### 7.2.5 Qualification Execution

Quite simply, this comprises the completion of the TQAs proposed in the Qualification Plan. During this period, there could be one or multiple progress review meetings including the stakeholders. This allows for better quality control and incorporation of feedback into the activities.

The TQAs should be documented in a series of reports, which might or might not be condensed in a single document (e.g., Technology Qualification Close-out Report). At this stage, it is up to the executors of the TQAs to evaluate whether the acceptance criteria set in the Qualification Plan were successfully fulfilled or not. Additionally, the executors can propose an extension of the TQP, an inclusion of additional TQAs, etc.



### 7.2.6 Performance Assessment

Finally, the stakeholders must analyse the TQA documentation and decide whether it is agreed that the acceptance criteria have been successfully met. If the negative holds true, the stakeholders might propose new qualification activities or demand that the technical solution is revisited – either to minimise risks via contingencies or to propose an entire shift in technical approach. Alternatively, perhaps it is the technical and critical targets that must be revisited. The details on how to proceed from this point forward must be agreed upon by all parties.

In conclusion, the TQP intends to comprehensively examine a technological solution in terms of its maturity, its risks, and its likelihood of delivering the intended targets given said risks. In a best-case scenario, all risks will be entirely eliminated by the completion of the TQP. Most likely, however, when doing a TQP for a FOAK project, one should expect to end up with several uncertainties and risks that cannot be fully quelled. It is extremely important that these uncertainties are fully understood by all parties before the project can proceed.



## 7.3 AURORA end-users and case-studies



	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

As one can conclude from the previous section, the definition of a study case is an extremely important step in the Technology Qualification Program. This is because the TQP does not aim to answer the question “*is this technology adequate?*”, but “*is this technology adequate for achieving this specific result?*”. In AURORA, each case study will be tailored for one of the end-user cases as described in Section 2.1 (PART A). In this way, we hope that we have cast a net wide enough to evaluate a range of different scenarios covering a diversity of CESAR1 carbon capture applications. More importantly, all of these scenarios are typical of carbon source emitters who are eager to decarbonize their industrial activities. Hence, we believe that the four cases evaluated in AURORA have obvious contemporary relevance.



	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

## 8 Basis for Qualification

This section will deal with the selection of a basis for qualification of large-scale carbon capture operations with the CESAR1 solvent. Notice that a precise definition of the basis for qualification is not entirely necessary at this stage – for example, we can foresee that the availability of the carbon capture plant and the amount of CO<sub>2</sub> captured will play an important role in the basis for qualification, though we are not forced to commit to values for these parameters at the current stage. In fact, we could simply state that any technical uncertainty that jeopardizes either of these parameters shall be viewed as a real threat, even though we are not able to quantify at this preliminary stage how much of a threat said uncertainty really is.

### 8.1 Selection of general technical parameters

The general technical parameters proposed for the Technology Qualification of the CESAR1 solvent are given in Table 3-1.

*Table 3-1: General technical parameters for the CESAR1 TQP*



Technical Parameter	Design Requirement
Safety and working environment issues	ALARP principle
Emissions to land, sea, and air	Minimise
Energy consumption	Efficient utilization
Waste production	Minimisation and adequate handling
Selection of processes, equipment & methods	Based on BAT and ALARP principles
Discharge of captured CO <sub>2</sub>	Minimise
Impacts to existing end-user facility	No impact of CO <sub>2</sub> capture process on operations

These general technical parameters are based on the ones proposed by DNV-GL during the Technology Qualification Program for the Heidelberg Materials project. Note that there are no fixed requirements for energy consumption nor waste production, but simply an indication that such and such resources should be employed efficiently and that such and such environmental impacts should be minimised. More precise technical parameters are given in the functional requirements.

Notice also that the BAT (Best Available Technique) and ALARP (As Low As Reasonably Practicable) are mentioned. This means that a review of the existing BAT and its supporting documentation<sup>18,19</sup> is recommended as part of the TQP.

### 8.2 Selection of functional requirements

As mentioned previously, there is no necessity right now of committing to specific values for the functional requirements. This is particularly true since there are four distinct end-user cases that

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

shall be evaluated in AURORA, and it is expected that the requirements might differ from case to case. Again, Table 3-2 is only meant to indicate which classes of functional requirements should become relevant when discussing technical uncertainties and threats to the project.

*Table 3-2: Functional requirements for the CESAR1 TQP*

Functional Requirements	Design Requirement
Carbon capture capacity	Depends on the case. Aim at 95% capture overall
Availability of CO <sub>2</sub> capture plant	Depends on the case
Proportion of flue gas treated	Depends on the case
Purity of CO <sub>2</sub> product	Depends on the case. Needs to be specified, but preliminarily follow Northern Lights specifications.
Solvent consumption	Depends on the case. Minimise, aim at <1kg/ton
Liquid effluent production	Depends on the case
Reclaimer waste production	Depends on the case
Cooling demands	Depends on the case



### 8.3 Selection of energy requirements

*Table 3-3: Energy requirements for the CESAR1 TQP*

Energy Requirements	Design Requirement
Power consumption for major equipment	Depends on the case
Externally supplied steam	Depends on the case

### 8.4 Selection of environmental requirements

Table 3-4 shows a list of tentative environmental requirements for the carbon capture plant operating with CESAR1 solvent. Notice that said requirements with regards to emissions employ the concentrations of pollutants that might build up in the vicinities of the carbon capture plant (e.g., nitrosamines are regulated based on their final concentrations at ground level), and not the concentrations that are directly discharged at the absorber stack. As such, a series of dispersion studies and atmospheric chemistry studies would be required to close-out this TQP as applied to each end-user case. Conversely, if said environmental requirements are updated to reflect the concentrations of pollutants in the cleansed gas as it is discharged from the absorber stack, then

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

we become unable of taking advantage of stack height / flue gas reheating alternatives to aid dispersion. There are good arguments for and against each methodology.

