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Carbon Capture, Utilization and Storage in Switzerland. Volume 1 – The Technological and Scientific Framework

Cahier de l'IDHEAP 315/2021

Unité *Politiques publiques et durabilité*

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MELiSSA

MICRO-ECOLOGICAL
LIFE SUPPORT SYSTEM
ALTERNATIVE

SUMMARY

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GENERAL INTRODUCTION

Since at least the 1960s, and following decades of scientific studies on the topic, it has been known in the public sphere that increasing concentration in the Earth's atmosphere of anthropogenic greenhouse gases (GHGs), in particular carbon dioxide, resulting from deforestation and the burning of fossil fuels by human activities is responsible for the long-term rise in the average temperature of the Earth's climate system, commonly known as "global warming" or "(anthropogenic) climate change". The physical process driving this change is known as "(anthropogenic) greenhouse effect". Back in 1963, the Conservation Foundation first assembled a conference of scientists and academics to discuss the issue of rising carbon dioxide content of the atmosphere. In this occasion, a consensus that such a rise was connected with a worrisome increase in the temperature of the atmosphere and oceans was already present (Conservation Foundation 1963). In 1979, the Charney Report, a scientific document produced by an "ad hoc" study group on carbon dioxide and climate chaired by J. G. Charney and nominated by the U. S. National Research Council, first warned the Carter Administration of the dire consequences of the increase of the amount of CO_2 in the atmosphere:

"[. . .] We now have incontrovertible evidence that the atmosphere is indeed changing and that we ourselves contribute to that change. Atmospheric concentrations of carbon dioxide are steadily increasing, and these changes are linked with man's use of fossil fuels and exploitation of the land. Since carbon dioxide plays a significant role in the heat budget of the atmosphere, it is reasonable to suppose that continued increases would affect climate. [The consensus is that] increasing carbon dioxide will lead to a warmer earth with a different distribution of climatic regimes" (Charney et al. 1979).

Six years later, in 1985, a technical report of the United States Department of Energy (U. S. DoE), titled "Detecting the climate effects of increasing carbon dioxide", summarized the scientific findings on the important role played by carbon dioxide of anthropogenic origin in changing the Earth's climate and acknowledged the “responsibility [of the citizens of today’s nations] for the stewardship of all the Earth, including their actions which may affect its climate” (MacCracken and Luther 1985). Almost 35 years after, however, concrete political action to reduce the impact of human activities on the Earth’s climate appears to be still outright inadequate, while the concentration of carbon dioxide in the atmosphere has reached an all-times high of 415 ppm in May 2019[1].

Carbon dioxide, or CO_2, is currently the second most abundant GHG in the atmosphere (after water vapor) and the most abundant GHG of anthropogenic origin. With the goal of mitigating the greenhouse effect, carbon capture and storage (CCS) technologies, as well as carbon capture and utilization (CCU) technologies, have been proposed and developed. These two processes include a common part, the capture of CO_2, followed by a series of different operations in the two cases.

There are two main ways to capture CO_2:

- directly from the atmosphere (“direct air capture”), or
- at the exit of industrial and energy sources such as cement plants, thermal power stations, etc.

The subsequent steps differentiate CCS and CCU. CCS plans to adequately store (i.e., minimizing or avoiding gas leakage) CO_2 from the atmosphere in the long term, which can be done in several ways. CCU involves the use of captured CO_2, either (1) in the manufacture or synthesis of new products through different types of process (thermal, electrochemical, photochemical), or (2) as a solvent or active fluid for various industrial processes.

The basic idea of CCS – capturing CO_2 and preventing it from being released into the atmosphere again – was first suggested in 1977; however, CO_2 capture technology has been used since the 1920s for

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[1] *For the definition of ppm, cf. appendix B.*

separating carbon dioxide sometimes found in underground natural gas reservoirs from the saleable methane gas.

CCU is a topic that has been heavily discussed and developed in recent years and is seen by a significant number of experts as one of the key technologies and innovations for a sustainable future. Albeit this subject seems to be new, already more than 100 years ago, some pioneers thought about a future based on photochemistry[2]. One of them was Giacomo Ciamician (1857-1922), professor of chemistry at the universities of Padova, Roma and Bologna, who can be seen as the scientific father of green chemistry and photochemistry (Carus et al. 2019). In a visionary paper, "The photochemistry of the future", he described the world's need for an energy transition from fossil fuels to renewable energy and saw the possibility to use photochemical devices utilizing solar energy to produce fuels and chemicals to power the human civilization. Ciamician called for their development to make humanity independent from fossil feedstocks and also to reduce the economic gap between rich and poor countries, many decades before such topics became popular in the light of climate change and sustainability issues (Ciamician 1912).

Nowadays, in Switzerland, the development of CCUS (i.e. Carbon Capture, Utilization and Storage) technologies is however still in the early stages although, as noticed above, these technologies could be very useful in reducing carbon dioxide concentration in the atmosphere. The Intergovernmental Panel on Climate Change (IPCC), whose perspective (unless explicitly stated otherwise) is endorsed in the framework of the present research, considers that the CCU should play a role in the future to ensure that the rise in temperatures caused by the anthropogenic greenhouse effect remains "well below" the bar of 2°C set by the Paris Agreement on Climate Change, and possibly even below 1.5°C (IPCC 2018). The link between the public problem to be solved (the many risks

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[2] *Photochemistry is the branch of chemistry which deals with the chemical effects of light. Photochemical reactions such as photosynthesis are at the basis of a number of conversion processes of CO_2 which are involved in a number of CCU techniques such as algae cultivation, cf. 3.4.*

posed by the negative effects of climate change) and the CCU as one of its possible solutions is therefore well established. Scientific models suggest that, to meet the 1.5°C target of the Paris Agreement, around 5 to 15 Gt of CO_2 will have to be removed from the atmosphere by 2050 per year, with a median value of 810 Gt of cumulative CO_2 extracted expected by the year 2100. This median value is equivalent to 20 years of global carbon emissions at the current emission rates (UNEP 2017). The creation of a consistent public policy in this area is therefore necessary to master the many issues related to this topic.

The main objective of this work is the analysis of the current legal and institutional framework (i.e. the institutional regime) that revolves around the complex public policy issues related to CCUS, to conclude with the presentation of our proposals to create a coherent, integrated and sustainable framework for the development of CCUS in Switzerland. In particular, we aim to investigate the issues related to CO_2 recycling from the perspective of institutional rules and property rights to be set up or redefined in order to regulate as effectively as possible the process of transforming CO_2 emissions from waste status to that of (new) exploitable resource. This will provide the institutional basis for a possible public policy of carbon dioxide recycling at the Swiss level.

