ENAC PROJECT
ECOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
SPRING 2021

Key CCS topics: Worldwide deployment, EOR side-effects and Switzerland's potential

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IN COLLABORATION WITH PHD CANDIDATE SASCHA NICK

Author:
Jean-André Davy Guidicelli

Professor:
Philippe Thalmann

August 30, 2021

Executive summary

This study provides an evaluation of the industrial CO_2 management potential thanks to Carbon Capture and Sequestration (CCS), thanks to an analysis of the current worldwide deployment and near future projections of these technologies. To produce these results, the methodology used is based mainly on a literature review, databases constructions on CCS project, and data analysis.

Then, a special attention is accorded to the distinction between Permanent Geological Storage (GEO) and carbon dioxide Enhanced Oil Recovery (CO_2-EOR) for the sequestration options. To do so, a modification of a peer-reviewed life-cycle analysis spreadsheet model was performed. Main results show that 2021 CCS deployment represents an annual capacity of 40.12 $MtCO_2$, which is 1 ‰ of global emissions, moreover 70% of this capacity is dedicated to EOR, which drastically reduces the emissions reduction potential of CCS. To reach a significant Gt-scale, humanity should should focus on permanent geological storage projects and build a new facility every 1 or 2 days during the next 30 years.

We finally take a closer look to Switzerland that has a strong potential concerning the cement and waste-to-energy industries. The national capacity could reach 5 $MtCO_2$/y and it becomes particularly interesting when biomass is burned, generating 4 $MtCO_2$/y of additional negative emissions. Finally, these results are discussed to emphasise the limitations and implications of CCS technologies deployment.

Acknowledgements

I would like to sincerely thank Mr. Philippe Thalmann, Professor of environmental economics and head of the Laboratory of Environmental and Urban Economics – LEURE - at EPFL for having heard my interest in his research fields and offered me the opportunity to work on this ENAC Semester Project.

I would like to give also a special thanks to Mr. Sascha Nick, PhD Candidate at LEURE laboratory, Professor at the Business School Lausanne and lecturer at the University of Lausanne, for having taken the time the supervise this project and having guided me with his advises and passionate discussions on sustainable societal pathway. His availability, interest, and consideration were really precious to me.

Acronyms

AR	Afforestation and Reforestation
BC	Biochar
BECCS	Bio-Energy Carbon Capture and Storage
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilisation and Storage
CDR	Carbon Dioxide Removal
CO_2e	Equivalent carbon dioxide
DACCS	Direct Air Carbon Capture and Storage or Direct Air Capture
EOR	Enhanced Oil Recovery
EGR	Enhanced Gas Recovery
EW	Enhanced Weathering
GHG	GreenHouse Gas
IAM	Integrated Assessment Model
IPCC	Intergovernmental Panel on Climate Change
LUC	Land-Use Change
NDC	Nationally Determined Contributions
NET	Negative Emissions Technologies
NE	Negative Emissions
OF	Ocean Fertilization
OL	Ocean Liming
SCS	Soil Carbon Sequestration
SRM	Solar Radiation Management

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Introduction

While the IPCC Sixth Assessment Report is being written and COP26 organized in Glasgow, the world Greenhouse Gases (GHG) emissions keep rising years after years, leading to an increase in atmospheric carbon dioxide (CO_2) concentration and global temperature. The carbon budget to remain under the 1.5°C goal being surely already exceeded [1].

Today's annual GHG emissions are around 55 $GtCO_2e$[2] and, among them, the annual CO_2 emissions represent approximately 40 Gt. To respect the COP21 Paris Agreement, we would need an annual 5% decrease of these emissions from now until 2030 as shown by the Intergovernmental Panel on Climate Change (IPCC) [3], this is exactly the reduction in emissions observed in 2020 due to the Coronavirus crisis. In other words, humanity would need the equivalent of a new global pandemic effect every year to maintain to global temperature trajectory bellow 2°C. But such an abatement in emissions need to be done in a sustainable way.

Global CO_2 emissions must therefore follow a trajectory towards net zero emissions by 2050, and then become negative as shown in the IPCC Special Report on Global Warming of 1.5°C (SR1.5). But there is no sign of GHG emissions peaking in the next few years, and every year of postponed peaking means that deeper and faster cuts will be required as illustrated in Figure 14 of Appendix.

Decarbonizing humans activities is then a very hot topic for research to reach Net-Zero Emissions Pathway for 2050. Different approaches are considered involving for example the development of renewable energy, electrification or change in behaviour to reduce emissions, but a certain amount of inevitable emissions will need to be balanced, and the accumulated years of delay in emissions abatement need to be made up for. To do so, Negative Emissions Technologies (NETs) are studied and developed to proceed to Carbon Dioxide Removal (CDR) from the atmosphere. But another way to reduce emissions is to capture the anthropogenic CO_2 before being released into the atmosphere, these technologies are called Carbon Capture, Utilisation and Storage (CCUS).

This study will focus on evaluating the industrial CO_2 management potential thanks to Carbon Capture and Sequestration (CCS), by looking to the worldwide deployment and projection of these technologies, and according a special attention in the distinction between Permanent Geological Storage (GEO) and Enhanced Oil Recovery (EOR) for the sequestration options, before taking a closer look to Switzerland potential.

Research Questions

Terminology

It is important to set precise definitions to lay clear foundations and give an appropriate context to this study.

Carbon Dioxide Removal (CDR), synonymously referred to as negative emissions (NETs), are part of the human response options to the climate problem. It consists of a range of technological or practical approaches that aim to remove CO_2 directly from the atmosphere by either (1) increasing natural sinks for carbon or (2) using chemical engineering to remove the CO_2, with the intent of reducing the atmospheric CO_2 concentration, as define by the IPCC AR5 [4].

As shown in Figure 15 and 16 in the Appendix, this definition subsumes all approaches that focus on natural sink enhancement such as afforestation and reforestation (AR), soil carbon sequestration (SCS), ocean fertilization (OF), biochar (BC) or enhanced weathering (EW) as an integral part of climate mitigation, but also technologies that geologically store the sequestered CO_2 such as Bio-Energy carbon capture and storage (BECCS) or direct air capture with carbon capture and storage (DACCS). NETs must be differentiated from Geo-Engineering processes as Solar Radiation Management (SRM) since the last one addresses only the impacts of global warming due to climate change, being considered as an adaptation response, whereas NETs try to prevent GHG emissions which is a cause of global warming and is then considered as a mitigation response.

Carbon Capture, Utilization, and Storage (CCUS) encompasses methods and technologies to remove CO_2 from flue gases and from the atmosphere, followed by recycling the CO_2 for utilization and determining safe and permanent storage options. It is possible to distinguish three main categories of CCUS technologies :

- BECCS for which the carbon is fixed from the atmosphere in biomass thanks to photosynthesis,
- DACCS that aims to capture CO_2 directly from the ambient air through chemical and engineering processes,
- CCS and CCU which refers to the Carbon Capture and Storage, and Carbon Capture and Utilisation, for which the CO_2 is captured from the flue gas of large stationary sources using industrial processes.

BECCS and DACCS are considered as NETs because they remove CO_2 directly from the atmosphere, whereas CCS and CCU are not since they capture the CO_2 before it is released in the atmosphere and are therefore considered as emissions reduction technologies. The CO_2 final destination is also crucial since in the case of CCS, it is geologically stored, and in the case of CCU, its utilisation makes that it is either released again in the atmosphere or sequestrated in materials, but then the life cycle of the material is to be considered to know what happens to the CO_2 in the long-term. The final effect of CCUS technologies on climate is then dependant of the CO_2 origin and final destination, and can go from negative to positive emissions. This distinction is illustrated in Figure 1.

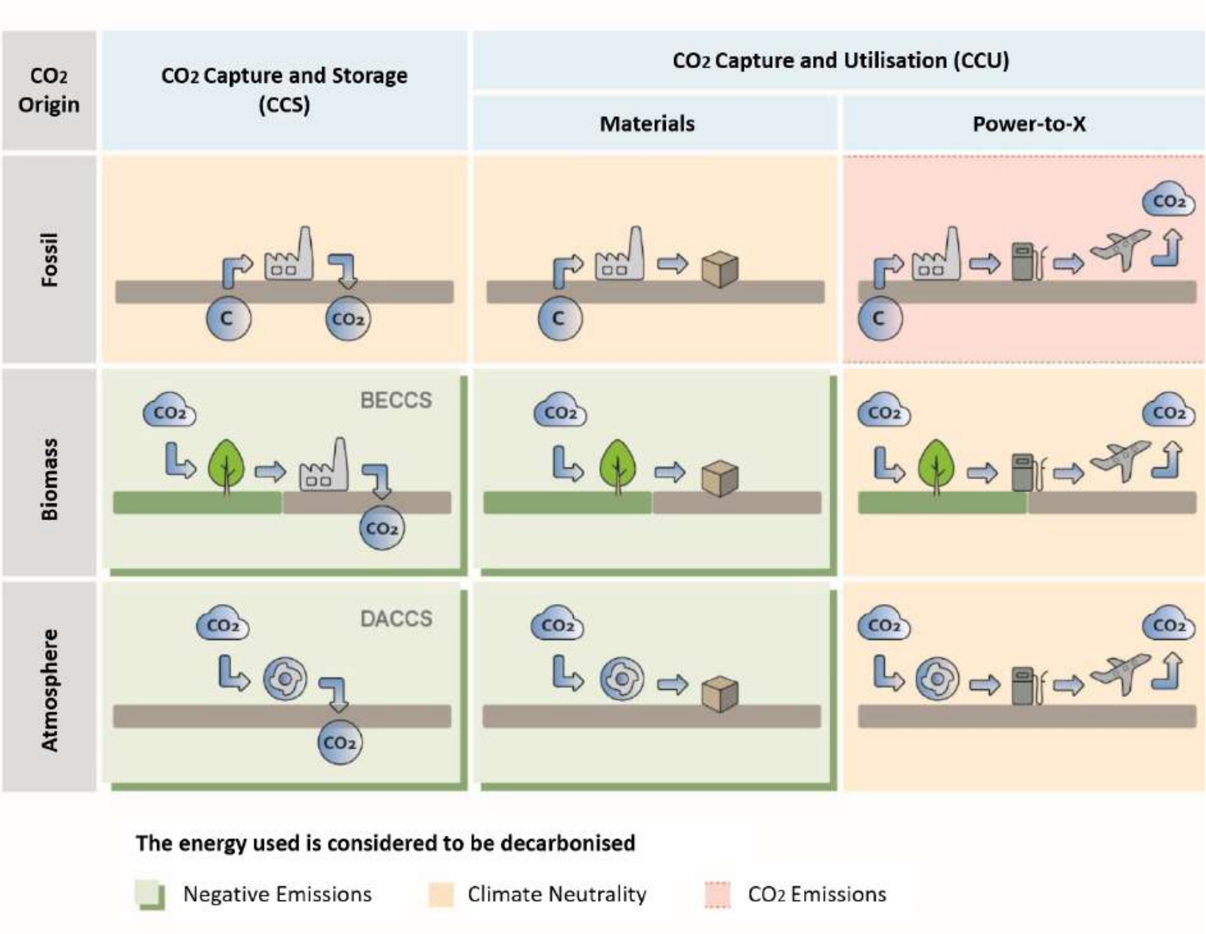


Figure 1: CCUS technologies and their related effects on climate, source: FOEN, adapted from [5]

The CCS process is composed of 3 basic stages : (1) Capture (2) Transport and (3) Storage. CO_2 capture refers to the separation of CO_2 from other gases produced at large industrial process facilities such as coal and natural-gas-fired power plants, steel mills, cement plants, waste treatment plant and refineries. Once separated, the CO_2 is compressed and transported via pipelines, trucks, ships or other methods to a suitable site for geological storage. Here the CO_2 is injected into deep underground rock formations, usually at depths of one kilometre or more.

Several geological systems are able to store CO_2, but to main options considered are either a permanent geological storage, or oil and gas companies can proceed to Enhanced Oil Recovery (EOR) or Enhanced Gas Recovery (EGR), which involves injecting CO_2 to increase oil or gas production from mature fields. The life-cycle analysis of these last processes are totally different since oil or gas are produced and will be ultimately burned, creating other new emissions.

Scope of the study

This study will focus on the industrial point-sources CO_2 emissions management potential offered by CCS technologies, represented by the top left cell in Figure 1, by looking at the 2021 deployment and announced projects for future years.

Indeed, considering the Gt-scale need in emissions reduction as represented in Figure 14 of Appendix, CCU seems to offer a too weak potential to represent a significant advance in emissions reduction, and the long-term fate of CO_2 sequestrated in materials or biomass produced depend on each product end-of-life. On the contrary the IPCC estimates the geological world's potential storage capacity at two trillion tonnes of CO_2 [6], moreover injecting CO_2 underground is a well-known process since more than nearly 50 years, it can already be achieve in significant quantity and there is a urgent need to cut point sources emissions. It is economically more effective to capture CO_2 directly in the flue gas before it is released in the atmosphere since it is more concentrated (3-15% compared in flue gas to 0.04% in the atmosphere) and then require less energy to be captured. In 2005 there were more than 7500 large CO_2 emissions point sources (larger than 0.1 $MtCO_2/y$) that emitted more than 13 $GtCO_2$, approximately 1/2 of global emissions at this time [6].

However, the challenge to evaluate the CCS technologies potential to have a positive effect on climate is to assess the life-cycle emissions of the whole process, especially in the case of EOR storage, and estimate the feasibility of a Gt-scale deployment considering the technological readiness and the socio-economical factors as the political and economical incentives needed to insure a rapid development.

Then, the research questions of this project can be summarized by the following questions. *Regarding the 2021 deployment and announced project in the near future, what is the worldwide CCS emissions reduction potential ? What are the element to be taken in consideration to estimate its plausible future deployment ? How EOR is altering the CCS emissions reduction potential ? And how relevant is it for Switzerland ?*

To provide an attempt to answer these questions, the first part of this report will focus on the CCS facilities database built during the project to estimate today's deployment and near future projects announced. Then, in a second time, the potential capacity extracted from the database is differentiated between permanent geological storage and EOR facilities, showing the implication of enhanced oil recovery on the life-cycle analysis of CCS projects. Finally, this study takes a closer look to Switzerland potential applications of CCS.

1 CCS projects Database

The first part of this project aims to review the existing and announced CCS projects to estimate the 2021 and near future deployment of this technology with its related effect on emissions reduction. The database is able to sort and display the facilities according the desired criteria selected by the user, show the temporal evolution of worldwide capacity and realize statistical analysis according to the user's desires parameters. A brief overview of the database is illustrated in Figure 17 of the Appendix, the complete Excel spreadsheet file of the database is enclosed to this report and can be found in the following **link**.

1.1 Methodology

1.1.1 Sources of data

The database was build using an Excel Spreadsheet. It compiles the data from several other existing databases and studies as :

- The CO_2RE Global CCS Institute facility database [7]
- The US Department of Energy (DOE) National Energy Technology Laboratory (NETL) CCS database [8]
- The International Association of Oil & Gas Producers (IOGP) Europe CCS projects list [9]
- The Zero Emission Resource Organisation (ZERO) CCS database [10]
- The MIT Carbon Capture and Sequestration Technologies (CC&ST) project database [11]
- Several press releases, scientific publications and company presentations.

For each of the facilities, several information were collected as : (1) the types of facilities, (2) the stage of development, (3) the capture system, (4) the storage option, (5) the facility industry sector, (6) the date of operation start and potential termination, (7) the capacity of the facility, (8) the country in which the facility is and (9) a description of the facility.

Depending on data availability, some other information on the facilities were added as the dates of study and construction start, the cumulative storage until 2020, and related website, press release and scientific publication links.

1.1.2 Types of facilities

CCS projects can be separated in 3 mains groups, commercial facilities, the hubs, and pilot and demonstrations facilities. For each commercial facility and hub, the related websites and scientific publications links were added to the database.

Commercial CCS Facilities that are typically large-scale projects (0.1 $MtCO_2/y$) in which the CO_2 captured and transported for storage as part of an ongoing commercial operation. Generally they have economic lives similar to the host facility whose CO_2 they capture, they must support a commercial return while operating and meet a regulatory requirement.

CCS Hubs, Network and Clusters describes commercial facilities for which the operation is not full-chain capture, transport and storage. Several models could apply as CO_2 transport and/or storage infrastructure available for utilisation by more than one commercial CCS facilities. A CO_2 *cluster* may refer to a grouping of individual CO_2 sources, or to storage sites such as multiple fields within a region. For example, the Permian Basin in the US has several clusters of oilfields undergoing CO_2-EOR fed by a network of pipelines. A CO_2 *hub* collects CO_2 from various emitters and redistributes it to single or multiple storage locations. Finally a CO_2 *network* is an expandable collection and transportation infrastructure providing access for multiple emitters. In the database a particular attention was dedicated to be sure that no project is double-counted by its status of commercial facility and its participation in a CCS Hub.

CCS Pilot and Demonstration Facilities describes small-scale projects that capture CO_2 for testing, developing or demonstrating CCS technologies or processes. The captured CO_2 may or may not be permanently stored. Generally they have a short life compared to commercial facilities, determined by the time required to complete tests and development processes or achieve demonstration milestones, they are not expected to support a commercial return during operation.

1.1.3 Stage of development

Several projects are listed whereas they are not fully operational, but already engaged in a stage of the their life-cycle. The Global CCS institute [7] define theses different stages as the following.

The "*Early Development*" stage refers to facilities for which companies are carrying out studies and comparisons of alternative concepts in terms of costs, benefits, risks and opportunities. At this stage, there is still the consideration of alternative solution from all relevant aspects (i.e. stakeholder management, regulatory approvals, infrastructure, etc.). Then the best option is selected and a pre-feasibility study is done to estimate the project costs (capital and operating) but also to assess the site that will welcome the facility.

The project is then considered in "*Advanced Development*" when the previous stage validated a selected option and further explore it through the feasibility and preliminary front-end engineering design (FEED). It consists of the determination of the technology used, project costs, permitting, and key risks to the development. The feasibility studies also research finance and funding opportunities. After this stage a final investment decision is done.

If the investment is accepted, the project enters "*In Construction*" which refers to the assets construction and commissioning.

The facility is considered as "*Operating*" when the operations are successfully done under a regulatory framework. It also includes the maintenance of the facilities and modifications to improve performance. In its end-of-life, the last step of this stage is the preparation for decommissioning. Some projects can have their "*operation suspended*" for technical or economical reasons.

Finally, the last stage of "*Completion*" is defined by the assets decommissioning and the implementation of a post-injection monitoring program.

1.1.4 Capture systems

Several technologies to capture the CO_2 from flue gas exists, the selection of which one is the most appropriate for a project depend on the concentration of CO_2, the pressure and fuel type (solid or gas). But they can be summarized to the following 3 main approaches.

Post-combustion processes separate CO_2 from combustion flue gases, it is captured using a liquid solvent or other separation methods as membrane. In an absorption-based approach, once absorbed by the solvent, the CO_2 is released by heating to form a high purity CO_2 stream. This technology seems to be the most widely used.

Pre-combustion processes use fuel that will be converted into a gaseous mixture of hydrogen and CO_2. The fuel conversion steps required for this process are more complex than the processes involved in post-combustion, making the technology more difficult to apply to existing power plants. The CO_2 is then compressed for transport and storage while the hydrogen can separated to be burnt without producing any CO_2.

Finally, *Oxyfuel combustion* processes use oxygen rather than air for combustion of fuel. This produces a flue gas that is mainly composed of water vapour and CO_2 and that can be easily separated to produce a more concentrated CO_2 stream. The removal of water can be done by cooling and compressing the gas mixture. Even if the process is simple, the main barriers to its development is the high cost to obtain pure oxygen.

Some systems are called "*Industrial separation*" when they combine one of these CO_2 capture technologies with the manufacturing of a product from raw materials, as the production of hydrogen or ammonia.

1.1.5 Storage options

Several geological systems can permanently store CO_2 :

- Deep saline formations that refer to any saline water bearing formation that is sealed by a caprock for permanent storage.
- Coal-bed methane, in which CO_2 is injected into coalbeds to exchange CO_2 with methane. CO_2 binds to the coal and is stored permanently.
- Depleted oil or gas fields that are no longer economic for oil or gas production but have established trapping and storage characteristics.

The storage efficiency is the same in the 3 geological systems, however, regarding the last reservoir, oil companies can proceed to Enhanced Oil Recovery (EOR), which involve injecting CO_2 to increase oil production from mature fields. It can be done with gas (EGR) but the process is less common.

Therefore, the database do the distinction only between permanent geological storage (GEO) which simply store CO_2, and EOR.

