Full title: **Clean clinker production via calcium looping process**
Acronym: **CLEANKER**
Type of action: **H2020-LCE-2016-2017/LCE-29-2017**
Grant Agreement number: **764816**
Project starting date – Duration: **1st October 2017 – 48 months**

Definition of a methodology for the development of a techno-economic study for CO_2 transport, storage and utilization

WP7 – Deliverable D7.1

Deliverable number	D7.1
Deliverable title	Definition of a methodology for the development of a techno-economic study for CO_2 transport, storage and utilization
Work package	WP7: Transport, utilization and storage study
Due delivery date	30 November 2019
Actual delivery date	December 2019
Deliverable Leader	Alla Shogenova
Dissemination level (PU, CO)	PU
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PU=Public
CO=Confidential, only for members of the consortium (including the Commission Services)

Short description
Available approaches and data for economic modelling are used and updated according to the national requirements for CO_2 storage sites monitoring and with data required for CO_2 use suitable for the selected CCUS scenarios. Version 10.6 of the ArcGIS software and MS Excel datasheets are designed for the spatial data collection and analysis.

History of changes

Version	DATE	Changes	Author
V0.1	2019-12-19	First release	Alla Shogenova and Kazbulat Shogenov, TUT
V0.2	2019-12-27	Second release	
V0.3	2020-01-05	Third release	

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 764816. This work is supported by the China Government (National Natural Science Foundation of China) under contract No.91434124 and No.51376105.

Abstract

Different approaches could be used to estimate costs for a full chain CCS project including capture, transport and storage. TUT participated in the FP6 EU GeoCapacity Project where stochastic analysis of costs using Monte-Carlo simulation in DSS (Decision Support System) were used, based on the collected GIS. In Australian Power Generation Technology Report (EPRI, 2015), the University of Sydney estimated the cost for transport and storage of CO_2 from power plants in Australia using information collected from Australian stakeholders. This report provides building block datasets in the form of figures, tables and equations to enable users to estimate costs and performance for the pipeline transportation and geological storage of CO_2.

In this task TUT combined and incorporated approaches and data collected in the cited above reports, updated them according to the national requirements for CO_2 storage sites monitoring and with data required for CO_2 use for enhanced hydrocarbon recovery (EHR), enhanced geothermal recovery and CO_2 mineral carbonation options suitable for the selected CCUS scenarios. Spatial data analysis will be based on the ArcGIS platform, version 10.6. MS Excel datasheets are designed for data collection and easy use by the project partners. Petrel software will be applied for geological modelling of the storage sites.

Methodology for cost estimation of the CO_2 mineral carbonation with the studied in TUT laboratory prospective waste materials are developed for Mineral Carbonation Plant, or cement plant-based Mineral Carbonation Reactor. For techno-economic estimation and optimization of CO_2-EOR operations and for techno-economic analyses of CO_2 use for Geothermal Energy Recovery, publicly available at US DOE software will be used.

CO_2 supply price for CO_2 use will be based on the CO_2 capture, compression and transport costs and revenues from European Emission Allowance Price (EEAP) and national carbon and waste taxes.

CO_2 capture cost for the cement plants will be based on the results of the CLEANKER project. CO_2 capture cost of the power plants in the Baltic Scenario will be based on the available results of economic modelling of the Estonian-Latvian CCS scenario (Shogenova et al, 2011), and for Italian scenario it will be based on the published data.

Total cost of CCUS scenarios will be analysed based on CO_2 supply price, sharing of infrastructure, CO_2 injection and monitoring costs and revenues obtained from the CO_2 use. In addition to EEAP, analyzed scenarios will be sensitive to the world market oil price and geological uncertainties.

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ABBREVIATIONS, TERMS AND UNITS

Abbreviations

CCS – CO_2 Capture and Storage
CCUS – CO_2 Capture, Utilization and Storage
CDW – Concrete Demolition Waste
CO_2 – Carbon Dioxide
CO_2 – EOR – Enhanced Oil Recovery using CO_2
CO_2 – GER – Enhanced Geothermal Energy Recovery using CO_2
CO_2SP - CO_2 Supply Price
CP – Cement Plant
CPG – CO_2 Plume Geothermal
EEAP – European Emission Allowance Price (EEAP)
EHR – Enhanced Hydrocarbon Recovery
EOR – Enhanced Oil Recovery
EU – European Union
EU ETS – EU Emissions Trading System
GER – Geothermal Energy Recovery
GFD – Geological Formation Datasheet
GHG – Greenhouse Gas
GIE – Gas Infrastructure Europe
GIS – Geographic Information System
GSE – Gas Storage Europe
GSS – Geological Storage site
HRC – Horizontal Reservoir Compartmentalization
KNC – AS Kunda Nordic Tsement
MgO – Magnesium oxide
Mln – Million
NCT – National Carbon Tax
NPV – Net Present Value
OS – other large industrial sources of CO_2
OSAT – Estonian Oil-Shale Ash Tax
PP – Power Plant
RD – Reservoir Datasheet
RS – Rock Samples
SD – Seal Datasheet
VRC – Vertical Reservoir Compartmentalization
WP7 – Work Package 7

Terms

Baltic States – Estonia, Latvia and Lithuania
London Protocol – Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter

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Units

m – metre
Gcal/hr – Giga calories per hour
g/l – gram per litre
kg – kilogram
kg/m^3 – kilogram per cubic metre
km – kilometre
km^2 – square kilometre
kt – kiloton
kt/y – kiloton per year
kw/h – kilowatt per hour
l – litre
MMBO – million barrels of oil
MPa – mega Pascal
Mt – million tonnes
Mt/y – million tonnes per year
MW – megawatt
MWh – megawatt hours
m – metre
m/s – metres per second
mD – milli Darci
t – tonne
T, ˚C – temperature by Celsius
TJ – Terajoule
W – watt
W/(m K) – watts per meter-kelvin

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1. INTRODUCTION

The main objective of the WP7 of the CLEANKER project is to explore local and regional transport, utilization and storage needs, options and solutions in the vicinity of the demo system Vernasca Cement Plant in Italy (Lombardy Region), the Kunda Nordic Cement plant (KNC) in Estonia and Slantsev Cement Plant "Cesla" OJSC in Russia located in 16 km from Estonia-Russian border and 25-30 km from the largest Estonian power plants (Eesti, Balti and Auvere power plants).

According to conclusions made in D7.3, CO_2 use options in the studied countries include CO_2 use for EOR, GER and mineral carbonation using waste materials. They should be used in synergy with CO_2 storage and can compose business cases in both Italian and Baltic Scenarios.

According to the planned activities described for the WP7, the "building blocks" approach described in (EPRI, 2015) could be used for techno-economic estimations of CO_2 transport, storage and monitoring operations and their costs. For CO_2 use options, which are not included in the EPRI report, additional approaches are needed. They include new methodology for CO_2 mineral carbonation cost estimation, developed by authors of this report and available published tools and sources. Technical parameters collected into data sets for CO_2 mineral carbonation, CO_2-EOR and CO_2-GER, described in the next chapters, will be the basis to determine capital and operational costs of the planned scenarios.

The special attention was paid to the estimations of the total costs of the synergy projects, when total capital and operational costs of the scenarios and revenues from the CO_2 use will be considered together. All CCUS cost estimations are sensitive to the world oil price and EU ETS CO_2 allowance cost. The total scenario costs should be compared versus its revenues to estimate total economic costs and feasibility of the proposed projects for the taken oil price and EU ETS CO_2 allowance cost, projected for 2020-2025.

CO_2 supply cost for CO_2 use will depend also on CO_2 capture cost. As analysis of CO_2 capture costs is not target of this task, their numbers will be based on some reported and published data and assumptions, including modelling results from available publications and reports of the authors.

Techno-economic modelling task in WP7 should begin with data collection into GIS datasets for the areas of the selected cement plants about:

- Large industrial sources of CO_2 and power plants with emissions >100.000 t/y, which will be mapped using public European data bases such as EC ETS and other public national and international databases.
- Local and regional CO_2 storage options, including CO_2-EHR (Enhanced Hydrocarbon Recovery): this will include location, geological, technical parameters, properties of the reservoir and cap rocks, calculated storage capacity, maps of the top of the reservoir rocks, and geological sections of the storage sites, available boreholes, exploration data, including geophysical logging and seismic maps.

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- Public GIS databases collected during EU GeoCapacity and CO2Stopt projects, European and national geological databases and publications will be used. Already available and published national and regional CO_2 storage atlases will be used in some cases.
- Available natural gas pipelines as the most economic possible routes for CO_2 gas pipelines.
- CO_2 mineral carbonation options using waste materials: the amount of industrial waste (e. g. oil shale ash in the Baltic Scenario, its chemical composition, the capacity to produce by-products, estimated costs of by-products) available in the vicinity of the selected plants and their capacity to bind CO_2 will be estimated.

Based on the data collected, a techno-economic modelling of the selected local and regional CCUS scenarios will be made using methodology described in this report. Several suitable reservoir layers at the same storage site will be estimated. Synergy with renewable energy at the storage sites will be considered when suitable to provide CO_2-free energy support during storage operation and monitoring. The most cost-effective scenarios will be recommended for more detailed feasibility studies and business cases.

2. DATA BASE

Geographic Information System (GIS) software ArcGIS Desktop Platform (version 10.6) will be used for database collection, unification and mapping. ArcGIS Desktop includes two primary applications that will be used for mapping and visualization: ArcMap and ArcGIS Pro.

ArcMap will be used in ArcGIS Desktop for mapping, editing, analysis, and data management. ArcMap Google Map will be used as a basic map for Europe. ArcMap represents geographic information as a collection of layers and other elements in a map view. The map could be viewed in the ArcMap as the data view and the layout view. Maps could be designed from the collected set of layers, saved in the ArcMap in .mxd format files and could be printed and exported into Adobe PDF maps.

To compile data into GIS, Geographic coordinate system (Datum, Unit of measure, Zone for UTM, or State Plane), Projection and Projection parameters should be used. For the CLEANKER project we will use WGS 1984 coordinate system.

ArcGIS Pro will be applied for creating and working with spatial data on the desktop. It provides tools to visualize, analyse, compile, and share project data, in both 2D and 3D environments.

For easy database collection MS Excel data sheet files will be used. Collected data will be imported into ArcGIS data modules.

2.1 CO_2 EMISSIONS DATA

Detailed information on the CO_2 emission sources should be added at this stage to the data file "CO2E_country000.xls" (Figure 2.1). The data file includes three datasheets. According

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to the type of the CO_2 emission source, one of the three Excel sheets should be chosen within the file:

- CP for Cement plant
- PP for Power plant
- OS for other large industrial sources.

All the data must be given in maximum details using presented tables.

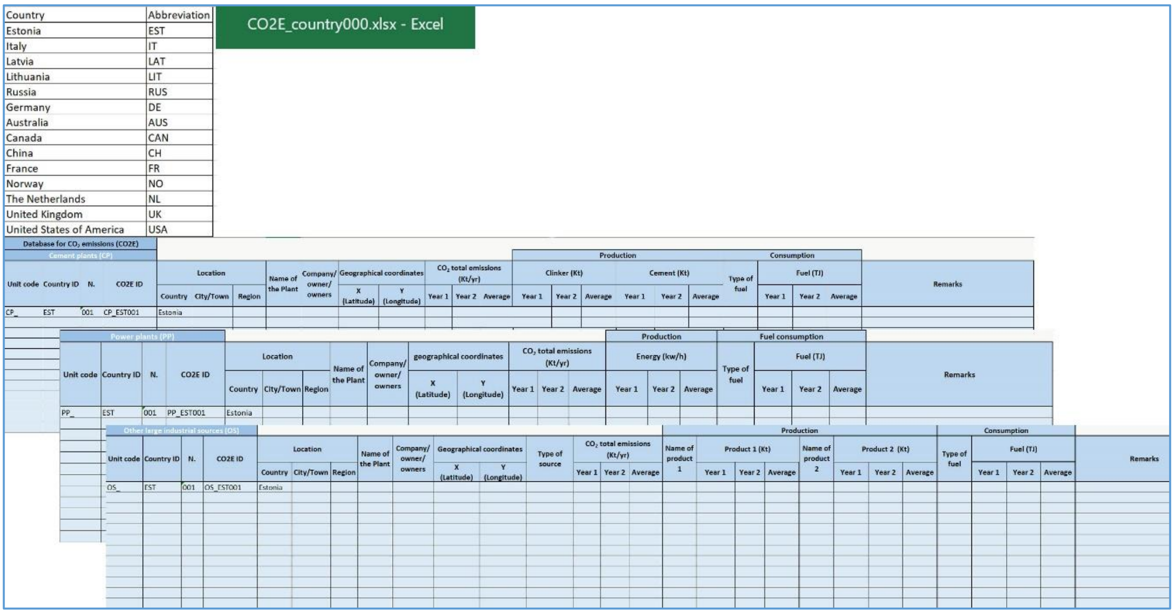

Figure 2.1: Data sheets for CO_2 emission sources (CO2E_country000.xlsx)

2.1.1 Cement plants

Each unit (Cement plant, CP) will get unique ID consisted of definition of unit – "CP" and initials of the country located (two, or three letters according to international rules, e.g. "IT", "EST" or "US") and random serial number. E.g. if Italy has two sites, they will have ID in a form of CP_IT001, CP_IT002, etc. (Table 2.1).

To present data on CP you will get table named "CO2E_country" (Figure 2.1). The table should be renamed according to your country, as described above. In the MS Excel table sheet "CP" in the column "Country ID" change example "EST" to your country abbreviation (abbreviation could be chosen in the drop-down menu in the cell). The CP ID will be generated automatically. You can copy this line, changing serial number of the structure in the column "N.", to present all sources.

Following parameters are needed for characterisation of the *Cement Plant (CP):*

- Location (country, city/town/region, onshore/offshore)
- Official name of the plant (brand)
- Geographical coordinates of the plant: X (latitude) & Y (longitude).