This work is critical since, if CCUS has not been developed yet in Switzerland on a significant scale, it is also due to a lack in any kinds of public incentives and especially to a lack of legal, institutional and political recognition. This is in contrast with public policies for CCUS which have been developed in other Western countries. For instance, in February 2018 the United States Congress passed a budget bill which expanded the corporate income tax credit for CCUS; such a tax credit, known as "45Q", was adopted to stimulate additional deployment of CCUS projects in the United States (*H.R.1892* 2018; Nagabhushan and Thompson 2019). Analogously, European Union political institutions have enacted legal provisions to promote and regulate CCUS which are contained in a number of Directives such as the Directive 2009/31/EC of 23 April 2009, known as "CCS Directive" (*Directive 2009/31/EC* 2009), or the Directive 2010/75/EU, known as "Industrial Emissions Directive". However, it is worth noticing that in Switzerland we are assisting to an awakening of interest in CCUS: for example, the Federal Office for the Environment (FOEN) has recently commissioned a report on atmospheric greenhouse gas removal which deals broadly with the same topics investigated in the present work (Beuttler et al. 2019). Still, our work has a more far-reaching approach to the issue of CO_2 recycling and storage, especially for what concerns the analysis of the institutional regime connected to CCUS and our detailed proposals of modifications to a set of current laws to further advance CCUS development.

Since CCUS is a vast subject which encompasses various policy sectors, it is also essential to analyze the interdependencies which can occur, at the legislative and institutional level, between different public policies which have different, and possibly contradictory, objectives: climate policy, industrial policy, policy of waste management, transportation policy, land use planning, etc. While we will not examine in depth every single connection, their large number proves that the topic of CCUS is one of the most complex and multifaceted themes that can be found in a public policy framework.

CO_2 capture is a phase that is common to CCS and CCU. A first part of the analysis of the institutional regime should therefore be equal in both cases. The successive stages are different for the CCS and the CCU, since CCS deals with the storage and CCU with various utilization pathways of the captured CO_2, consequently the institutional regime of carbon dioxide is divided into different sub-regimes according to the various processes analyzed. CCS and CCU entail two different models of economic valuation of CO_2: if CO_2 is considered a real resource in the case of CCU, giving rise to the production of goods and market services, we can nevertheless give an economic value to CO_2 in the case of CCS too, for example by establishing a certificated exchange market for stored CO_2. This will establish a CO_2 storage business, similar to the CO_2 recycling business.

The main analytical instrument that we will use in this work to investigate the ensemble of regulations which can apply to the different uses of carbon dioxide in the context of CCUS in Switzerland is the Institutional Resource Regime (IRR). The IRR is a conceptual approach which allows to examine the provisions which govern the different possible uses of the resource 'carbon dioxide' resorting to both the analysis of property rights (PRs) to the resource and to the public policies (PP) regulating the use and protection of the resource, thus enabling the integration of policy analysis and property-rights theory into the same analytical framework with the scope to evaluate the degree of sustainability in the use of CO_2 as a resource[3] (cf. Gerber et al. 2009). The framework is particularly indicated for the analysis of carbon dioxide in the context of CCUS deployment, since this deployment has potentially a great impact on the redefinition of the PRs connected with the different uses of CO_2, redefinition which is in turn connected with the PPs: for instance, the large-scale development of CCS projects requires a clear definition of the PRs and liability rules connected with the exploitation of the underground space to store carbon dioxide, whereas in the case of CCU applications it would be useful to clarify the use rights of CO_2.

The main research questions that we would like to answer in this work, hence, are the following:

- what are the main sources of CO_2 in Switzerland and in which economic sectors does the greatest potential for carbon recycling lie?
- what are the most important existing public policies and legal provisions, in the current state of their formulation and implementation, which could regulate a hypothetical future development of a large-scale CCUS sector in Switzerland?

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[3] *As it will be explained in detail in Volume 2, by "sustainable use of the resource CO_2" we mean a use which would allow to reduce the concentration of carbon dioxide in the atmosphere, then to stabilize it at a level comparable to the one which existed at the onset of the Industrial Revolution.*

- in particular, which opportunities can be found within these provisions to encourage such a development?
- using the IRR conceptual approach, what can be said about the degree of coherence and integration of the provisions contained in the existing institutional and legal framework of CCUS?
- finally, which legislative changes are desirable and/or conceivable in order to create a coherent and integrated IRR of CCUS, following the remarks of the previous IRR analysis?

This work is divided into two volumes.

In Volume 1 we review the most important concepts from natural sciences and process engineering which are fundamental to understand CCS and CCU systems. Therefore, we mainly approach topics of natural sciences and process engineering, although from a generalist perspective. We investigate the carbon cycle in nature and in the anthropogenic world, discuss the anthropogenic greenhouse effect and then introduce CCUS and its potential role in mitigating climate change. Finally, two chapters deal respectively with a description of CCS along with some of the main CCU processes from a technical viewpoint, and with a short analysis of the potential of CCUS deployment in Switzerland, e.g. according to the data on carbon emissions from the various industrial and economic sectors.

In Volume 2 we treat the legal, institutional and policy-related aspects of the development of CCUS in Switzerland. We start by investigating the legal status of carbon dioxide, according to the current legal provisions, in an attempt to clarify the issue surrounding the somehow ambiguous status of CO_2: a waste, a pollutant, or, more interestingly, a resource? We then analyze the pieces of current legislation which form the IRR of carbon dioxide, regarded as a resource for CCUS processes, and propose a set of new provisions in order to stimulate the development of CCUS in Switzerland.

INTRODUCTION TO VOLUME 1

In this first volume, we wish to document the technological and scientific conditions that frame the capture, storage and use of CO_2, in the perspective of its possible development in Switzerland.

In chapter 1, we examine the main scientific aspects of our topic, including the global (natural and anthopogenic) carbon cycle and the greenhouse effect.

In chapter 2, we describe the role that CCUS can play in climate change mitigation from a political perspective.

In chapter 3, we provide a general description of the main CCUS processes by decomposing them in their constituent parts (CO_2 capture, CO_2 storage, CO_2 utilization).

In chapter 4, we discuss the technical potential of CCUS in Switzerland, looking into the carbon dioxide emissions by economic sector, main industrial activities and geological storage potential.

The volume also includes three appendices: the first and second ones deal respectively with the definitions and acronyms for the technical lexicon, and the gas concentration units used throughout the volume, whereas the third one deals with the detailed breakdown of CO_2 emissions in Switzerland.