Table 3-4: Environmental requirements for the CESAR1 TQP



Environmental Requirements	Design Requirement
Liquid effluent quality	E.g., remove mercury.
<b>Emissions to air from stack</b>	Control according to limits given in dispersion study, total concentration of nitrosamines and nitramines in surrounding air should not exceed 0.3 ng/m <sup>3</sup> and 4 ng/l in drinking water (recommendations from Norwegian Environmental Agency). See also Table 3-1

## 8.5 Breaking down the technological elements

The technological elements in which the carbon capture plant has been divided in the AURORA project are as such:

- Direct contact cooler
- Other pre-treatment alternatives (e.g., BDU, NO<sub>2</sub> removal)
- Flue gas fan
- Absorber column
- Desorber column
- Emission control
- Reboiler
- Energy saving alternatives
- Reclaimer
- Lean-Rich heat exchanger
- Solvent filtration system (Activated Carbon Filter)
- Solvent health
- Other topics

Once these technical elements were selected, a workshop was carried out internally to identify what are technical uncertainties in each of these categories that pose positive threats to the requirements pointed out in Section 7.2. The workshop was carried out on 23<sup>rd</sup> August 2023 and 6<sup>th</sup> September 2023. The technical uncertainties identified are described below.

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

Here there are at least two important points that must be made regarding the takeaways of the workshops carried out for this TQP.



The first one is that many technical uncertainties were raised that could be quelled simply by providing enough documentation regarding process design. For example: the DCC design and operation is considered an uncertainty in as much as there is a need for documenting that the design proposed in AURORA for each end-user case is adequate for the service needed. However, this documentation is already part of the expected deliverables for any engineering project, hence it seems superfluous to deem this item as a “technical uncertainty”. At the same time, since this documentation will exist by the end of AURORA, there is no harm in highlighting that there are technical uncertainties which rely on it for being closed.

The second one is that there are technical uncertainties which have more to do with value improvement practices (VIP) than with technology qualification itself. One such example would be evaluating the shape of the absorber column (i.e., whether it should have a circular section, squared or rectangular). A circular-shaped absorber might be adequate for the service needed, even if a squared absorber might bring advantages in terms of procurement and erection. Comparing the advantages and disadvantages of a squared absorber should not be a technology qualification exercise if one can say that the circular absorber is already technically qualified – value improvement should be seen as an added benefit to the project, not as a necessity. However, for the sake of registering all comments raised during the workshops, some VIP items are listed below as well.

### 8.5.1 Direct contact cooler

Technical uncertainties identified in the DCC:

- DCC performance in removing contaminants. In essence, there is uncertainty whether the DCC as it is designed is actually capable of efficiently scrubbing out the SO<sub>2</sub> and the rough particulates from the flue gas. This uncertainty leads to a threat of high solvent consumption, high waste production, inefficient energy utilization, and a decrease in CO<sub>2</sub> capture capacity (the last two threats are in case the SO<sub>2</sub> is allowed to go to the solvent and affect CO<sub>2</sub> capture performance). There could also be a threat of increased emissions in case a large quantity of SO<sub>2</sub> is fed into the absorber column, leading to airborne mist.
- DCC caustic dosing. There is uncertainty whether the proposed caustic dosing philosophy (e.g., at which pH should the DCC wash-water be maintained, etc.) could lead to collateral scrubbing of CO<sub>2</sub> and/or simply prove to be inefficient. In the former case, one would end up with excessive caustic consumption, excessive waste production, and a loss of carbon capture capacity (because the CO<sub>2</sub> captured in the DCC will not be regenerated). In the latter case, one would end up with the first item in this list.
- DCC effluent quality. There is uncertainty whether the DCC effluent might pose challenges in its treatment. It is not clear whether this effluent can be treated on-site for all different end-user cases. This leads to threats in terms of waste production exceeding expectations.

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

- DCC water balance. There is uncertainty whether the DCC control philosophy might be conducive to accumulation of salts (e.g.,  $\text{Na}_2\text{SO}_4$ ) that could lead to precipitation and clogging. As a worst-case scenario, this could jeopardize the proposed availability of the carbon capture plant. Additionally, bad control of the DCC water balance might lead to a loss in DCC scrubbing performance, returning thusly to the first item in this list.
- DCC sizing and performance. There is uncertainty whether the DCC can operate in the turndown rates required by the different end-users and still provide efficient  $\text{SO}_2$  scrubbing and cooling capacity. If this fails to be the case, it could lead to a decrease in plant availability and/or bad DCC performance, returning to the first item in this list. This item should be closed with adequate design documentation.

## 8.5.2 Other pre-treatment alternatives



Technical uncertainties identified in additional flue gas pre-treatment:

- Brownian Demister Unit (BDU). Depending on the end-user case, the potential for aerosol nuclei (e.g., fine dust) will warrant the application of a BDU downstream of the DCC. If this turns out to be part of the design, then the one must evaluate how scalable this solution is and how much pressure drop will be introduced to the system. An increase in pressure drop will provoke an increase in flue gas fan size and power consumption, ultimately affecting the energy requirements of the carbon capture plant. Conversely, a bad BDU design (due to lack of scalability for example) would lead to increased solvent consumption and emissions to air.
- $\text{NO}_2$  removal. Depending on the end-user case,  $\text{NO}_2$  removal might be deemed absolutely necessary in order to prevent high airborne emissions, high solvent losses, and high waste production. At any rate, if  $\text{NO}_2$  removal is necessary to reach these performance parameters, then it will become necessary to qualify said  $\text{NO}_2$  removal strategy.

## 8.5.3 Flue gas fan

Technical uncertainties identified in the flue gas fan:

- Flue gas balance between stacks. If there are several flue gas stacks feeding to the same carbon capture unit, then the flue gas fans must be controlled in a way that ensures adequate flue gas balance. Failure to do so would jeopardize the carbon capture capacity (e.g., if one of the stacks is not feeding at desired rates to the carbon capture unit), might affect the end-user operations (e.g., via misrouting of the flue gas), etc.
- Adequacy of flue gas fan for service. Depending on the properties of the flue gas entering the flue gas fan, there might be potential harm to the equipment (e.g., if the gas is excessively acidic, if there is a high concentration of droplets). This uncertainty might affect the availability of the carbon capture plant and potentially its carbon capture capacity as well.
- Position of flue gas fan. This technical uncertainty refers to whether the proposed position for the flue gas fan (downstream of the DCC) is the most appropriate one though it is in

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	



terms of energy requirement for the fan. In a way, this item is a mixture of VIP and required technical documentation. Worst case scenario, the current location of the flue gas fan is inadequate for service, in which case this item degenerates into the previous item.