GPS-coordinates should be given in decimal degrees (59.499902; 26.534199) Example is given for the Kunda Nordic Cement Plant.

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- CO_2 total emissions (Kt/yr, add the previous available year of the plant produced CO_2 emissions – Year 1 and the last available year of the plant produced CO_2 emissions – Year 2; in the column "Average" the average emissions for two years should be calculated.
- Amount of the produced clinker (t, data from the previous available years in the Year 1 and last available year in the Year 2 (change the names of the columns according to the real year) and average amount of the clinker should calculated in the column "Average". You can add additional columns for the years if needed).
- Amount of produced Cement (t, data from the previous available year in Year 1 and last available year in the Year 2, (change the names of the columns according to the real year) and average amount of the cement should be calculated in the column "Average". You can add additional columns for the years if needed).
- Type of fuel used for energy production
- Consumption of fuel (TJ, data from the previous available year – Year 1 and the last available year - Year 2), (the names of the columns should be changed according to the real year) and average consumption of fuel should be calculated in the column "Average". You can add additional columns for the years if needed.
- Comments or additional description of the plant could be added in the Remarks column, if necessary.

Table 2.1: Specification of parameters for CO_2 emissions database (CO_2E)

Attribute	Unit/Entry	Single/ Range/ List	Format	Comments
Unit code	CP_,PP_, OS_	single	text	Cement plant, Power plant, Other sources
Country ID	EST, IT, LAT, LIT, RUS, etc.	single	text	Country abbreviation
N.	Number	single	number	Object number
CO_2E_ID	Unique ID number	single	text & number	Unique identification number in ArcGIS
Country		single	text	Country name
City/Town		single	text	City name
Region		single	text	Region name
Plant Name		single	text	Official Plant Name
Company/Owner/owners		Single, list	text	One or several Plant owners
X (Latitude)	Decimal degrees	Single	number	Centre point latitude in WGS 1984
Y (Longitude)	Decimal degrees	single	number	Centre point longitude in WGS 1984

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CO_2 total emissions, Year 1	Kt/y (Kilo tonnes/year)	single	number	Annual total CO_2 emissions
CO_2 total emissions, Year 2	kt/y (kiloton per year)	single	number	Annual CO_2 emissions
CO_2 total emissions, average	kt/y (kiloton per year)	single	number	Average for last 2 years
Type of fuel	Oil shale, gas, etc	Single, list	text	Additional columns could be added
Fuel consumption	TJ	single	number	Annual fuel consumption of the plant
Energy production	kw/h	Single	number	Annual energy production of the power plant
Clinker	kt/y (kiloton per year)	Single	number	Annual production of the cement plant
Cement	kt/y (kiloton per year)	Single	number	Annual production of the cement plant
Name of the product	Steel, iron, etc	Single, list	text	Name of the product for other sources of emissions
Production of Product 1, Year 1	kt/y (kiloton per year)	Single	number	Annual production of the product in Year 1
Production of Product 1, Year 2	kt/y (kiloton per year)	Single	number	Annual production of the product in Year 2
Production of Product 1, Average	kt/y (kiloton per year)	Single	number	Average production of the product will be calculated

2.1.2 Power plants

Each unit (Power plant, PP) will get unique ID consisted of definition of unit – “PP” and initials of the country located (two or three letters according to international rules, e.g. “IT”, “EST” or “US”) and random serial number. E.g. if Italy has two sites, they will have ID in a form of PP_IT001, PP_IT002, etc. (Table 2.1).

To present data on PP you will get table named “CO_2E_country” (Figure 2.1). The table should be renamed according to your country, as described above. In the MS Excel table sheet “PP” in the column “Country ID” change example “EST” to your country abbreviation (abbreviation could be chosen in the drop-down menu in the cell). The PP ID will be generated automatically. This line could be copied, serial number of the structure could be changed in the column “N.” to present all sources.

Following parameters are needed for characterisation of the *Power Plant (PP):*

- Location (country, city/town/region, onshore/offshore)
- Official name of the plant (Brand)

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- Geographical coordinates of the plant: X (latitude) & Y (longitude). GPS-coordinates could be given in decimal degrees (59.499902; 26.534199). Example is given for the Kunda Nordic Cement Plant.
- CO_2 total emissions (kt/yr, add the previous available year of the plant produced CO_2 emissions – Year 1 and the latest available year of the plant produced CO_2 emissions – Year 2; in the column "Average" the average emissions for two years will be calculated
- Amount of produced energy (kw/h, data from the previous available year – Year 1 and the latest available year - Year 2 (change the names of the columns according to the real year) and average amount of the energy will be calculated in the column "Average". You can add additional columns for the years if needed.
- Type of fuel used for energy production
- Consumption of fuel (TJ, data from the previous available year – Year 1 and the latest available year - Year 2), (change the names of the columns according to the real year) and average consumption of fuel will be calculated in the column "Average". Additional columns for the years could be added, if needed. Comment or additional description of the plant could be added into the Remarks column, if necessary.

2.1.3 Other large industrial sources

Each unit (Other sources, OS) will get unique ID consisted of definition of unit – "OS" and initials of the country located (two or three letters according to international rules, e.g. "IT", "EST" or "US") and random serial number. E.g. if Italy has two sites, they will have ID in a form of OS_IT001, OS_IT002, etc (Table 2.1).

To present data on OS you will get table named "CO_2E_country" (Figure 2.1). The table should be renamed according to your country, as described above. In the MS Excel table sheet "OS" in the column "Country ID" change example "EST" to your country abbreviation. Abbreviation could be chosen in the drop-down menu in the cell. The OS ID will be generated automatically. This line could be copied, and serial number of the structure could be changed in the column "N." to present all sources.

Following parameters are needed for characterisation of the *Other Industrial Sources (OS):*

- Location (country, city/town/region, onshore/offshore)
- Official name of the plant (brand)
- Geographical coordinates of the plant: X (latitude) & Y (longitude). GPS-coordinates could be given in decimal degrees (59.499902; 26.534199). Example is given for the Kunda Nordic Cement Plant.
- CO_2 total emissions (kt/y, add the previous available year of the plant produced CO_2 emissions – Year 1 and the latest available year of the plant produced CO_2 emissions – Year 2; in the column "Average" the average emissions for two years should be calculated.
- Name of the produced product.
- Amount of produced product (t, the name of the cell "Product 1-2" should be changed

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to the real name of the produced stuff, the previous available year of the plant – Year 1 and the latest available year of the plant produced the product – Year 2; in the column “Average” the average amount of the produced product for two years should be calculated.

- Type of fuel used for energy production.
- Consumption of fuel (TJ, data from the previous available year – Year 1 and the latest available year - Year 2), the names of the columns should be changed according to the real year) and average consumption of fuel should be calculated in the column “Average”. Additional columns for the years could be added if needed. Comment or additional description of the plant could be added in the Remarks column, if necessary.

2.2 CO_2 MINERAL CARBONATION

Detailed information on the CO_2 use options must be added at this stage to the data file “CO2U_country000.xls” (Figure 2.2). Excel sheet should be chosen within the file “MinCar” to add data for the site using mineral carbonation option. All the data must be given in maximum details using presented tables.

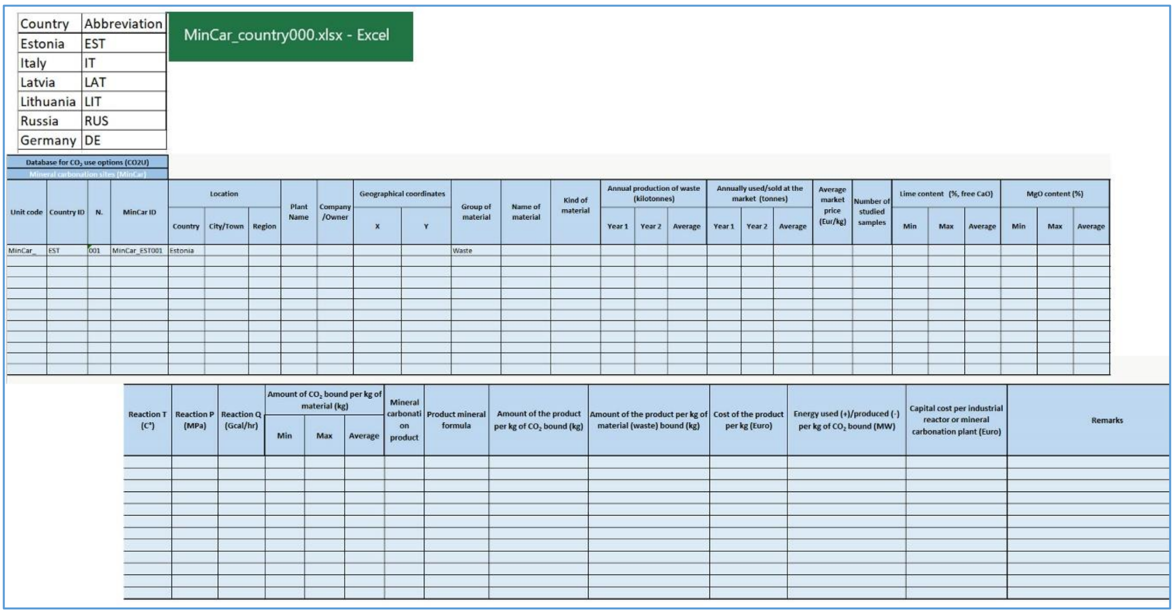

Figure 2.2: Data sheet for CO_2 mineral carbonation (MinCar_country000.xlsx)

Each unit (Mineral carbonation site, MinCar) will get unique ID consisted of definition of unit – “MinCar” and initials of the country located (two or three letters according to international rules, e.g. “IT”, “EST” or “US”) and random serial number. E.g. if Italy has two sites, they will have ID in a form of MinCar_IT001, MinCar_IT002, etc.

To present data on MinCar you will get a table named “MinCar_country”. The table should be renamed according to your country, as described above. In the MS Excel table sheet “MinCar” in the column “Country ID” the example “EST” should be changed to your country abbreviation (country abbreviation could be chosen from the drop-down menu in

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the cell) and press enter. The MinCar ID will be generated automatically. This line could be copied and serial number of the structure could be changed in the column "N.", to present all sources.

Following parameters are needed for characterisation of the *Mineral Carbonation* (MinCar, Table 2.2):

- Location (country, city/town/region, onshore/offshore)
- Official name of the plant (Brand)
- Geographical coordinates of the plant: X (latitude) & Y (longitude).

GPS-coordinates could be given in decimal degrees (59.499902; 26.534199). Example is given for the Kunda Nordic Cement Plant.

- Group of material (waste or rock should be selected from the drop-down menu in the cell)
- Name of material (must be written in a free form in the cell)
- Source of material (power plant, cement plant or rock mine could be selected from the drop-down menu in the cell)
- Annual production of waste (tonnes), produced waste in the previous year where data available – "Year 1", the latest available data for the plant operation – "Year 2" and "Average amount of the produced waste" during two last years will be calculated. The year of the latest available data "Year 2" and previous year "Year 1" – could be edited.
- Annually sold at the market (tonnes), used or sold at the market waste in the previous available data for plant operation – "Year 1", the latest available data for the plant operation – "Year 2" and "Average amount of the used waste" during two last years will be calculated). The year of the latest available data "Year 2" and previous year "Year 1" – should be edited into actual years (2018, 2017, etc.).
- Number of the studied samples
- Lime content (%, free CaO, min, max and average amount must be added)
- MgO content (%, min, max and average amount must be added)
- Reaction temperature (T, C°)
- Reaction pressure (P, MPa)
- Reaction Q (Gcal/hr)
- Amount of CO_2 bound per kg of material (kg, min, max and average amount must be added)
- Reaction product
- Product mineral formula
- Amount of the product per kg of CO_2 bound (kg)
- Amount of the product per kg of material (waste) bound (kg)
- Cost of the product per kg (Euro)
- Energy used (+)/produced (−) per kg of CO_2 bound (MW)
- Capital cost per industrial reactor or mineral carbonation plant

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Table 2.2: Specification of parameters for CO_2 mineral carbonation database (MinCar)

Attribute	Unit/Entry	Single/ Range/ List	Format	Comments
Unit code	MinCar_	single	text	
Country ID	EST, IT, LAT, LIT, RUS, etc	single	text	Country abbreviation
N.	Number	single	number	Object number
MinCarb ID	Unique ID number	single	text & number	Unique identification number in ArcGIS
Country		single	text	Country name
City/Town		single	text	City name
Region		single	text	Region name
Plant Name		single	text	Official Plant Name
Company/Owner/owners		Single, list	text	One or several plant owners
X (Latitude)	Decimal degrees	Single	number	Centre point latitude in WGS 1984
Y (Longitude)	Decimal degrees	single	number	Centre point longitude in WGS 1984
Group of material	Waste, mine waste, etc.	single	text	Group of material used for MC
Name of material	Oil shale ash, CDW, slag, olivine, etc.	single	text	Name of material used for MC
Kind of material	Bottom ash, fly ash, furnace slag, etc.	Single, range, list	text	Kind of material used for MC
Annual production of waste, Year 1	kiloton (kt)	Single	number	Annual production of waste by this plant
Annual production of waste, Year 2	kiloton (kt)	Single	number	Annual production of waste by this plant
Annual production of waste, Average	kiloton (kt)	Single	number	Average from Year 1 and Year 2
Annually used/sold at the market	tonnes (t)	Single	number	Amount of waste annually used/sold at the market

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Average market price	Euro/kg	Single	number	Average market price of the waste material
Number of studied samples		Single	number	Number of studied samples in CLEANKER task 7.5
Free CaO content	%	Single	number	Free CaO content in waste material
MgO content	%	Single	number	MgO content in waste material
Reaction Temperature (T)	Degrees, C	Single	number	
Reaction Pressure (P)	MPa	Single	number	
Reaction heat (Q)	Gcal/hr	Single	number	
Amount of CO_2 bound per kg of material	kg	Single	number	
Mineral carbonation product		Single/list	text	Name of produced minerals
Product mineral formula		Single/list	text	Chemical formula of the mineral
Amount of the product per kg of CO_2 bound (kg)	kg	Single	number	
Cost of the product per kg (Euro)	Euro	Single, range	number	
Energy used (+)/produced (−) per kg of CO_2 bound	MW (+, −)	single	number	Used energy in endothermic reaction/ produced energy in exothermic reaction
Capital cost per industrial reactor or mineral carbonation plant	Euro	single	number	
Remarks		List	text	References, data sources and comments

2.3 CO_2 TRANSPORT

Available natural gas pipelines infrastructure for European Countries including Russia will be taken from the Gas Storage Europe (GSE) storage map publically available at the Gas Infrastructure Europe (GIE) website at http://www.gie.eu/index.php/maps-data/gse-storage-map. Countries included in the CLEANKER scenarios (Estonia, Italy, Latvia, Lithuania and Russia), as well as EU countries for cluster projects are covered in this database. The 2018 version of GSE storage map are publically available and will be used for mapping gas pipelines infrastructure of the CLEANKER scenarios.