1 THE CARBON CYCLE AND THE GREENHOUSE EFFECT

1.1 THE PHYSICS AND CHEMISTRY OF THE AIR

The atmosphere of Earth is the layer of gases, commonly referred to as "air", which surrounds our planet and is physically retained by Earth's gravity attraction. Three main gases make 99.9% of the air volume: nitrogen gas or molecular nitrogen (chemical formula: N_2), oxygen gas or molecular oxygen (O_2) and argon (Ar). In general, the proportion of the different gases in the atmosphere is relatively stable: however, this is not true for water vapor (H_2O), whose concentration varies significantly from around 0.001% by volume in the coldest portions of the atmosphere to as much as 5% by volume in hot, humid air masses. Therefore, concentrations of other atmospheric gases are typically expressed in terms of dry air (without water vapor).

Besides these four major constituents, there are other remaining gases, or "traces", such as carbon dioxide (CO_2), methane (CH_4), helium (He), neon (Ne) or ozone (O_3).

Finally, in the atmosphere we find trace amounts of other chemical compounds, such as aerosols, which can be both natural or anthropogenic. An aerosol is defined as a suspension system of solid or liquid particles in a gas. Natural aerosols are for example dust, fog or geyser steam, whereas anthropogenic aerosols can be particulate air pollutants or smoke. Various industrial pollutants may also be present as other gases such as chlorine, fluorine compounds and elemental mercury vapor (Fleagle and Businger 1980).

The relative abundance of a particular gas in the air is not automatically related to the importance of the role it plays in fundamental physical and biological processes, such as the greenhouse effect or photosynthesis. For example, argon, while constituting 0.9340% of atmosphere volume (and being therefore the third most-abundant gas in the Earth's atmosphere), is a chemically inert gas (meaning that it does not undergo chemical reactions) under most conditions and does not play any significant role in terrestrial biological or climatic processes. Conversely, carbon dioxide plays an essential role in both photosynthesis and the greenhouse effect, being actually one of the major gas contributors to the latter process.

Carbon dioxide is not just a naturally occurring constituent of the atmosphere but also a product of human activities, mainly the burning of fossil fuels for energy production and the clearing of land for agriculture and urbanization. Hence, a sharp increase in the concentration of CO_2 in the Earth atmosphere has been observed during the last decades: it raised from 315 ppm in 1957, to 370 ppm in 2000, until it reached 415 ppm in May 2019, cf. Fig. 1.1.

1.2 THE CARBON CYCLE

Carbon is a chemical element with symbol C and atomic number 6, meaning that its nucleus contains 6 protons. It is the main component of biological compounds as well as a major component of many minerals such as limestone.

Many characteristics have enabled carbon to serve as a common element of all known life. Here we list the main ones:

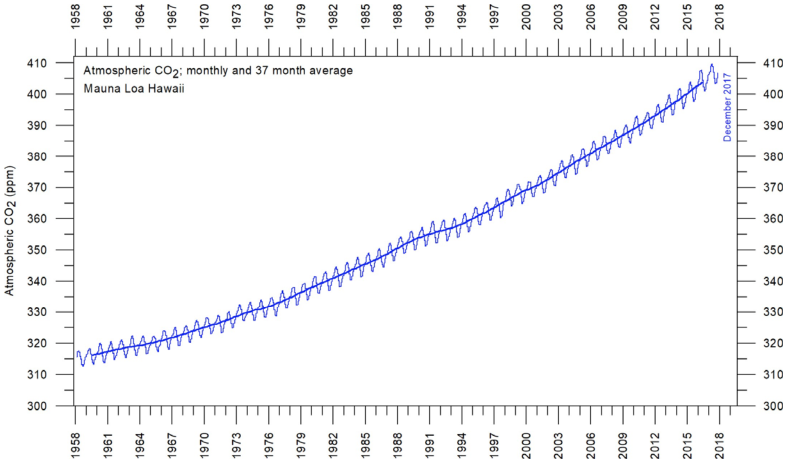

Figure 1.1: Monthly amount of atmospheric CO_2 since March 1958.
As measured at the Mauna Loa Observatory, Hawaii. The thin line and the thick line show the monthly values and the simple running 37-month average, nearly corresponding to a running 3-year average, respectively. These measurements show a strong and continuous increase in mean atmospheric carbon dioxide concentration from 313 parts per million by volume (ppm) in March 1958 to 406 ppm in November 2018, corresponding to an increase of 2 ppm carbon dioxide per year. This graph is also known as the Keeling curve. Source: NOAA 2018.

- Carbon’s abundance: carbon is the 15th most abundant element in the Earth’s crust, and the fourth most abundant element in the universe by mass after hydrogen, helium, and oxygen.

- Carbon’s unique diversity of compounds, that is, of chemical substances containing carbon. In fact, more compounds of carbon exist than any other chemical element except for hydrogen. In particular, there are many oxides of carbon (oxocarbons), among which the most prominent is carbon dioxide (CO_2), a minor but very important component of the Earth’s atmosphere today.

- Carbon’s unusual ability to form polymers at the temperatures commonly encountered on Earth. A polymer is a large molecule made

> of many repeated subunits. Polymers (both synthetic and natural) play fundamental roles in everyday life, ranging from familiar synthetic plastics such as polystyrene to natural biopolymers such as DNA and proteins that are essential for biological structures and functions. Most commonly, the continuously linked backbone of a polymer used for the preparation of plastics consists mainly of carbon atoms.

Under terrestrial conditions, conversion of one element to another is very rare. Therefore, the amount of carbon on Earth is effectively constant. Hence, processes that use carbon must obtain it from somewhere and dispose of it somewhere else. The ensemble of the paths of carbon in the Biosphere constitutes the carbon cycle. More precisely, the carbon cycle describes the biogeochemical processes in which carbon is exchanged among atmosphere, ocean, land and geological reservoirs of the Earth[4], i.e. the movement of carbon as it is recycled and reused throughout the environment, as well as long-term processes of carbon sequestration to and release from carbon sinks. Along with the nitrogen cycle and the water cycle, the carbon cycle comprises a sequence of events that are indispensable to make Earth capable of sustaining life.

Fig. 1.2 provides a detailed depiction of the global carbon cycle, included the human influence on it, with storages (expressed in PgC) and fluxes (expressed in PgC/yr) estimated for the 1980s[5] (IPCC 2001).