1.1.6 Statistical analysis tool

After the database construction, the goal of this project was to create an interface able to generate the statistical analysis wanted by the user. To do so, an dedicated section was created in the Excel spreadsheet. An overview of this section is illustrated in Figure 19 of the Appendix.

To have the statistics of a desire sub-group of facilities in the database, the users can select : (1) the type, (2) the status, (3) the minimum threshold capacity and (4) the temporal frame he wants to study. In return, for the parameters selected, the database will display tables and graphs for the number of facilities and capacity, per country, capture type, storage option and industry, in absolute value and relative percentage. It also displays the total, mean and median capacities of the selected facilities.

1.1.7 Visualisation of temporal evolution

Another goal was to represent the evolution of the capacity across the years. To do so, another section of the spreadsheet model was dedication to it. The overview of this section is illustrated in Figure 20 of the Appendix.

Similarly to the previous section, the user can select the type of facilities he want to study, and the data of each facility are rearranged per year to display the total capacity [$MtCO_2/y$] and number of facility installed per year, the cumulative capacity [$MtCO_2/y$] and cumulative number of facility, the cumulative quantity of CO_2 sequestrated [$MtCO_2$], and finally the mean and median capacity per year [$MtCO_2/y$].

1.2 Results

The database built for this project represents one of the most recent, detailed and complete database on past, current, and announced future CCS projects. It is easily searchable and configurable by an user. It forms the basis to estimate the bottom of the CCS technology deployment S-curve and allowed the possible realisation of a complete distinction between EOR and simple permanent geological storage as detailed in part 2.

According to this database, there are a total 183 CCS projects identified in 2021, precisely 95 Pilots and Demonstrations facilities, 70 commercial facilities, and 18 CCS Hubs. Among the commercial facilities 26 are currently in operation and all of them have a capacity superior to 0.1 $MtCO_2/y$, more than half of them are in the US. Figure 2 shows the main results obtained thanks to the statistical analysis section for theses 26 facilities.

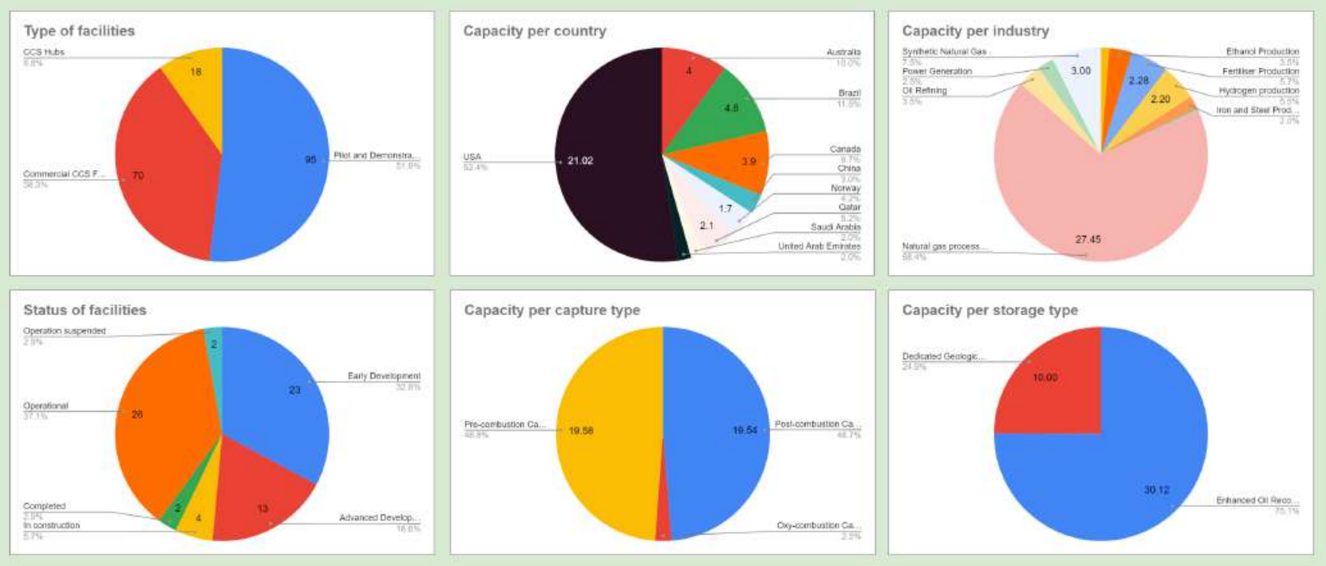


Figure 2: Statistics for the 26 operational commercial facilities in 2021, capacity in [$MtCO_2/y$].

The current capacity deployment in 2021 for the 26 currently operational commercial CCS facilities is 40.12 $MtCO_2/y$, which represent 0,1% of current anthropogenic annual emissions of CO_2 that are estimated to 40 $GtCO_2/y$. However more than 75% of this deployed capacity is dedicated to EOR, 20 facilities over 26, for a total capacity of 30.12 $MtCO_2/y$, the remaining 10 $MtCO_2/y$ being injected only for permanent geological storage (GEO). If we look at cumulative data in the temporal evolution section, it means that in 2021 the cumulative CO_2 captured is estimated at max 599.76 $MtCO_2$. EOR injections represent 533.86 $MtCO_2$ and the 64.26 $MtCO_2$ were simply injected in a permanent geological reservoir. These cumulative quantities are to be considered more like orders of magnitude than exact values. Indeed, estimate them is highly uncertain, no value was found in the litterature and Dr. Julio Friedmann presented at the April 13th 2021 EPFL CCUS workshop a value of approximately 260 $MtCO_2$, for which the source is unknown. but this is still plausible and coherent with our data if we assuming an effective cumulative capacity equal to 50% the theoretical one in our model.

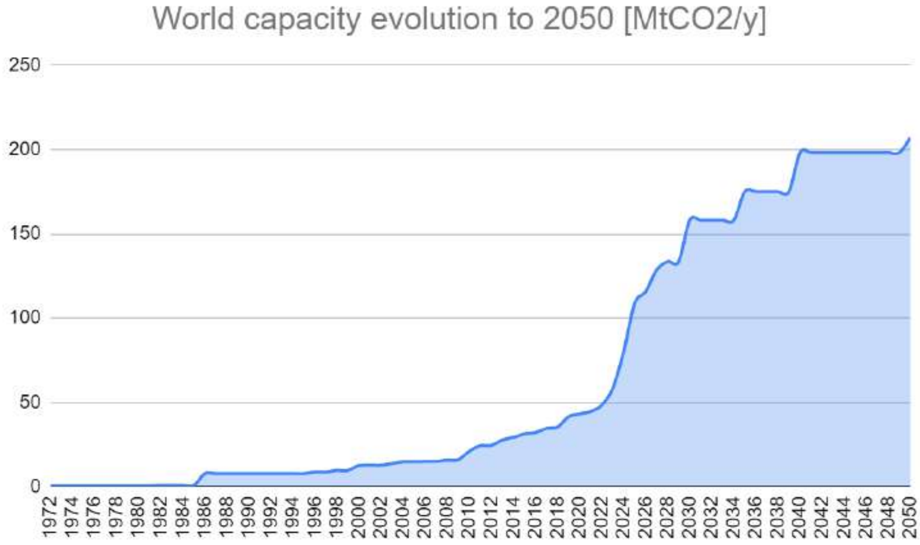


Figure 3: Worldwide CO_2 capture capacity evolution.

According to the current operational projects, the ones in construction and the predictive studies, the capacity in 2025 is estimated to be around 108.52 $MtCO_2$/y with approximately 50% EOR and 50% GEO. It is important to notice that some of the facilities were planned for "mid 2020s" and were assigned to 2025 during database construction, explaining the fast increase in 2025, a more detail look show potentials for 2024 at 79.65 $MtCO_2$/y and for 2026 at 115.62 $MtCO_2$/y. It is more than the double of today's deployment, but still less than 0.25% of global emissions.

Given past cycles and 2021 declared intentions, 2030 and 2035 capacity is likely to be at least 158.07 $MtCO_2$/y (33% EOR, 66% GEO) and 175.07 $MtCO_2$/y (30% EOR, 70% GEO). But it is important to notice than most of the future projects tCO_2 announced between 2020 and 2030 only, so the data after 2030 are not really relevant and does not represent the plausible capacity that would exist if CCS technology are correctly deployed. The capacity of 2035 rise simply due to the increase in capacity from CCS hubs improvements that are planned to be constructed in the next decade, this is why it is possible to see different bearings between 2030 and 2050.

The proportion of EOR projects is decreasing with time for the benefit of permanent geological storage, which is a good news for climate, but it invite us to precisely estimate what is the real effect on climate of CCS if the CO_2 is used for EOR project, to put into perspective the results of this first part.

2 Distinction between EOR and Permanent Geological Storage

As described in part 1, once the CO_2 is captured, compressed, and transported, there are several options for its storage. The CO_2 is injected underground either for a permanent geological storage - there are several geological system as saline formations, deep unmineable coal seams, or depleted oil and gas reservoirs able to store it - or it will be used for EOR to increase oil production from mature oil fields. Of course, the whole process of injecting CO_2 to extract crude oil is energy-intensive and the additional oil extracted will be refined and ultimately burned. Both of these processes lead to additional GHG emissions. The goal of this part is then to estimate the net effect of CCS technologies on climate.

2.1 Methodology

2.1.1 Boundaries of the system

To estimate net effect of CCS technologies on climate, results from the database in part 1 are used as inputs to express the quantity of CO_2 captured purchased to be used in Permanent Geological Storage (GEO) or Enhanced oil recovery (EOR).

Then, this study estimates the emissions of EOR processes based on the work of Azzolina and al [12] that derives the CO_2e emissions per barrel of oil produced considering a complete life-cycle analysis of upstream, Gate-to-Gate and downstream emissions. For both storage options, either GEO or EOR, we will not consider the CO_2e emissions resulting from the downstream processes, that are mainly emissions coming from the energy required for the capture, fugitive losses from the compressors and transport. We won't do it for several reasons, first the great variety of capture facilities and processes makes the estimation particularly difficult, but especially because we consider that the capture will happen anyway, whether it is for GEO or EOR, and the emissions from capture process are the same in both scenario, so it is not relevant to count it in an analysis that compares both practises and we can remove it from our system boundaries.

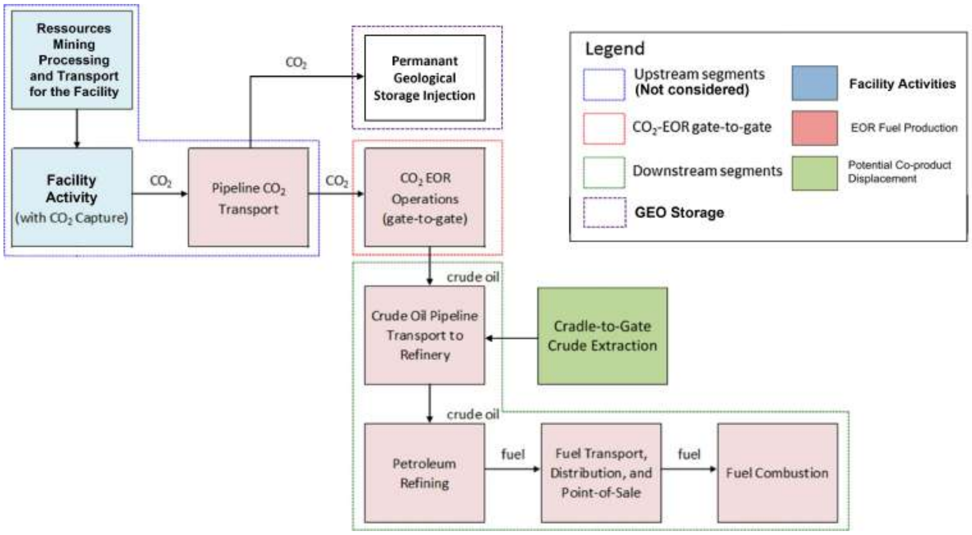


Figure 4: System boundaries to evaluate life cycle CO_2 emissions associated with CO_2-EOR modified from Azzolina et al [12]

Then net emissions of EOR process need to include the short term effect of this new EOR-oil on the global oil market [13], and the long term effect on economically feasible oil supplies. Finally the net CCS technologies effect on climate is simply the difference between the net storage and net emissions. In our calculations, all values are reflecting emissions, a negative value meaning a storage - i.e. flux of CO_2 that would have been emitted in the atmosphere from capture facilities to geological formation - and a positive value meaning emissions directly into the atmosphere.

2.1.2 Permanent Geological Storage

The quantity of CO_2 purchased per year to be permanently injected in a geological storage can be extracted from the CCS database detailed in part 1. This CO_2 will arrive at the injection facility, but fugitive losses will happen in the process before the injection, and we can assume a small but existing leakage from the storage. Azzolina et al [12] assumes these rates to be respectively equal to 2% of the CO_2 purchased and 0.5% of the CO_2 injected.

$$InjectedCO_2\,_{GEO} = PurchasedCO_2\,_{GEO} \cdot (1 - Fugitive\ Loss\ Rate) \tag{1}$$

$$LeakageCO_2\,_{GEO} = InjectedCO_2\,_{GEO} \cdot (Leakage\ Rate) \tag{2}$$

$$StoredCO_2\,_{GEO} = InjectedCO_2\,_{GEO} - LeakageCO_2\,_{GEO} \tag{3}$$

Where :

$PurchasedCO_2\,_{GEO}$, $InjectedCO_2\,_{GEO}$, $StoredCO_2\,_{GEO}$ and $LeakageCO_2\,_{GEO}$ in [tCO_2]
$Leakage\ Rate$, $Fugitive\ Loss\ Rate$ in [%]
So we can summarize equations 1, 2 and 3 to the following :

$$StoredCO_2\,_{GEO} = PurchasedCO_2\,_{GEO} \cdot (1 - Fugitive\ Loss\ Rate) \cdot (1 - Leakage\ Rate) \tag{4}$$

2.1.3 Enhanced Oil Recovery Storage

Similarly to GEO storage, The quantity of CO_2 purchased per year to be injected for EOR purpose can be extracted from the CCS database detailed in part 1n and some this CO_2 will be lost in the EOR process through fugitive losses and leakage from the reservoirs.

$$StoredCO_2\,_{EOR} = PurchasedCO_2\,_{EOR} \cdot (1 - Fugitive\ Loss\ Rate) \cdot (1 - Leakage\ Rate) \tag{5}$$

2.1.4 EOR-Oil Production

In his paper, Azzolina et al [12] computes the quantity of CO_2 needed to be purchased to extract a desired quantity of crude oil. This study does basically the contrary, we evaluate the quantity of EOR-oil thanks to the quantity of CO_2 captured via CCS facilities.

The most sensitive parameter [14] in this study is then the *crude oil recovery ratio* [RR_{CO2}], expressing how many barrel of oil we can extract for 1 ton of CO_2 injected [bbl/tCO_2] or how many ton of oil per ton of CO_2 injected [t/tCO_2]. Another way to express this parameter is the *net CO_2 utilization rate* [$UF_{CO2,net}$], that is simply the reciprocal of the crude oil recovery ratio with unit conversions, it gives how many ton of CO_2 we have to inject to extract 1 barrel [tCO_2/bbl] or 1 ton of oil [tCO_2/t]. This parameter allow us to calculate the EOR-oil production per year. Typical values of this parameter extracted from literature are shown in Table 1.

$$InjectedCO_{2\ EOR} = PurchasedCO_{2\ EOR} \cdot (1 - Fugitive\ Loss\ Rate) \tag{6}$$

$$EOR\ Oil = InjectedCO_{2\ EOR} \cdot RR_{CO2} \tag{7}$$

Where :
$EOR\ Oil$ = tons of EOR crude oil produced [t]
RR_{CO2} = crude oil recovery ratio [t/tCO_2]

Typical values of RR from litterature [bbl/tCO_2]			
Sources	Low	Expected	High
Azzolina et al. (2015) [15]	1.83	2.21	4.02
R. Farajzadeh et al. (2020) [16]	2	-	4
Cooney et al. (2015) [14]	2	-	4.35
IEA (2015) [13] [17] [18]	-	3.33	-
Jaramillo et al. (2009) [19]	4.6	-	6.5
Examples from important plants [bbl/tCO_2]			
Boundary Dam Power Station, Canada [20]	-	7.22	-
Elm Coulee/Cedar Creek oil fields, USA [21]	-	6.11	-

Table 1: Recovery ratio in literature

2.1.5 CO_2-EOR Emissions

To compute the emissions generated by the EOR process, this study focus on the **gate-to-gate emissions** - considering what happen between the moment when CO_2 arrives at the injection facility and the moment when crude oil leave the extraction facility - and **downstream emissions** that detail what happen to the EOR oil next. This life-cycle analysis is based the model of Azzolina et al (2016) [12]. Dr. Nicholas A. Azzolina was contacted and shared his Excel spreadsheet model used to compute the results of his study, so it was possible to modify his model and adapt it to this project.

Gate-to-gate emissions include five key unit processes: (1) injection and recovery, (2) bulk separation and storage (gas–liquid separation, crude oil/natural gas liquids storage, and brine water storage and injection), (3) gas separation (Ryan–Holmes process), (4) supporting processes (e.g. venting and flaring, gas combustion for process heat), and (5) land use. Basically, Azzolina et al computes the emissions for an expected fictitious facility built with theoretical data from literature and the statistical data of 31 EOR facilities in the US collected by Azzolina et al (2015) [15]. Then he normalized every steps of emissions by the number of barrel produced to obtain emission factors of each unit process in [tCO_2e/bbl].

These emissions factors are highly sensitive to the crude oil recovery ratio presented in Table 1. To create a dynamic model and enable the user to study the effect of changing the Recovery Ratio on EOR emissions, the Azzolina et al (2016) Excel spreadsheet model was merged to the database analysis model developed in Part 1, it allows to calculate the emissions factors as function of the crude oil recovery ratio.

Downstream emissions include crude oil transport from the CO_2-EOR field to the refinery, refining of the crude oil, fuel transport and distribution from the refinery to point-of-sale, and combustion of the refined petroleum fuel. Each unit process is estimated in the spreadsheet model but these ones are not dependant of the crude oil recovery ratio.

EOR emissions are then the sum of the the gate-to-gate and downstream emissions. Finally, to compute the net EOR emissions, we subtract to the EOR emissions the CO_2 stored in EOR reservoirs.

$$EF_{EOR} = EF_{gate-to-gate} + EF_{downstream} \tag{8}$$

$$Emissions_{EOR} = EOR\ Oil \cdot EF_{EOR} \tag{9}$$

$$Emissions_{NET,EOR} = Emissions_{EOR} - StoredCO_2\ _{EOR} \tag{10}$$

Where :

EF_{EOR}, $EF_{gate-to-gate}$ and $EF_{downstream}$ in [tCO_2e/t]
$StoredCO_2\ _{EOR}$ in [tCO_2]
$Emissions_{EOR}$ and $Emissions_{NET,EOR}$ in [tCO_2e]

2.1.6 Emissions correction by short-term effect on Global Oil Market

Th net emissions value calculated in Equation 10 would be very advantageous for EOR processes since we simply subtract the quantity of CO_2 stored to the emissions of the oil produced. By doing so the EOR oil would be less CO_2 intensive than the conventional oil, but this is considering that all EOR-supplied oil displaced existing supply of conventional oil.

Unfortunately, the operation of global oil markets does not allow for this one-for-one displacement. IEA's global oil market analysis [13] estimates that when oil produced through CO_2-EOR hits the global market, 84% of EOR-supplied oil displaces existing supply and satisfies existing oil demand. The remaining 16% percent represents an increase in oil supply, which lowers the price of oil and results in increased oil consumption.

To illustrate this, we will based ourselves on the CATF factsheets [17] [18] example, illustrated by Firgures 5 and 6, in which they fixed the conventional oil emissions factor to be equal to 0.51 tCO_2e/bbl, and the EOR oil emissions factor to 0.54 tCO_2e/bbl with a net utilisation ratio of 0.3 tCO_2/bbl, meaning a crude oil recovery ratio of 3.33 bbl/tCO_2. This results are coherent with the calculations made by the Excel Spreadsheet model of Azzolina et al [12].