- Flue gas fan design and performance. Whether the flue gas fan design is able to cope with the turndown rates expected from each end-user, etc. This item should be closed with adequate design documentation.

#### 8.5.4 Absorber column

Technical uncertainties identified in the absorber column (notice that “emission control”, e.g., water wash and acid wash, are a separate technical item):

- Absorber liquid and/or gas distribution. Risk of solvent maldistribution and/or gas maldistribution in the absorption sections of the absorber column could lead to insufficient capture rates and a loss of CO<sub>2</sub> capture capacity. Conversely, the capture capacity might be adequate, but the rich loadings attained in the absorber column could be too low to deliver the energy performance expected from the energy efficiency requirements.
- Absorber packing. Risk of fouling in the packing material or insufficient contact between gas and liquid could end up leading to either a loss of capture performance or energy performance (same as the item above). In case of fouling, there is an added effect of pressure drop to the absorber column, which will lead to an increase in flue gas fan power consumption and consequent decrease in energy efficiency. Furthermore, since it is known that the CESAR1 requires less liquid circulation to capture CO<sub>2</sub> when compared to MEA 30 %wt., the sensitivity between packing wetting and plant performance have to be better understood.
- Absorber intercooling. In case intercooling is proposed for the absorber design, its optimal placement and cooling rate has to be evaluated. Additionally, the effects of intercooling towards solvent degradation and emissions should be investigated and documented. In case of a negative interaction, high solvent consumption and increased waste production might be a consequence.
- Absorber material. There is uncertainty regarding the interaction of the flue gas, the CESAR1 solvent, and the material in which the absorber is constructed. However, precisely because of this uncertainty, it is imaginable that the material selection in AURORA will be informed by conservatism – i.e., stainless steel will be chosen instead of carbon steel for costing the absorber and other equipment used for solvent service. Hence, this item should consider the risk of corrosion in stainless steel and its effects to the performance requirements (especially availability). The interaction between carbon steel and CESAR1 can be investigated as a VIP activity, meaning that, if there is a possibility of shifting from a more conservative to a bolder material selection philosophy, this would undoubtedly bring benefits to the project.

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	



- Absorber shape. Another VIP activity would be to understand if there are possibilities of cost-saving by shifting from a circular absorber design towards a square or rectangular-shaped one.
- Precipitation in absorber sump. The risk of solvent precipitation in the absorber sump can potentially lead to a loss of CO<sub>2</sub> capture capacity, loss of plant availability, and an increase in energy consumption (if rich loadings cannot be attained). We are specifying the absorber sump because that is the location where the CESAR1 solvent will be at its highest CO<sub>2</sub> loading and lowest temperature, hence being particularly vulnerable to solid separation.
- Absorber design and performance. Similar to the uncertainties regarding sizing and performance discussed for the DCC and for the flue gas fan. Notice that, differently from the aforementioned two cases, understanding the interaction between solvent (CESAR1) performance and absorber design is of fundamental relevance for closing-out this uncertainty. Hence, the pilot plant experience generated in AURORA will be fundamental in qualifying the absorber design.

### 8.5.5 Desorber column

Technical uncertainties identified in the desorber column:

- Desorber liquid and/or gas distribution. Risk of solvent maldistribution and/or gas maldistribution in the desorption sections of the desorber column could lead to excessive energy consumption (and perhaps loss of capture capacity if the desired lean loadings cannot be attained). This uncertainty is particularly high if the design requires a multiple number of reboilers for the same desorber column, in which case their production of vapour to the desorber will need to be evenly distributed.
- CO<sub>2</sub> quality at desorber overhead condenser. The compression & conditioning plant will be designed based on a certain estimated concentration of CO<sub>2</sub> product contaminants (e.g., ammonia, aldehydes, O<sub>2</sub>, NO<sub>x</sub>). However, there is certainly some uncertainty regarding the reliability of said estimates. As a worst-case scenario, the CO<sub>2</sub> compression & conditioning plant will need to be stopped if the concentration of contaminants exceeds the design basis, in which case the CO<sub>2</sub> capture plant itself might need to be stopped, thus impacting its availability and capture capacity. Additionally, treating an excess of CO<sub>2</sub> product contaminants might lead to an increase of energy consumption even if said treatment is technically feasible.
- Desorber water wash. The design of the desorber water wash section (e.g., either a pump-around section or an overhead condenser followed by a short, packed section) and its operations will need to be validated. Maloperation of the desorber water wash will lead to higher CO<sub>2</sub> temperatures and higher flow of saturated moisture flowing to the compression & conditioning unit, which will lead to higher energy consumption. Also, maloperation of the desorber water wash will lead to more contaminants in the CO<sub>2</sub> product, thus degenerating this item into the previous one.



	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	



- Desorber design and performance. Like the uncertainties regarding sizing and performance discussed for the absorber column. We should add here that the type of packing is also an uncertainty. The risk of insufficient contact between gas and liquid could end up leading to either a loss of capture performance or energy performance.

### 8.5.6 Emission control

Technical uncertainties identified relating to emission control:

- Emission monitoring strategy. There is uncertainty regarding whether the choice of Continuous Emissions Measurement Systems (CEMS) is suitable for keeping track of all relevant pollutants emitted by the carbon capture plant. This will depend on the sensitivity of the CEMS, their reliability, and what is the strategy for integrating online monitoring with offline monitoring. A bad emission monitoring approach might lead to periods of high emissions and potential solvent losses. As a worst-case scenario, the carbon capture plant will be completely unable to operate if it cannot keep track of its emissions, which will have an effect on availability and carbon capture capacity as well.
- HSSE impact of absorber emissions. There is uncertainty regarding the toxicological / environmental impacts of the airborne emissions that could be expected of the CESAR1 solvent. Though there are no specific requirements regarding toxicology laid down in Section 7.2, this technical item should be clarified to ensure that the carbon capture plant is even able to operate with CESAR1.
- Aerosol and volatile emissions over absorber. If airborne mist and volatile emissions do happen even with the implementation of the emission control system, one will be obliged to retrofit alternative emission mitigation solutions and/or more sophisticated flue gas pre-treatment to maintain the emissions as per environmental permit requirements.
- Absorber demister performance. Uncertainties regarding the performance of the demister might lead to higher-than-expected emissions of liquid droplets, be it solvent mist, or entrained material from the water wash or from the acid wash (when applicable). This could lead to solvent losses, or it could lead to higher acid consumption, and in both cases, there is a consequent deterioration of the environmental performance of the carbon capture plant.
- Absorber acid wash design and performance. If applicable, the uncertainties in acid wash performance must be addressed. The location of the acid wash section must be evaluated and justified. If mounted atop the absorber column, the risk and the consequences of acid wash leakage to the lower sections of the absorber must be assessed. The wash strategy must also be evaluated to guarantee that there is no excessive acid consumption / effluent production. Malfunctioning of the acid wash will lead to high emissions, in which case one might be unable to achieve the environmental specifications of the carbon capture plant (and might end up consuming an excess amount of acid and producing an excess amount of liquid effluent).
- Absorber water wash design and performance. Though uncertainties include the water wash configuration (whether it's one or two beds, whether one of them is once-through), its



	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

dimensions, and the packing type, the consequences of bad water wash performance will be high solvent losses and high emissions of amines and volatile degradation products.

### 8.5.7 Reboiler

Technical uncertainties identified relating to reboilers:



- Reboiler design and performance. Uncertainties include the type of reboiler (e.g., kettle-type, thermosyphon-type). A bad design could lead to (a) insufficient heat exchange area, leading to loss of carbon capture capacity and increased energy consumption, (b) maldistribution of the returning vapour to the desorber column, leading again to loss of carbon capture capacity and increased energy consumption, and (c) foaming in the desorber column, leading to all two items again plus the risk of high concentration of contaminants in the CO<sub>2</sub> product, which could affect the plant availability.
- Fouling in reboiler and heat exchangers. Rapid fouling in the reboilers could lead to an excess of energy consumption, loss of carbon capture performance, and decreased plant availability. As a sidenote: even though heat exchangers in general have not been particularly addressed as a technological item in this document, the risk of fouling in the heat exchangers in amine service should also be assessed during the TQP, with the consequences of fouling in said heat exchangers being similar to those in the reboiler (though impacts on plant availability should be reduced).
- Reboiler material selection. Uncertainties regarding corrosion phenomena could lead to a decrease in plant availability.

### 8.5.8 Energy savings alternatives

Technical uncertainties identified relating to other energy saving alternatives:

- Heat pump. When applicable. Everything about heat pumps should be verified, from its rating, capacity, reliability, transient operations, etc. The risk that the entire carbon capture plant operations are jeopardized via failure of the heat pump should be assessed. Naturally, the affected technical requirements are thus carbon capture capacity, energy consumption, and reliability.
- Lean vapour recompression (LVR). Same as the previous item. The affected technical requirements are thus carbon capture capacity, energy consumption, and reliability.
- Once-through heat pump (OTHP). Same as the previous item. The affected technical requirements are thus carbon capture capacity, energy consumption, and reliability.

Notice here that the level of maturity of these three heat saving alternatives (heat pumps, LVR and OTHP) is quite lower than that of steam-powered kettle reboilers, hence the inclusion of these items in the design of large-scale carbon capture plants will inevitably increase the scope of work of associated TQPs. In a certain way, this is illustrative of the trade-off between coming up with a conservative, mature design that does not excel in energy performance, and a bold, innovative

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

design that, though potentially more efficient, could require a high degree of qualification (and introduces a high degree of risk).

## 8.5.9 Reclaimer



Technical uncertainties identified relating to reclaimer and reclaiming operations:

- Reclaimer design and performance. There is uncertainty regarding the reclaimer separation efficiency wrt. removing degradation products from the solvent and regarding the reclaimer separation efficiency wrt. how much amine is lost during reclamation. An upset in the first item would lead to more accumulation of degradation products in the solvent, which could lead to a loss of carbon capture performance and an increase in energy consumption. An upset in the second item would lead to higher solvent losses (i.e., losses to reclaimer waste). Also, the choice of reclaimer strategy should be justifiable (e.g., thermal reclamation as opposed to ion-exchange or similar).
- Solvent degradation during reclaiming. There is a risk that prolonged solvent reclamation might ironically lead to increased solvent degradation. The resulting impact would thus be increased solvent losses.
- Impact of reclamation on carbon capture process. There is a risk that batch thermal reclamation might negatively impact the carbon capture process as it operates, e.g., via disruption of the vapour distribution in the desorber. This could lead to a decrease in carbon capture capacity and increase in energy consumption. As a worst-case scenario, it could be that the carbon capture plant cannot operate while the batch reclamation is happening, which would lead to a decrease in carbon capture availability.
- HSSE impact of reclaimer waste. Similar to the HSSE impact of emissions discussed above, with the difference that the consequences of this risk can be mitigated by devising strategies that minimise operator-reclaimer waste interactions.
- Reclaimer waste disposal. There are uncertainties regarding the ideal waste disposal strategy, especially if the minimisation of operator-reclaimer waste interaction is a requirement. In other words, the risk is that the disposal of said waste demands intensive action from the operators, which would go against the ALARM principles stated in Table 3-1.
- Reclaimer hazard area classification. There are uncertainties regarding the formation of a flammable fluid during the batch reclamation of the CESAR1 solvent. If that is found to be the case, the reclaimer hazard area classification should be updated to reflect that.

## 8.5.10 Solvent health

Technical uncertainties identified relating to the CESAR1 solvent and its health:

- Solvent degradation impact on capture rate and efficiency. Though it is understood that solvent degradation will impact capture rates and the energy efficiency of the process (i.e., rich loadings), it is not clear how much solvent degradation is acceptable before a

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

reclamation campaign needs to be carried out. A too strict conservative approach will result in too frequent solvent reclamation, which will naturally lead to an increase in waste production. On the other hand, a less conservative approach might incur in inevitable losses in terms of energy efficiency and capture rates. Hence, there is a need for better understanding of the trade-off between degradation and capture rates in the CESAR1.