2.4 GEOLOGICAL STORAGE SITE DATA

Detailed information on the geological storage site must be added at this stage as much as

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possible. Many of these fields are important for estimations so must be filled in wherever possible. If some of important real data is not available, rock physical relations will be implemented to estimate them according to existing data (Castagna et al., 1993). In case of absence of important data try to find data from similar geological structures in the studied area. All the data must be given in maximum details using presented tables. All available samples with measurements should be added according to fields in the tables.

Each unit (Geological storage site, GSS) will get unique ID consisted of definition of unit – "GSS" and initials of the country located (two or three letters according to international rules, e.g. "IT", "EST" or "US") and random serial number. E.g., if Italy has two sites, they will have ID in a form of GSS_IT001, GSS_IT002, etc. To present data on GSS you will get table named "GSS_country" (Figure 2.3). The table should be renamed according to your country, as described above. In the table sheet "GFD" in the column "Country ID" example "LT" should be changed to your country abbreviation and press enter. The GSS ID will be generated automatically. This line could be copied, and serial number of the structure should be changed in the column "N." to present all structures.

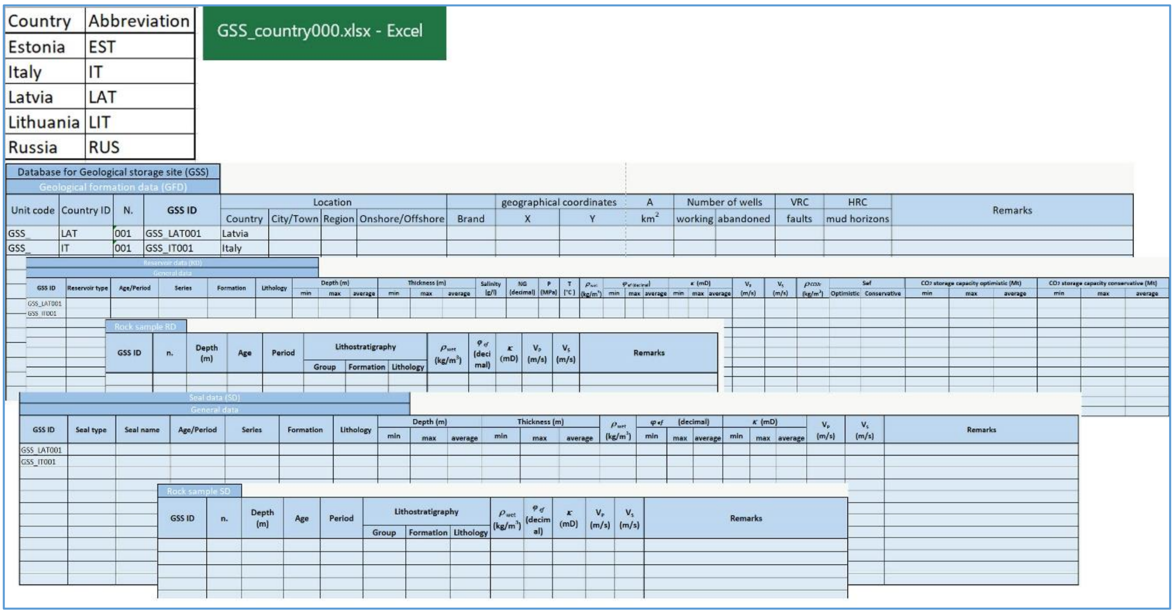

Figure 2.3: Data sheet for CO_2 geological storage site (GSS_country000.xlsx)

2.4.1 Geological Formation data (GFD)

Following data are needed to characterize geological formation of the CO_2 storage site (Table 2.3):

- Location (country, city/town/region, onshore/offshore)
- Official name of the geological site (Brand)
- Geographical coordinates: X (latitude) & Y (longitude) coordinates for the centre point of the formation
- Areal extension (A, km^2)

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- Number of wells penetrating the storage unit (“working” wells)
- Abandoned wells
- Vertical reservoir compartmentalization (VRC). If the reservoir contains barriers (e.g. faults) that are vertical, or inclined and form barriers to fluid flow, and thus divide the reservoir into compartments “YES” should be entered. If not, then “NO”. A comment about the type of barriers should be added into the Remarks box in the General table, sheet GFD after “VRC” and “HRC” columns
- Horizontal reservoir compartmentalization (HRC). If the reservoir contains horizontal barriers (e.g. mudstone horizons) that you consider likely to form barriers to fluid flow and thus divide the reservoir into stacked compartments, “YES” should be entered. If not, enter “NO”. A comment about the type of barriers should be added into the Remarks box in the General table, sheet GFD after “VRC” and “HRC” columns
- Graphical shape of the structure/geological basin linked to the projection (WGS84) should be sent to the work package administrator, if available.

Table 2.3: Specification of parameters for geological storage site database (GSS). Geological Formation Data (GFD).

Attribute	Unit/Entry	Single/ Range/ List	Format	Comments
Unit code	GSS_	single	text	Geological Storage Site
Country ID	EST, IT, LAT, LIT, RUS, etc.	single	text	Country abbreviation
N.	Number	single	number	Object number
GSS ID	Unique ID number	single	text & number	Unique identification number in ArcGIS
Country		single	text	Country name
City/Town		single	text	City name
Region		single	text	Region name
Onshore/offshore		single	text	
Brand		Single	text	Name of the site
X (Latitude)	Decimal degrees	Single	number	Centre point latitude in WGS 1984
Y (Longitude)	Decimal degrees	single	number	Centre point longitude in WGS 1984
Area (A)	km^2	single	number	
Number of wells working		single	number	
Number of wells abandoned		single	number	
Vertical reservoir compartmentalization (VRC) faults	Yes/No	single	text	

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Horizontal reservoir compartmentalization (*HRC)* mud horizons	Yes/No	single	text	
Remarks		list	text	References, data sources and comments

2.4.2 Reservoir datasheet (RD)

All available data on the reservoir must be given at this step (Table 2.4). Type of the reservoir should be selected from the drop-down menu in the Excel sheet "RD" in the General data table after column "GSS ID". The name of the reservoir should be entered into the appropriate column.

Following parameters are needed for *General Data* of the RD datasheet:

- Reservoir type (aquifer, salt formation, salt cavern, etc.)
- Age/Period (e.g. Cambrian, Ordovician)
- Series (Upper, Lower, Series 3)
- Formation (e.g. Deimena, etc.)
- Source rock (e.g. sandstone, salt, etc.)
- Depth of the top of reservoir (m, from the surface, min/max/average)
- Thickness (m, min/max/average)
- Salinity of the reservoir brine (g/l, grams per litter of water)
- Average net to gross ratio of the aquifer in the trap (NG, decimal fraction)
- Pressure (P, MPa)
- Temperature (T, °C)
- Bulk density of brine-saturated rock samples (ρ_{wet}, kg/m^3)
- Effective or open porosity (φ_{ef} ,decimal, min/max/average)
- Permeability (κ, mD, min/max/average)
- P- and S-wave velocities (V_P and V_S, m/s, respectively)
- CO_2 density in reservoir conditions (ρ_{CO2r})
- Storage efficiency factor (S_{ef}) - optimistic and conservative
- CO_2 storage capacity optimistic (M_{CO2}-opt, min, max, avg.)
- CO_2 storage capacity conservative (M_{CO2}-cons, min, max, avg.)

Petrophysical properties of reservoir rocks (if available) will be estimated from the rock samples list data or could be given manually

Following parameters are needed for *Rock Samples (RS*) datasheet of RD:

- Sample serial number (n., 1, 2, 3)
- Sample depth (m, from the surface)
- Age (e.g. Jurassic, Cambrian)
- Period (e.g. Upper, Lower)
- Lithostratigraphy (group, formation, lithology, e.g. Deimena Formation, sandstone)

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- Bulk density of brine-saturated rock samples (ρ_{wet}, kg/m^3)
- Effective or open porosity (φ_{ef}, decimal)
- Permeability (κ, mD)
- P- and S-wave velocities (V_P and V_S, m/s, respectively).

Table 2.4: Specification of parameters for geological storage site database (GSS). General reservoir data and reservoir rock samples in Reservoir Datasheet (RD).

Attribute	Unit/Entry	Single / Range / List	Format	Comments
GSS ID	Unique ID number	single	text & number	Unique identification number in ArcGIS
Reservoir type	Aquifer, salt formation, etc.	single	text	Type of storage reservoir
Age/Period	e.g. Cambrian, Ordovician, etc.	single, List	text	Geological age
Series	e.g. Upper, Lower, Series 3	single	text	Geological age
Formation	e.g. Deimena, etc.	single	text	Name of geological formation
Lithology	e.g. Sandstone, carbonate, salt	single, List	text	Rock name
Depth (min/max/average)	m	single	number	Depth from the surface
Thickness (*h*, min/max/average)	m	single	number	Reservoir thickness
Salinity	g/l – gram per litre	single	number	Water salinity
Average net to gross ratio of the aquifer in the trap (NG)	%	single	number	
Pressure (P)	MPa	single	number	Reservoir pressure
Temperature (T)	Degrees, C	single	number	Reservoir temperature
Bulk density of brine-saturated rock samples (ρ_{wet})	kg/m^3 – kilogram per cubic metre	single	number	
Effective or open porosity (min/max/average) φ_{ef}	Decimal fraction	single	number	
Permeability (κ, min/max/average)	mD (milli Darcy)	single	number	
P- wave velocity (V_P)	m/s	single	number	
S-wave velocity (Vs)	m/s	single	number	

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CO_2 density in reservoir conditions (ρ_{CO2r})	kg/m^3	single	number	Depends on temperature and pressure in storage reservoir
Storage efficiency factor (S_{ef}) - optimistic and conservative	Decimal fraction	single	number	
CO_2 storage capacity optimistic (M_{CO2}-opt, min, max, avg.)	Million tonnes (Mt)	single	number	CO_2 storage capacity calculated with formula (2.1) using optimistic S_{ef}.
CO_2 storage capacity conservative (M_{CO2}-cons, min, max, avg.)	Million tonnes (Mt)	single	number	CO_2 storage capacity calculated with formula (2.1) using conservative S_{ef}
Remarks		list	text	References, data sources and comments

2.4.3 CO_2 storage capacity calculation

The theoretical storage capacity of structures is calculated using formula for the estimation of the capacity of a structural trap (Bachu et al., 2007) and parameters that are already described above:

$$M_{CO2t} = A \times h \times NG \times \varphi \times \rho_{CO2r} \times S_{ef}, \quad 2.1$$

where

- M_{CO2t} is storage capacity (kg)
- A is the area of the reservoir in the trap (m^2)
- h is the average thickness of the reservoir in the trap (m)
- NG is an average net to gross ratio of the reservoir in the trap (decimal)
- φ is the average porosity of the reservoir in the trap (decimal)
- ρ_{CO2r} is the in situ CO_2 density in reservoir conditions (kg/m^3)
- S_{ef} is the storage efficiency factor (for the trap volume, decimal)

If NG is not known, it will be estimated using available geological cross-sections of the structure/reservoir. CO_2 density in reservoir conditions will be estimated as a function of temperature and storage pressure in the reservoir. The CO_2 storage efficiency factor is the volume of CO_2 that could be stored in the reservoir per unit volume of original fluids in place. S_{ef} will be estimated according to Bachu et al. (2007) and Vangkilde-Pedersen et al. (2009). Optimistic CO_2 storage capacity is calculated with formula (1) and using optimistic storage efficiency factor (S_{ef}). Conservative CO_2 storage capacity is calculated with formula (2.1) and using conservative storage efficiency factor (S_{ef}). Minimum, maximum and average

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CO_2 storage capacity is calculated using minimum, maximum and average porosity correspondingly and should be added to the Excel sheet "RD".
All available data should be sent to the work package administrator (geological maps with location of faults, cross-sections, petrophysical properties).

2.4.4 Seal datasheet (SD)

All available data on the cap rock must be given at this step. Type of the seal should be selected in the drop-down menu (Primary or Secondary) in the Excel sheet "SD" in the General data table after column "GSS ID" (Table 2.5). The name of seal must be entered into the appropriate column. If your structure has also secondary seal, the name of any secondary seal that lies above the primary seal should be added.
Following parameters are needed for *General Data* datasheet of SD:

- Source rock
- Depth of the top of cap rock (m, below surface, min/max/average)
- Thickness (m, min/max/average)
- Bulk density of brine-saturated rock samples (ρ_{wet}, kg/m^3)
- Effective or open porosity (φ_{ef}, decimal, min/max/average)
- Permeability (κ, mD, min/max/average)
- P- and S-wave velocities (V_P and V_S, m/s, respectively)

Petrophysical properties of reservoir rocks (if available) will be estimated from the rock samples list data or could be given manually
Following parameters are needed for *Rock Sample* datasheet of SD:

- Sample serial number (n., 1, 2, 3)
- Sample depth (m, from the surface)
- Age (e.g. Silurian, Ordovician)
- Period (e.g. Upper, Lower)
- Lithostratigraphy (group, formation, lithology, e.g. Zebre Formation, limestone)
- Bulk density of brine-saturated rock samples (ρ_{wet}, kg/m^3)
- Effective or open porosity (φ_{ef}, decimal)
- Permeability (κ, mD)
- P- and S-wave velocities (V_P and V_S, m/s, respectively)

Table 2.5: Specification of parameters for geological storage site database (GSS). General and rock samples data for Seal Datasheet (SD).