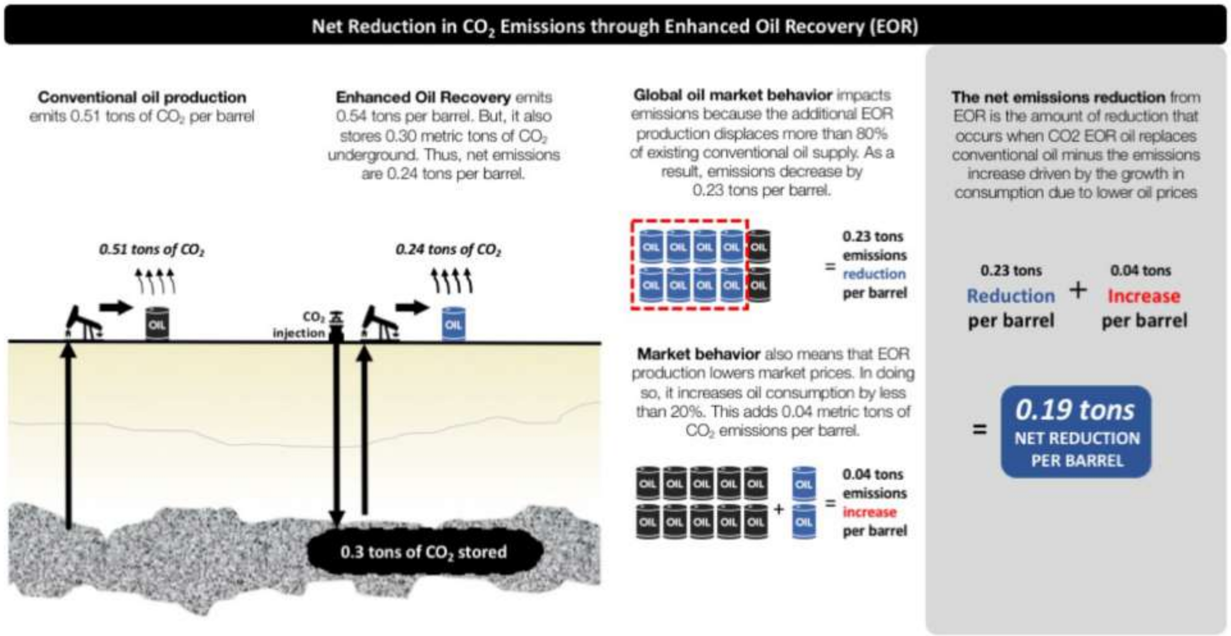


Figure 5: Effect of global oil market on EOR emissions from CAFT 2018 [17]

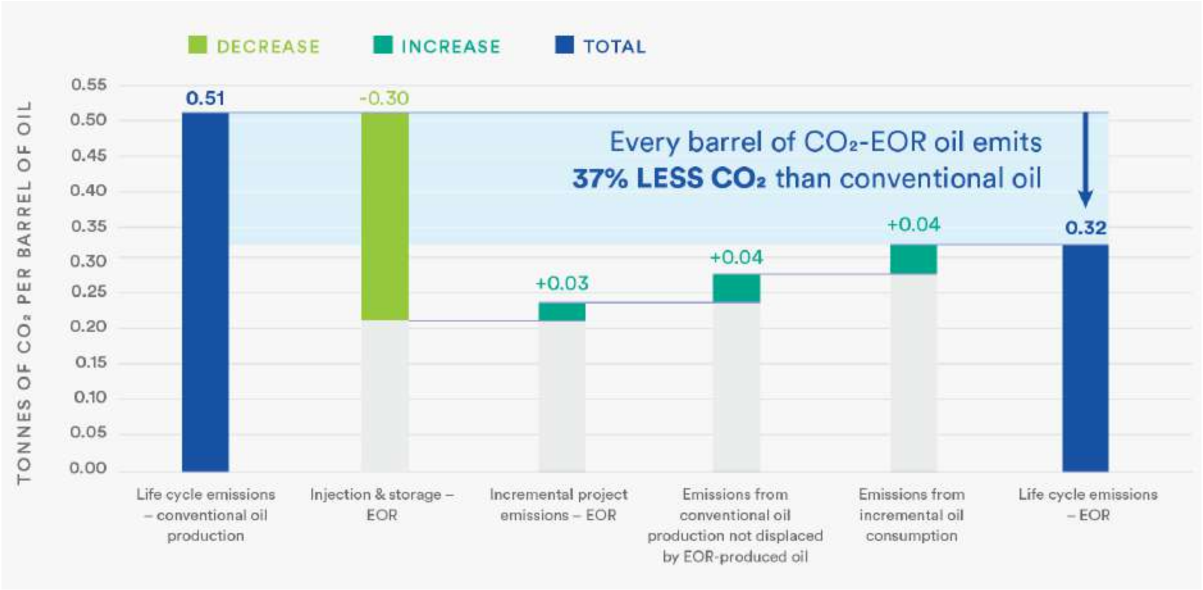


Figure 6: Detailed calculus steps of oil market effect on EOR emissions from CAFT 2019 [18]

To account for market impacts, first, it is needed to calculate net reduction only to the extent there is displacement. As shown in Figure 6, we "add back" the unrealized net reduction from oil that is not displaced, i.e. 16% (1-84%) of the 0.27 tons reduction (0.51 - (0.54-0.3)) = 0.04 tCO_2.

Next, we "add back" emissions from the increase in oil consumption that would not have occurred if not for the increase in oil supply from EOR i.e. 16% of 0.24 tons (0.54-0.3) = 0.04 tCO_2.

Thanks to this analysis we can now calculate the corrected net EOR emissions.

$$\begin{aligned} Emissions_{NET,EOR}^{corr} = \; & Emissions_{NET,EOR} \\ & + (1 - R_{dis}) \cdot (Emissions_{conv} - Emissions_{NET,EOR}) \\ & + R_{add} \cdot Emissions_{NET,EOR} \end{aligned} \tag{11}$$

Where :

$Emissions_{conv} = EOR\ oil \cdot EF_{conv}$

$Emissions_{conv}$ are the emissions of the same quantity but for conventional oil in [tCO_2e]

EF_{conv} the emission factor for conventional oil in [tCO_2e/t]

R_{dis} and R_{add} the rates of EOR oil respectively displaced and additional on the market in [%]

In the end, with this life cycle basis considering gate-to-gate and downstream emissions, with the effect on global market, it is true to say the CO_2-EOR process produces a crude oil that is less CO_2 intensive than the production of conventional oil, but it still emits more CO_2 in the atmosphere than what is stored, exactly 0.32 tCO_2e per barrel of crude oil produced. So before saying that EOR delivers net CO_2 reductions we have to be really careful with what we compare these emissions.

2.1.7 Long-term effect on economically accessible oil

As shown in Figure 5 and 6, the CAFT factsheets present that every barrels of oil produced through CO_2-EOR result in a net emission reduction of 0.19 tons of CO_2e (51-32), so that compared to life cycle emissions of conventionally produced oil, EOR-produced oil emits 37% less CO_2e (0.19 = 37% of 0.51 tons). But this result is based on the assumption that 100% of the oil produced thanks to CO_2-EOR would have been produced anyway even if CO_2-EOR with CCS technologies would not exist, and in a more polluting way [17]. It is said that if oil companies won't use this captured industrial anthropogenic CO_2, they would still be able to extract the same quantity of oil from depleted field by injecting "Natural Geologically-sourced CO_2 [...] surfactants, polymers, and detergents [...] or Methane" or by doing "infield drilling, horizontal drilling and fracking", but without delivering the "climate benefit" of CCS CO_2-EOR.

It is reasonable to express some doubts regarding this assumption. Indeed, if today oil companies are using anthropogenic CO_2 captured by industrial facilities that want to sequestrate it, it is not by climate charity but because is it more economically advantageous than using some other products for the injection. So one could say that on the contrary, the oil produced thanks to CCS EOR processes would not be produced otherwise because it would not be cost-effective due to technical or economical reasons.

To express this difference of assumptions in our model, we can introduce a variable α that can take any value between 0 and 1 to express this concern :

$$\alpha = \begin{cases} 1 & \text{(100\% of the EOR-oil extracted would have been produced otherwise)} \\ 0.5 & \text{(only 50\% of the EOR-oil extracted would have been produced otherwise)} \\ 0 & \text{(the EOR-oil extracted would not have been produced otherwise)} \end{cases}$$

This α variable allow us to calculate the net effect in CO_2e emissions due to EOR in a scenario in which [0-100]% of the EOR-oil would still have been produced otherwise.

$$Effect_{EOR} = Emissions^{corr}_{NET,EOR} - \alpha \cdot Emissions_{conv} \tag{12}$$

If $\alpha = 1$, then we have the same results than the ones presented in the CAFT factsheets, the effect is the net reduction between the EOR emissions and what they would have been if the oil was extracted in a conventional way, a benefit for climate.

If $\alpha = 0$, since the oil would not have been produced otherwise, the effect is just the additional net emissions of EOR-oil production in the atmosphere.

In reality, the value of α varies between 0 and 1 and we cannot properly determine what would have been the hypothetical oil production if CO_2-EOR wouldn't exist, so the user can modify it freely in the spreadsheet model to see how sensitive the final results are. But it is very important to realize than the potential benefit of CCS technology for climate depend on a such important assumption that is often hidden.

2.1.8 Total CCS effect on climate

The last step of the model is to sum the net effect of EOR calculated in equation 13 to the quantity CO_2 stored permanently in equation 3 to obtain to total effect of both CCS technologies.

$$Effect_{CCS} = Effect_{EOR} + StoredCO_{2\ GEO} \tag{13}$$

Where :

$Effect_{EOR}$ and $Effect_{CCS}$ are the final emissions (positive value) or sequestrations (negative value) of CO_2 for only EOR and CCS processes in [tCO_2e]

In the developed spreadsheet model, all the calculations presented in this part were done for every years for which we have data in the database, from 1972 to 2050, and for 3 different quantities :

- The new capacity installed per year
- The capacity per year
- The cumulative capacity

Parameters of the study can be changed so that tables and graphs are automatically updated. Finally, tables of conversion between barrels, tons, net CO_2 utilisation rate and crude oil recovery ratio were built to help the users to easily set the desired parameters. Detailed calculation tables and related graphs for this section are illustrated in Figure 21 of the Appendix.

2.2 Results

According to the literature review done for this project, the addition of an α factor to an EOR life-cycle emissions model was never done before. It allows to calculate the effect of CO_2-EOR CCS compared to a world in which this technology wouldn't exist, in order to estimate what is its effect on climate in terms of emissions reduction or addition. Therefore it was possible to compute the normalized EOR effect, i.e. the net CO_2 emissions reduction or addition per ton of CO_2 injected underground, as a function of both α and crude oil recovery ratio parameters. The following Figure 7 illustrated the possible values of the EOR effect from the recovery ratios range showed in Table 1 and α's range [0-1].

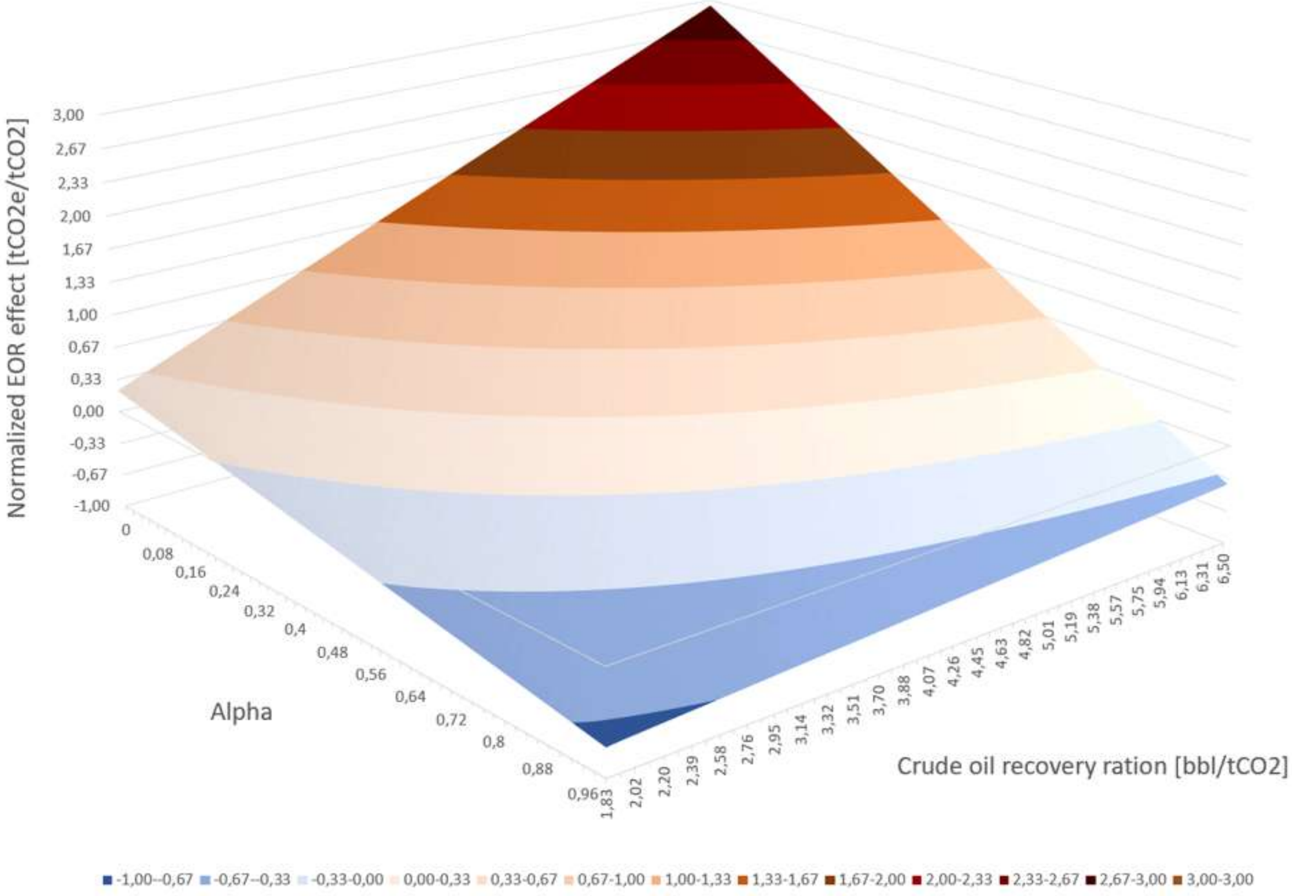


Figure 7: Normalized EOR effect as a function α and RR, reduction in emissions appears in blue and additional emissions in red

We can conclude from this analysis that for every ton of CO_2 injected for EOR purpose, the net effect on climate is between the net storage of 0.72 tCO_2 (when $\alpha = 1$ and $RR = 1.83$ bbl/tCO_2) and the net emissions of 2.94 tCO_2 (when $\alpha = 0$ and $RR = 6.5$ bbl/tCO_2). It shows that is if difficult to predict if enhanced oil recovery benefits the climate or not in terms of contribution to global emissions reduction effort.

In section 1.2, we saw that the 2021 CCS capacity is 40.12 $MtCO_2/y$, with 75% of the capture capacity dedicated to EOR and 25% to a simple permanent geological storage. We can now nuances this results by saying that in 2021, due to CCS technology and assuming a expected crude oil recovery ratio of 3.33 bbl/tCO_2e according to IEA [13], the total effect on climate this year was between the reduction of 27.76 tCO_2e and the addition of 22.42 tCO_2e, which is really not the same.

The following table shows the high variation of possible values for the CCS effect in 2021 according to the methodology developed in this part and our two parameters. The main message appearing from this analysis is that communicating only the capture capacity of 40.12 $MtCO_2/y$ can be highly misleading.

		Crude oil recovery ratio [bbl/tCO$_2$]							
		1.83	**2**	**2.21**	**3.33**	**4**	**4.35**	**4.6**	**6.5**
α	**0**	-3.39	-0.38	3.22	22.42	33.82	39.80	44.08	76.57
	0.5	-17.17	-15.43	-13.42	-2.67	3.71	7.06	9.46	27.64
	1	-30.94	-30.48	-30.05	-27.76	-26.40	-25.68	-25.17	-21.28

Table 2: 2021 CCS effect on global emissions in [$MtCO_2e$] according to α and RR

EOR is therefore partially or completely offsetting the CCS potential for emissions reduction. Fortunately the percentage of EOR projects announced is decreasing in the following years since more and more permanent geological storage project are announced, as illustrated in Figure 8.

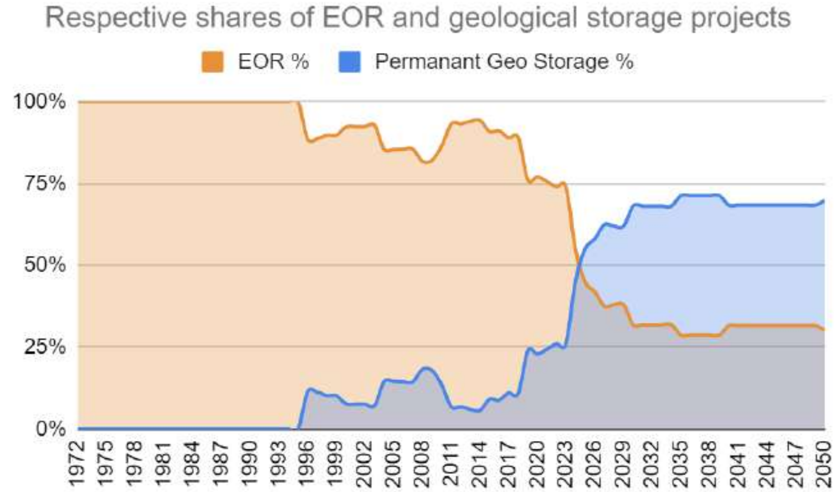


Figure 8: Respective shares of EOR and geological storage projects

Assuming an expected crude oil recovery ratio of 3.33 bbl/tCO_2 and α equals to 0.5 - meaning that without CO_2-EOR, only half of the quantity of oil produced thanks to it would have been effectively produced otherwise - we can compute the evolution CCS effect per year according to the database of CCS projects, as illustrated in Figure 9.

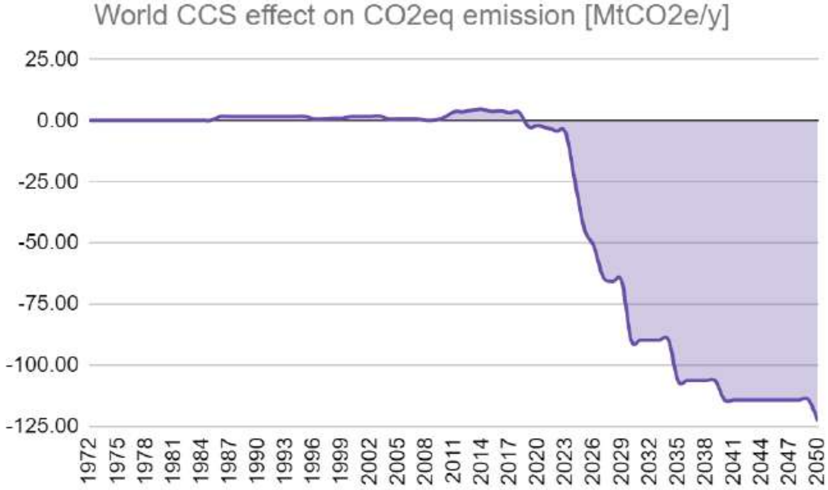


Figure 9: Evolution of CCS effect on CO_2e emissions [$MtCO_2e/y$]

According to this graph, until now CCS projects never helped to reduce global emissions, mainly due to the high percentage of EOR project. Indeed we can see on 8 that this is only when the permanent geological storage become the majority around 2024 than there is an important improvement in the CCS potential to reduce global emissions. But it reaches only approximately 100 $MtCO_2e/y$, which is still just 0.25% of today's global emissions. Cumulative CO_2 sequestrated quantity follows approximately the same path than Figure 9, revealing that CCS projects will effectively start to sequestrate CO_2 only after 2024. Of course, these graphs are extremely sensitive the α parameter and the crude oil recovery ratio, as shown with the 2021 example in Table 2.

For the same reasons than in part 1.2, data after 2030 are not relevant since only announced projects are accounted and it is not represented of the potential development after this period. There is more than 40 already announced CCS projects worldwide for the next 10 years, but it is still far to be enough to reach a Gt-Scale deployment. Regarding this finding, we can wonder what could be the CCS potential for Switzerland.

3 CCS potential for Switzerland

Switzerland recently showed an increasing interest for negative emissions technologies and carbon removal. After the postulate 18.4211 submitted on the 12th of December 2018 by Mrs. Adèle Thorens Goumaz at the Federal Assembly (The Swiss Parliament) on "*How important could negative CO_2 emissions be for Switzerland's future climate policies?*" [22], the Federal Office for the Environment (FOEN) commissioned the Risk Dialogue Foundation to produce a report on "*The Role of Atmospheric Carbon Dioxide Removal in Swiss Climate Policy*" released in August 2019 [23]. This report was used as a basis to produce the Federal Council response to Mrs. Thorens postulate, released on the 2nd of December 2020 [5]. Finally, this report was synthesised and add as a sub-chapter to the *Switzerland's Long Terms Climate Strategy* published on the 27th of January 2021.