Fig. 1.2(a) shows the main components of the natural carbon cycle. The thick arrows denote the two most important fluxes from the perspective of the CO_2 present in the atmosphere: that is, gross primary production and respiration by the land biosphere, and the physical exchange of carbon dioxide between the atmosphere and the oceans. These main fluxes "are approximately balanced each year, but imbalances can affect atmospheric

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[4] *Actually, the cycle described in this section is the biological, or physical, carbon cycle. It exists another category of carbon cycle, the geological carbon cycle, which is mainly driven by the movement of the Earth's tectonic plates and the related geologic processes. However, this cycle it is not relevant in the context of the topic of this memoir since it operates over time scales of millions of years, much larger than those of the biological cycle (days to thousands of years).*

[5] *PgC = petagram (Pg) of carbon (1 Pg = 1015 grams = 1 billion metric tonnes).*

CO_2 concentration significantly over years to centuries" (IPCC 2001). Additionally, there are other natural fluxes of CO_2 denoted by the thin arrows, as well as by dashed lines for fluxes of carbon as in the $CaCO_3$ compound, which become important on longer time-scales. These additional fluxes take into account a large number of natural processes: "the flux of 0.4 PgC/yr from atmospheric CO_2 via plants to inert soil carbon is approximately balanced on a time-scale of several millennia by export of dissolved organic carbon (DOC) in rivers. A further 0.4 PgC/yr flux of dissolved inorganic carbon (DIC) is derived from the weathering of $CaCO_3$, which takes up CO_2 from the atmosphere in a 1:1 ratio. These fluxes of DOC and DIC together comprise the river transport of 0.8 PgC/yr. In the ocean, the DOC from rivers is respired and released to the atmosphere, while $CaCO_3$ production by marine organisms results in half of the DIC from rivers being returned to the atmosphere and half being buried in deep-sea sediments, which are the precursor of carbonate rocks. Also shown are processes with even longer time-scales: burial of organic matter as fossil organic carbon (including fossil fuels), and outgassing of CO_2 through tectonic processes (vulcanism). Emissions due to vulcanism are estimated as 0.02 to 0.05 PgC/yr" (IPCC 2001).

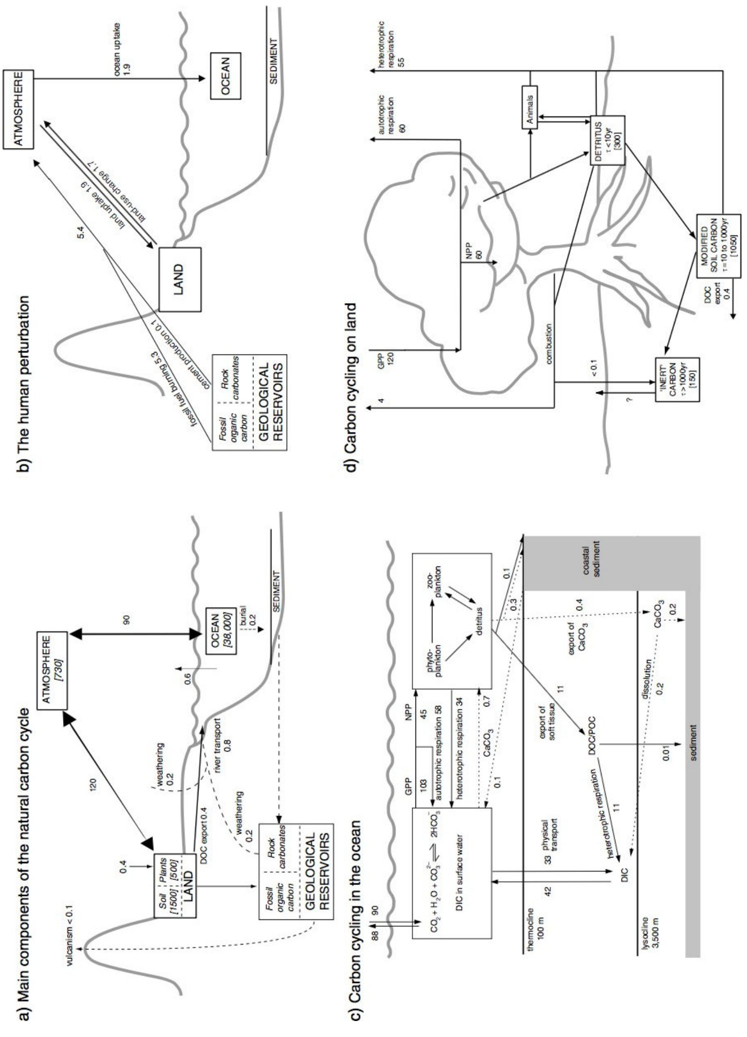

Figure 1.2: The global carbon cycle.
Source: IPCC 2001

Fig. 1.2(b) shows the human modification of the global carbon cycle. Fossil fuel burning and land-use change release CO_2 to the atmosphere: a part of this CO_2 stays in the atmosphere, the rest is taken up by the land or by the ocean, creating imbalances in the natural two-way fluxes between atmosphere and ocean on one side, and between atmosphere and land on the other, represented in Fig. 1.2(a).

Fig. 1.2(c) shows carbon cycling in the ocean. As described in IPCC 2001, "CO_2 that dissolves in the ocean is found in three main forms (namely, CO_2, CO_3^{2-}, HCO_3^-, the sum of which is DIC). DIC is transported in the ocean by physical and biological processes. Gross primary production (GPP) is the total amount of organic carbon produced by photosynthesis; net primary production (NPP) is what remains after autotrophic respiration, that is, respiration by photosynthetic organisms. Sinking of DOC and particulate organic matter (POC) of biological origin results in a downward flux known as export production. This organic matter is transported and respired by non-photosynthetic organisms (heterotrophic respiration) and ultimately upwelled and returned to the atmosphere. Only a tiny fraction is buried in deep-sea sediments. Export of $CaCO_3$ to the deep ocean is a smaller flux than total export production (0.4 PgC/yr) but about half of this carbon is buried as $CaCO_3$ in sediments; the other half is dissolved at depth, and joins the pool of DIC. Also shown are approximate fluxes for the shorter-term burial of organic carbon and $CaCO_3$ in coastal sediments and the re-dissolution of a part of the buried $CaCO_3$ from these sediments".

Finally, fig. 1.2(d) shows carbon cycling on land. "By contrast with the ocean, most carbon cycling through the land takes place locally within ecosystems. About half of GPP is respired by plants. The remainer (NPP) is approximately balanced by heterotrophic respiration with a smaller component of direct oxidation in fires (combustion). Through senescence of plant tissues, most of NPP joins the detritus pool; some detritus decomposes (i.e., is respired and returned to the atmosphere as CO_2) quickly while some is converted to modified soil carbon, which decomposes more slowly. The small fraction of modified soil carbon that is further converted to compounds resistant to decomposition, and the small amount of black carbon produced in fires, constitute the "inert" carbon pool. It is likely that biological processes also consume much of the "inert" carbon as well but little is currently known about these processes. 'τ ' denotes the turnover time for different components of soil organic matter" (IPCC 2001).