Attribute	Unit/Entry	Single/ Range/ List	Format	Comments
GSS ID	Unique ID number	single	text & number	Unique identification number in ArcGIS

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Seal type	Primary, secondary	single	text	Both primary and secondary seals should be described
Seal Name	e.g. Zebre Formation, etc.	Single	text	Geological name of seal
Age/Period	e.g. Cambrian, Ordovician, etc.	single, List	text	Age of seal
Series	e.g. Upper, Lower, Series 3, etc.	single	text	Age of seal
Formation	e.g. Zebre, etc.	single	text	Name of Formation
Lithology	e.g. claystone, shale, siltstone, etc.	single, list	text	Name of rock
Depth (min/max/average)	m	single	number	Depth from the surface
Thickness (min/max/average)	m	single	number	
Bulk density of brine-saturated rock samples (ρ_{wet})	kg/m^3	single	number	
Effective or open porosity (min/max/average, φ_{ef})	Decimal fraction	single	number	
Permeability (κ, min/max/average)	mD (milli Darcy)	single	number	
P- wave velocity (V_P)	m/s	single	number	
S-wave velocity (Vs)	m/s	single	number	
Remarks		list	text	References, data sources and comments

2.4.5 Maps, sections and models

All available geological maps, cross-section and models must be sent at this stage to provide complete evaluation of the storage site. If graphical shape files of the maps and sections linked to the projection (for example WGS84) are available they should be sent to work package administrator together with coordinates of the central point for each shape file.

2.5 ENHANCED HYDROCARBON RECOVERY (EHR)

Each unit (Enhanced hydrocarbon recovery site, EHRS) will get an unique ID consisted of definition of unit – “EHRS” and initials of the country located (two or three letters according to international rules, e.g. “IT”, “EST” or “US”) and random serial number. E.g. if Italy has two sites, they will have ID in a form of EHRS_IT001, EHRS_IT002, etc.

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To present data on Enhanced hydrocarbon recovery site (EHRS) you will get table named "EHRS_country" (Figure 2.4). The file must be renamed according to your country, as described above. In the table sheet "GFD" in the column "Country ID" the example "LT" must be changed to your country abbreviation. The EHRS ID will be generated automatically. You can copy this line, changing serial number of the structure in the column "N.", to present all structures.

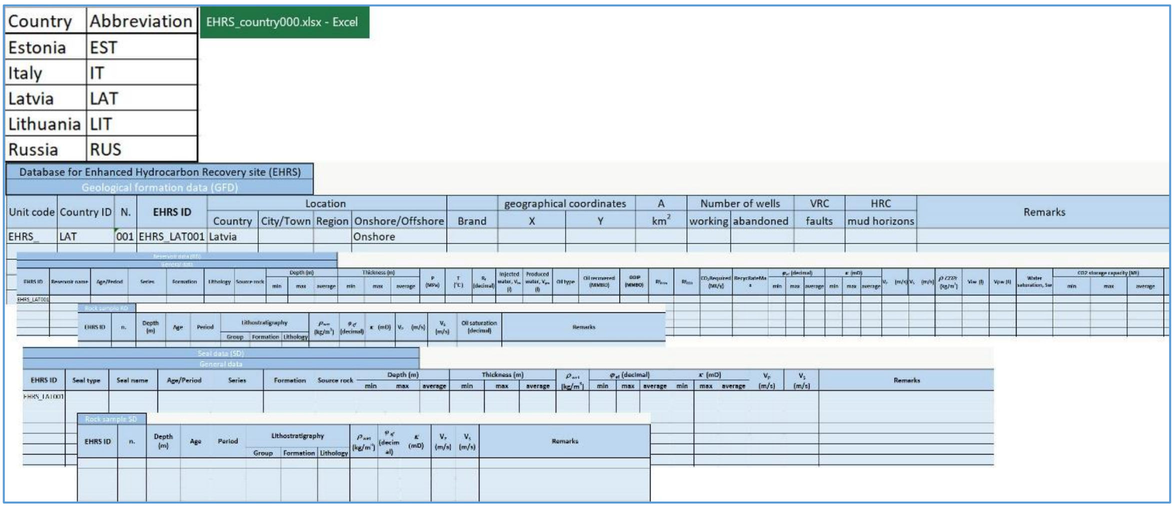

Figure 2.4: Data sheet for CO_2 Enhanced hydrocarbon recovery site (EHRS _country000.xlsx)

2.5.1 Geological Formation data (GFD)

Data needed to be collected for characterization of the geological formation of the CO_2 Enhanced hydrocarbon recovery and storage site are similar to that of the geological storage site (Table 2.3):

- Location (country, city/town/region, onshore/offshore)
- Official name of the geological site (Brand)
- Geographical coordinates: X (latitude) & Y (longitude) coordinates for the centre point of the formation
- Areal extension (A, km^2)
- Number of wells penetrating the storage unit ("working" wells)
- Abandoned wells
- Vertical reservoir compartmentalization (VRC). If the reservoir contains barriers (e.g. faults) that are vertical or inclined and form barriers to fluid flow and thus divide the reservoir into compartments "YES" should be entered. If not, then "NO". A comment about the type of barriers should be added into the Remarks box in the General table, sheet GFD after "VRC" and "HRC" columns
- Horizontal reservoir compartmentalization (HRC). If the reservoir contains horizontal barriers (e.g. mudstone horizons) that you consider likely to form barriers to fluid flow and thus divide the reservoir into stacked compartments, "YES" should be entered. If

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not, enter “NO”. A comment about the type of barriers shoul be added into the Remarks box in the General table, sheet GFD after “VRC” and “HRC” columns

- Graphical shape of the structure/geological basin linked to the projection (WGS84), should be sent to the work package administrator, if available.

2.5.2 Reservoir data (RD)

All available data on the reservoir must be given at this step. Please enter the name of the oil reservoir in the appropriate column in the Excel sheet “RD” in the General data table after column “EHRS ID”.

General RD. Following data are needed for characterization of storage reservoir of the CO_2 storage site (Table 2.6):

- Reservoir type (oil or gas field)
- Age/Period (e.g. Cambrian, Ordovician)
- Series (e.g. Upper, Lower, Series 3)
- Formation (e.g. Deimena, etc)
- Source rock
- Depth of the top of reservoir (m, from the surface, min/max/average)
- Thickness (m, min/max/average)
- Pressure (P, MPa)
- Temperature (T, °C)
- Recovery factor (R_f)
- Volumes of injected (V_{iw})
- Volumes of produced water (V_{pw})
- Oil type (in the drop-down menu the type must be selected from the cell: Very light, Light, Medium, Heavy)
- Oil recovered (in millions barrels of oil, MMBO)
- OOIP, Oil originally in place (Mbbl, physical amount of oil available in the reservoir)
- R_{Prim} (Primary recovery rate; fraction of the OOIP that is recovered without tertiary production)
- R_{EOR} (EOR recovery rate; fraction of the OOIP oil that can be recovered with CO_2-EOR)
- CO_2Required (Mt/y, Maximum amount of CO_2 required for injection)
- RecycRateMax (Maximum recycling rate of CO_2, expressed as a fraction of CO_2 injected)
- Bulk density of brine-saturated rock samples (ρ_{wet}, kg/m^3)
- Effective or open porosity (φ_{ef} , decimal, min/max/average)
- Permeability (κ, mD, min/max/average)
- P- and S-wave velocities (V_P and V_S, m/s, respectively)

Petrophysical data of the reservoir rock will be estimated from the rock samples list data (if available) or could be given manually.

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Rock sample data RD. Following data are needed for characterization of rock samples from the storage reservoir (Table 2.6):

- Sample serial number (n., 1, 2, 3)
- Sample depth (m, from the surface)
- Age (e.g. Jurasic, Cambrian)
- Period (e.g. Upper, Lower)
- Lithostratigraphy (group, formation, lithology, e.g. Deimena Formation, sandstone)
- Bulk density of brine-saturated rock samples (ρ_{wet}, kg/m^3)
- Effective or open porosity (φ_{ef} , decimal)
- Permeability (κ, mD)
- P- and S-wave velocities (V_P and V_S, m/s, respectively)
- Oil saturation (decimal)

Table 2.6: Specification of parameters for Enhanced Hydrocarbon Recovery site (EHRS). Reservoir Data (RD) and Rock samples (RS).

Attribute	Unit/Entry	Single/ Range/ List	Format	Comments
GSS ID	Unique ID number	single	text & number	ARCGIS Unique identification number
Reservoir type	Oil or gas field	single	text	
Age/Period	e.g. Cambrian, Ordovician, etc	single, List	text	Geological age
Series	e.g. Upper, Lower, Series 3	single	text	Geological age
Formation	e.g. Deimena, etc.	single	text	Geological Formation
Lithology	e.g. Sandstone, carbonate	single, List	text	Rock name
Source rock	e.g. Sandstone, carbonate	single	text	Rock name
Depth (min/max/average)	m	single	number	Depth from the surface
Thickness (min/max/average)	m	single	number	
Pressure (P)	MPa	single	number	
Temperature (T)	Degrees, C	single	number	
Recovery factor (R_f)	Decimal fraction	single	number	
Water saturation (Sw)	Decimal fraction	single	number	

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Volumes of injected water (V_{iw})	Litre (l)	single	number	Water test results
Volumes of produced water (V_{pw})	Litre (l)	single	number	Water test results
Oil type	Very light, Light, Medium, Heavy	Sandstone, carbonate	single	Select from menu
Oil recovered	Millions barrels of crude oil (MMBO)	single	number	Oil produced from the reservoir
Oil originally in place (OOIP)	Million barrels of oil in place (MMBO)	single	number	Physical amount of oil available in the reservoir
Rf_{prim} (Primary recovery rate)	Decimal fraction	single	number	Fraction of the OOIP that is recovered without tertiary production
Rf_{EOR} (EOR recovery rate)	Decimal fraction	single	number	Fraction of the OOIP oil that can be recovered with CO_2-EOR)
Reservoir water saturation (Sw)	Decimal fraction	single	number	
CO_2Required (Maximum amount of CO_2 required for injection)	Million tonnes (Mt)	single	number	
RecycRateMax (maximum recycling rate of CO_2)	Decimal fraction	single	number	Fraction of CO_2 injected
Bulk density of brine-saturated rock sample (ρ_{wet})	kg/m^3	single	number	
Effective or open porosity (min/max/ average, φ_{ef})	Decimal fraction	single	number	
Permeability (κ, Min/max/average)	mD (milli Darcy)	single	number	
Oil saturation	Decimal fraction			
P- wave velocity (V_P)	m/s	single	number	
S-wave velocity (Vs)	m/s	single	number	
CO_2 density in reservoir conditions (ρ_{CO2r})	kg/m^3	single	number	Depends on temperature and pressure in reservoir

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CO_2 storage capacity (M_{CO2}, min, max, avg.)	Mt	single	number	CO_2 storage capacity calculated with formula (2.2)
Remarks		list	text	References, data sources and comments

2.5.3 Storage capacity calculation

Equation (2.2) for calculating the CO_2 storage capacity in oil and gas reservoirs is based on the geometry of the reservoir (areal extent and thickness), as given in reserves databases (Bachu, 2008), includes parameters that have been already described above:

$$M_{CO2t}=\rho_{CO2r}\times[Rf\times A\times h\times \varphi\times(1-S_w)-V_{iw}+V_{pw}], \qquad 2.3$$

where

- ρ_{CO2r} - CO_2 density in reservoir conditions (kg/m^3)
- Rf - recovery factor (decimal)
- A - reservoir area (m^2)
- h – reservoir thickness (m)
- φ - reservoir porosity (decimal)
- S_w - reservoir water saturation (decimal)
- V_{iw} and V_{pw} - the volumes of injected and produced water, respectively.

Minimum, maximum and average CO_2 storage capacity is calculated using minimum, maximum and average porosity, correspondingly.

2.5.4 Seal data (RD)

Seal data for EHRS has the similar data sheet and parameters as described in the chapter 2.4.3 for GSS and in the table 2.5.

2.5.5 Maps, sections and models

All available geological maps, cross-section and models should be sent at this stage to provide complete evaluation of the storage site. If graphical shape files of the maps and sections linked to the projection (for example WGS84) are available, they should be sent to work package administrator together with coordinates of the central point for each shape file.

2.6 ENHANCED GEOTHERMAL ENERGY RECOVERY (CO_2-GER)

Each unit (Enhanced Geothermal Recovery site, EGRS) will get unique ID consisted of definition of unit – “EGRS” and initials of the country located (two or three letters according to international rules, e.g. “IT”, “EST” or “US”) and random serial number. E.g. if Italy has two sites, they will have ID in a form of EGRS_IT001, EGRS_IT002, etc.

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To present data on Enhanced geothermal energy recovery site (EGRS) you will get table named “EGRS_country” (Figure 2.5). The file should be renamed according to your country, as described above. In the table sheet “GFD” in the column “Country ID” the example “LT” must be changed into your country abbreviation. The EHRS ID will be generated automatically. This line could be copied and serial number of the structure should be changed in the column “N.” to present all structures.