The goal of this part is then to estimate how relevant CCS deployment could be for Switzerland.

3.1 Methodology

3.1.1 Swiss point-sources database

The first step of the project was to identify the Swiss important emitters. In 2021, Switzerland's emissions are approximately 50 $\mathrm{MtCO_2}e/\mathrm{y}$ on the territory, and 150 $\mathrm{MtCO_2}e/\mathrm{y}$ if the emissions coming from foreign products imported for Swiss consumption are accounted. The industry and waste sectors represent around 11 $\mathrm{MtCO_2}e/\mathrm{y}$. To identify where does these emissions come from, CO_2 emissions data of 13 last years were collected from SwissPRTR, the publicly accessible Swiss Pollutant Release and Transfer Register. Facilities enter in the registry when they emit more than 100'000 $\mathrm{tCO_2/y}$, however some of them are bellow this threshold, this can be explained by the fact that they should exceed another pollutant threshold, so even if CO_2 is not the problem, the values of its emissions are still reported. An overview of the Database is illustrated in Figure 23 of the Appendix, the original file is enclosed to this report and can be found in the following **link**.

Analysis were performed on these data to extract the relative part in CO_2 emissions from each industry, and to display the distribution of the facilities according to their emissions capacities to estimate how many CCS projects could be implemented.

3.1.2 Case study : The KVA Linth Waste-to-Energy plant

Most of industrial Switzerland's emissions are coming from the wastes management due to their incineration and the cement production. Once the total potential was estimated, it was interesting to focus on a study-case to better understand the feasibility of CCS implementation in Switzerland. Precisely, the Sustainability in Business Laboratory at ETH Zürich (ETH sus.lab) just finished a feasibility study funded by Innosuisse and the Association of Operators of Swiss Waste Incineration plants (VBSA) on the waste incineration plant KVA Linth in Switzerland [24]. A particular attention was then dedicated to understand this study and estimate its implication on the potential future CCS deployment in Switzerland.

3.1.3 Additional sustainable potential for biomass use

According the study case of KVA-Linth, CCS extensions could be installed on existing waste incineration plants. The fraction of biogenic wastes in incineration plants being around 50%, it is possible to imagine that in a more sustainable future, the quantity of wasted produced decrease and this biogenic fraction could then increase. This is particularly interesting because burning biomass in existing incineration plants equipped with CCS could produce energy and negative emissions, similarly to BECCS.

To estimate the potential of this scenario, researches were done to estimate the additional quantity of biomass that could be used in a sustainable way for CCS. The results were extracted from the WSL Institute's study on "*The role of biomass in Switzerland's future energy system*" [25].

3.2 Results

The Swiss point-sources database built for this project contains a total of 92 facilities across years, from 2007 to 2019, with approximately 60 facilities per year. Among them, approximately 30 facilities are emitting more and 100'000 tCO_2/y. In 2019, it was precisely 31 facilities over a total of 56 in the register. Similarly to the database in section 1, this one is also totally searchable and configurable by the user. It highlights and analyses the facilities above the threshold of 100'000 tCO_2/y that can be modified.

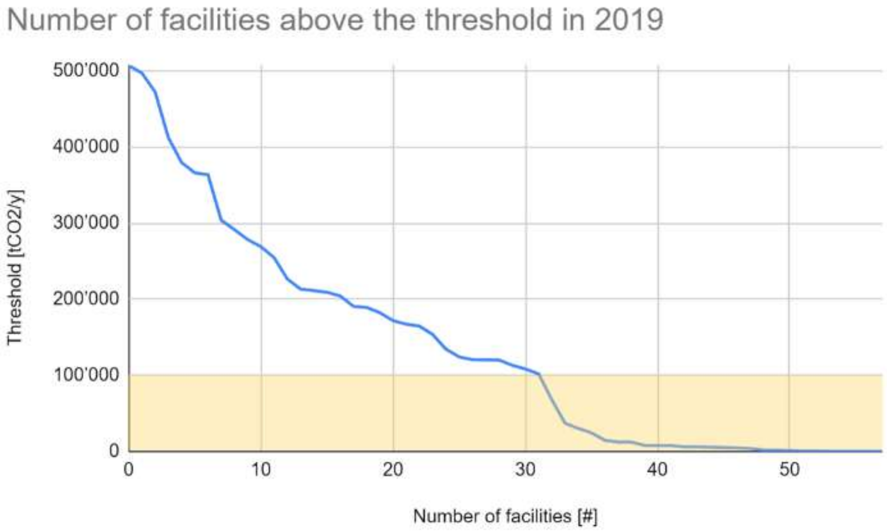


Figure 10: Distribution of facilities according to their emissions in 2019

Figure 10 shows the number of facilities above a given threshold. We can read for example that there are 8 facilities emitting more than 300'000 tCO_2/y, that are part of the 16 emitting more than 200'000 tCO_2/y, etc. The yellow area is a disclaimer to represent the SwissPRTR threshold of 100'000 tCO_2/y, the facilities after this threshold are not relevant for this study since they are in the registry for other reasons that significant CO_2 emissions. The same disclaimer is put on Figure 11 that illustrates the 2019 emissions of the facilities sorted from the biggest to the smallest emitters.

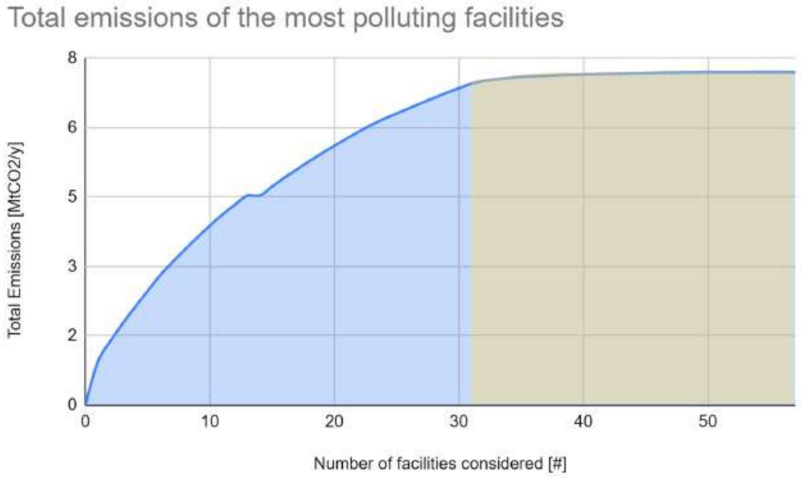


Figure 11: Emissions of the Switzerland biggest point-sources

We can conclude from this data that the 31 important Swiss point-sources emitted 7.42 MCO_2 in 2019, that is more that 96% of the total industrial point-sources CO_2 emissions reported in the registry. Theses facilities are affiliated to an industrial sector, which allow us display in figures 11 the relative part of each sector in total emissions, for both the number of facilities and the emissions capacities.

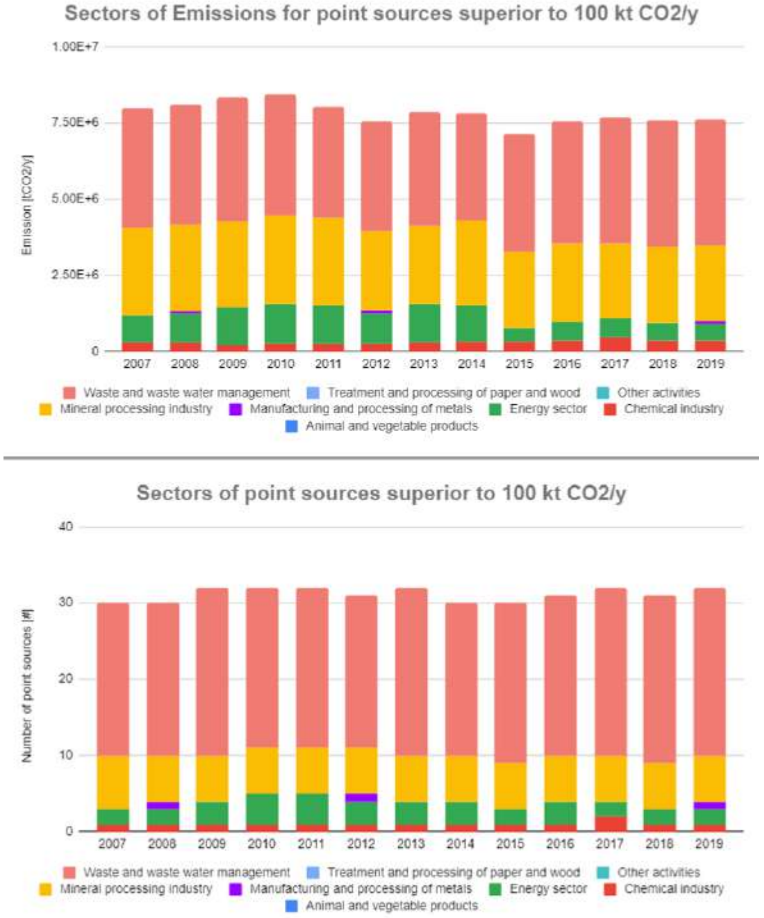


Figure 12: Number of facilities and emissions capacity of industrial sectors across years

In 2019 in Switzerland, there were 22 waste treatment plants emitting 4.1 $MtCO_2$ with a mean capacity of 188'000 tCO_2/y per facility with 50% of biogenic waste, 6 cement plants emitting 2.5 $MtCO_2$ with a mean capacity of 412'000 tCO_2/y per facility, 2 energy production plants emitting 0.5 $MtCO_2$ with a mean capacity of 277'000 tCO_2/y per facility, 1 chemical production plant emitting 366'000tCO_2/y and 1 steel production plant emitting 100'000 tCO_2/y.

By the time CCS could be developed in Switzerland, to convert these emissions in a CCS potential order of magnitude, we have to take into account 3 multipliers : the emissions reductions of the industry due to political incentives, the percentage of facilities equipped with a CCS system, and the efficiency rate. We can take the assumption than in 2050 that emissions will have decreased by 10%, 90% of the facilities will be equipped and the efficiency of carbon capture is equal to 85%. With these numbers we have an estimation of the CCS potential around **5.1 $MtCO_2/y$**, with 1.4 of negative emissions from the biogenic waste of incineration plants.

Moreover, going toward a more sustainable future we can estimate that the quantity of waste will decrease, allowing the biogenic waste to represent a bigger portion in incineration plants. The WSL study [25] precisely estimated the additional sustainable potential of dry-biomass that could be used for the energy to 2.8 Mt, mainly composed of animal manure, forest wood, wood from landscape maintenance and green waste. We know the molar of the carbon and CO_2 being respectively equal to 12 and 44 g/mol, the carbon fraction of dry-biomass around 50% and the capture efficiency still equal to 85%. With these parameters we can estimate the quantity of CCS negative emissions from this additional biomass around **4.3 $MtCO_2/y$**. This biomass could be used in waste incineration plant, but also in cement facilities since for now they use 1/3 of their energy from fossil fuels and 2/3 from other oil-based combustibles to produce the required heat and that they are thinking about shifting toward biomass. Finally, more recent gasification technologies as the Allam-Fetvedt process could be used since it has a CO_2 capture efficiency superior to 99% of the emissions. Even if we hope that in the more sustainable future the quantity of waste and cement produced will decreasing, decreasing at the same time the potential of CCS, it is important to take into account that we could apply land-use changes that could generated even more negative emissions.

The ETH sus.lab presented the potential costs for CCS deployment based on the feasibility study of the KVA Linth waste incineration plant conversion to CCS [24]. The first-of-a-kind facility would cost between 25 and 30 Millions CHF for a 0.1 $MtCO_2/y$ capacity, and will then be stabilized around 20 Millions CHF thanks to the technology learning curve and the economies of scale. Switzerland has the geological potential to store 2.7 billions tCO_2 [26] but it will take at least 20 years of research and development to be able to perform injections at the desired scale. In the meantime, Switzerland could count on European collaboration to deliver the captured CO_2 to be stored in Norway thanks to the Northern Lights project, opening in 2024, but this solution increase the transport costs. Transport costs also include the construction of a new pipeline network and the reallocation of old ones across Switzerland.

All of this could estimate the full CCS chain costs to be around 150-200 CHF/ton for a first of a kind facility in an optimist case (40-50 CHF for capture, 80 CHF for transport and 40-70 for storage) and a bit more than 100 CHF/ton at scale. This rapid estimation shows that with the current price for the ton of CO_2 is not sufficient to push companies to invest in CCS, and Switzerland would need stronger political and economical incentives to allow the development of CCS.

In total, if Switzerland requires the construction of approximately 40 facilities costing 20 millions CHF each, with a pipeline network and some injection facilities estimated for 3 Billions CHF [27], the total investment to develop CCS could rise to 4 billions CHF for 2050.

Discussion

The database presented in this study allowed the estimation of the current worldwide deployment of CCS technology and a near future projection. Since most of future projects announcements are before 2030, data after 2030 are highly uncertain and certainly not representative of what could be the real deployment for this period, but at least, it allows us to estimate the bottom the technology deployment S-curve. Another limitation is the fact that companies and states may communicate the values of the maximal theoretical capacities of CCS projects, then the actual capture and sequestration rates could be less important. This uncertainty would explain the different numbers presented by Dr. Julio Friedmann during EPFL CCUS workshop. But in any case the orders of magnitude presented in this study remain plausible.

2021's deployment shows a CCS capacity of 40 $MtCO_2/y$ which is negligible since it represents only 0.1% global emissions. But even this small quantity needs to be put in perspective, it's even worst due to the intensive utilisation of this captured CO_2 for EOR purpose. Section 3 shows that the total CCS effect on global emissions for this year could be in fact less than 30 $MtCO_2e$ emissions reduction in the best case, or in the worst case the additional emissions of 22 $MtCO_2e$. Moreover, this is considering the assumption that 100% of the CO_2 used in EOR facilities is anthropogenic CO_2 captured from facilities. One could argue that the deployment of CCS could accelerate the development of EOR facilities that could use natural geological CO_2, generating even more emissions. To have a positive effect on climate, CCS should turn itself towards permanent geological storage projects, and EOR should change its purpose from extracting the biggest quantity of oil possible, to storing the biggest quantity of CO_2. Political and economical incentives may help this transition.

In a way, CCS can be seen as an approach to extend the threshold of "burnable" oil and coal to remain under the 2°C target from Paris Agreement. Taking the assumption that all the possible fossil fuels that can be burned will be, this perspective may question who is really benefiting from CCS development. Since the 2°C target remains the same, CCS just allows the fossil fuels companies to extract and burn fossil fuels for a longer time, their business model being preserved for some additional years. However business as usual scenarios are still worse and CCS may have a climate-beneficial effect with industrial activities that are difficult to stop as waste incineration or cement, steel and chemical production.

To estimate the feasibility of CCS deployment, the IEA released in May 2021 its Net-Zero Emissions scenario for 2050 [28]. This scenario assumes a needed CCS capacity of 7 $GtCO_2/y$ by 2050, considering that the mean capacity of a facility is 1 $MtCO_2/y$ (still 10 times bigger than the ones that Switzerland could develop), it implies the construction of 1 facility every 2 days until 2030, following by 1 facility every day until 2040, and coming back to 1 facility every 2 days between 2040 and 2050. An effort even bigger than China building a new large scale coal power plant every week. If we compare the deployment curve estimated by IEA to the current and announced projects of our database, we obtain the following graph.

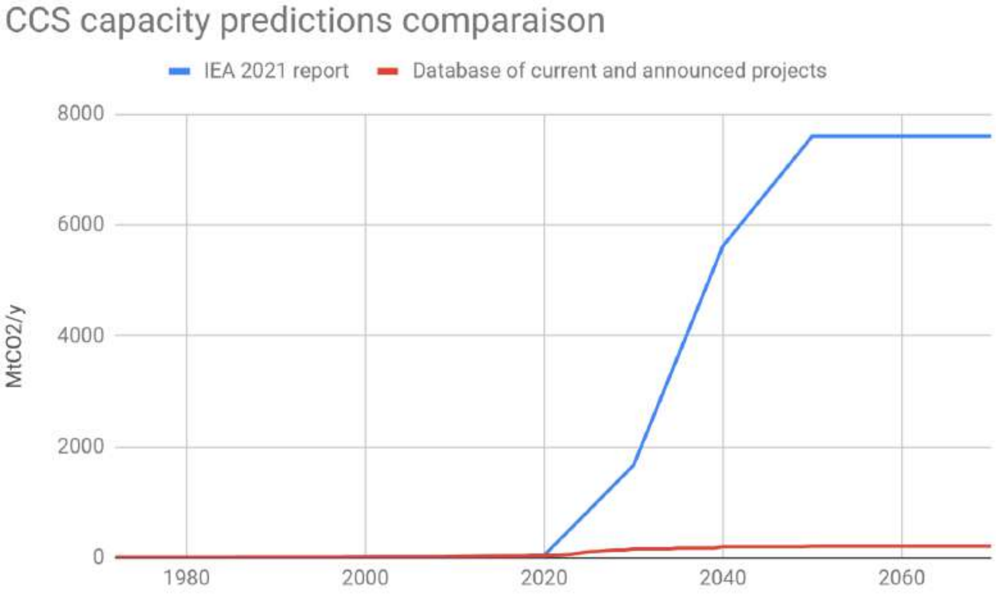


Figure 13: Comparison between IEA CCS deployment scenario and database of current and announced projects

This illustration represents well the big step to pass. In terms of potential limits, the IEA NZE scenario remains plausible even if extremely ambitious. By 2050, humanity should have built 7'600 facilities of 1 $MtCO_2/y$ capacity, which represent a cumulative capital investment of \$750 bn (\$100 mn per facility considering the scaling factor from a 0.1 $MtCO_2/y$ facility at \$25 mn) and cumulative operation costs over 30 years for \$12'000 bn, which total is a bit more than 1% of the \$1.2 Quadrillion of global economy. All of these facilities would use 21 km^3 of water per year, which is 0.5% of the planetary boundary regarding fresh water. Such a deployment would require 200'000 qualified workers per year for the installation and another 200'000 for the operation and maintenance, which is 1% of the total number of workers in these sectors. Based on the electricity requirements for a 1 $MtCO_2/y$ facility estimated at 160 GWh/y, we arrive at a total of 1'200 TWh needed for 2050, which is 3% of the predicted clean electricity production of 40'000 TWh/y estimated by the IEA NZE-2050 report. Same for the heat requirement, 1 kg of CO_2 requires 3000 kJ to be captured, so the total need of heat production for CCS in 2050 would be around 23 EJ, which is 3% of the estimated 761 EJ of total energy produced in the NZE-2050 IEA report. However, some studies show that the CCS capacity may have to rise up to 20-25 $GtCO_2/y$ in 2050 to insure a world bellow 2°C [29], such a deployment would implies 10% of total energy produced worldwide, which start to be concerning.

Even if the limits detailed previously are respected, we have to consider the implications of such a deployment. First, the promise of CCS future development constitutes a moral hazard for the future. Indeed talking about the possibility of continuing current unsustainable activities without the related pollution makes the changes of behaviour more difficult, whether this change is the shift to renewable energy or even the decrease in energy and goods production and consumption. Finally, according to IEA, the deployment of CCS technology allows an energy mix for 2050 in which coal and oil still represent an important part, which implies to continue living in a world in which millions of persons die every year from industrial accidents and air pollution, due to particulate matters, in similar magnitude, being the 4^{th} most important cause of death nowadays.

Regarding Switzerland potential, part 3 shows an interesting potential of 5 $MtCO_2/y$ from industrial activities, which become even better if the quantity of waste decreases and the biomass used increases. If major land use changes occur, an increase in the potential of negative emissions for the same CCS installations could be possible. These values rapidly computed in the previous section are very similar to the ones presented in the Switzerland's Long-term Climate strategy [30] and therefore seem coherent and plausible. It will take a long time to develop Switzerland own geological reservoir, therefore Switzerland remains dependant on Norway for now, which increases costs. Even if future costs are hard to assume due technological learning curve, economy of scale, saturation of other low-cost methods, and future electricity cost, etc., CCS doesn't have a valid financial model for now. Its deployment would require either a higher cost of carbon (around 200 CHF/tCO_2) or the introduction a fundamentally different mechanism, as the climate clean up fund.

Finally, even if the total investment cost of 4 billions CHF until 2050 presented by ETH sus.lab seems to be an important sum, it is relevant to remember that it is not without precedent for Switzerland. When water pollution became a concerning issue, Switzerland invested more than 40 billions CHF, around 80 billions CHF today, to build 800 water treatment plants and more than 40'000 km of pipelines network.