- Drift from solvent specification and its impact on capture rate and efficiency. Similar as above, but instead of focusing on the accumulation of degradation products, one should evaluate the effect that drifting solvent alkalinities and concentrations of AMP / PZ have on carbon capture rates and the energy efficiency of the process. While the previous item should justify the reclamation philosophy, this item should inform the amine make-up philosophy.
- Solvent residence time. It should be evaluated whether the residence times of the solvent in the carbon capture plant (and particular in the “hot spots” of the carbon capture plant, e.g., desorber sump) are optimised for enabling high carbon capture performance while decreasing solvent degradation. (This is a VIP item.)
- HSSE impact of aged solvent. Similar to the HSSE impact of emissions discussed above, though this risk can be mitigated by devising strategies that minimise operator-aged solvent interactions.
- Solvent make-up strategy. There is uncertainty regarding how to more efficiently procure and store the mother-amines of the CESAR1 solvent, and specifically so in the case of piperazine. If piperazine is procured and stored as sludge, mixed with water, then the make-up tanks need to be sized accordingly. Conversely, if piperazine is procured in solid form, then there must be an alternative to dilute it in water and feed it to the carbon capture plant.
- Solvent procurement strategy. Complementary to the item above, a strategy for procuring and stocking make-up solvent onsite should be devised. The risk of disruptions in supply chain signifying the possibility of running out of some of the mother-amines for a period of time needs to be assessed.

### 8.5.11 Other items

Other technical uncertainties:

- Transient operations. There are technological risks which could arise only when considering the transient, non-steady operations of the carbon capture plant with the CESAR1 solvent. It should be investigated whether the start-up procedure is sufficiently well understood, and similarly to the flue gas ramping procedure, the shutdown procedure, etc. A poor design for enabling efficient transient operations could lead to a decrease in overall carbon capture capacity and energy efficiency, as well as potential spikes in solvent emissions during start-up.

## 8.6 Risk categorization

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

Risk categorization is typically a part of the preparation for Technology Qualification Activities. If a risk identified in the discussion about technical uncertainties is deemed inconsequential, then no TQA needs to be proposed to solve it.



However, due to the educational nature of this study and the different backgrounds of the people involved in the technical discussions, it has been found excessively challenging to properly assess categories of risk without delving further into the specific topics at hand. For that reason, this step of risk categorization has been moved to the TQAs directly. Therefore, it is part of the objectives of the AURORA TQAs to deem whether the consequences of a technical challenge are manageable or not.

This is beneficial for the reader, as the discussion on risk consequences will then be moved to an open forum, rather than maintained in the privacy of workshops.

**Table 6-1 Risk categorization**

Category	Description
High	Critical threat with severe consequence and/or uncertainty, requiring solid evidence that the threat is under control
Medium	Threat that requires detailed review of available documentation to reduce uncertainty
Low	Threat that only requires high level review of documentation, if deemed necessary

*Figure 8-1: Risk categorization for Technology Qualification Program*

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	



## 9 Technology Qualification Activities

Based on the technical uncertainties observed in Section 7.2, the following Technology Qualification Activities are proposed.



Each one of these activities consists in compiling and producing evidence that the risks regarding carbon capture operations with the CESAR1 solvent are bearable and should not pose an unsurmountable challenge for achieving the technical requirements presented in Section 7.2. Much of this evidence will come from simple flowsheet calculations and documentation from vendors and literature (see also PARTB), while other items will demand some dedicated work during the pilot testing campaigns and the bench scale investigations.

These activities will be prepared and delivered in a Close-Out Report as appendices to deliverable “D4.5 – Qualification of the CESAR1 solvent technology”. Ultimately, the results of the close-out report will be positive if all acceptance criteria for all TQAs can be met, or if there is only a limited number of follow-up activities (knowledge gaps) identified by the time that AURORA comes to end.

TQA number and title	Objectives	Technical items	Acceptance criteria
01 DCC design	<ul style="list-style-type: none"> <li>Document DCC removal efficiency from different flue gases (pilot testing, flowsheet calculations)</li> <li>Document consequences of failing to achieve target contaminant scrubbing (flowsheet calculations, review material selection)</li> <li>Document caustic dosing strategy and justify choices (pilot testing, flowsheet calculations)</li> <li>Document water balance strategy and justify choices (pilot testing, flowsheet calculations)</li> <li>Provide documentation of columns with similar design for similar service</li> </ul>	<ul style="list-style-type: none"> <li>DCC performance in removing contaminants</li> <li>DCC caustic dosing</li> <li>DCC water balance</li> <li>DCC sizing and performance</li> </ul>	<ul style="list-style-type: none"> <li>Confirm that SO<sub>2</sub> removal efficiency is acceptable (e.g., SO<sub>2</sub> downstream of DCC &lt;1 mg/Nm<sup>3</sup>), find documentation from vendors</li> </ul>
02 DCC effluent characterisation	<ul style="list-style-type: none"> <li>Estimate DCC effluent rates and concentrations for different end-users (pilot testing, flowsheet calculations)</li> <li>Evaluate requirements for onsite treatment or disposal</li> </ul>	<ul style="list-style-type: none"> <li>DCC effluent quality</li> </ul>	<ul style="list-style-type: none"> <li>Document whether DCC effluent disposal is bottleneck or not for the different end-users, propose suitable treatment/utilization option if there is a bottleneck</li> </ul>
03 Flue gas pre-treatment	<ul style="list-style-type: none"> <li>Determinate what is acceptable level of contaminants, e.g., NO<sub>2</sub> in the flue gases coming from to the absorber (pilot testing, flowsheet calculations)</li> <li>Document flue gas qualities and evaluate whether pre-treatment is necessary</li> </ul>	<ul style="list-style-type: none"> <li>Brownian Demister Unit (BDU)</li> <li>NO<sub>2</sub> removal</li> </ul>	<ul style="list-style-type: none"> <li>Document if the acceptable levels of contaminants can be reached, and whether required pre-treatment is bottleneck or not for</li> </ul>