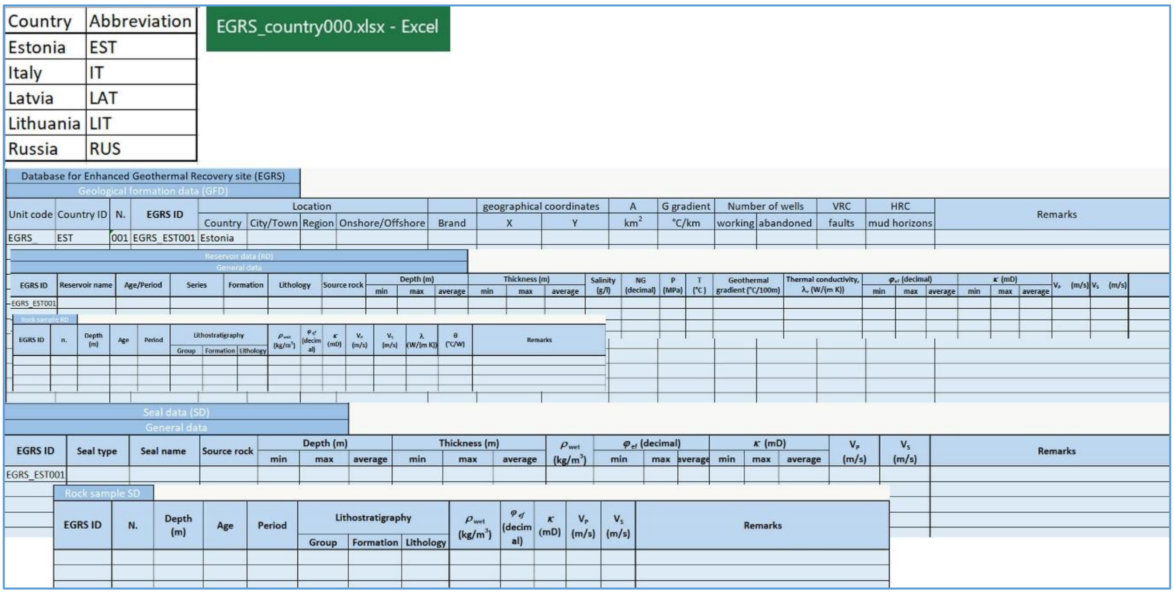

Figure 2.5: Data sheet for CO_2 Enhanced geothermal energy recovery site (EGRS _country000.xlsx)

2.6.1 Geological Formation data (GFD)

Following data are needed to characterize geological formation of the CO_2 storage and GER site:

- Location (country, city/town/region, onshore/offshore)
- Official name of the geological site (Brand)
- Geographical coordinates: X (latitude) & Y (longitude) coordinates for the centre point of the formation
- Areal extension (A, km^2)
- Number of wells penetrating the storage unit (“working” wells)
- Abandoned wells
- Vertical reservoir compartmentalization (VRC). If the reservoir contains barriers (e.g. faults) that are vertical or inclined and form barriers to fluid flow and thus divide the reservoir into compartments “YES” should be entered. If not, then “NO”. A comment about the type of barriers should be added into the Remarks box in the General table, sheet GFD after “VRC” and “HRC” columns
- Horizontal reservoir compartmentalization (HRC). If the reservoir contains horizontal barriers (e.g. mudstone horizons) that you consider likely to form barriers to fluid flow and thus divide the reservoir into stacked compartments, “YES” should be entered. If

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not, enter “NO”. A comment about the type of barriers shoul be added into the Remarks box in the General table, sheet GFD after “VRC” and “HRC” columns

- Graphical shape of the structure/geological basin linked to the projection (WGS84), should be sent to the work package administrator, if available.

2.6.2 Reservoir data (RD)

Data needed for characterization of the reservoir and rock samples for CO_2 storage and GER site are given in Table 2.7.

Table 2.7: Specification of parameters for Enhanced Geothermal Recovery site (EGRS). Reservoir Data (RD) and Rock samples (RS).

Attribute	Unit/Entry	Single/ Range/ List	Format	Comments
GSS ID	Unique ID number	single	text & number	Global System Unique identification number
Reservoir type	Aquifer, oil or gas field, etc.	single	text	Type of geothermal reservoir
Age/Period	e.g. Cambrian, Ordovician, etc.	single, List	text	Geological age
Series	e.g. Upper, Lower, Series 3	single	text	Geological age
Formation	e.g. Deimena, etc.	single	text	Geological Formation
Lithology	e.g. Sandstone, carbonate, salt	single, List	text	Rock name
Depth (min/max/average)	m	single	number	Depth from the surface
Thickness (*h*, min/ max/ average)	m	single	number	
Salinity	g/l	single	number	
Pressure (P)	MPa	single	number	
Temperature (T)	Degrees, °C	single	number	
Geothermal gradient (°C/100m)	Degrees, °C	single	number	
Thermal conductivity (λ)	W/(mK) – watts per meter-kelvin	single	number	
Bulk density of brine-saturated rock samples (ρ_{wet})	kg/m^3	single	number	
Effective (open) porosity (min/max/ average, φ_{ef})	Decimal fraction	single	number	

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Permeability (κ, min/max/average)	mD (milli Darcy)	single	number	
P- wave velocity (V_P)	m/s	single	number	
S-wave velocity (Vs)	m/s	single	number	
CO_2 density in reservoir conditions (ρ_{CO2r})	kg/m^3	single	number	Depends on temperature and pressure in storage reservoir
Thermal conductivity (λ) of wet samples	W/(mK) – watts per meter-kelvin	single	number	
Thermal resistance (θ) of wet samples	(mK)/W – meter-kelvin per watt	single	number	
Remarks		list	text	References, sources and comments

2.6.3 Seal data (SD)

Seal data for EGRS has the similar data sheet and parameters as described in the chapter 2.4.3 for GSS and in the Table 2.5.

2.7 CLUSTER PROJECTS

In addition to the specific local and regional scenarios, the opportunities of first-of-a-kind (FOAK) commercial exploitation of CaL in cement plants operated by BUZZI and HeidelbergCement Group in the vicinity of large CO_2 clusters and hubs will be assessed. A CCS hub and cluster network brings together multiple CO_2 emitters and/or multiple storage locations using shared transportation infrastructure. Areas, where there is both a high concentration of CO_2 emitting industries and a nearby capacity to store emissions, are considered prime sites for hub and cluster developments. Hub and cluster networks offer several distinct advantages for network participants, compared with 'point-to-point' projects. The hub and cluster approach reduces costs and risks for many potential CCS projects, and enables CO_2 capture from small volume industrial facilities. A number of industrial regions have the potential to develop CCS hubs and clusters (IEA, 2015a).

2.7.1 List of cluster projects

Each unit (Cluster project, CLUSTER) will get unique ID consisted of definition of unit – "CLUSTER" and initials of the country located (two or three letters according to international rules, e.g. "AUS", "UK" or "USA") and project ID. Project ID could be found in the table "Project Abbreviation" in the Excel sheet "Countries & Projects" and could be selected from the drop-down menu in the "Total data" sheet. E.g. if the Netherlands project of the Rotterdam have to be selected, it will get ID in a form of CLUSTER_NL_ROTT, etc. (Figure 2.6).

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To present data on CLUSTER you will get Microsoft Excel table-file named "CLUSTER_country_project.xlsx". The table should be renamed according to your country and project, as described above. In the MS Excel table sheet "Total data" in the column "Country ID" the example "AUS" should be changed to your country abbreviation (abbreviation could be chosen in the drop-down menu in the cell). The same way, the example of Project ID "_COLL" should be changed (abbreviation could be chosen in the drop-down menu in the cell). After described manipulations the "Cluster ID" will be generated automatically.

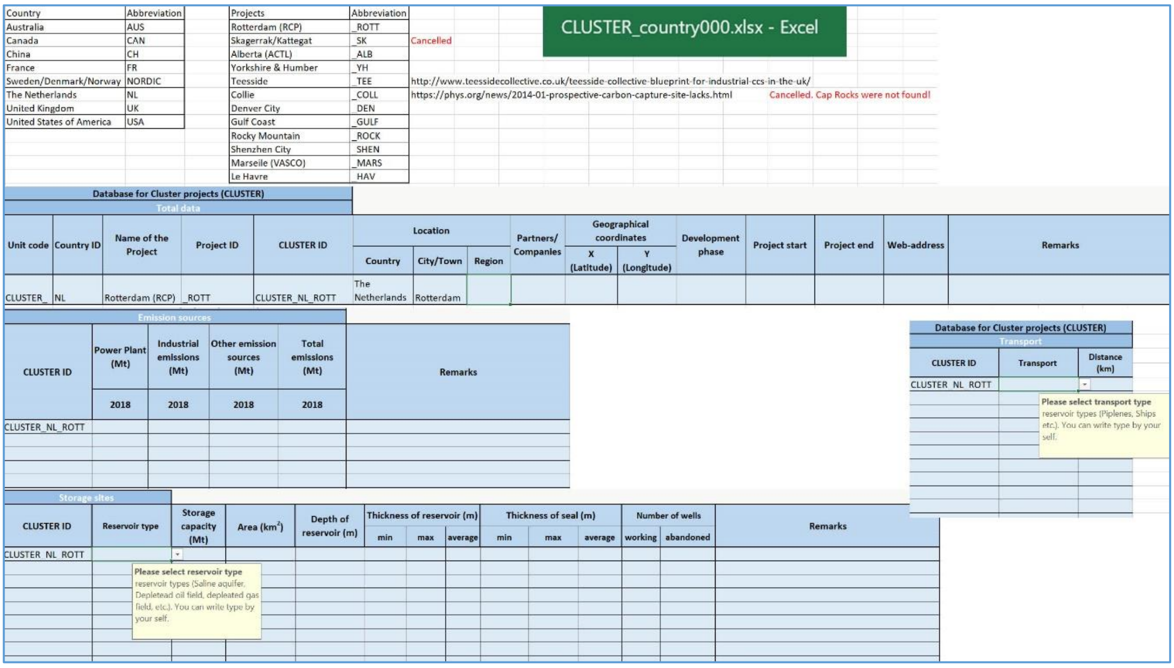

Figure 2.6: Data sheet for CLUSTER projects (CLUSTER _country000.xlsx)

Total data datasheet for the cluster projects (CLUSTER) includes the following parameters, also described in Table 2.8:

- Location (country, city/town, region)
- Partners (Companies)
- Geographical coordinates of the plant: X (latitude) & Y (longitude). GPS-coordinates could be given in decimal degrees (59.499902; 26.534199). Example is given for the Kunda Nordic Cement Plant.
- Development phase
- Project start
- Project end
- Web-addresses
- Comments or additional description of the plant could be added in the Remarks column, if necessary.

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2.7.2 Clusters of emissions

Emission clusters are described in the data sheet *Emission Sources* (Figure 2.6) by four columns:

- Power Plants
- Industrial Emissions
- Other emissions Sources
- Total emissions

In these columns annual volumes of CO_2 emissions produced by plants included in this Cluster should be added.

2.7.3 Storage sites

Storage sites datasheet (Figure 2.6) includes the following parameters of the storage sites included in the cluster projects:

- Reservoir type (should be selected from the drop-down menu)
- Storage capacity (Mt)
- Area (km^2)
- Depth of reservoir (m)
- Thickness of reservoir (m) – min, max, average
- Thickness of seal (m) – min, max, average
- Number of wells: working, abandoned
- Comments or additional description of the plant could be added in the Remarks column, if necessary.

2.7.4 CO_2 transport

CO_2 transport in the cluster project will be described by the following parameters in the datasheet *Transport* (Figure 2.6):

- Transport (pipelines, ferry, truck, train)
- Distance (km)

Table 2.8: Specification of parameters for Cluster projects database (Cluster)

Attribute	Unit/Entry	Single/ Range/ List	Format	Comments
Unit code	CLUSTER_	single	text	
Country ID	AUS, CAN, CH, etc.	single	text	Country abbreviation could be selected from the drop-down menu
Name of the project	Project's name	single	text	Project's name could be selected from drop-down menu

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Project ID	Unique project abbreviation	single	text	Global System Unique identification number
CLUSTER ID	Unique ID number	single	text	Global System Unique identification number
Country		single	text	Country name could be selected from drop-down menu
City/Town		single	text	City name
Region		single	text	Region name
Partners		single	text	Companies
X (Latitude)	Decimal degrees	Single/list	number	
Y (Longitude)	Decimal degrees	single/list	number	
Development phase	Operating, Construction, Planning, Study	single	text	
Project start	dd.mm.yyyy	single	date	
Project end	dd.mm.yyyy	single	date	
Web-address		Single/list	text	
Emission sources: Power plant, Industrial, Other Sources	Million tonnes, Mt	single	number	Annual CO_2 emissions of every emission source
Emission sources: Total emissions	Million tonnes, Mt	single	number	Total annual CO_2 emissions of the cluster
Reservoir type	Saline aquifer, Depleted oil or gas field, etc.	single	text	Reservoir type could be selected from drop-down menu
Storage capacity	Million tonnes, Mt	single	number	
Area	km^2	single	number	
Depth of reservoir	m	single	number	Depth from the surface
Thickness of reservoir	m	single	number	
Thickness of seal	m	single	number	
Number of wells: working		single	number	
Number of wells: abandoned		single	number	
Transport type	Pipelines. ferry	single	text	
Transport distance	km	Single, list	number	

3. GEOLOGICAL MODELLING OF STORAGE SITES

For geological modelling step, in order to build a 3D numerical static model, it is

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recommended to use Petrel software (Schlumberger), a common 3D geological modelling, simulation, visualization and reservoir engineering software often used for the oil and gas exploration. This is an advanced tool for accurate spatial analysis of geological structures and reconstruction of the 3D geological models. Petrel provides different modelling techniques, such as facies modelling and stochastic simulations by using different geostatistical algorithms and evaluating geostatistical data. The main benefits of this software are integration of different type of available and modelled geoscientific data into one common 3D numerical model of the geological object and permitting population of the constructed layers with various rock properties.