Conclusion

This study provides an evaluation of the industrial CO_2 management potential thanks to Carbon Capture and Sequestration (CCS). Even if CCS is not a NET, both should be considered as an integrated system since CCS and BECCS share the same know-how, barriers and technological learning curves.

By looking at the 2021 worldwide deployment and projection of future announced projects, today's annual capacity is estimated to 40 $MtCO_2$, which is only 1 ‰ of global emissions, moreover 70% of this capacity is dedicated to EOR, which drastically reduces the emissions reduction potential of CCS.

By according a special attention to the distinction between Permanent Geological Storage (GEO) and carbon dioxide Enhanced Oil Recovery (CO_2-EOR) for the sequestration options, it was possible to estimate that for every ton of CO_2 injected for EOR purpose, the net effect on climate is between the net emissions reduction of 0.7 tCO_2 and the net additional emissions of 2.9 tCO_2, depending on technical parameters as the crude oil recovery ratio, and economical assumptions as the quantity of oil that could have been extracted without CO_2-EOR.

To reach an significant Gt-scale, humanity should focus on permanent geological storage projects and build a new 1 $MtCO_2$/y facility every 1 or 2 days during the next 30 years, which is highly ambitious but not entirely unrealistic.

Switzerland has a solid potential concerning the cement and waste-to-energy industries, and could reach a capacity of 5 $MtCO_2$/y, which become particularly interesting when biomass is burned, generating 4 $MtCO_2$/y of additional negative emissions. Land use changes should therefore be considered with CCS as an integrated strategy to reduce CO_2 emissions.

Future research

This study is the fruit of a 3 months ENAC Project, many assumptions and results could be investigated furthermore.

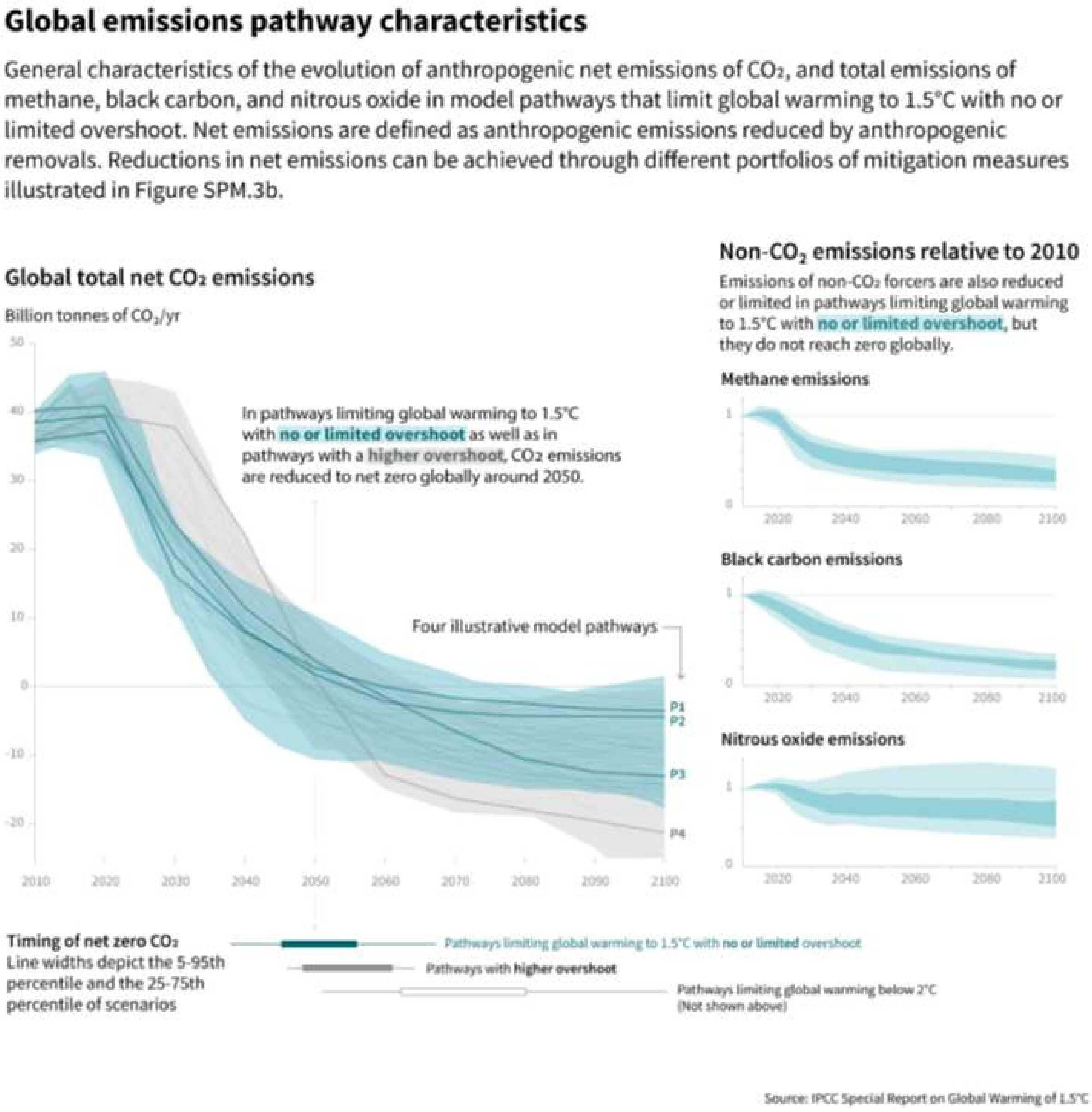
First, it would be very interesting to extend this analysis to all negative emissions technologies, and produce a scenario combining them to study the competitions and substitutions that exist between the different approaches. As a first step, BECCS and DACCS future projects announced could be added to the database. But it can be especially interesting to include nature-based NETs and the restoration of ecosystems to regenerate natural carbon sinks, and compare either the emissions reduction potential and costs of NETs to the ones of CCUS approaches.

Secondly, a sensitivity analysis of the parameters used in the EOR life-cycle analysis model should be produced.

Finally, a closer look to the CCS limits, costs and barriers mentioned in the discussion should be done to properly estimate them. Such a study could result in the construction of the technology deployment S-curve for CCS, and if the methodology is valid, it could be possible to extend it to every other NETs approaches.

Appendix

1. Global Emissions



Global emissions pathway characteristics

General characteristics of the evolution of anthropogenic net emissions of CO_2, and total emissions of methane, black carbon, and nitrous oxide in model pathways that limit global warming to 1.5°C with no or limited overshoot. Net emissions are defined as anthropogenic emissions reduced by anthropogenic removals. Reductions in net emissions can be achieved through different portfolios of mitigation measures illustrated in Figure SPM.3b.

In pathways limiting global warming to 1.5°C with no or limited overshoot as well as in pathways with a higher overshoot, CO_2 emissions are reduced to net zero globally around 2050.

Non-CO_2 emissions relative to 2010

Emissions of non-CO_2 forcers are also reduced or limited in pathways limiting global warming to 1.5°C with no or limited overshoot, but they do not reach zero globally.

Timing of net zero CO_2
Line widths depict the 5-95th percentile and the 25-75th percentile of scenarios

Source: IPCC Special Report on Global Warming of 1.5°C

Figure 14: Compilation of scenarios showing global emissions pathway characteristics Source: IPCC SR1.5 [3].

2. CDR and NETs

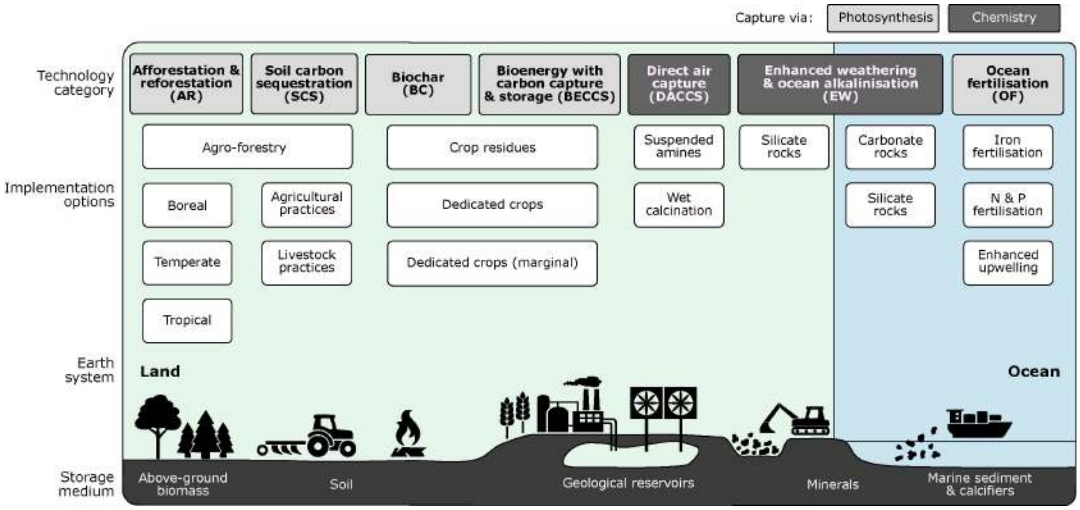
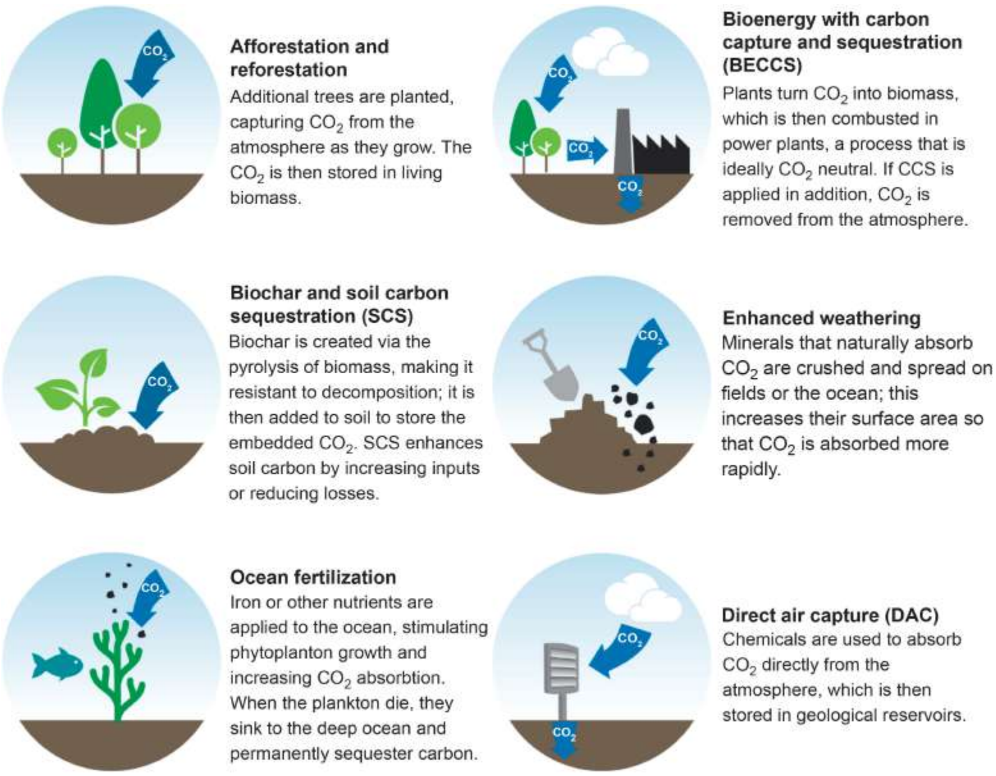


Figure 15: A taxonomy of negative emissions technologies (NETs). NETs are distinguished by approach to carbon capture, earth system and storage medium, from Minx et al. 2018 [31].



Afforestation and reforestation
Additional trees are planted, capturing CO$_2$ from the atmosphere as they grow. The CO$_2$ is then stored in living biomass.

Bioenergy with carbon capture and sequestration (BECCS)
Plants turn CO$_2$ into biomass, which is then combusted in power plants, a process that is ideally CO$_2$ neutral. If CCS is applied in addition, CO$_2$ is removed from the atmosphere.

Biochar and soil carbon sequestration (SCS)
Biochar is created via the pyrolysis of biomass, making it resistant to decomposition; it is then added to soil to store the embedded CO$_2$. SCS enhances soil carbon by increasing inputs or reducing losses.

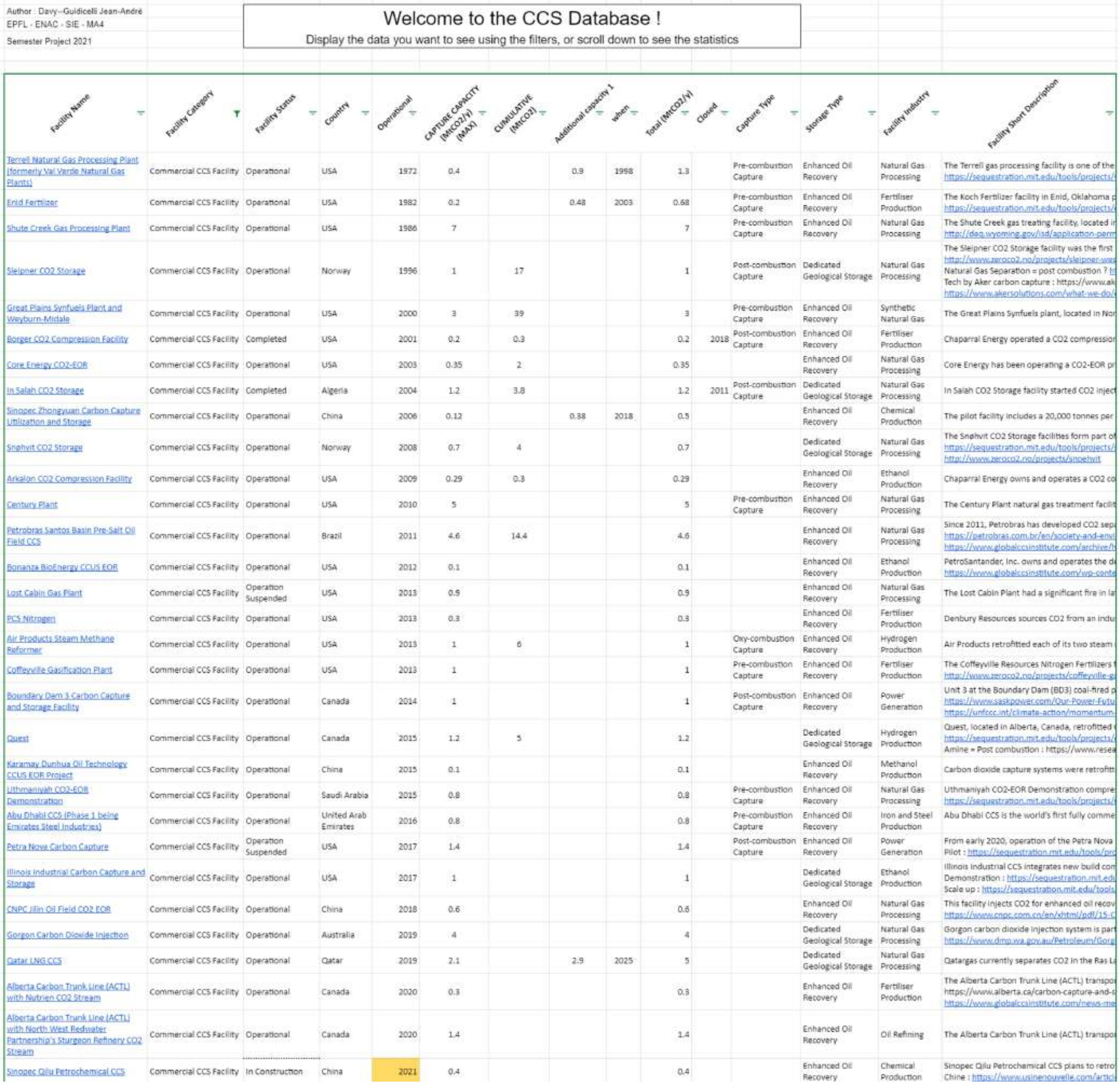
Enhanced weathering
Minerals that naturally absorb CO$_2$ are crushed and spread on fields or the ocean; this increases their surface area so that CO$_2$ is absorbed more rapidly.

Ocean fertilization
Iron or other nutrients are applied to the ocean, stimulating phytoplanton growth and increasing CO$_2$ absorbtion. When the plankton die, they sink to the deep ocean and permanently sequester carbon.

Direct air capture (DAC)
Chemicals are used to absorb CO$_2$ directly from the atmosphere, which is then stored in geological reservoirs.

Figure 16: Detailed description of Negative Emission Technologies from Minx et al. 2018 [31].

3. CCS Database



Author : Davy--Guidicelli Jean-André
EPFL - ENAC - SIE - MA4
Semester Project 2021

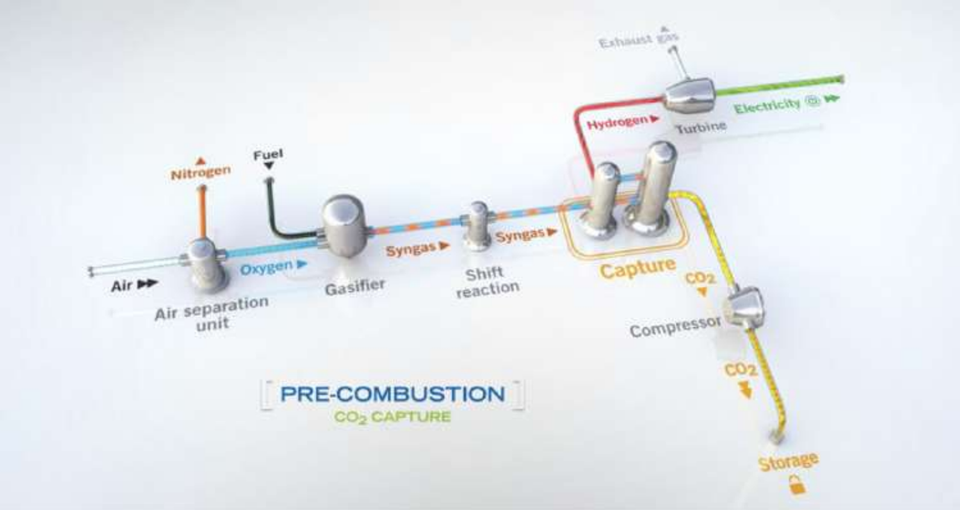
Welcome to the CCS Database !