	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

	<ul style="list-style-type: none"> <li>• Employ aerosol modelling if possible to support above</li> <li>• Evaluate scalability and performance impact of pre-treatment solutions</li> </ul>		the different end-users
04 Flue gas fan design	<ul style="list-style-type: none"> <li>• Evaluate that flue gas fan position is adequate (flowsheet calculations)</li> <li>• Evaluate that the flue gas fan sizing is adequate (sensitivity analysis of pressure drop in the downstream path)</li> <li>• Provide documentation of fans with similar design for similar service, including verifying tolerance wrt. droplets and acidity</li> </ul>	<ul style="list-style-type: none"> <li>• Adequacy of flue gas fan for service</li> <li>• Position of flue gas fan</li> <li>• Flue gas fan design and performance</li> <li>• Absorber packing</li> </ul>	<ul style="list-style-type: none"> <li>• Document that fan is adequate for service (e.g., wrt. tolerance to acid mist) and that dimensions are not a bottleneck</li> </ul>
05 Flue gas balance	<ul style="list-style-type: none"> <li>• Provide simplified dynamic simulation or similar study to support flue gas balance between stacks or when more than one flue gas fan is needed for the same absorber</li> </ul>	<ul style="list-style-type: none"> <li>• Flue gas balance between stacks</li> </ul>	<ul style="list-style-type: none"> <li>• Propose suitable flue gas balance strategy for the case where there are multiple stacks</li> </ul>
06 Absorber column design	<ul style="list-style-type: none"> <li>• Quantify uncertainties regarding absorber design wrt. capture rates and energy consumption (pilot testing, flowsheet calculations)</li> <li>• Evaluate adherence between modelling and pilot plant results wrt. absorber only (e.g., approach to equilibrium, etc)</li> <li>• Evaluate material compatibility at absorber conditions</li> <li>• When applicable, document effect of intercooling wrt. capture rates and energy consumption (pilot testing, flowsheet calculations)</li> <li>• Review material selection philosophy for CESAR1 service</li> <li>• Document advantages and disadvantages of current absorber cross-section shape</li> <li>• Provide documentation of packed columns with similar design for similar service, including column internals (packing, distributors)</li> <li>• Evaluate if design is fit for avoiding foaming, or even whether this criteria exists or not</li> </ul>	<ul style="list-style-type: none"> <li>• Absorber liquid and/or gas distribution</li> <li>• Absorber packing</li> <li>• Absorber intercooling</li> <li>• Absorber material</li> <li>• Absorber shape</li> <li>• Absorber design and performance</li> </ul>	<ul style="list-style-type: none"> <li>• Confirm that absorber specifications are fit for purpose and document how much confidence the suppliers have with designs up to the proposed scale/size</li> </ul>
07 CESAR1 precipitation	<ul style="list-style-type: none"> <li>• Document VLSE of CO<sub>2</sub>-loaded CESAR1 at relevant temperatures (25-45°C)</li> <li>• Document strategy for how to identify and how to deal with solvent precipitation</li> </ul>	<ul style="list-style-type: none"> <li>• Precipitation in absorber sump</li> </ul>	<ul style="list-style-type: none"> <li>• Propose adequate strategy to deal with the challenge of precipitation</li> </ul>

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	



	<ul style="list-style-type: none"> <li>Document operating conditions (temperature, concentrations) across carbon capture plant (pilot testing, flowsheet calculations)</li> </ul>		
08 Desorber column design	<ul style="list-style-type: none"> <li>Quantify uncertainties regarding desorber design wrt. capture rates and energy consumption (pilot testing, flowsheet calculations)</li> <li>Evaluate material compatibility at desorber conditions</li> <li>Evaluate adherence between modelling and pilot plant results wrt. desorber only (e.g., approach to equilibrium, etc)</li> <li>Provide documentation of packed columns with similar design for similar service, including column internals (packing, distributors)</li> <li>Document desorber water wash performance (pilot testing, flowsheet calculations)</li> <li>Evaluate if design is fit for avoiding foaming, or even whether this criterium exists or not</li> </ul>	<ul style="list-style-type: none"> <li>Desorber liquid and/or gas distribution</li> <li>Desorber water wash</li> <li>Desorber design and performance</li> </ul>	<ul style="list-style-type: none"> <li>Confirm that desorber specifications are fit for purpose and document how much confidence the suppliers have with designs up to the proposed scale</li> </ul>
09 CO <sub>2</sub> product quality	<ul style="list-style-type: none"> <li>Qualify CO<sub>2</sub> product obtained in pilot plant testing with different operational modes</li> <li>Perform evaluation of possible CO<sub>2</sub> product contaminants based on pilot testing and subsequent chemical analyses and thermodynamics, considering different water wash performances</li> <li>Assess consequences of different degrees of contaminants to downstream compression &amp; conditioning</li> </ul>	<ul style="list-style-type: none"> <li>CO<sub>2</sub> quality at desorber overhead condenser</li> <li>Desorber water wash</li> </ul>	<ul style="list-style-type: none"> <li>Confirm that CO<sub>2</sub> product specifications can be reliably achieved</li> </ul>
10 Emission control	<ul style="list-style-type: none"> <li>Evaluate and document choices regarding water wash configuration, acid wash configuration, acid wash design (pilot testing, flowsheet calculations)</li> <li>Assess airborne mist and volatile emissions (pilot testing, flowsheet calculations, aerosol modelling)</li> <li>Provide documentation of packed columns with similar design for similar service, including column internals (packing, distributors, collectors, demister), to be applicable to water wash and acid wash sections</li> <li>Review local environmental legislation wrt. emission monitoring</li> <li>Propose emission monitoring strategy</li> </ul>	<ul style="list-style-type: none"> <li>Emission monitoring strategy</li> <li>Aerosol and volatile emissions over absorber</li> <li>Absorber demister performance</li> <li>Absorber acid wash design and performance</li> <li>Absorber water wash design and performance</li> </ul>	<ul style="list-style-type: none"> <li>Document that emissions will not be a bottleneck for the carbon capture plant for permitting purposes, and that threats to the environment have been minimised</li> </ul>