1.3 THE GREENHOUSE EFFECT

The fundamental factor responsible for the maintenance of the Earth's climate, and thus a potential cause of its variation, is the shortwave radiation received from the Sun. Of the incoming solar radiation, about 50% is absorbed at the Earth's surface and 20% by the atmosphere. The remainder is reflected to space. If it were not for the atmosphere and oceans, however, this solar radiation would only be able to create a climate such as the one which exists on the Moon. The radiatively active gases in the atmosphere, including water vapor, CO_2, and other gases present in trace amounts (trace gases), act together as an essentially invisible blanket, letting the solar radiation enter but restricting the emission of terrestrial infrared radiation. This effect, often referred to as the greenhouse effect[6], accounts for a net warming of the overall Earth-atmosphere system by about 30°C. Changes in the solar radiation at the top of the atmosphere or changes in the concentration of CO_2 and other radiatively active trace gases ("greenhouse gases") are, therefore, possible external factors that may result in climate change (MacCracken and Luther 1985). Actually, the increase in concentration of atmospheric carbon dioxide and other greenhouse gases in the atmosphere through human activities, especially during the last decades, has caused a strengthening of the greenhouse effect which is known as the enhanced (or anthropogenic) greenhouse effect. Atmospheric concentrations of carbon dioxide, methane and nitrous oxide are higher than they have been

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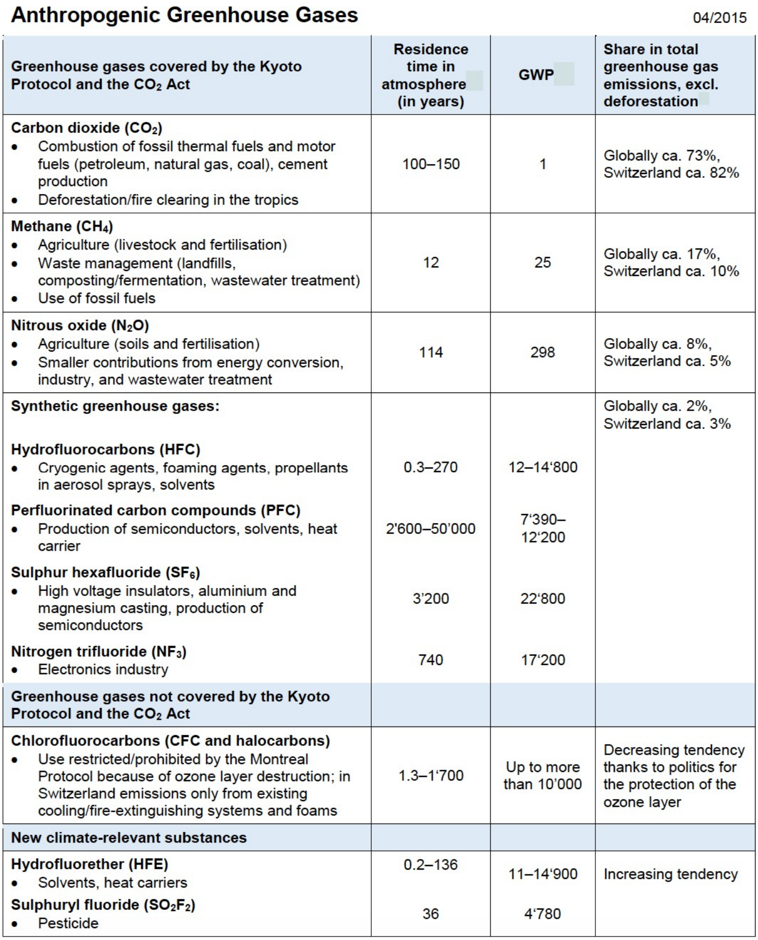
[6] *Trapping of radiation by the atmosphere is typical of the atmosphere and therefore correctly may be called the "atmosphere effect"; however, the term "greenhouse effect" continues to be used more widely (Fleagle and Businger 1980).*

in at least the last 800,000 years and are extremely likely to have been at the origin of the observed global warming since the mid-20th century (IPCC 2013).

The fact that the recent and continuing increase of atmospheric carbon dioxide is caused by anthropogenic CO_2 emissions is confirmed not only by the parallelism between this steady increase and the global rising of industrialization and agricultural development, but by other lines of evidence: “first, atmospheric O_2 is declining at a rate comparable with fossil fuel emissions of CO_2 (combustion consumes O_2). Second, the characteristic isotopic signatures of fossil fuel (its lack of ^{14}C, and depleted content of ^{13}C) leave their mark in the atmosphere. Third, the increase in observed CO_2 concentration has been faster in the northern hemisphere, where most fossil fuel burning occurs” (IPCC 2001).

Because continued economic and population growth drive the increase in CO_2 emissions, the levels of emissions, if left unchecked, are projected to pass 530 ppm by 2100. In order to avoid serious impacts to the environment and human health, goals for stabilizing CO_2 levels at 450 ppm were set in 2007 (IPCC 2007). Meeting these goals, however, requires massive improvements in energy efficiency, increased deployment of renewable and nuclear energy, and the substantial development of new technologies for mitigating CO_2 emissions arising from the use of fossil fuels and other anthropogenic sources (IPCC 2014). A number of international environmental treaties have therefore been adopted since the early ’90s by a majority of countries in order to attempt to tackle anthropogenic emissions of greenhouse gases. The first one was the United Nations Framework Convention on Climate Change (UNFCCC), in 1992. This framework outlines how specific international treaties (called “protocols” or “Agreements”) may be negotiated to specify further action towards the objective of the UNFCCC. Within this framework, both the Kyoto protocol in 1997 and the Paris Agreement in 2015 have been negotiated to control and reduce GHG emissions (in particular, CO_2 emissions) worldwide. In particular, the Paris Agreement main goal is to keep the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, since it is estimated that this would significantly reduce the risks and impacts of climate change (*Paris Agreement* 2015).



Anthropogenic Greenhouse Gases 04/2015

Greenhouse gases covered by the Kyoto Protocol and the CO_2 Act	**Residence time in atmosphere (in years)**	**GWP**	**Share in total greenhouse gas emissions, excl. deforestation**
Carbon dioxide (CO_2) • Combustion of fossil thermal fuels and motor fuels (petroleum, natural gas, coal), cement production • Deforestation/fire clearing in the tropics	100–150	1	Globally ca. 73%, Switzerland ca. 82%
Methane (CH_4) • Agriculture (livestock and fertilisation) • Waste management (landfills, composting/fermentation, wastewater treatment) • Use of fossil fuels	12	25	Globally ca. 17%, Switzerland ca. 10%
Nitrous oxide (N_2O) • Agriculture (soils and fertilisation) • Smaller contributions from energy conversion, industry, and wastewater treatment	114	298	Globally ca. 8%, Switzerland ca. 5%
Synthetic greenhouse gases:			Globally ca. 2%, Switzerland ca. 3%
Hydrofluorocarbons (HFC) • Cryogenic agents, foaming agents, propellants in aerosol sprays, solvents	0.3–270	12–14‘800	
Perfluorinated carbon compounds (PFC) • Production of semiconductors, solvents, heat carrier	2'600–50'000	7‘390–12‘200	
Sulphur hexafluoride (SF_6) • High voltage insulators, aluminium and magnesium casting, production of semiconductors	3'200	22‘800	
Nitrogen trifluoride (NF_3) • Electronics industry	740	17‘200	
Greenhouse gases not covered by the Kyoto Protocol and the CO_2 Act			
Chlorofluorocarbons (CFC and halocarbons) • Use restricted/prohibited by the Montreal Protocol because of ozone layer destruction; in Switzerland emissions only from existing cooling/fire-extinguishing systems and foams	1.3–1‘700	Up to more than 10'000	Decreasing tendency thanks to politics for the protection of the ozone layer
New climate-relevant substances			
Hydrofluorether (HFE) • Solvents, heat carriers	0.2–136	11–14‘900	Increasing tendency
Sulphuryl fluoride (SO_2F_2) • Pesticide	36	4‘780	