Display the data you want to see using the filters, or scroll down to see the statistics

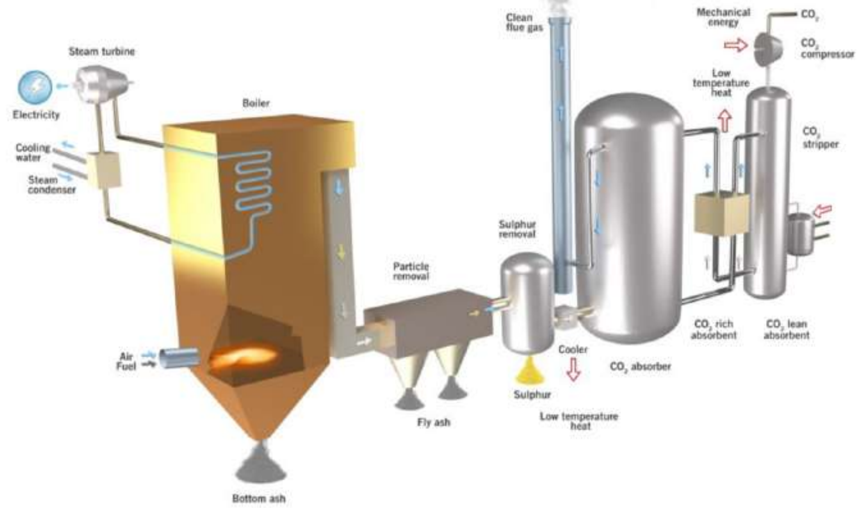
Facility Name	Facility Category	Facility Status	Country	Operational	CAPTURE CAPACITY (MtCO2/y) (MAX)	CUMULATIVE (MtCO2)	Additional capacity 1	when	Total (MtCO2/y)	Closed	Capture Type	Storage Type	Facility Industry	Facility Short Description
Terrell Natural Gas Processing Plant (formerly Val Verde Natural Gas Plants)	Commercial CCS Facility	Operational	USA	1972	0.4		0.9	1998	1.3		Pre-combustion Capture	Enhanced Oil Recovery	Natural Gas Processing	The Terrell gas processing facility is one of the https://sequestration.mit.edu/tools/projects/
Enid Fertilizer	Commercial CCS Facility	Operational	USA	1982	0.2		0.48	2003	0.68		Pre-combustion Capture	Enhanced Oil Recovery	Fertiliser Production	The Koch Fertilizer facility in Enid, Oklahoma https://sequestration.mit.edu/tools/projects/
Shute Creek Gas Processing Plant	Commercial CCS Facility	Operational	USA	1986	7				7		Pre-combustion Capture	Enhanced Oil Recovery	Natural Gas Processing	The Shute Creek gas treating facility, located i http://deq.wyoming.gov/isd/application-perm
Sleipner CO2 Storage	Commercial CCS Facility	Operational	Norway	1996	1	17			1		Post-combustion Capture	Dedicated Geological Storage	Natural Gas Processing	The Sleipner CO2 Storage facility was the first http://www.zeroco2.no/projects/sleipner-we Natural Gas Separation = post combustion ? Tech by Aker carbon capture : https://www.ak https://www.akersolutions.com/what-we-do/
Great Plains Synfuels Plant and Weyburn-Midale	Commercial CCS Facility	Operational	USA	2000	3	39			3		Pre-combustion Capture	Enhanced Oil Recovery	Synthetic Natural Gas	The Great Plains Synfuels plant, located in No
Borger CO2 Compression Facility	Commercial CCS Facility	Completed	USA	2001	0.2	0.3			0.2	2018	Post-combustion Capture	Enhanced Oil Recovery	Fertiliser Production	Chaparral Energy operated a CO2 compressio
Core Energy CO2-EOR	Commercial CCS Facility	Operational	USA	2003	0.35	2			0.35			Enhanced Oil Recovery	Natural Gas Processing	Core Energy has been operating a CO2-EOR p
In Salah CO2 Storage	Commercial CCS Facility	Completed	Algeria	2004	1.2	3.8			1.2	2011	Post-combustion Capture	Dedicated Geological Storage	Natural Gas Processing	In Salah CO2 Storage facility started CO2 injec
Sinopec Zhongyuan Carbon Capture Utilization and Storage	Commercial CCS Facility	Operational	China	2006	0.12		0.38	2018	0.5			Enhanced Oil Recovery	Chemical Production	The pilot facility includes a 20,000 tonnes per
Snøhvit CO2 Storage	Commercial CCS Facility	Operational	Norway	2008	0.7	4			0.7			Dedicated Geological Storage	Natural Gas Processing	The Snøhvit CO2 Storage facilities form part o https://sequestration.mit.edu/tools/projects/ http://www.zeroco2.no/projects/snoehvit
Arkalon CO2 Compression Facility	Commercial CCS Facility	Operational	USA	2009	0.29	0.3			0.29			Enhanced Oil Recovery	Ethanol Production	Chaparral Energy owns and operates a CO2 c
Century Plant	Commercial CCS Facility	Operational	USA	2010	5				5		Pre-combustion Capture	Enhanced Oil Recovery	Natural Gas Processing	The Century Plant natural gas treatment facil
Petrobras Santos Basin Pre-Salt Oil Field CCS	Commercial CCS Facility	Operational	Brazil	2011	4.6	14.4			4.6			Enhanced Oil Recovery	Natural Gas Processing	Since 2011, Petrobras has developed CO2 sep https://petrobras.com.br/en/society-and-env https://www.globalccsinstitute.com/archive/
Bonanza BioEnergy CCUS EOR	Commercial CCS Facility	Operational	USA	2012	0.1				0.1			Enhanced Oil Recovery	Ethanol Production	PetroSantander, Inc. owns and operates the d https://www.globalccsinstitute.com/wp-conte
Lost Cabin Gas Plant	Commercial CCS Facility	Operation Suspended	USA	2013	0.9				0.9			Enhanced Oil Recovery	Natural Gas Processing	The Lost Cabin Plant had a significant fire in la
PCS Nitrogen	Commercial CCS Facility	Operational	USA	2013	0.3				0.3			Enhanced Oil Recovery	Fertiliser Production	Denbury Resources sources CO2 from an indu
Air Products Steam Methane Reformer	Commercial CCS Facility	Operational	USA	2013	1	6			1		Oxy-combustion Capture	Enhanced Oil Recovery	Hydrogen Production	Air Products retrofitted each of its two steam
Coffeyville Gasification Plant	Commercial CCS Facility	Operational	USA	2013	1				1		Pre-combustion Capture	Enhanced Oil Recovery	Fertiliser Production	The Coffeyville Resources Nitrogen Fertilizers http://www.zeroco2.no/projects/coffeyville-g
Boundary Dam 3 Carbon Capture and Storage Facility	Commercial CCS Facility	Operational	Canada	2014	1				1		Post-combustion Capture	Enhanced Oil Recovery	Power Generation	Unit 3 at the Boundary Dam (BD3) coal-fired https://www.saskpower.com/Our-Power-Futu https://unfccc.int/climate-action/momentum-
Quest	Commercial CCS Facility	Operational	Canada	2015	1.2	5			1.2			Dedicated Geological Storage	Hydrogen Production	Quest, located in Alberta, Canada, retrofitted https://sequestration.mit.edu/tools/projects/ Amine = Post combustion : https://www.rese
Karamay Dunhua Oil Technology CCUS EOR Project	Commercial CCS Facility	Operational	China	2015	0.1				0.1			Enhanced Oil Recovery	Methanol Production	Carbon dioxide capture systems were retrofit
Uthmaniyah CO2-EOR Demonstration	Commercial CCS Facility	Operational	Saudi Arabia	2015	0.8				0.8		Pre-combustion Capture	Enhanced Oil Recovery	Natural Gas Processing	Uthmaniyah CO2-EOR Demonstration compre https://sequestration.mit.edu/tools/projects/
Abu Dhabi CCS (Phase 1 being Emirates Steel Industries)	Commercial CCS Facility	Operational	United Arab Emirates	2016	0.8				0.8		Pre-combustion Capture	Enhanced Oil Recovery	Iron and Steel Production	Abu Dhabi CCS is the world's first fully comme
Petra Nova Carbon Capture	Commercial CCS Facility	Operation Suspended	USA	2017	1.4				1.4		Post-combustion Capture	Enhanced Oil Recovery	Power Generation	From early 2020, operation of the Petra Nova Pilot : https://sequestration.mit.edu/tools/pr
Illinois Industrial Carbon Capture and Storage	Commercial CCS Facility	Operational	USA	2017	1				1			Dedicated Geological Storage	Ethanol Production	Illinois Industrial CCS integrates new build co Demonstration : https://sequestration.mit.ed Scale up : https://sequestration.mit.edu/tools
CNPC Jilin Oil Field CO2 EOR	Commercial CCS Facility	Operational	China	2018	0.6				0.6			Enhanced Oil Recovery	Natural Gas Processing	This facility injects CO2 for enhanced oil reco https://www.cnpc.com.cn/en/xhtml/pdf/15-C
Gorgon Carbon Dioxide Injection	Commercial CCS Facility	Operational	Australia	2019	4				4			Dedicated Geological Storage	Natural Gas Processing	Gorgon carbon dioxide injection system is par https://www.dmp.wa.gov.au/Petroleum/Gorg
Qatar LNG CCS	Commercial CCS Facility	Operational	Qatar	2019	2.1		2.9	2025	5			Dedicated Geological Storage	Natural Gas Processing	Qatargas currently separates CO2 in the Ras L
Alberta Carbon Trunk Line (ACTL) with Nutrien CO2 Stream	Commercial CCS Facility	Operational	Canada	2020	0.3				0.3			Enhanced Oil Recovery	Fertiliser Production	The Alberta Carbon Trunk Line (ACTL) transpo https://www.alberta.ca/carbon-capture-and- https://www.globalccsinstitute.com/news-me
Alberta Carbon Trunk Line (ACTL) with North West Redwater Partnership's Sturgeon Refinery CO2 Stream	Commercial CCS Facility	Operational	Canada	2020	1.4				1.4			Enhanced Oil Recovery	Oil Refining	The Alberta Carbon Trunk Line (ACTL) transpo
Sinopec Qilu Petrochemical CCS	Commercial CCS Facility	In Construction	China	2021	0.4				0.4			Enhanced Oil Recovery	Chemical Production	Sinopec Qilu Petrochemical CCS plans to retro Chine : https://www.usinenouvelle.com/artic

Figure 17: CCS Database built during this project displaying commercial facilities, the excel version is enclosed to this report or can be found in the following **link**.

4. CCS Capture systems



Post-combustion capture (absorption process)



O_2/CO_2 recycle (oxyfuel) combustion capture

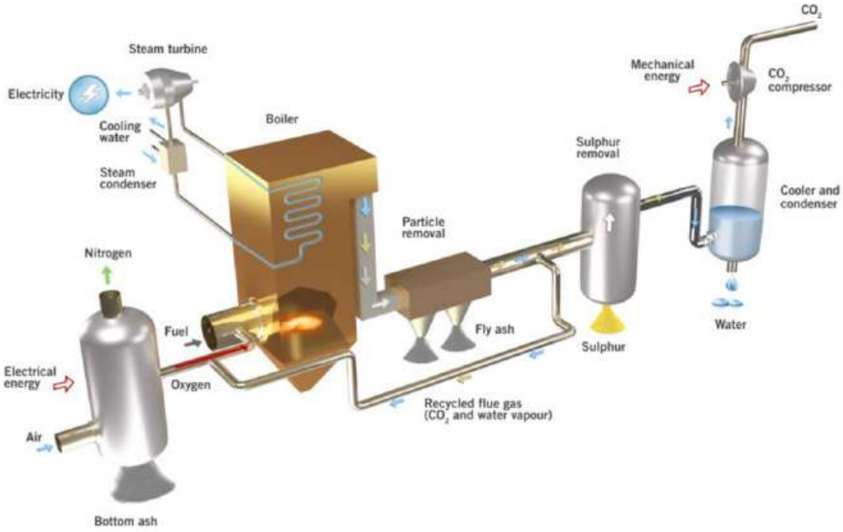


Figure 18: Schematic representation of capture systems from the Global CCS Institute [7].

5. Database Statistical analysis tool

STATISTICS

Which Facilities do you want to study ?

Total :	183	100.00%
Pilot and Demonstration CC	95	51.91%
Commercial CCS Facility	70	38.25%
CCS Hubs	18	9.84%

*

Focus on : * 183

	Early Development	34	18.58%
	Advanced Development	30	16.39%
	In construction	10	5.46%
(closed)	Completed	49	26.78%
	Operational	58	31.69%
	Operation suspended	2	1.09%

* 100.00%

Focus on : * 183

Superior to [MtCO2/y] 0 183

From 1972
to 2050 183

Capacité max : 207.17 MtCO2/y

Mean capacity :	1.13	MtCO2/y
Median capacity :	0.00	MtCO2/y

Origin

Country	Unit	%	Capacity	%
Algeria	1	0.55%	0	0.00%
Australia	13	7.10%	6.7	3.23%
Belgium	1	0.55%	0.018	0.01%
Brazil	3	1.64%	4.6	2.22%
Canada	12	6.56%	16	7.72%
China	20	10.93%	3.01	1.45%
Croatia	2	1.09%	0.61	0.29%
Denmark	3	1.64%	3.5	1.69%
France	4	2.19%	1	0.48%
Germany	4	2.19%	0.1	0.05%
Iceland	1	0.55%	0.012	0.01%
India	1	0.55%	0	0.00%
Indonesia	1	0.55%	0	0.00%
Ireland	1	0.55%	2.5	1.21%
Italy	2	1.09%	0	0.00%
Japan	6	3.28%	0	0.00%
Netherlands	6	3.28%	18.5	8.93%
New Zealand	1	0.55%	1	0.48%
Norway	8	4.37%	2.5	1.21%
Qatar	1	0.55%	5	2.41%
Saudi Arabia	1	0.55%	0.8	0.39%
South Africa	1	0.55%	0	0.00%
South Korea	3	1.64%	1	0.48%
Spain	4	2.19%	0	0.00%
Sweden	3	1.64%	0.5	0.24%
United Arab Emi	3	1.64%	3.1	1.50%
United Kingdom	15	8.20%	73	35.24%
USA	62	33.88%	63.72	30.76%
		100.00%		100.00%

Capture type

Methods	Unit	%	Capacity	%
Post-combustion Capture	56	30.60%	107.83	52.05%
Oxy-combustion Capture	3	1.64%	2.82	1.36%
Pre-combustion Capture	12	6.56%	23.08	11.14%
Under Evaluation	1	0.55%	1.00	0.48%
Natural Gas Separation	0	0.00%	0.00	0.00%
Various	19	10.38%	71.70	34.61%
Empty	92	50.27%	0.74	0.36%
		100.00%		100.00%

Storage type

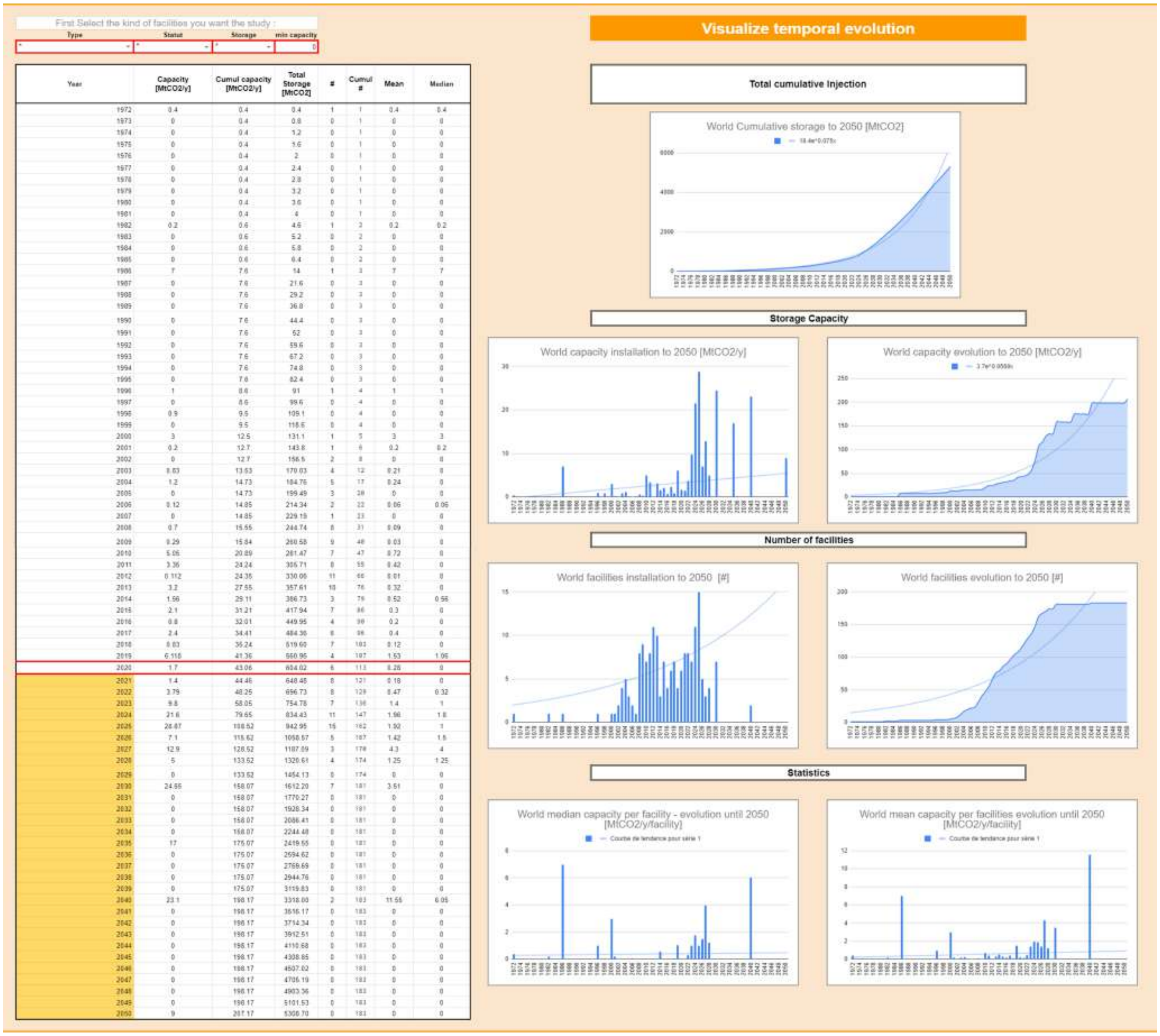
Methods	Unit	%	Capacity	%
Enhanced Oil Recovery	40	21.86%	59.32	28.63%
Dedicated Geological Storage	48	26.23%	140.39	67.77%
In evaluation	6	3.28%	7.44	3.59%
Empty	89	48.63%	0.02	0.01%
*		100.00%		100.00%

Utilisation

Purpose	Unit	%	Capacity	%
Air	1	0.55%	1.00	0.48%
Cement Production	7	3.83%	1.24	0.60%
Chemical production	7	3.83%	8.51	4.11%
Coal-to-liquids (CTL)	2	1.09%	0.00	0.00%
Ethanol Production	8	4.37%	2.20	1.06%
Ethanol Production and Fertil	1	0.55%	0.00	0.00%
Fertiliser Production	7	3.83%	4.03	1.95%
Fertiliser Production and Pow	1	0.55%	0.00	0.00%
Hydrogen production	8	4.37%	7.10	3.43%
Industrial Applications	2	1.09%	0.00	0.00%
Iron and Steel Production	5	2.73%	1.80	0.87%
Methanol production	1	0.55%	0.10	0.05%
N/A	15	8.20%	0.00	0.00%
Natural gas processing	27	14.75%	39.31	18.97%
Oil Refining	5	2.73%	5.40	2.61%
Power Generation	57	31.15%	60.06	28.99%
Power Generation and Hydro	3	1.64%	1.32	0.64%
Power Generation and Refini	2	1.09%	2.50	1.21%
Synthetic Natural Gas	1	0.55%	3.00	1.45%
Under evaluation	3	1.64%	0.00	0.00%
Various	19	10.38%	69.20	33.40%
Empty	0	0.00%	0.00	0.00%
Waste incineration	1	0.55%	0.40	0.19%
		100.00%		100.00%

Figure 19: Database statistical analysis tool, accessible at the following link.

6. Database visualisation of capacity temporal evolution



First Select the kind of facilities you want the study :

Type	Statut	Storage	min capacity
*	*	*	0

Year	Capacity [MtCO2/y]	Cumul capacity [MtCO2/y]	Total Storage [MtCO2]	#	Cumul #	Mean	Median
1972	0.4	0.4	0.4	1	1	0.4	0.4
1973	0	0.4	0.8	0	1	0	0
1974	0	0.4	1.2	0	1	0	0
1975	0	0.4	1.6	0	1	0	0
1976	0	0.4	2	0	1	0	0
1977	0	0.4	2.4	0	1	0	0
1978	0	0.4	2.8	0	1	0	0
1979	0	0.4	3.2	0	1	0	0
1980	0	0.4	3.6	0	1	0	0
1981	0	0.4	4	0	1	0	0
1982	0.2	0.6	4.6	1	2	0.2	0.2
1983	0	0.6	5.2	0	2	0	0
1984	0	0.6	5.8	0	2	0	0
1985	0	0.6	6.4	0	2	0	0
1986	7	7.6	14	1	3	7	7
1987	0	7.6	21.6	0	3	0	0
1988	0	7.6	29.2	0	3	0	0
1989	0	7.6	36.8	0	3	0	0
1990	0	7.6	44.4	0	3	0	0
1991	0	7.6	52	0	3	0	0
1992	0	7.6	59.6	0	3	0	0
1993	0	7.6	67.2	0	3	0	0
1994	0	7.6	74.8	0	3	0	0
1995	0	7.6	82.4	0	3	0	0
1996	1	8.6	91	1	4	1	1
1997	0	8.6	99.6	0	4	0	0
1998	0.9	9.5	109.1	0	4	0	0
1999	0	9.5	118.6	0	4	0	0
2000	3	12.5	131.1	1	5	3	3
2001	0.2	12.7	143.8	1	6	0.2	0.2
2002	0	12.7	156.5	2	8	0	0
2003	0.83	13.53	170.03	4	12	0.21	0
2004	1.2	14.73	184.76	5	17	0.24	0
2005	0	14.73	199.49	3	20	0	0
2006	0.12	14.85	214.34	2	22	0.06	0.06
2007	0	14.85	229.19	1	23	0	0
2008	0.7	15.55	244.74	8	31	0.09	0
2009	0.29	15.84	260.58	9	40	0.03	0
2010	5.05	20.89	281.47	7	47	0.72	0
2011	3.35	24.24	305.71	8	55	0.42	0
2012	0.112	24.35	330.06	11	66	0.01	0
2013	3.2	27.55	357.61	10	76	0.32	0
2014	1.56	29.11	386.73	3	79	0.52	0.56
2015	2.1	31.21	417.94	7	86	0.3	0
2016	0.8	32.01	449.95	4	90	0.2	0
2017	2.4	34.41	484.36	8	98	0.4	0
2018	0.83	35.24	519.60	7	103	0.12	0
2019	6.118	41.36	560.95	4	107	1.53	1.06
2020	1.7	43.06	604.02	6	113	0.28	0
2021	1.4	44.46	648.48	8	121	0.18	0
2022	3.79	48.25	696.73	8	129	0.47	0.32
2023	9.8	58.05	754.78	7	136	1.4	1
2024	21.6	79.65	834.43	11	147	1.96	1.8
2025	28.87	108.52	942.95	15	162	1.92	1
2026	7.1	115.62	1058.57	5	167	1.42	1.5
2027	12.9	128.52	1187.09	3	170	4.3	4
2028	5	133.52	1320.61	4	174	1.25	1.25
2029	0	133.52	1454.13	0	174	0	0
2030	24.55	158.07	1612.20	7	181	3.51	0
2031	0	158.07	1770.27	0	181	0	0
2032	0	158.07	1928.34	0	181	0	0
2033	0	158.07	2086.41	0	181	0	0
2034	0	158.07	2244.48	0	181	0	0
2035	17	175.07	2419.55	0	181	0	0
2036	0	175.07	2594.62	0	181	0	0
2037	0	175.07	2769.69	0	181	0	0
2038	0	175.07	2944.76	0	181	0	0
2039	0	175.07	3119.83	0	181	0	0
2040	23.1	198.17	3318.00	2	183	11.55	6.05
2041	0	198.17	3516.17	0	183	0	0
2042	0	198.17	3714.34	0	183	0	0
2043	0	198.17	3912.51	0	183	0	0
2044	0	198.17	4110.68	0	183	0	0
2045	0	198.17	4308.85	0	183	0	0
2046	0	198.17	4507.02	0	183	0	0
2047	0	198.17	4705.19	0	183	0	0
2048	0	198.17	4903.36	0	183	0	0
2049	0	198.17	5101.53	0	183	0	0
2050	9	207.17	5308.70	0	183	0	0

Figure 20: Visualisation of the CCS capacity evolution, accessible at the following **link**.