	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

11 Reboiler and heat exchanger design	<ul style="list-style-type: none"> <li>Evaluate fouling in reboiler and heat exchangers and justify sizing philosophy (pilot testing)</li> <li>Evaluate design alternatives for heat exchangers that minimise the risks and consequences of leakages</li> <li>Evaluate material compatibility at service conditions (pilot testing)</li> <li>Document advantages and disadvantages of reboiler type choice design, e.g., whether forced circulation is necessary</li> <li>Assess threat of vapour maldistribution in the return lines between multiple reboilers and desorber</li> <li>Provide documentation of kettle boilers with similar design for similar service</li> </ul>	<ul style="list-style-type: none"> <li>Reboiler design and performance</li> <li>Fouling in reboiler and heat exchangers</li> <li>Reboiler material selection</li> </ul>	<ul style="list-style-type: none"> <li>Confirm that reboiler and heat exchanger specifications are fit for purpose and in the realm of previous industrial design</li> </ul>
12 Reclaimer design	<ul style="list-style-type: none"> <li>Document advantages and disadvantages of reclaimer type choice</li> <li>Document thermal reclamation efficiency and whether there is collateral solvent degradation (bench scale testing, pilot testing, flowsheet calculations)</li> <li>Evaluate impact of solvent reclamation to carbon capture process (flowsheet calculations)</li> <li>Evaluate risk of production of flammable fluids during thermal reclamation of CESAR1 (flowsheet calculations)</li> <li>Propose operation narrative for reclaimer campaigns with focus on (a) when to reclaim and (b) minimisation of contact between operators and waste</li> </ul>	<ul style="list-style-type: none"> <li>Reclaimer design and performance</li> <li>Solvent degradation during reclaiming</li> <li>Impact of reclamation on carbon capture process</li> <li>Reclaimer waste disposal</li> <li>Reclaimer hazard area classification</li> <li>Solvent degradation impact on capture rate and efficiency</li> </ul>	<ul style="list-style-type: none"> <li>Confirm that solvent reclamation will not be a bottleneck for operations with the CESAR1 solvent</li> </ul>
13 Energy integration	<ul style="list-style-type: none"> <li>Document state-of-the-art of heat pumps for service (capacity, reliability)</li> <li>Document state-of-the-art of LVR for service (capacity, reliability)</li> <li>Document state-of-the-art of OTHP for service (capacity, reliability)</li> <li>Document state-of-the-art of desorber interheating</li> <li>Investigate freedom to operate with these different solutions</li> </ul>	<ul style="list-style-type: none"> <li>Heat pump</li> <li>Lean vapour recompression (LVR)</li> <li>Once-through heat pump (OTHP)</li> </ul>	<ul style="list-style-type: none"> <li>Provide documentation</li> </ul>
14 HSSE impacts of CESAR1 operations	<ul style="list-style-type: none"> <li>Evaluate HSSE profiles of emissions over absorber, reclaimer waste, and aged solvent</li> </ul>	<ul style="list-style-type: none"> <li>HSSE impact of absorber emissions</li> </ul>	<ul style="list-style-type: none"> <li>Document that threats to operators and environment posed by</li> </ul>



	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

	<ul style="list-style-type: none"> <li>• Provide preliminary chemical datasheet for aged CESAR1</li> <li>• Identify knowledge gaps wrt. degradation products and their toxicities</li> </ul>	<ul style="list-style-type: none"> <li>• HSSE impact of reclaimers waste</li> <li>• HSSE impact of aged solvent</li> <li>• Reclaimer waste disposal</li> </ul>	operations with the CESAR1 solvent are acceptable
15 Solvent health and impacts on plant performance	<ul style="list-style-type: none"> <li>• Document plant performance with fresh and aging CESAR1 solvent (pilot testing)</li> <li>• Document plant performance with off-spec CESAR1 solvent (bench scale testing, pilot testing, flowsheet calculations)</li> <li>• Evaluate accumulation of degradation products and metals in solvent (bench scale testing, pilot testing)</li> <li>• Evaluate risk of foaming and effects of anti-foam on solvent performance (bench scale testing, pilot testing)</li> <li>• Assess impact of absorber intercooling on solvent degradation vis-à-vis plant performance</li> <li>• Review supply chain for CESAR1 mother amines</li> <li>• Document strategy for solvent health monitoring, procurement and make-up</li> </ul>	<ul style="list-style-type: none"> <li>• Solvent degradation impact on capture rate and efficiency</li> <li>• Drift from solvent specification and its impact on capture rate and efficiency</li> <li>• Solvent residence time</li> <li>• Solvent make-up strategy</li> <li>• Solvent procurement strategy</li> </ul>	<ul style="list-style-type: none"> <li>• Confirm that plant performance will not deviate significantly from design, and provide comprehensive documentation of solvent management strategies</li> </ul>
16 Carbon capture in transient mode	<ul style="list-style-type: none"> <li>• Document transient operations with carbon capture plants (pilot testing)</li> <li>• Simulate transient operations in large-scale carbon capture plants (pilot testing, dynamic modelling)</li> <li>• Evaluate losses in carbon capture efficiency and energy consumption during transient periods (pilot testing, flowsheet calculations, dynamic modelling)</li> <li>• Evaluate emissions during transient periods (pilot testing)</li> <li>• Document expectations wrt. transient operations in end-user cases</li> </ul>	<ul style="list-style-type: none"> <li>• Transient operations</li> </ul>	<ul style="list-style-type: none"> <li>• Document whether carbon capture plant transient operations bottleneck or not for the different end-users</li> </ul>

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	



## 10 Summary for Technology Qualification

Part B has illustrated how to carry out the first stages of a Technology Qualification Programme for any novel technology in a novel application. More importantly, it has discussed common technical requirements, functional specifications, technical risks and knowledge gaps proper to the CESAR1 solvent-based carbon capture technology.

By identifying said knowledge gaps, we have prepared a tentative list of activities focused on de-risking applications of the CESAR1 solvent. This list will act as a basis for the following years of investigations in AURORA.



The 16 activities range from intrinsic solvent investigations (e.g., solvent management alternatives, confirmation of performance expectations) to general explorations in solvent-based CO<sub>2</sub> capture technologies. Most solvent-based technologies require qualifying packed columns for absorption and desorption, integration between source emitters and capture plants, and flue gas pre-treatment. Therefore, there is much value in the discussion carried out in Part B not only to AURORA but to the larger CCUS community.