Figure 1.3: List of anthropogenic greenhouse gases.
Source: FOEN (Federal Office for the Environment).

2 THE ROLE OF CCUS

In this chapter, we introduce the concept of Carbon Capture, Utilization, and Storage (CCUS), which is at the core of this work. We discuss how the introduction of CCUS modifies the representation of the global carbon cycle, i.e. the mutual interaction of the natural and the anthropogenic carbon cycle. In the last section, we describe the way these technological advancements are currently perceived in the public sphere from a technological viewpoint, in the context of the issue of climate change mitigation.

2.1 THE ROLE OF CCUS IN CLIMATE CHANGE MITIGATION

In order to tackle anthropogenic emissions of greenhouse gases and to meet the goals of the Paris Agreement, the current scientific and policymaking literature generally stresses the importance of deep changes in our economic and energy system. The first one is the so-called “energy transition”, that is, the gradual phase-out of fossil fuels in our energy system on a global scale and their replacement with renewable energy sources such as wind and solar power, hydropower, geothermal, and tidal energy, as well as nuclear fuel (uranium and plutonium)[7]; in parallel measures for energy conservation and improvement of energy efficiency also play a major role in the transition. Another one is the development and deployment of a class of technologies broadly referred to as Carbon Capture, Utilization, and Storage (CCUS), a definition which encompasses methods and technologies to mitigate CO_2 emissions following a two-step multi-processes scheme, as anticipated in the General Introduction:

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[7] *It is however worth noticing that, contrarily to other developed countries such as the United Kingdom, Switzerland envisages only further renewable energies development and calls for a gradual phase-out of nuclear power in its “Energy Strategy 2050”, cf. section 4.1.*

- the first step concerns capture of CO_2 from large-emission sources such as the flue gases produced in power and industrial plants, or directly from the atmosphere;
- the second step, concerning subsequent conditioning for direct use or transformation via chemical and biological pathways, allows to recycle the captured CO_2, mainly as a feedstock for useful products, for the synthesis of various chemicals and fuels, thus simultaneously decreasing its accumulation in the atmosphere and promoting its value as raw material. Alternatively, the captured CO_2 may be injected in deep geological reservoirs for long-term, stable storage. The two strategies encompassed within this last step allow to discriminate between two distinct classes of technological processes: Carbon Capture and Storage (CCS) and Carbon Capture and Utilization (CCU). The phase of capture of carbon dioxide is common to these two classes.

CCS techniques contribute to mitigating climate change by trapping CO_2 emitted by human activities or extracted from the atmosphere into geological formations. CCU technologies can contribute to mitigating climate change by reducing net CO_2 emissions in the following ways (CO_2 Value Europe 2018):

- The conversion of carbon dioxide into building materials binds carbon dioxide in the form of calcium carbonate, a compound which is known to be stable, therefore permanently reducing the amount of CO_2 which is present in our atmosphere.
- If CCU technologies are used to recycle CO_2 molecules emitted by an industrial process into useful fuels or chemicals, CO_2 gets only emitted once (at the end of its residence time in the product, unless it is recycled again) instead of twice (through the flue gases at the chimney of the industrial process, and at the end of its residence time). In addition, less fossil feedstock (at least per unity of product) needs to be extracted from the ground to feed the industrial processes when CCU technologies are in place, as illustrated in Fig. 2.1. This is an

especially important opportunity, particularly given that, according to the United Nations, “resource extraction and processing make up about half of the total global GHG emissions” (UNEP 2019).

- In the transportation sector, CO_2-based synthetic fuels can immediately contribute to reduce net CO_2 emissions because they can be used in existing combustion engines and do not require any change to the existing fuel distribution infrastructure, unlike other solutions such as electrification or hydrogen.
- CCU can facilitate the energy transition by offering options for the storage and transportation of renewable electricity, in the form of liquid or gaseous fuels (cf. also section 3.4.1).

In general, the positive effects that CCU can have on climate change mitigation can be summed up as a storage effect and a substitution effect. The storage effect is present whenever the carbon dioxide is bounded permanently in the utilization process, although, as we said in section 2.2, even a non-permanent residence time of the CO_2 in a product can have a positive, albeit not easily quantifiable, impact on climate change mitigation. The substitution effect occurs whenever the utilization of the carbon dioxide allows to replace, in part or in full, the extraction and the utilization of fossil resources for the manufacture of products per unity of product.

Ultimately, CCU allows us to attempt to establish a closed anthropogenic carbon cycle, as we can see in Fig. 2.5. A “circular economy” can therefore emerge, at least conceptually, where carbon dioxide is no longer considered as a waste emission but as a carbon source, ideally in replacement of fossil feedstock, cf. Fig. 2.2.

The role of CCUS with respect to the energy transition necessitates some remarks. In fact, CCUS processes require in general vast amounts of energy and hence tend to increase total energy consumption, which is at first glance in contradiction with the goals of the energy transition. For example, it has been estimated that the percent values of the energy penalty[8] for post-combustion capture and storage of CO_2 from pulverized-coal (PC) fired power plants have a theoretical absolute lower bound of about 11% whereas the lower bound for the additional fuel requirement in order to keep the energy output constant in the PC power plants which have been retrofitted with CCS is about 13% (House et al. 2009). In general, the environmental impacts of CCUS technologies, in particular regarding climate change, need to be carefully assessed through comprehensive Life Cycle Assessment (LCA) methods, i.e. methods which assess the environmental impacts associated with all the stages of a product's lifetime. This impact can be reduced by using renewable energy to power CCUS processes instead of energy derived from fossil fuels and it could be reduced even more so by using intermittent excesses of electricity caused by a high penetration of renewables in the electricity mix (Meylan, Piguet, and Erkman 2017), therefore providing a possible solution to the phenomenon of curtailment of wind and solar power (Bird, Cochran, and Wang 2014) in absence of adequate, and possibly expensive, battery storage conditions for such power. Moreover, as previously mentioned, the substitution of fossil-sourced chemicals and other products with CCU-based chemicals and products would ideally allow to extract less fossil feedstock from the ground to feed the industrial process, which aligns with the goals of the energy transition.