Proposed methodology includes the following steps:

- Available cross sections of the wells of the geological structure and available seismic profiles should be studied to estimate the geological horizons and their depths. Then horizons and its depths should be inserted into the Petrel with coordinates of the wells cross section locations.
- Structural maps of the top reservoir, cap rock and other horizons (if available) should be constructed in ASCCI format by digitizing of available maps in e.g., Golden Software Surfer, or available digitized maps could be used. Structural maps must be inserted into Petrel and linked with geographical coordinates. Wells location must be linked with geographical coordinates. Fault system, if exists, should be added.
- Stratigraphic boundaries must be considered. Minimum three boundary must be specified: (1) top of the cap rock, (2) top of the reservoir and (3) bottom of the reservoir. Points' sets representing geological horizons must be then converted into gridded surfaces.
- Main zones of the model must be defined. At least two main zones have to be defined in the model representing, (1) cap rock and (2) reservoir units.
- Using available log data of the wells, more precise internal layering within the reservoir, the cap rock or other layers could be specified in the model in order to increase the vertical resolution of the grid and to take the lithological and petrophysical partitioning of the reservoir into account. The size of the cell must be set up.
- Geological lithofacies will be modelled in order to constrain the distribution of porosity and permeability in the geological model.
- The volumetric grid must be populated with obtained data (using different modelling algorithms, e.g. Stochastic algorithm).
- The model must be populated with facies and petrophysical properties using different modelling algorithms of Geostatistical Software Library (e.g. Truncated Gaussian Simulation, Sequential Indicator Simulation, Gaussian Random Function).

Proposed methodology should be applied to construct geological models of the storage sites in two CLEANKER scenarios (Italian and Baltic).

The data availability could be the main risk factor. If there is not enough exploration data (seismic, well logging, etc.), then the nearest available geological data could be used for

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characterisation for example of secondary cap rocks. The reservoir and primary cap rocks of the storage site and their properties should be known from the drilling exploration data and studied rock samples.

4. SCENARIO MODELLING

For modelling of CCUS scenarios planned in the CLEANKER project, the database described in chapter 2 including data on cement plants and other large emission sources located in the vicinity, or in one emission cluster, will be used. For modelling of the transport routes, available (and collected into the database) natural gas pipelines infrastructure will be considered. Storage sites for scenarios will be chosen among the most prospective structures in saline aquifers and depleted oil and gas fields. Parameters which are sensible for cost estimation will be considered to decrease transport and storage costs. The following pros and contras will be considered during scenarios selection:

- Onshore storage is cheaper than offshore. However, public communication of onshore storage is more complicate than for offshore projects.
- Transboundary offshore CO_2 storage is not yet permitted, because of not yet ratified amendment to the article 6 of the London protocol.
- CO_2 storage capacity could be increased using more than one storage reservoir at the same storage site. However this approach could also increase CO_2 storage monitoring costs and uncertainties during CO_2 storage modelling.
- CO_2 use options, their costs and revenues should be estimated in details in order to demonstrate their influence on the cost of one tonne of CO_2 avoided in the full chain CCUS project.

4.1 TECHNICAL PARAMETERS

4.1.1 CO_2 emissions

To calculate CO_2 emissions (produced by the cement plant and other large emission sources) which will be included into the scenario, the most recent data collected into the datasheets, will be considered. Average annual emissions, calculated from the produced and reported for the last two years, will be considered for scenario modelling.

To calculate amount of CO_2 captured and transported the following assumptions will be taken:

- CO_2 will be captured at the cement plants using Ca-looping technology developed by CLEANKER project.
- CO_2 will be captured at the power plants using Oxyfuel combustion process.
- For any other CO_2 large emission source involved, the best practice for CO_2 capture will be considered and applied, considering available studies and modelling results (Shogenova et al, 2011).
- It is assumed that high-purity CO_2 has been collected from the cement and power plants and compressed to a maximum of 15 Mpa for introduction to the pipeline and transport.

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- The cost estimates therefore will not include calculation of costs of CO_2 capture and compression, as these costs are the subject for research in the other work packages of the CLEANKER project.
- However, when these costs will be needed for estimation of CO_2 mineral carbonation costs, or CO_2 supply price, the ready values will be taken from the CLEANKER project results, or other available reports and publications.

4.1.2 Pipelines design and specifications

The best practices and standards for CO_2 pipelines currently exist in Europe like (DNV-RP-J202, 2010). The International Standard ISO 27913 "Carbon dioxide capture, transportation and geological storage. Pipeline transportation Systems" was published in 2016 (ISO 27913, 2016). This standard was developed in 2016 by the Technical Committee of the ISO/TC 265 (Carbon dioxide capture, transportation, and geological storage) and was purchased at the Estonian ISO Standards organisation by the WP7 of the CLEANKER project to be used for the CLEANKER scenarios technical specifications.

The pipelines will be designed using X70 steel and 1500 lb flange rating (rated to 25.5 Mpa upper working pressure) with a maximum allowable working pressure of 15 MPa. The pipeline diameter will be selected depending on the distance and flow-rate of CO_2 calculated for the specific scenario. Fig. 102 from (EPRI, 2015) will be applied. Number of boosters needed for CO_2 recompression, their capital and operating costs will be discussed in the "Costs" section.

4.1.3 Injection infrastructure

Injection infrastructure will include wells, storage site facilities and monitoring equipment. Operation can include old wells reuse (if any available), new wells drilling, geophysical well logging and well-head pressure and temperature monitoring, CO_2 injection and monitoring of the storage site. It will include baseline monitoring, operational monitoring and post-closure monitoring. The number of wells needed is a function of the CO_2 flow-rate, and storage reservoir properties including thickness, total injection depth and permeability (EPRI, 2015).

4.2 CRITERIA FOR PROJECT DURATION AND SUSTAINIBILITY

The project duration D is calculated by formula:

$$D = \frac{MCO_2}{CO_2 total\_inj} \quad (4.1)$$

where

MCO_2 – average storage capacity of the structure, Mt (million tonnes)

CO_2total_inj– CO_2 emission flow total to be injected during the project duration, Mt

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The project could be considered sustainable if it is able to cover the full lifetime of the emission sources (usually 30 years) and if the storage capacity is enough for emissions produced during this project duration. The shorter project duration will cause increase of the costs per one tonne of CO_2 avoided.

5. ECONOMIC MODELLING

Economic estimations for CCUS scenarios will strongly depend on two parameters: the oil price and European Emissions Allowance Price (EEAP) defined by EU Emissions Trading System (EU ETS).

5.1 OIL PRICE

In the Australian Power Generation Technology Report (EPRI, 2015), which will be used for techno-economic estimation of transport and storage costs, two oil prices per barrel (bb) are applied for some of the costs. These are 50 AUD/bb and 100 AUD/bb. The currency rate of Australian dollar to Euro for the time of the modelling will be applied to recalculate these oil prices and all economic estimations available in EPRI report (2015). For recalculation of all costs from AUD (EPRI, 2015) to EURO, the fixed relation AUD=0.68 EUR available in 2015, will be applied. For example, 50 AUD=34 EURO and 100 AUD=68 EURO will be used.

The oil price, which is closer for the actual oil price at the market during time of the modelling, will be applied. For example, for the average oil price of 62 Euro in 2018, the costs calculated for the 100 AUD=68 EURO will be applied.

If the difference between actual oil price at the time of modelling and one of two given prices by EPRI for 2015 is distinguished by more than 10%, then additional correction coefficients for the higher, or lower oil prices could be applied additionally.

5.2 EUROPEAN EMISSIONS ALLOWANCE PRICE (EEAP)

EU Emission Trading System (EUETS) previously known as the EU Emissions Trading Scheme, currently is known in four operating phases (EU ETS, 2018):

Phase I (2005 - 2007) and was a 'learning by doing phase'; *Phase II* **(**2008 - 2012 and includes revised monitoring and reporting rules, more stringent emissions caps and additional combustion sources; *Phase III* (2013 - 2020) brings major changes including, harmonised allocation methodologies and additional greenhouse gases and emission sources.

For ongoing Phase *III*, European Commission Regulations have been published for monitoring and reporting, and for verification and accreditation of verifiers. A monitoring plan is required for every installation and aircraft operator (approved by competent authority). Enforcement Entities must pay an 'excess emissions penalty' of EUR 100/tCO2 emitted for which no allowance has been surrendered in due time. The name of the non-

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compliant operator is also published. Different penalties exist at the national level for other forms of non-compliances (ICAP, 2018).

Phase IV, is proposed for 2021-2030. In July 2015, the European Commission presented a legislative proposal for the revision (EC, 2015b) of the EU ETS for the fourth trading period. The proposed changes include an increase in the pace of emissions cuts (the overall number of allowances will decline at an annual rate of 2.2% from 2021 onwards, compared with 1.74% currently), the better targeted and more dynamic allocation of free allowances, and several support mechanisms to help the industry and power sectors meet the innovation and investment challenges of the transition to a low-carbon economy.

The EU ETS works on the "cap and trade" principle. This means there is a "cap", or limit, on the total amount of certain greenhouse gases that can be emitted by the factories, power plants and other installations in the system. Within this cap, companies receive emission allowances which they can sell to or buy from one another as needed. The limit on the total number of allowances available ensures that they have a value. At the end of each year each company must surrender enough allowances to cover all its emissions, otherwise heavy fines are imposed.

If a company reduces its emissions, it can keep the spare allowances to cover its future needs or else sell them to another company that is short of allowances. The flexibility that trading brings ensures that emissions are cut where it costs least to do so.

The EU ETS has proved that putting a price on carbon and trading in it can work. Emissions from installations in the system are falling as intended – by slightly over 8% compared to the beginning of phase 3.

In 2020**,** emissions from sectors covered by the system will be 21% lower than in 2005**.** In 2030**,** under the revised system they will be 43% lower**.** The 2013 cap for emissions from stationary installations was set at 2 084 301 856 allowances. This cap decreases each year by a linear reduction factor of 1.74% of the average total quantity of allowances issued annually in 2008-2012, thus ensuring that the number of allowances that can be used by stationary installations will be 21% lower in 2020 than in 2005.

The EU ETS now operates in 31 countries (the 28 EU Member States plus Iceland, Liechtenstein and Norway). It covers around 45% of the EU's GHG emissions.

As of Phase 3 (2013-2020), the sectors with stationary installations regulated by the EU ETS are energy intensive industries, including power stations and other combustion plants with >20MW thermal rated input (except hazardous or municipal waste installations), oil refineries, coke ovens, iron and steel, cement clinker, glass, lime, bricks, ceramics, pulp, paper and board, aluminium, petrochemicals, ammonia, nitric, adipic, glyoxal and glyoxylic acid production, CO_2 capture, transport in pipelines and geological storage of CO_2.

Several support mechanisms help the industry and the power sectors meet the innovation and investment challenges of the transition to a low-carbon economy.

Two new funds: Innovation Fund – extending existing support for the demonstration of innovative technologies to breakthrough innovation in industry and Modernisation Fund –

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facilitating investments in modernising the power sector and wider energy systems and boosting energy efficiency in 10 lower income Member States. Free allowances continue to be available to modernise the power sector in these lower-income Member States (EC, 2017, EU ETS, 2018).
Since its creation in 2005, the European emission trading system (EU ETS) has been through several periods of turmoil. With EEAP averaging around 7 euros per ton from 2012 to 2017. Much to everyone's surprise, 2018 has finally set a radically different trend, with EEAP rising beyond double-digit levels (up to 25 Euro) and more than trebling since the start of the year. With current prices around 20-25 euros per ton even before the implementation of the new market stability reserve rules (starting from 2019), most analysts have reviewed their figures and estimate the carbon price will reach 35 to 40 euros per ton in 2023 (Roig-Ramos, 2018).

5.3 CO_2 SUPPLY PRICE (CO_2SP)

The cost of CO_2 supplied for CO_2 use is assumed for simplicity according to the approach used in (IEA, 2015b).
The cost of CO_2 supplied (CO_2SP) is equal to the difference between CO_2 capture cost (NPVcapture) and the European Emission Allowance Price (EEAP) from EU ETS and National Carbon Tax (NCT) for CO_2 emissions already set up in some EU countries.

$$CO_2SP = NPVcapture - EEAP - NCT$$

A positive CO_2SP indicates that it costs more to capture CO_2 than to pay for the emissions allowance through EU ETS and paying NCT. In this case the CO_2 emitter would sell CO_2 to the operator of CO_2 use activity, as is commonly the case today for CO_2-EOR. A negative CO_2SP means that the CO_2 emission allowance price together with NCT are higher than the cost to capture CO_2. This creates incentive for the CO_2 emitter to pay for the CO_2 to be verifiably stored.
NCT is implemented in Estonia since 2000 to CO_2 emissions from industry and power sector and covers all fossil fuels used for thermal energy (heat) production and it is 2 Euro per tonne of CO_2 emissions produced (RT I 2005, 67, 512). Estonian NCT is partly overlapping with EU ETS, but considering that only part of the Power Plants capacity is used for heat production, Estonian NCT is not fully overlapping with EEAP) from EU ETS. The national Estonian income from this NCT was 3 million Euros in 2017, meaning that NCT was paid for only 1.5 mln tonnes of CO_2, produced during heat production.
In Latvia NCT (5 Euro per tonne of CO_2 produced) is implemented since 2004 and applies to CO_2 emissions from industry and power sector not covered under the EU ETS (Saema, 2018).
CO_2SP for the Baltic Scenario could be calculated using some results available from the economic modelling of the Estonian-Latvian CCS scenario (Shogenova et al, 2011). The

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NPVcapture cost of 25.5 Euro per tonne of CO_2 avoided which was modelled for Estonian two largest PP (Eesti and Balti) using oxyfuel combustion technology will be applied. Additionally CO_2 compression cost (NPVcompression is 2.8 Euro per tonne CO_2 avoided) and CO_2 transport cost (NPVtransport is 5.3 Euro per tonne of CO_2 avoided) could be added when transport is needed for the long distance.

Considering that EEAP has already reached 25 Euro in 2018 and is modelled as 35-40 Euro for 2023, it is very probable to reach negative supply price at the nearest terms.