7. EOR calculus tables and graphs

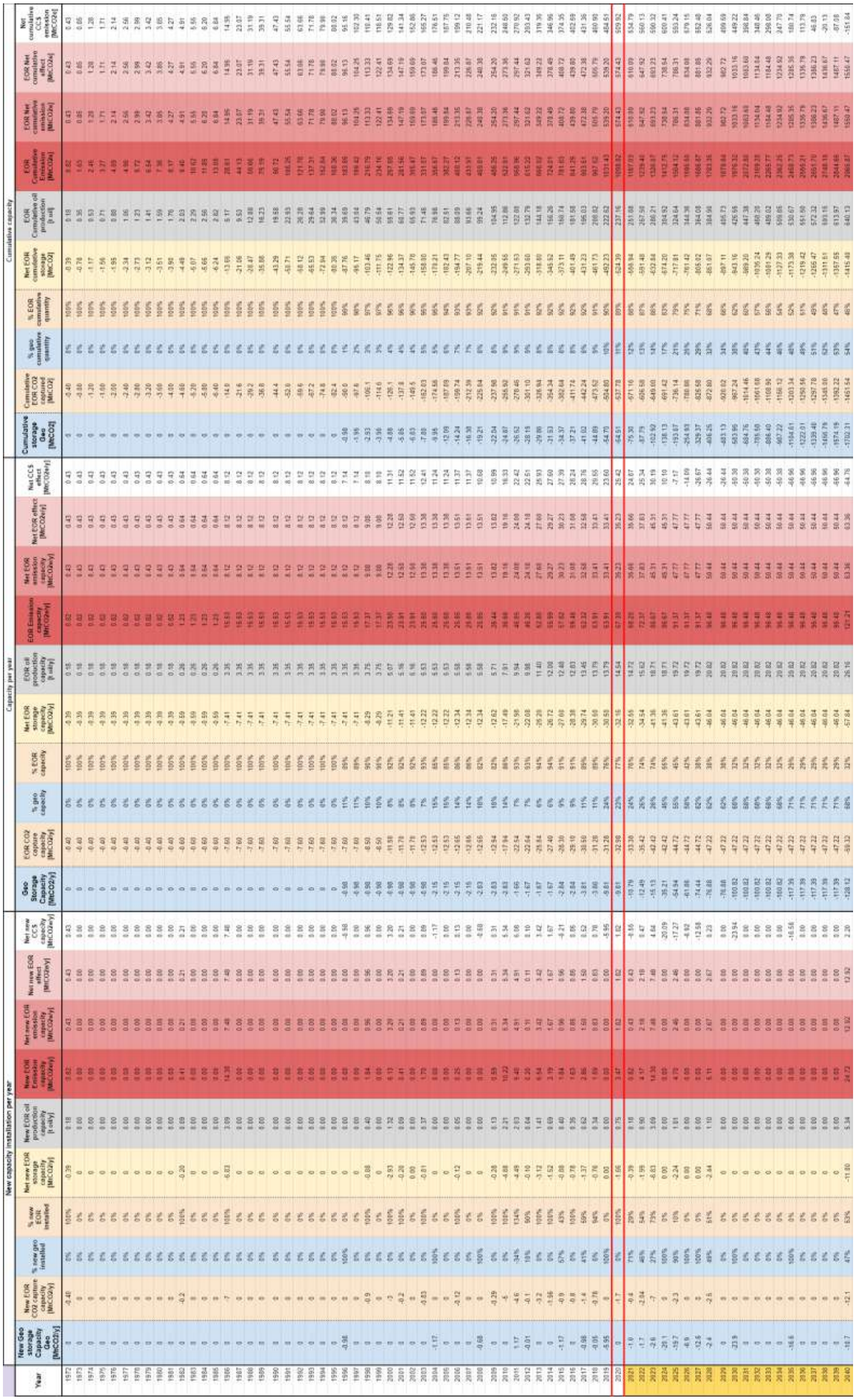


Figure 21: EOR calculation tables for all facility types, $\alpha = 0$, and $RR = 3.33$ bbl/tCO$_2$.

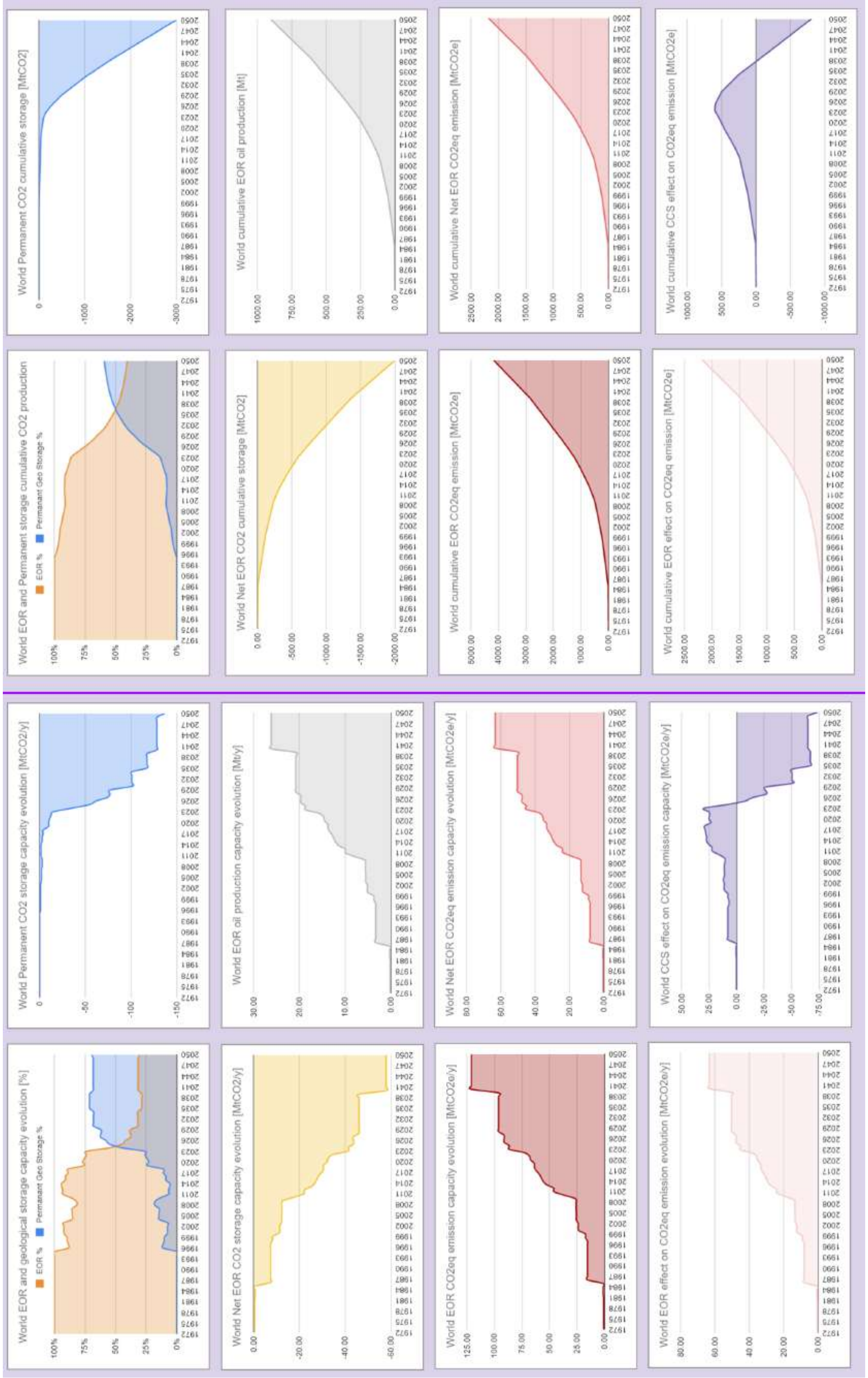
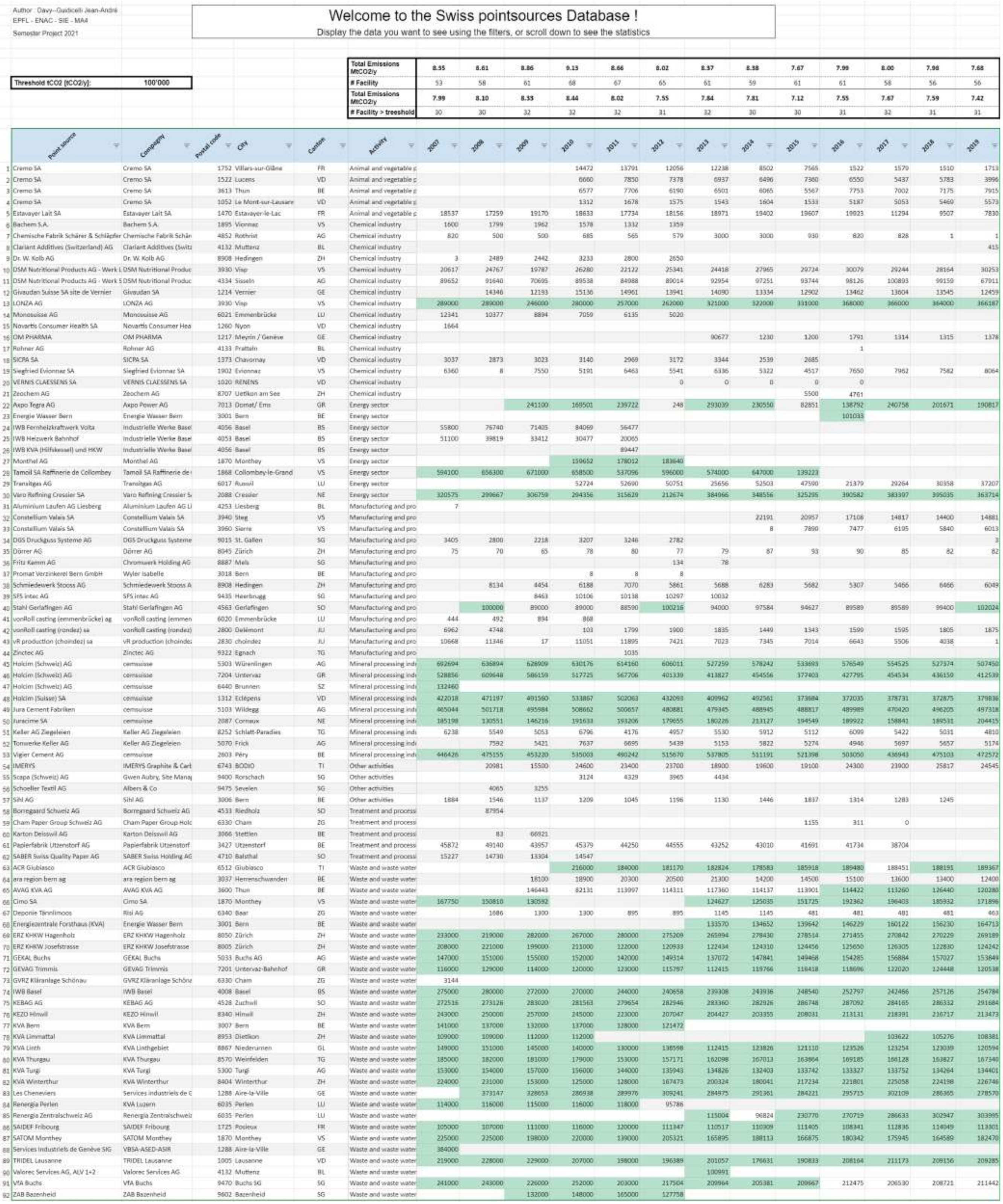


Figure 22: EOR distinction graphs extracted from tables illustrated in Figure 21 for all facility types, $\alpha = 0$, and $RR = 3.33$ bbl/tCO$_2$.

8. Switzerland point-sources database



Author : Davy--Guidicelli Jean-André
EPFL - ENAC - SIE - MA4
Semester Project 2021

Welcome to the Swiss pointsources Database !
Display the data you want to see using the filters, or scroll down to see the statistics

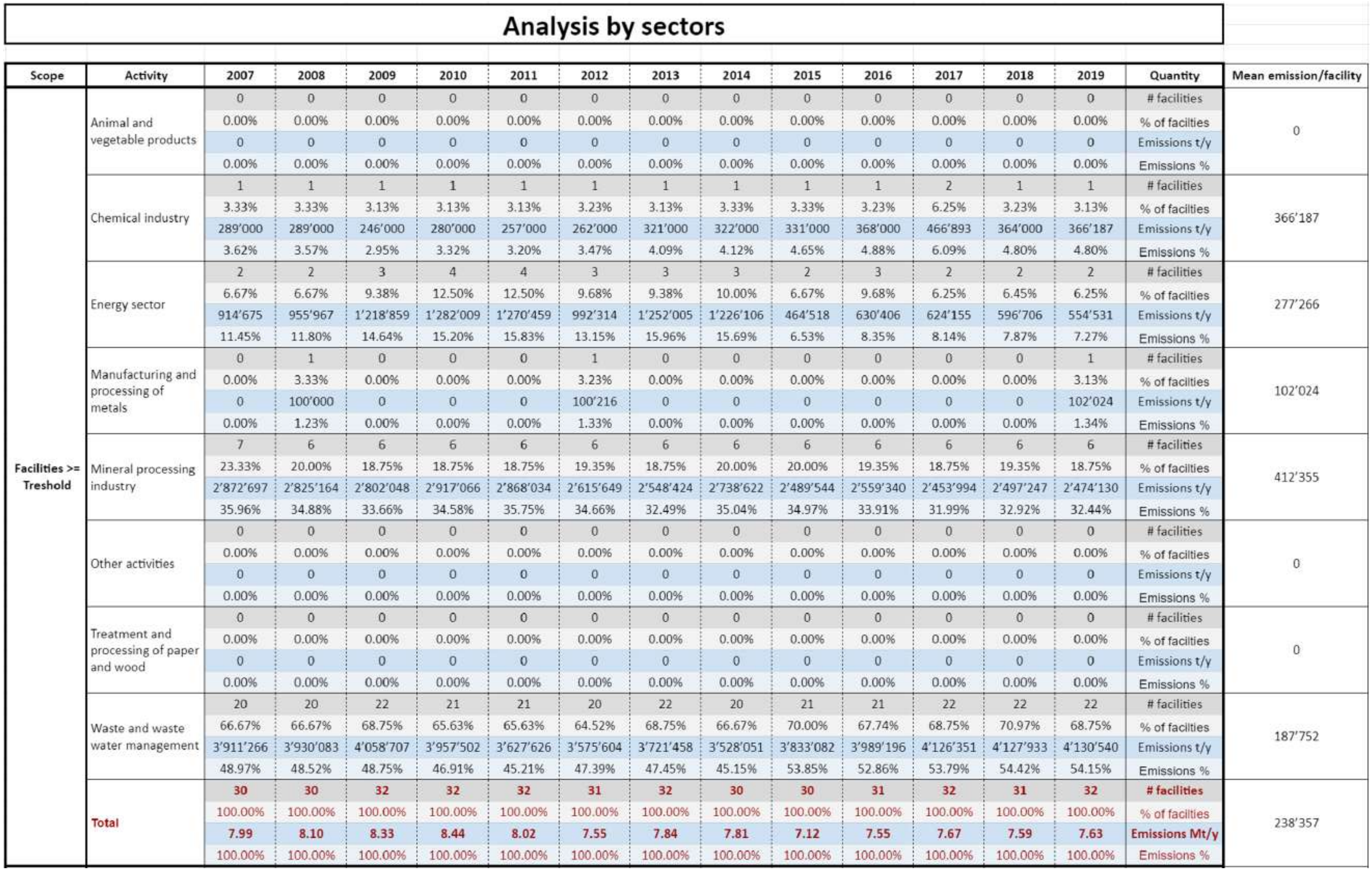
Threshold tCO2 [tCO2/y]:	100'000

Total Emissions MtCO2/y	8.55	8.61	8.86	9.15	8.66	8.02	8.37	8.38	7.67	7.99	8.00	7.98	7.68
# Facility	53	58	61	68	67	65	61	59	61	61	58	56	56
Total Emissions MtCO2/y	7.99	8.10	8.33	8.44	8.02	7.55	7.84	7.81	7.12	7.55	7.67	7.59	7.42
# Facility > treeshold	30	30	32	32	32	31	32	30	30	31	32	31	31