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[8] *The energy penalty is the fraction of the fuel that must be dedicated to CCS activities for agiven quantity of fuel input, cf. House et al. 2009.*

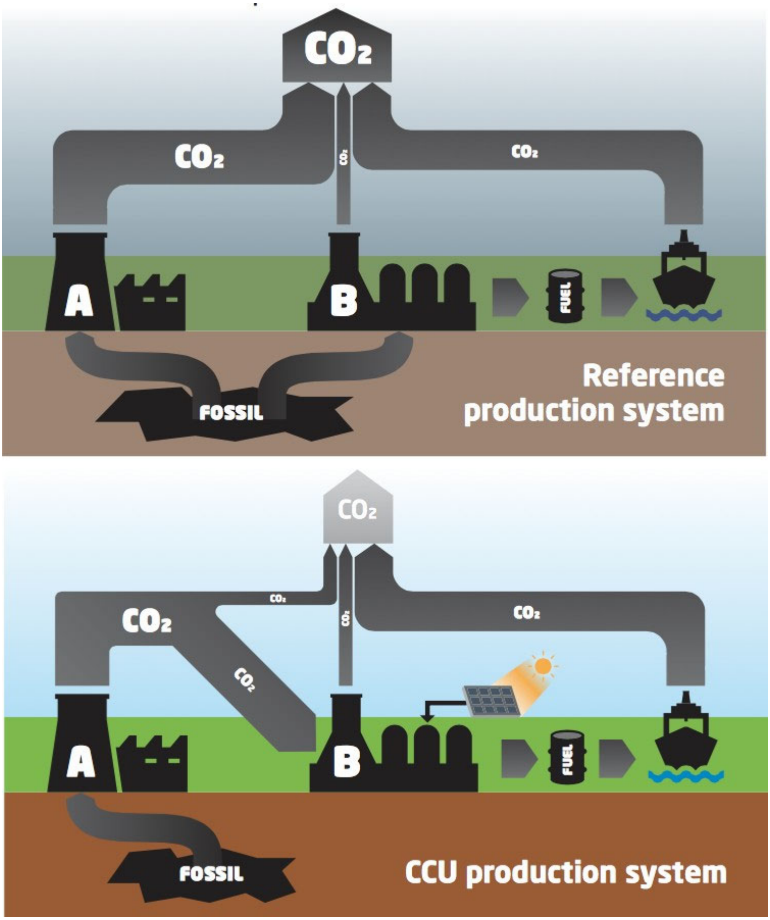

Figure 2.1: Graphic visualization of the differences in total net CO_2 emissions without and with CCU technologies.

Here we can see that CCU allows the installation B to use the carbon dioxide emitted by the installation A as feedstock in place of fossil resources, thereby decreasing total CO_2 emissions with respect to the reference production system with no CCU. Source: CO_2 Value Europe 2018.

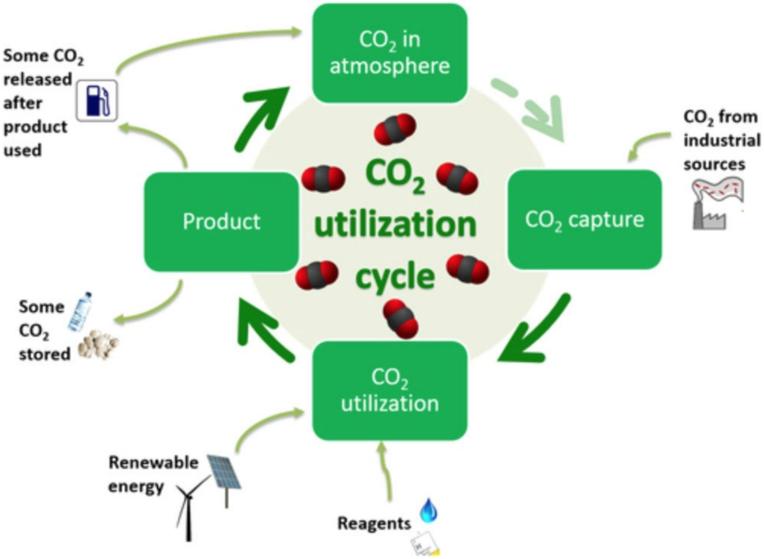

Figure 2.2: Schematic representation of the cyclic CCU process.
Source: Styring, Quadrelli, and Armstrong 2014.

There is international consensus that CCUS will be a critical component of an economically sustainable pathway to the emissions cuts needed to limit global warming to 2°C, in line with the goals of the Paris Agreement (US DoE 2016). In particular, in 2014 the IPCC concluded that without CCS, the costs of climate change mitigation to achieve a 450 ppm scenario could increase by 138% compared with a scenario that includes CCS, and further, that realizing a 2°C scenario may not even be possible without the contribution of CCS (IPCC 2014). CCS has been studied for more time than CCU and hence a larger literature exists for CCS than for CCU at this moment[9]. Nevertheless, CCU has witnessed a growing attention from both the scientific and the political communities in the last years. A report from the United Nations Environment Program (UNEP)

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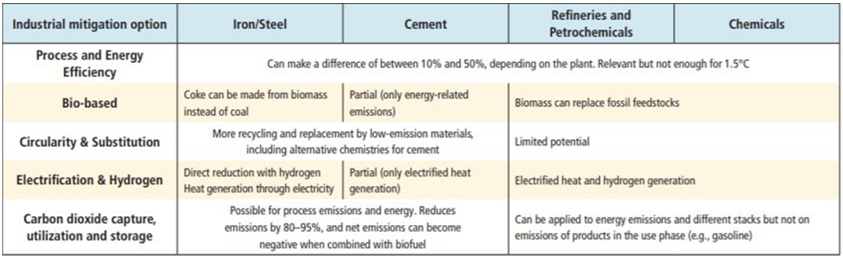
[9] *The IPCC even published, in 2005, a special report on CCS (IPCC 2005), of which only one chapter expressly deals with CCU.*

estimates for example the annual market for long-lived materials based on captured carbon dioxide (including carbonates, polymers, carbon fibre composites, graphene and even diamonds) to be between 1 and 7 Gt CO_2 per year, although this is contingent on policy- and market-support actions (UNEP 2017). Eventually, in its 2018 special report on a global warming of 1.5°C, the IPCC explicitly recognized the role played by CCU, alongside with CCS, in the field of possible options for climate change mitigation, particularly in the industry sector (IPCC 2018), cf. Fig. 2.3.