For CO_2 mineral carbonation applied in the vicinity of the produced and captured CO_2:

$$CO_2SP = NPVcapture + NPVcompression - EEAP \quad 5.1$$

If CO_2 will be used for EOR and GER in the Baltic Scenario, then additionally transport costs will be added:

$$CO_2SP = NPVcapture + NPVcompression + NPVtransport - EEAP \quad 5.2$$

In case when cement plant and oil operator from Russia will be involved in the common Baltic scenario, the mechanism known as "joint implementation", defined in Article 6 of the Kyoto Protocol, allows a country with an emission reduction or limitation commitment under the Kyoto Protocol (Annex B Party) to earn emission reduction units (ERUs) from an emission-reduction or emission removal project in another Annex B Party, each equivalent to one tonne of CO_2, which can be counted towards meeting its Kyoto target.

Joint implementation offers Parties a flexible and cost-efficient means of fulfilling a part of their Kyoto commitments, while the host Party benefits from foreign investment and technology transfer (UNFCCC, 2018).

5.4 CO_2 USED VERSUS CO_2 CAPTURED, PRODUCED AND AVOIDED

CO_2 captured is lower than CO_2 produced, while CO_2 avoided is lower than CO_2 captured (Figure 5.1). CO_2 used ex-situ for mineral carbonation (CO_2used_{MC}) should be calculated and excluded from CO_2 flow transported and injected (Table 5.1). For example, for Estonian oil shale ash the maximum value of K_{MC} is 0.18, as up to 180 kg of CO_2 could be bound by 1000 kg of oil shale ash.

Table 5.1: CO_2 used versus CO_2 injected and CO_2 avoided equations for CCUS project

Parameter	Equation/explanation	Units	Comments	N
$CO_{2usedMC}$	$M_{waste} * K_{MC}$	Mt/y	CO_2 used for mineral carbonation	5.3
$CO_{2injected}$	$CO_{2captured} - CO_{2usedMC} - CO_{2produced\text{-}ESS}$	Mt/y	CO_2 injected for MC and storage	5.4

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$CO_{2avoided(MC+St)}$	CO_2used_{MC} + $CO_{2injected}$ – $CO_{2produced-ESS}$	Mt/y	CO_2 avoided for MC and storage	5.5
$CO_{2avoided-EOR}$	$CO_{2injected}$ – $CO_{2emitted-ESS}$ – $CO_{2emitted-Separation}$	Mt/y	CO_2 avoided for EOR and storage project	5.6
M_{waste}	Amount of waste available per year	Mt/y		
K_{MC}	CO_2 storage coefficient of the specific waste	decimal		
$CO_{2produced-ESS}$	Additional CO_2 produced at the storage site due to energy use	Mt/y		
$CO_{2emitted-Separation}$	Additional CO_2 produced at the storage site due to energy use for CO_2 separation	Mt/y		

However, if geothermal energy will be used at the storage site, then no additional CO_2 will be produced during CO_2 use and storage operations at the storage site, because geothermal energy is not associated with CO_2 production.

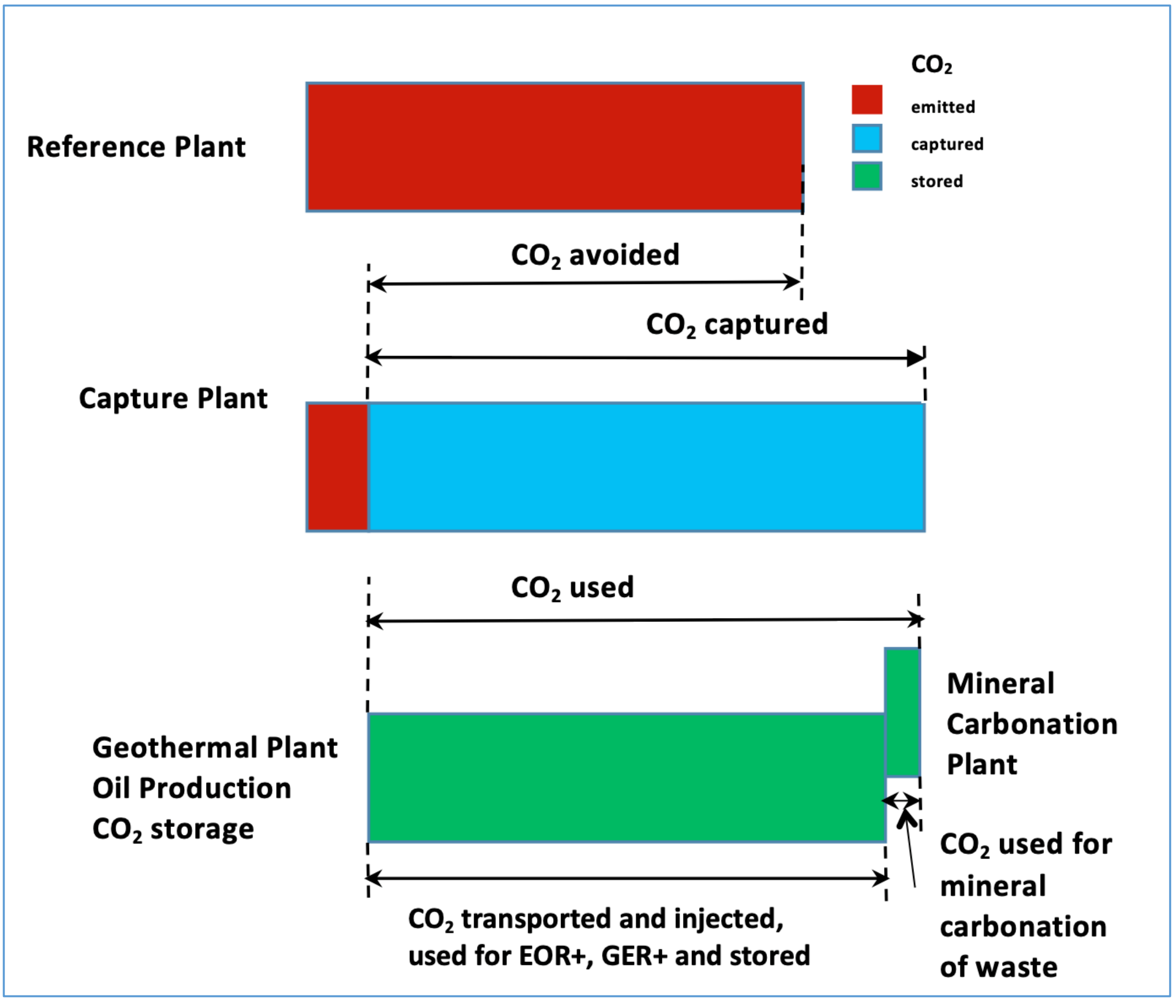

Figure 5.1: CO_2 avoided (green) versus CO_2 produced (red), captured (blue) and used

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5.5 CO_2 TRANSPORT

5.5.1 Pipelines

The cost of pipelines will be estimated using Pipelines Capex as a function of transport distance and CO_2 flow-rate (EPRI, 2015, Fig. 104) and operating cost for pipelines will taken as 1% from the capital costs. Costs for offshore pipelines are higher than onshore.

5.5.2 Boosters

Recompression using booster pumps will be needed to keep CO_2 in a dense phase when the pressure will drop below 8 Mpa. The capital costs of booster pumps is a function of CO_2 flow-rate, and recompression duty is a function of discharge pressure, which is different for various CO_2 flow-rates (EPRI, 2015, Fig. 107). Operating costs for boosters will be taken as fixed 4% from the capital costs and additionally variable operating cost. The last one will determined using booster pump duty and energy required for their operation. CO_2 emissions produced during this operation will be included in calculation of CO_2 emissions avoided.

5.6 INJECTION

5.6.1 Wells

Wells drilling costs depend on oil prices and different for offshore and onshore drilling. Operating and maintaining costs for wells will be taken as 2% from the capital cost. If horizontal wells are needed, their more expensive drilling costs than for vertical wells should be considered. If new wells will be drilled, then logging and coring cost will be added. In case of old abandoned wells will be used, the costs of their reopening will be applied instead of the drilling costs.

5.6.2 Storage facilities

Onshore storage facilities include a simple distribution network to take the CO_2 from the pipeline out to one or more injection wells. The capital costs per km of well spacing depend on the number of wells and CO_2 flow-rate. Operation costs will be taken as 2% from capex. Offshore storage facilities will include the offshore platform with a simple distribution network. The cost of the platform depends on the number of wells and limited by five well slots per platform. Operation costs will be taken as 4% from the capital cost.

5.7 MONITORING AND VERIFICATION

Monitoring costs will depend on monitoring plan designed by the operator according to the article 13 of EU CCS Directive and Annex I and II of the Directive. These plans should be composed according to the best available practice and have to be updated every 5 years. Operator is reporting the results of the monitoring to Competent Authority every year. The state of the art and requirements for monitoring methods is given in (Rütters et al, 2013, Niemi et al, 2017). Considering the requirement of EU CCS Directive (EC, 2009), monitoring plan will include seismic exploration (baseline, operational, post-closure)

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permitting to monitor CO_2 plume behaviour; measurements of CO_2 fugnitive emissions, CO_2 volumetric flow, temperature and pressure at injection wellheads and reservoir temperature and pressure.

The coring and logging costs will be included in the budget of the well drilling and logging operating costs and will be added to the overall monitoring cost of the project.

The cost of the additional logging equipment stored in the well outside or inside casing will be added to the capital costs of the project. As an example, such equipment for integrated monitoring well can include: U-tube fluid sampling, pressure-temperature gauges and integrated fiber-optic bundle for temperature, seismic and heat-pulse monitoring, etc (Niemi et al, 2017). The costs of such innovative equipment for integrated monitoring of well designed specifically for CO_2 monitoring projects will be asked from geophysical worldwide companies like Schlumberger Carbon or similar. The monitoring of the onshore projects could require additional soil monitoring to detect possible CO_2 leakage pathways. This could be done using available shallow wells (if any available) usually used for water monitoring. These costs will be added to monitoring and verification costs.

6. DATA ASSUMPTION AND METHODOLOGY

Specifications of economic assumption for the transport and storage scenarios are given in (Table 6.1). The average cost per tonne of CO_2 injected, or per tonne of CO_2 avoided for the project duration (30-years) is calculated using formula:

$$\text{CAPEX}/t_{CO_2} = \frac{CCRxTPC+FOM}{CO_2\ injected}\text{, (Euro/tonne } CO_2\text{)} \quad 6.1$$

$$\text{OPEX}/t_{CO_2} = \frac{CCRxCOSToper}{CO_2\ injected}\text{, (Euro/tonne } CO_2\text{)} \quad 6.2$$

$$\text{MVEX}/t_{CO_2} = \frac{COSTmv}{CO_2\ injected}\text{, (Euro/tonne } CO_2\text{)} \quad 6.3$$

$$\text{ENEREX}/t_{CO_2} = \frac{COSTenergy}{CO_2\ injected}\text{, (Euro/tonne } CO_2\text{)} \quad 6.4$$

$$\text{COSTtotal}/t_{CO_2} = \text{CAPEX}/t_{CO_2} + \text{OPEX}/t_{CO_2} + \text{MVEX}/t_{CO_2} + \text{ENERGEX}/t_{CO_2} \quad 6.5$$

where

- CAPEX/t_{CO_2} – total capital expenses (pipeline, booster, wells or/and storage facilities) per one tonne of CO_2 injected/avoided during project duration
- OPEX/t_{CO_2} – operational and maintenance expenses per one tonne of CO_2 injected/avoided during project duration
- MVEX/t_{CO_2} – monitoring and verification expenses per one tonne of CO_2 injected/avoided during project duration

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- ENEREX/t_{CO_2} – energy expenses per one tonne of CO_2 injected/avoided during project duration
- COSTtotal/t_{CO_2} - total transport and storage costs per one tonne of CO_2 injected/avoided during project duration
- CCR – capital charge rate (%)
- TPC – total plant cost (Euro) = BEC + decom + interest
- BEC – bare erected cost for pipeline, booster, wells or/and storage facilities
- Decom – decommissioning cost (Euro)
- Interest – interest paid during construction (Euro)
- FOM – annual fixed operating and maintaining cost (Euro/year)
- COSToper - annual onsite operating costs, including design, engineering, environmental assessment, project/site supervision, management, logistics fees and equipment/project contingencies (Euro/year)
- COSTmv – annual monitoring and verification cost (Euro/year)
- COSTenergy – annual energy cost (Euro/year)
- CO_2 injected – annual amount of CO_2 injected (Mt/y)

Table 6.1: Specifications of economic assumption for the transport and storage scenarios (updated from Table 99, EPRI, 2015)

Parameter	Units
Nominal cost of equity	%
Nominal cost of debt	%
Percentage debt	%
Inflation	%
Company tax rate	%
Property tax/insurance	%
Year of analysis	2017/2018
Currency	Euro
Asset book life	years
Asset tax life	years
EEAP	Euro/tCO_2
Real equity	%
Real debt	%
Nominal before tax WACC	%
Nominal after tax WACC	%
Real before tax WACC	%
Real after tax WACC	%
Total capital requirement	Euro
Grid power cost	Euro/MWh
CO_2 emission intensity	t/MWh
Capacity factor	%

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Load factor	hours
Real capital charge rate (CCR)	%
Operation cost	Euro
Construction period	years

6.1 COSTS AND REVENUES OF CO_2 USE

6.1.1 CO_2 mineral carbonation

The costs for mineral carbonation will be estimated based on the technical and economic parameters collected into the Mineral Carbonation dataset and incorporated into GIS.

Minimum, maximum and average values obtained duting CO_2 mineral carbonation experiments with the studied materials and samples will be considered. For the cost estimation average values of parameters studied and obtained during laboratory experiments and pilot activities in Vernasca cement plant will be considered.

Capital cost will include the costs of mineral carbonation plant erection. It is considered that mineral carbonation plant will be built near, or at the largest producer of CO_2 emissions and waste material. For the Baltic scenario such producer is Eesti Power Plant (the largest CO_2 and ash produced among three Baltic States).