	Point source	Company	Postal code	City	Canton	Activity	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
1	Cremo SA	Cremo SA	1752	Villars-sur-Glâne	FR	Animal and vegetable p				14472	13791	12056	12238	8502	7565	1522	1579	1510	1713
2	Cremo SA	Cremo SA	1522	Lucens	VD	Animal and vegetable p				6660	7850	7378	6937	6496	7360	6550	5437	5783	3996
3	Cremo SA	Cremo SA	3613	Thun	BE	Animal and vegetable p				6577	7706	6190	6501	6065	5567	7753	7002	7175	7915
4	Cremo SA	Cremo SA	1052	Le Mont-sur-Lausanne	VD	Animal and vegetable p				1312	1678	1575	1543	1604	1533	5187	5053	5469	5573
5	Estavayer Lait SA	Estavayer Lait SA	1470	Estavayer-le-Lac	FR	Animal and vegetable p	18537	17259	19170	18633	17734	18156	18971	19402	19607	19923	11294	9507	7830
6	Bachem S.A.	Bachem S.A.	1895	Vionnaz	VS	Chemical industry	1600	1799	1962	1578	1332	1359							
7	Chemische Fabrik Schärer & Schläpfer	Chemische Fabrik Schär	4852	Rothrist	AG	Chemical industry	820	500	500	685	565	579	3000	3000	930	820	828	1	1
8	Clariant Additives (Switzerland) AG	Clariant Additives (Switz	4132	Muttenz	BL	Chemical industry													415
9	Dr. W. Kolb AG	Dr. W. Kolb AG	8908	Hedingen	ZH	Chemical industry	3	2489	2442	3233	2800	2650							
10	DSM Nutritional Products AG - Werk L	DSM Nutritional Produc	3930	Visp	VS	Chemical industry	20617	24767	19787	26280	22122	25341	24418	27965	29724	30079	29244	28164	30253
11	DSM Nutritional Products AG - Werk S	DSM Nutritional Produc	4334	Sisseln	AG	Chemical industry	89652	91640	70695	89538	84988	89014	92954	97251	93744	98126	100893	99159	67911
12	Givaudan Suisse SA site de Vernier	Givaudan SA	1214	Vernier	GE	Chemical industry		14346	12193	15136	14961	13941	14090	13334	12902	13462	13604	13545	12459
13	LONZA AG	LONZA AG	3930	Visp	VS	Chemical industry	289000	289000	246000	280000	257000	262000	321000	322000	331000	368000	366000	364000	366187
14	Monosuisse AG	Monosuisse AG	6021	Emmenbrücke	LU	Chemical industry	12341	10377	8894	7059	6135	5020							
15	Novartis Consumer Health SA	Novartis Consumer Hea	1260	Nyon	VD	Chemical industry	1664												
16	OM PHARMA	OM PHARMA	1217	Meyrin / Genève	GE	Chemical industry							90677	1230	1200	1791	1314	1315	1378
17	Rohner AG	Rohner AG	4133	Pratteln	BL	Chemical industry										1			
18	SICPA SA	SICPA SA	1373	Chavornay	VD	Chemical industry	3037	2873	3023	3140	2969	3172	3344	2539	2685				
19	Siegfried Evionnaz SA	Siegfried Evionnaz SA	1902	Evionnaz	VS	Chemical industry	6360	8	7550	5191	6463	5541	6336	5322	4517	7650	7962	7582	8064
20	VERNIS CLAESSENS SA	VERNIS CLAESSENS SA	1020	RENENS	VD	Chemical industry						0	0	0	0	0			
21	Zeochem AG	Zeochem AG	8707	Uetikon am See	ZH	Chemical industry									5500	4761			
22	Axpo Tegra AG	Axpo Power AG	7013	Domat/ Ems	GR	Energy sector			241100	169501	239722	248	293039	230550	82851	138792	240758	201671	190817
23	Energie Wasser Bern	Energie Wasser Bern	3001	Bern	BE	Energy sector										101033			
24	IWB Fernheizkraftwerk Volta	Industrielle Werke Basel	4056	Basel	BS	Energy sector	55800	76740	71405	84069	56477								
25	IWB Heizwerk Bahnhof	Industrielle Werke Basel	4053	Basel	BS	Energy sector	51100	39819	33412	30477	20065								
26	IWB KVA (Hilfskessel) und HKW	Industrielle Werke Basel	4056	Basel	BS	Energy sector					89447								
27	Monthel AG	Monthel AG	1870	Monthey	VS	Energy sector				159652	178012	183640							
28	Tamoil SA Raffinerie de Collombey	Tamoil SA Raffinerie de	1868	Collombey-le-Grand	VS	Energy sector	594100	656300	671000	658500	537096	596000	574000	647000	139223				
29	Transitgas AG	Transitgas AG	6017	Ruswil	LU	Energy sector				52724	52690	50751	25656	52503	47590	21379	29264	30358	37207
30	Varo Refining Cressier SA	Varo Refining Cressier S	2088	Cressier	NE	Energy sector	320575	299667	306759	294356	315629	212674	384066	348556	325295	390582	383397	395035	363714
31	Aluminium Laufen AG Liesberg	Aluminium Laufen AG Li	4253	Liesberg	BL	Manufacturing and pro	7												
32	Constellium Valais SA	Constellium Valais SA	3940	Steg	VS	Manufacturing and pro								22191	20957	17108	14817	14400	14881
33	Constellium Valais SA	Constellium Valais SA	3960	Sierre	VS	Manufacturing and pro								8	7890	7477	6195	5840	6013
34	DGS Druckguss Systeme AG	DGS Druckguss Systeme	9015	St. Gallen	SG	Manufacturing and pro	3405	2800	2218	3207	3246	2782							3
35	Dörrer AG	Dörrer AG	8045	Zürich	ZH	Manufacturing and pro	75	70	65	78	80	77	79	87	93	90	85	82	82
36	Fritz Kamm AG	Chromwerk Holding AG	8887	Mels	SG	Manufacturing and pro						134	78						
37	Promat Verzinkerei Bern GmbH	Wyler Isabelle	3018	Bern	BE	Manufacturing and pro				8	8	8							
38	Schmiedewerk Stooss AG	Schmiedewerk Stooss A	8908	Hedingen	ZH	Manufacturing and pro		8134	4454	6188	7070	5861	5688	6283	5682	5307	5466	6466	6049
39	SFS intec AG	SFS intec AG	9435	Heerbrugg	SG	Manufacturing and pro			8463	10106	10138	10297	10032						
40	Stahl Gerlafingen AG	Stahl Gerlafingen AG	4563	Gerlafingen	SO	Manufacturing and pro		100000	89000	89000	88590	100216	94000	97584	94627	89589	89589	99400	102024
41	vonRoll casting (emmenbrücke) ag	vonRoll casting (emmen	6020	Emmenbrücke	LU	Manufacturing and pro	444	492	894	868									
42	vonRoll casting (rondez) sa	vonRoll casting (rondez)	2800	Delémont	JU	Manufacturing and pro	6962	4748		103	1799	1900	1835	1449	1343	1599	1595	1805	1875
43	vR production (choindez) sa	vR production (choindez	2830	choindez	JU	Manufacturing and pro	10668	11346	17	11051	11895	7421	7023	7345	7014	6643	5506	4038	1
44	Zinctec AG	Zinctec AG	9322	Egnach	TG	Manufacturing and pro					1035								
45	Holcim (Schweiz) AG	cemsuisse	5303	Würenlingen	AG	Mineral processing ind	692694	636894	628909	630176	614160	606011	527259	578242	533693	576549	554525	527374	507450
46	Holcim (Schweiz) AG	cemsuisse	7204	Untervaz	GR	Mineral processing ind	528856	609648	586159	517725	567706	401339	413827	454556	377403	427795	454534	436159	412539
47	Holcim (Schweiz) AG	cemsuisse	6440	Brunnen	SZ	Mineral processing ind	132460												
48	Holcim (Suisse) SA	cemsuisse	1312	Eclépens	VD	Mineral processing ind	422018	471197	491560	533867	502063	432093	409962	492561	373684	372035	378731	372875	379836
49	Jura Cement Fabriken	cemsuisse	5103	Wildegg	AG	Mineral processing ind	465044	501718	495984	508662	500657	480881	479345	488945	488817	489989	470420	496205	497318
50	Juracime SA	cemsuisse	2087	Cornaux	NE	Mineral processing ind	185198	130551	146216	191633	193206	179655	180226	213127	194549	189922	158841	189531	204415
51	Keller AG Ziegeleien	Keller AG Ziegeleien	8252	Schlatt-Paradies	TG	Mineral processing ind	6238	5540	5053	6796	4176	4957	5530	5912	5112	6099	5422	5031	4810
52	Tonwerke Keller AG	Keller AG Ziegeleien	5070	Frick	AG	Mineral processing ind		7592	5421	7637	6695	5439	5153	5822	5274	4946	5697	5657	5174
53	Vigier Cement AG	cemsuisse	2603	Péry	BE	Mineral processing ind	446426	475155	453220	535003	490242	515670	537805	511191	521398	503050	436943	475103	472572
54	IMERYS	IMERYS Graphite & Car	6743	BODIO	TI	Other activities		20981	15500	24600	23400	23700	18900	19600	19100	24300	23900	25817	24545
55	Scapa (Schweiz) AG	Gwen Aubry, Site Mana	9400	Rorschach	SG	Other activities				3124	4329	3965	4434						
56	Schoeller Textil AG	Albers & Co	9475	Sevelen	SG	Other activities		4065	3255										
57	Sihl AG	Sihl AG	3006	Bern	BE	Other activities	1884	1546	1137	1209	1045	1196	1130	1446	1837	1314	1283	1245	
58	Borregaard Schweiz AG	Borregaard Schweiz AG	4533	Riedholz	SO	Treatment and process		87954											
59	Cham Paper Group Schweiz AG	Cham Paper Group Holc	6330	Cham	ZG	Treatment and process									1155	311	0		
60	Karton Deisswil AG	Karton Deisswil AG	3066	Stettlen	BE	Treatment and process		83	66921										
61	Papierfabrik Utzenstorf AG	Papierfabrik Utzenstorf	3427	Utzenstorf	BE	Treatment and process	45872	49140	43957	45379	44250	44555	43252	43010	41691	41734	38704		
62	SABER Swiss Quality Paper AG	SABER Swiss Holding AG	4710	Balsthal	SO	Treatment and process	15227	14730	13304	14547									
63	ACR Giubiasco	ACR Giubiasco	6512	Giubiasco	TI	Waste and waste water				216000	184000	181170	182824	178583	185918	189480	188451	188191	189367
64	ara region bern ag	ara region bern ag	3037	Herrenschwanden	BE	Waste and waste water			18100	18900	20300	20500	21300	14200	14500	15100	13600	13400	12400
65	AVAG KVA AG	AVAG KVA AG	3600	Thun	BE	Waste and waste water			146443	82131	113997	114311	117360	114137	113901	114422	113260	126440	120280
66	Cimo SA	Cimo SA	1870	Monthey	VS	Waste and waste water	167750	150810	130592				124627	125035	151725	192362	196403	185932	171896
67	Deponie Tännlimoos	Risi AG	6340	Baar	ZG	Waste and waste water		1686	1300	1300	895	895	1145	1145	481	481	481	481	463
68	Energiezentrale Forsthaus (KVA)	Energie Wasser Bern	3001	Bern	BE	Waste and waste water							133570	134652	139642	146229	160122	156230	164713
69	ERZ KHKW Hagenholz	ERZ KHKW Hagenholz	8050	Zürich	ZH	Waste and waste water	233000	219000	282000	267000	280000	275209	265994	278430	278514	271455	270842	270229	269189
70	ERZ KHKW Josefstrasse	ERZ KHKW Josefstrasse	8005	Zürich	ZH	Waste and waste water	208000	221000	199000	211000	122000	120933	122434	124310	124456	125650	126305	122830	124242
71	GEKAL Buchs	GEKAL Buchs	5033	Buchs AG	AG	Waste and waste water	147000	151000	155000	152000	142000	149314	137072	147841	149468	154285	156884	157027	153849
72	GEVAG Trimmis	GEVAG Trimmis	7201	Untervaz-Bahnhof	GR	Waste and waste water	116000	129000	114000	120000	123000	115797	112415	119766	116418	118696	122020	124448	120538
73	GVRZ Kläranlage Schönau	GVRZ Kläranlage Schöna	6330	Cham	ZG	Waste and waste water	3144												
74	IWB Basel	IWB Basel	4008	Basel	BS	Waste and waste water	275000	280000	272000	270000	244000	240658	239308	243936	248540	252797	242466	257126	254784
75	KEBAG AG	KEBAG AG	4528	Zuchwil	SO	Waste and waste water	272516	273126	283020	281563	279654	282946	283360	282926	286748	287092	284165	286332	291684
76	KEZO Hinwil	KEZO Hinwil	8340	Hinwil	ZH	Waste and waste water	243000	250000	257000	245000	223000	207047	204427	203355	208031	213131	218391	216717	213473
77	KVA Bern	KVA Bern	3007	Bern	BE	Waste and waste water	141000	137000	132000	137000	128000	121472							
78	KVA Limmattal	KVA Limmattal	8953	Dietikon	ZH	Waste and waste water	109000	109000	112000	112000							103622	105276	108381
79	KVA Linth	KVA Linthgebiet	8867	Niederurnen	GL	Waste and waste water	149000	151000	145000	140000	130000	138598	112415	123826	121110	123526	123254	123039	120594
80	KVA Thurgau	KVA Thurgau	8570	Weinfelden	TG	Waste and waste water	185000	182000	181000	179000	153000	157171	162098	167013	163864	169185	166128	163827	167340
81	KVA Turgi	KVA Turgi	5300	Turgi	AG	Waste and waste water	153000	154000	157000	156000	144000	135943	134826	132403	133742	133327	133752	134264	134401
82	KVA Winterthur	KVA Winterthur	8404	Winterthur	ZH	Waste and waste water	224000	231000	153000	125000	128000	167473	200324	180041	217234	221801	225058	224198	226746
83	Les Cheneviers	Services industriels de G	1288	Aire-la-Ville	GE	Waste and waste water		373147	328653	286938	289976	309241	284975	291361	284221	295715	302109	286365	278570
84	Renergia Perlen	KVA Luzern	6035	Perlen	LU	Waste and waste water	114000	116000	115000	116000	118000	95786							
85	Renergia Zentralschweiz AG	Renergia Zentralschweiz	6035	Perlen	LU	Waste and waste water							115004	96824	230770	270719	286633	302947	303995
86	SAIDEF Fribourg	SAIDEF Fribourg	1725	Posieux	FR	Waste and waste water	105000	107000	111000	116000	120000	111347	110517	110309	111405	108341	112836	114049	113301
87	SATOM Monthey	SATOM Monthey	1870	Monthey	VS	Waste and waste water	225000	225000	198000	220000	139000	205321	165895	188113	166875	180342	175945	164589	182470
88	Services Industriels de Genève SIG	VBSA-ASED-ASIR	1288	Aire-la-Ville	GE	Waste and waste water	384000												
89	TRIDEL Lausanne	TRIDEL Lausanne	1005	Lausanne	VD	Waste and waste water	219000	228000	229000	207000	198000	196389	201057	176631	190833	208164	211173	209156	209285
90	Valorec Services AG, ALV 1+2	Valorec Services AG	4132	Muttenz	BL	Waste and waste water							100991						
91	VfA Buchs	VfA Buchs	9470	Buchs SG	SG	Waste and waste water	241000	243000	226000	252000	203000	217504	209964	205381	209667	212475	206530	208721	211442
92	ZAB Bazenheid	ZAB Bazenheid	9602	Bazenheid	SG	Waste and waste water			132000	148000	165000	127758							

Figure 23: Switzerland's point-sources, facilities highlighted emit more than 0.1 $MtCO_2/y$. Original file accessible at the following link.

9. Switzerland point sources analysis



Analysis by sectors

Scope	Activity	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Quantity	Mean emission/facility
Facilities >= Treshold	Animal and vegetable products	0	0	0	0	0	0	0	0	0	0	0	0	0	# facilities	0
		0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	% of facilties	
		0	0	0	0	0	0	0	0	0	0	0	0	0	Emissions t/y	
		0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	Emissions %	
	Chemical industry	1	1	1	1	1	1	1	1	1	1	2	1	1	# facilities	366'187
		3.33%	3.33%	3.13%	3.13%	3.13%	3.23%	3.13%	3.33%	3.33%	3.23%	6.25%	3.23%	3.13%	% of facilties	
		289'000	289'000	246'000	280'000	257'000	262'000	321'000	322'000	331'000	368'000	466'893	364'000	366'187	Emissions t/y	
		3.62%	3.57%	2.95%	3.32%	3.20%	3.47%	4.09%	4.12%	4.65%	4.88%	6.09%	4.80%	4.80%	Emissions %	
	Energy sector	2	2	3	4	4	3	3	3	2	3	2	2	2	# facilities	277'266
		6.67%	6.67%	9.38%	12.50%	12.50%	9.68%	9.38%	10.00%	6.67%	9.68%	6.25%	6.45%	6.25%	% of facilties	
		914'675	955'967	1'218'859	1'282'009	1'270'459	992'314	1'252'005	1'226'106	464'518	630'406	624'155	596'706	554'531	Emissions t/y	
		11.45%	11.80%	14.64%	15.20%	15.83%	13.15%	15.96%	15.69%	6.53%	8.35%	8.14%	7.87%	7.27%	Emissions %	
	Manufacturing and processing of metals	0	1	0	0	0	1	0	0	0	0	0	0	1	# facilities	102'024
		0.00%	3.33%	0.00%	0.00%	0.00%	3.23%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	3.13%	% of facilties	
		0	100'000	0	0	0	100'216	0	0	0	0	0	0	102'024	Emissions t/y	
		0.00%	1.23%	0.00%	0.00%	0.00%	1.33%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1.34%	Emissions %	
	Mineral processing industry	7	6	6	6	6	6	6	6	6	6	6	6	6	# facilities	412'355
		23.33%	20.00%	18.75%	18.75%	18.75%	19.35%	18.75%	20.00%	20.00%	19.35%	18.75%	19.35%	18.75%	% of facilties	
		2'872'697	2'825'164	2'802'048	2'917'066	2'868'034	2'615'649	2'548'424	2'738'622	2'489'544	2'559'340	2'453'994	2'497'247	2'474'130	Emissions t/y	
		35.96%	34.88%	33.66%	34.58%	35.75%	34.66%	32.49%	35.04%	34.97%	33.91%	31.99%	32.92%	32.44%	Emissions %	
	Other activities	0	0	0	0	0	0	0	0	0	0	0	0	0	# facilities	0
		0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	% of facilties	
		0	0	0	0	0	0	0	0	0	0	0	0	0	Emissions t/y	
		0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	Emissions %	
	Treatment and processing of paper and wood	0	0	0	0	0	0	0	0	0	0	0	0	0	# facilities	0
		0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	% of facilties	
		0	0	0	0	0	0	0	0	0	0	0	0	0	Emissions t/y	
		0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	Emissions %	
	Waste and waste water management	20	20	22	21	21	20	22	20	21	21	22	22	22	# facilities	187'752
		66.67%	66.67%	68.75%	65.63%	65.63%	64.52%	68.75%	66.67%	70.00%	67.74%	68.75%	70.97%	68.75%	% of facilties	
		3'911'266	3'930'083	4'058'707	3'957'502	3'627'626	3'575'604	3'721'458	3'528'051	3'833'082	3'989'196	4'126'351	4'127'933	4'130'540	Emissions t/y	
		48.97%	48.52%	48.75%	46.91%	45.21%	47.39%	47.45%	45.15%	53.85%	52.86%	53.79%	54.42%	54.15%	Emissions %	
	Total	**30**	**30**	**32**	**32**	**32**	**31**	**32**	**30**	**30**	**31**	**32**	**31**	**32**	**# facilities**	238'357
		100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	% of facilties	
		7.99	**8.10**	**8.33**	**8.44**	**8.02**	**7.55**	**7.84**	**7.81**	**7.12**	**7.55**	**7.67**	**7.59**	**7.63**	**Emissions Mt/y**	
		100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	Emissions %	

Figure 24: Switzerland's point sources analysis accessible at the following link.

10. Biomass potential for Switzerland's energy system

	Biomass source	Fresh mass (million tonnes)	Dry mass (million tonnes dw)	Primary energy content (PJ)
Theoretical potential	Animal manure	24.2	3.1	48.8
	Agricultural crop by-products	2.8	0.8	14.9
	Sewage sludge	8.7	0.3	4.9
	Organic fraction of household garbage	0.8	0.4	6
	Green waste from households and landscape	0.8	0.3	4.3
	Commercial and industrial organic waste	2.2	1	13.6
	Waste wood	(1.0)*	(0.8)*	(14.4)*
	Wood residues	(2.5)*	(1.5)*	(24.0)*
	Forest wood	13.5	7.3	107.5
	Wood from landscape maintenance	1.2	0.6	9.4
	Total	*54.1*	*13.8*	*209.4*
Sustainable potential	Animal manure	14	1.7	26.9
	Agricultural crop by-products	0.2	0.1	2.6
	Sewage sludge	8.7	0.3	4.9
	Organic fraction of household garbage	0.4	0.2	3.9
	Green waste from households and landscape	1.1	0.4	5.8
	Commercial and industrial organic waste	0.7	0.2	2.7
	Waste wood	0.8	0.7	11.7
	Wood residues	0.8	0.5	7.6
	Forest wood	3.3	1.8	26.1
	Wood from landscape maintenance	0.6	0.3	4.8
	Total	*30.5*	*6.3*	*97*
Already used potential	Animal manure	1.3	0.2	2.6
	Agricultural crop by-products	0	0	0
	Sewage sludge	6.2	0.2	3.4
	Organic fraction of household garbage	0.8	0.4	6
	Green waste from households and landscape	0.4	0.2	2.2
	Commercial and industrial organic waste	0.5	0.2	2
	Waste wood	0.6	0.5	9.2
	Wood residues	0.7	0.5	7.8
	Forest wood	2.2	1.2	17.2
	Wood from landscape maintenance	0.3	0.1	2.3
	Total	13.1	3.4	52.8
Additional sustainable potential	Animal manure	12.6	1.5	24.3
	Agricultural crop by-products	0.2	0.1	2.6
	Sewage sludge	2.5	0.1	1.4
	Organic fraction of household garbage	-0.4	-0.1	-2.1
	Green waste from households and landscape	0.7	0.2	3.5
	Commercial and industrial organic waste	0.2	0.1	0.7
	Waste wood	0.2	0.1	2.5
	Wood residues	0	0	-0.2
	Forest wood	1.1	0.6	8.9
	Wood from landscape maintenance	0.3	0.2	2.5
	Total	17.4	2.8	44.2

Figure 25: Summary of biomass potential for Switzerland's energy system, from [25].

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