The resulting Technology Qualification Activities will be developed throughout this project and divulged in “D4.5 – Qualification of the CESAR1 solvent technology” at a later stage of AURORA.

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

## 11 References

- Booth, N. et al. (2011), European Best Practice Guidelines for Assessment of CO<sub>2</sub> Capture Technologies, deliverable D2.4.3 of the Cesar project
- Kvamsdal, H.M., Ehlers, S. Kather, A., Khakharia, P., Nienoord, M., and Fosbøl, P.L., (2016), Optimizing Integrated Reference Cases in the OCTAVIUS Project, *International Journal of Greenhouse Gas Control*, 50, pp. 23-36
- Garcia, S., Weir, H., Van der Spek, M., Saleh, A., Charalambous, C., Sanchez-Fernandez, E., Ros, J., Skylogianni, E., Garcia Moretz-Sohn Monteiro, J., Wiechers, G., Moser, P., Kvamsdal, H.M., Haugen, G., Eldrup, N.H., and Skagestad, R., (2021), Process Integration of Advanced Amine-based Solvents in Power and Industrial Plants: A New Benchmark for Post-combustion Carbon Capture? *Proceedings of the 15th Greenhouse Gas Control Technologies Conference 15-18 March 2021*. Available at SSRN: [https://papers.ssrn.com/sol3/papers.cfm?abstract\\_id=3816508](https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3816508)
- Northern Lights, Northern Lights CO<sub>2</sub> specifications, <https://norlights.com/wp-content/uploads/2023/11/Northern-Lights-co2specs-1.11.23.pdf>
- Kohl, A. L. and Nielsen, R.B., (1997), *Gas Purification*, 5th Edition, p 31, Gulf Publishing Company
- Kvamsdal, H.M., Hetland, J., Haugen, G., Svendsen, H.F., Major, F., Kårstad, V., and Tjellander, G. (2010), Maintaining a neutral water balance in a 450 MWe NGCC-CCS power systems with post-combustion carbon dioxide capture aimed at offshore operation, *International Journal of Greenhouse Gas Control*, 4(4), pp. 613-622
- Cansolv Technologies, Inc. "SaskPower Boundary dam 3 Project Updated & some Lessons Learned". Presentation available online at <http://7bf847d11d127c20fa70-cd6cb913bb8b30d5bcc03e5d889b94ba.r34.cf1.rackcdn.com/philippemicone.pdf> (accessed 30/01/2024).
- Kvamsdal et al. (2015), Report on methodology for benchmarking of large scale capture plants, public deliverable D13.2 in the OCTAVIUS project
- Knudsen et al., (2011), Evaluation of process upgrades and novel solvents for the post combustion CO<sub>2</sub> capture process in pilot-scale, *Energy Procedia*, 4, p. 1558-1565
- F.A. Tobiesen, H.F. Svendsen, Study of a Modified Amine-Based Regeneration Unit, *Ind. Eng. Chem. Res.* 45 (2006) 2489–2496. <https://doi.org/10.1021/ie050544f>.
- F.A. Tobiesen, H.F. Svendsen, O. Juliussen, Experimental validation of a rigorous absorber model for CO<sub>2</sub> post-combustion capture, *AIChE Journal*. 53 (2007) 846–865.
- F.A. Tobiesen, O. Juliussen, H.F. Svendsen, Experimental validation of a rigorous desorber model for CO<sub>2</sub> post-combustion capture, *Chemical Engineering Science*. 63 (2008) 2641–2656.
- F.A. Tobiesen, G. Haugen, A. Hartono, A systematic procedure for process energy evaluation for post combustion CO<sub>2</sub> capture: Case study of two novel strong bicarbonate-forming solvents, *Applied Energy*. 211 (2018) 161–173. <https://doi.org/10.1016/j.apenergy.2017.10.091>.

	Document:	D4.1 – Methodology for large-scale assessment and benchmarking D4.1 - Methodology for large-scale assessment and benchmarking	
	Issue date:	30/01/2024	
	Dissemination level:	PU	

- 
- 14 Reference: M. Gilardi, F. Bisotti, A. Tobiesen, H.K. Knuutila, D. Bonalumi, An approach for VLE model development, validation, and implementation in Aspen Plus for amine blends in CO<sub>2</sub> capture: the HS3 solvent case study, *International Journal of Greenhouse Gas Control*. 126 (2023) <https://doi.org/10.1016/j.ijggc.2023.103911>
- 15 H.M. Kvamsdal, G. Haugen, H.F. Svendsen, A. Tobiesen, H. Mangalapally, A. Hartono, T. Mejdell, Modelling and simulation of the Esbjerg pilot plant using the Cesar 1 solvent, in: Elsevier Ltd, 2011: pp. 1644–1651. <https://doi.org/10.1016/j.egypro.2011.02.036>
- 16 Hauger, S.O., Flø, N.E., Kvamsdal, H., Gjertsen, F., Mejdell, T., and Hillestad, M., (2019), Demonstration of non-linear model predictive control of post-combustion CO<sub>2</sub> capture processes, *Computers and Chemical Engineering*, 123, 6 April, pp. 184-195
- 17 Lie K.O., Gorset O., Bade O.M., Askestad I., Knudsen J.N., Andersson V. (2021) Technology qualification to mitigate technical risk in CCS Front End Engineering Design for the HeidelbergCement Norcem plant. Proceedings of the 15th Greenhouse Gas Control Technologies Conference, 15-18 March 2021. Available at SSRN: <https://ssrn.com/abstract=3813150> or <http://dx.doi.org/10.2139/ssrn.3813150>
- 18 Post-combustion carbon dioxide capture: best available techniques (BAT). Available at <https://www.gov.uk/guidance/post-combustion-carbon-dioxide-capture-best-available-techniques-bat>
- 19 Gibbins J., Lucquiaud M. (2022) BAT Review for New-Build and Retrofit Post-Combustion Carbon Dioxide Capture Using Amine-Based Technologies for Power and CHP Plants Fuelled by Gas and Biomass for Post-Combustion Capture Using Amine-Based and Hot Potassium Carbonate Technologies on EfW Plants as Emerging Technologies under the IED for the UK, ver. 2.0, December 2022. Available at <https://ukccsrc.ac.uk/best-available-technology-bat-information-for-ccs>