The case of concrete production using captured CO_2 and oil shale ash at the Kunda Nordic Cement Plant will be estimated. It is expected that not all waste material (oil shale ash) will be possible to use for the concreate production. Therefore, the mineral carbonation plant, producing neutralised carbonate material from captured CO_2 and oil shale ash will be considered. The costs of captured CO_2 will be considered for calculation of costs of the mineral carbonation products.

According to Estonian environmental law the Estonian national tax for oil shale ash production is 2.98 Euro per tonne of oil shale ash produced (RT I 2005, 67, 512). This cost could be extracted from the total oil shale ash mineral carbonation costs.

Operating costs will include transportation of the waste material to the carbonation plant and its loading into reactor. Operating costs for mineral carbonation will be taken as 2% from capital cost, considering exothermic nature of the mineral carbonation reaction and cost of water, which could be added to control increased temperature and to compensate the moisture loss due to evaporation in the reactor. In case in captured CO_2 at the cement plant will be wet, the water addition will be not needed. During upscaling from laboratory to pilot scale and from pilot to industrial scale the temperature of CO_2 mineralisation process could increase up to 900˚C. Theoretically this waste heat could be used together with other waste heat at the Mineral Carbonation Plant that can provide additional revenue. However the Capital and operational costs of such Waste Heat Plant should be estimated separately and is not target of this report.

The cost of the material produced during mineral carbonation reaction will be estimated based on the market price. The total amount of these product produced per year will be calculated based on the average values of the binding ability and amount of the available

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for carbonation material. It is expected that carbonated product will be used for concrete production. The capacity of the cement plant/plants included in the scenario for using carbonated product for concrete production should be calculated, considering annual production of the cement. The rest amount of the carbonated material should be calculated to be sold at the market. The possible input from the by-product will be subtracted from the total CCUS costs.

From the total cost for mineral carbonation per one tonne of CO_2 avoided the following costs will be subtracted:

- EEAP (EU ETS)
- OSAT - Estonian tax for oil-shale ash (calculated per one tonne of CO_2 bound)
- market price of the by-product (calculated per one tonne of CO_2 bound)

The total cost of mineral carbonation per one tonne of CO_2 avoided will be calculated as

$$COSTmincarb = COST(CO_2capt + compr)\frac{CCRxTMTPC + FOM}{CO2used} - EEAP - OSAT - MCPproduct \qquad 6.6$$

where:

- COSTmincarb - cost of mineral carbonation per one tonne of CO_2 avoided
- COST(CO_2capt+compr) is cost for one tonne CO_2 captured and compressed
- CCR is capital charge rate (%)
- TMCPC is total mineral carbonation plant cost (Euro)=MCPC+decom+interest
- MCPC is bare erected costs for Mineral Carbonation Plant
- FOM is annual fixed operating and maintaining cots (Euro/year)
- EEAP is European Emission Allowance Price (EEAP)
- OSAT is Estonian tax for oil-shale ash (calculated per one tonne of CO_2 bound)
- MCPproduct – market price of mineral carbonation product/per one tonne of CO_2 bound.

6.1.2 CO_2-EHR

Parameters collected for enhanced hydrocarbon recovery using CO_2 (CO_2-EHR) will be the base for technical and economic estimates. Revenue from the hydrocarbon recovery will be estimated based on the average oil-prices taken for the whole CCUS project and on the average oil/gas prices in the country of use during last year.

The possibility for reusing of abandoned hydrocarbon wells will be one of the most important benefit to save capital costs during CO_2 storage site construction.

The revenue from oil/gas production will be characterised by a set of parameters collected and calculated during techno-economic study, which are considered as input parameters in (Welkenhuysen et al, 2018):

- the amount of oil already recovered,
- the maximum amount of oil possible to recover using CO_2,
- the start of oil recovery after CO_2 injection,

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- duration of oil recovery,
- total duration of CO_2injection,
- duration of CO_2 injection after stop of hydrocarbon recovery.

According to (IEA, 2015b) operating costs for CO_2-EOR include five operations: CO_2 injection**,** oil-gas-water separation, storing CO_2 through Enhanced Oil Recovery, CO_2-gas separation and clean-up, CO_2 recycling and compression and long-term monitoring. We will analyse all there parts of the operation activities, considering assumed synergetic character of our scenarios.

Two of these operations - CO_2 injection operations and CO_2-storage site monitoring_are common operations for CO_2 storage and CO_2 use projects and will not need additional capital cost for the synergy project. These costs have been already described in the chapters 5.6 and 5.7.

Other three operations are to be added additionally to the storage projects and will comprise additional capital and operating costs.

Oil-gas-water separation – the collection of fluids from the production wells; their transport to production facilities; the separation of oil, gas and water; the treatment of water for disposal; and the collection of gases for further processing.

CO_2-gas separation and clean-up comprises activities to separate hydrocarbons from CO_2 and to adjust the composition of hydrocarbon streams to meet commercial specifications for export.

CO_2 recycling and compression includes the compression of separated CO_2 and its mixing with new-purchased CO_2.

The capital costs compared to pure CO_2 storage operations will additionally include CO_2 separation, cleaning and measuring unit. CO_2 separated from the produced oil will be reinjected back underground. Operating costs for separation and reinjection will be 4% from the capital costs of the separation unit. Additional monitoring costs could be needed to monitor leakage from the old abandoned wells, if any are available at the site and not used for operations (injection, recovery and monitoring). However, such costs are also needed for CO_2 storage projects, if any old abandoned wells are available in the vicinity of the storage site and are not reused for site operation.

For techno-economic estimation and optimization of CO_2-EOR operations COZView/COZSim software, developed by NITEC LLC under a Federal Assistance Agreement with the U.S. Department of Energy/National Energy Technology Laboratory in 2011-2012, could be applied. This software was developed to accomplish a technically respectable field-wide CO_2-EOR feasibility analysis in less than one month, and to make it affordable to small and mid-size companies. The software integrates an easy to use user interface for pre- and post- processing of the reservoir simulation results, a technically rigorous 3D, 3-phase, 4-component, extended black oil simulator, and a net present value (NPV) optimization functionality for evaluation of CO_2-EOR in oil reservoirs. COZView

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attempts to simplify the simulation model development process while emulating the actual reservoir under evaluation as closely as possible (NITEC LLC&US DOE-NETL, 2013).

6.1.3 CO_2-GER

It is expected that geothermal energy recovered at the CO_2-storage and CO_2-EOR site will be used for heating and cooling of operational infrastructure and energy providing for project operations including injection, well monitoring, CO_2 separation and recycling, heat separation from CO_2. This energy, if produced in excess, could also be stored underground. CO_2 power systems are very compact, reducing costs substantially compared to legacy systems. These power systems can be containerized, built off-site at low cost, and moved as needed. CPG systems can reuse existing wells in hydrocarbon fields, decreasing costs and construction time while turning old oil and gas fields into renewable energy resources - geothermal systems. Together, these benefits mean that, lower temperature and less permeable formations than are viable with water, can be used, greatly increasing areas where geothermal energy can be economically harnessed (http://www.terracoh-age.com/TCOH_CPG-EB.html). CPG geothermal technology will not need fluid pumping, because of the thermosiphon effect of CO_2. CO_2 is moving up because of large difference in pressures at the surface and underground (Adams et al, 2014, 2015).

The capital costs will include:

CO_2 small-scale geothermal power plant, the cost will be asked from the TerraCOH, Inc owned the CPG technology patents (Saar et al., 2012-2015).

Geothermal CO_2 production well – drilling of new one, if reusing of existing well is not possible.

CO_2 use for geothermal energy recovery is not yet mature technology.

For techno-economic analyses of CO_2-GER project in (Buschek et al, 2016) an advance copy of GETEM (U.S. DOE, 2015) was applied, which is a Microsoft Excel spreadsheet–based tool that uses financial and technical inputs and optimizes reservoir and power plant performance to estimate the levelized cost of electricity (LCOE) from a geothermal power plant. The GETEM incorporates updated information about economic well drilling costs. GETEM has five major sections:

- resource exploration and confirmation
- well-field development
- reservoir management
- conversion system and
- economics.

Default values in GETEM is a fixed charge rate of 10.8% and an operating lifetime of 30 yr. The adjustment of default parameters in GETEM to the multi-fluid system including CO_2, is explained in (Buschek et al., 2016).

The power plant size depends on total fluid flow rate, and the CO_2 and brine temperature and effectiveness. According to TerraCOH, Incorporation, the size of the developed there Geothermal Power Plant using CO_2 is 20 times smaller than traditional Power Plant using

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water. The plant cost is determined based upon this size, the plant design temperature and CO_2 effectiveness.

The public version of GETEM updated for 2016 is available from (U.S. DOE, 2018, https://www1.eere.energy.gov/geothermal/getem/ThankYou.aspx) and will be used for techno-economic analysis of the CLEANKER scenarios. Additional adjustment will be made for reservoir conditions and economic parameters which are suitable for the CLEANKER European scenarios in (Buschek et al., 2016) US scenarios are modelled.

At least one scenario will be modelled with GETEM, considering relatively high geothermal gradient in Italy, compared to the low for the Baltic scenario and considering that in GETEM the binary power plant performance and cost are based upon modelling results for geothermal temperatures between 75° and 200°C. The model can predict outside of those temperatures, however those temperatures represent scenarios that are beyond the model's capabilities. The costs for the binary plants in GETEM are based on sizes that are 3 MW and larger. Smaller plants are outside the range of the cost data used in developing the model's cost correlations (GETEM, 2016). Feasibility of using CO_2-GER for the Baltic scenario will be estimated first in general terms in order to take decision about its application for full scenario modelling.

6.2 TOTAL CCUS COSTS

The total cash flow from CO_2-EHR operations will be summarised with the revenues from CO_2 use options applied in the project (CO_2 mineral carbonation, geothermal energy recovery). The limited duration of the EHR revenues will be considered versus revenues from CO_2 mineral carbonation and geothermal energy recovery, which could have the similar duration as CO_2 geological storage part of the project. The list of shared and additional costs and possible revenues from different CO_2 uses is given in the (Table 6.2).

Table 6.2: Shared and specific costs and revenues of CO_2 use options

	Ex-situ Mineral Carbonation/MC	**CO_2-EOR**	**CO_2-GER**
COSTS			
CO_2 capture & compression	Should be added to the cost of the carbonated product	Shared cost for CCUS storage project	
CO_2 transport (pipelines and boosters)	Not needed at the Cement capture plant/ short distance to MC plant	Shared cost for CCUS storage project (from medium to long distance)	
Capital	Mineral Carbonation Reactor/ Mineral Carbonation Plant	Shared with CCUS storage project injection well and injection facility	
		Additional oil recovery wells	Additional energy recovery wells

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		Oil-gas-brine separation CO_2 separation and cleaning	CO_2 small-scale geothermal plant CO_2 -brine separation
		Shared CO_2 recycling and compression unit and brine reinjection well	
Operation	Fixed operation costs (2% of CAPEX)	Fixed operation costs (4% of CAPEX)	Fixed operation costs (4% of CAPEX)
	Transport of waste material could be needed (from short to medium distance)	On-site operation cost	On-site operation cost
Storage site monitoring	Not needed	Shared cost for storage project	Not needed
Monitoring in wells		Shared cost for CCUS storage project	
REVENUES			
Specific	Carbonated product	Recovered Oil	Recovered energy and heat
	National waste tax (OST)		
Common	CO_2 allowance price in EU ETS (EEAP)		
Common	National Carbon Tax*		

*In Estonia only from CO_2 from heat production

*In Latvia NCT is not overlapping with EEAP

*Not yet introduced in Italy, Lithuania and Russia

7. SENSITIVITY ANALYSIS

Sensitivity analysis will be made for all scenarios. It is already discussed that CCUS costs will depend on many parameters. The most important among them are oil price, CO_2 emission allowance price (EEAP) in the EU ETS and resulting from these parameters CO_2 supply price. Another important parameters are market prices for mineral carbonation products, energy prices and other market prices.

Geological uncertainties can also influence the future projects costs. From the other side some of the expensive costs of scenarios could decrease at the nearest years owing to the development of CO_2 capture technologies. But at the same time increasing in operational costs could be connected with steady, but constant increase of average salaries in the Baltic countries and Russia.

8. CONCLUSIONS

- The database is developed based on the MS Excel sheets to be easy used for the project partners.

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- Unique ID numbers of the objects will permit to incorporate collected in the MS Excel datasheets data into the ArcGIS (version 10.6) database.
- The spatial data will be incorporated and analysed using ArcGIS platform.
- Database developed for CO2 transport and storage scenarios includes databases for CO_2 emission sources, transport and geological storage sites.
- Databases for CO_2 use options are developed including CO_2 mineral carbonation, CO_2-EHR and CO_2-GER.
- Database developed for CO_2 cluster projects includes datasheets for CO_2 emission sources, transport and storage sites.
- Technical specifications are described for CO_2 transport and injection facilities.
- Methodology for cost estimation of the CO_2 mineral carbonation are developed.
- Economic analyses of CO_2 use for Geothermal Energy Recovery will be made with GETEM software (GETEM, 2016).
- For techno-economic estimation and optimization of CO_2-EOR operations COZView/COZSim software will be used (NITEC LLC and U.S. DOE, 2012).
- CO_2 supply price for CO_2 use will be based on the CO_2 capture, compression and transport costs and revenues from European Emission Allowance Price (EEAP) from EU ETS and national carbon and waste taxes.
- Increased EEAP from 7 Euro during last five years up to 20-25 Euro in 2018 with prognosis to continue increase up to 35-40 Euro, gives options for the negative CO_2 supply price, creating incentive for the CO_2 emitter to pay for the CO_2 to be verifiably stored.
- CO_2 capture cost for the Baltic Scenario will be calculated based on the results of the economic modelling of the Estonian-Latvian CCS scenario (Shogenova et al., 2011).
- CO_2 capture cost for Italian power plants will be based on the published data.
- Total costs of CCUS scenarios will be analysed based on the sharing of costs and revenues obtained from the CO_2 use, EEAP and Estonian national carbon and oil shale ash taxes for the Baltic scenario.

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