Industrial mitigation option	Iron/Steel	Cement	Refineries and Petrochemicals	Chemicals
Process and Energy Efficiency	Can make a difference of between 10% and 50%, depending on the plant. Relevant but not enough for 1.5°C			
Bio-based	Coke can be made from biomass instead of coal	Partial (only energy-related emissions)	Biomass can replace fossil feedstocks	
Circularity & Substitution	More recycling and replacement by low-emission materials, including alternative chemistries for cement		Limited potential	
Electrification & Hydrogen	Direct reduction with hydrogen Heat generation through electricity	Partial (only electrified heat generation)	Electrified heat and hydrogen generation	
Carbon dioxide capture, utilization and storage	Possible for process emissions and energy. Reduces emissions by 80–95%, and net emissions can become negative when combined with biofuel		Can be applied to energy emissions and different stacks but not on emissions of products in the use phase (e.g., gasoline)	

Figure 2.3: Overview of climate change mitigation options for the main industrial sectors in a scenario to keep global warming within 1.5°C.
Source: IPCC 2018.

Even if the processes of CCUS are still largely in an experimental phase, a report from the International Energy Agency (IEA) released in 2018 outlined some CCUS projects which are currently underway, such as equipping the Boundary Dam power station in Saskatchewan, Canada, with a CCS demonstration project in 2014 or the Petra Nova Carbon Capture project in Houston, Texas, which was commissioned in 2017 (Folger 2018). China currently accounts for about half of all CCUS projects under serious consideration or planning, including four projects which will apply CCUS to coal-fired power generation, such as the Yanchang CCUS project (OECD/IEA 2018).

These technological approaches seem particularly attractive to Switzerland, where the Parliament in 2016 accepted a motion, the Böhni Motion (n° 14.3837), which asked the Federal Council to create the legal and regulatory framework necessary for the promotion of carbon-neutral synthetic fuels made from CO_2 and renewable electricity (Böhni 2014). Moreover, the Message of the Federal Council relative to the complete revision of the Federal Act on the Reduction of CO_2 Emissions ("CO_2 Act" for short) incorporates the answer of the Government to the Böhni Motion (cf. pp. 273-274 of *Dispatch on the complete revision of the* CO_2 *Act for the period after 2020* 2017), although in general the references to policies relatives to CCUS are still quite vague[10]. Some disagreements remain over the technical and economic potential of these technologies, as well as over their acceptability from a legal point of view or from the public opinion.

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[10] *"[...] Moreover, this neutrality with respect to* CO_2 *implies, among others, the development of technologies for carbon capture and storage (CCS) in parallel to a reduction of emissions" (cf. p. 236 of* Dispatch on the complete revision of the CO_2 Act for the period after 2020 *2017).*

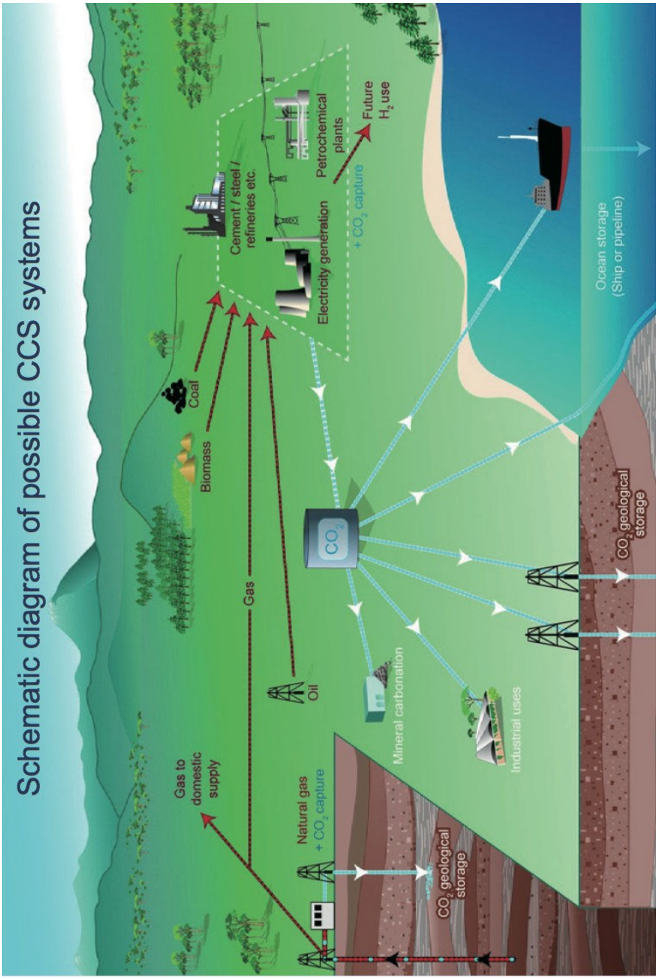

Figure 2.4: Schematic diagram of possible CCS systems showing the sources for which CCS might be relevant, transport of CO_2 and storage options.
Source: IPCC 2005.

2.2 THE EFFECT OF CCUS ON THE GLOBAL CARBON CYCLE

In order to include the effect of CCUS technologies into the dynamics of the global carbon cycle, we need to introduce the concepts of Biosphere and Anthroposphere. The Earth as a whole may be considered in terms of different spheres: the lithosphere, made up of the rocky foundations of our planet; the hydrosphere, representing the Earth's water; the cryosphere, comprising the frozen polar regions and high mountains; and the atmosphere, which is the air we breathe. We are also part of the Biosphere, made up of the Earth's ecosystems. These spheres have been in existence, in one form or another, for most, or all, of our planet's 4.6-billion-year existence. More recently, a new sphere has emerged: the Anthroposphere, or Technosphere, which may be defined as the part of the environment that is made or modified by humans through industrial and other economic activities. The Anthroposphere is therefore the sphere of the Earth system or its subsystems where human activities constitute a significant source of change through the use and subsequent transformation of natural resources, as well as through the deposition of waste and emissions (Baccini and Brunner 2012). Since the end of the 18th century, population growth and technological advances have made humans the dominant drivers of change to the Earth system as a whole and most of its subsystems (Crutzen 2002). It is crucial to realize that these spheres are not mutually exclusive: for example, as humans, we are both part of the Biosphere and the Anthroposphere. Also, parts of the other spheres such as the lithosphere or the hydrosphere can be part of the Anthroposphere too (e.g. rivers dammed for generation of hydroelectric power).

The inclusion of CCUS processes has important repercussions on the representation of the global carbon cycle that we have examined in Section 1.2 and which has now to be expanded in order to take into account additional fluxes of CO_2 between different parts of the Anthroposphere as well as between the Anthroposphere and the Biosphere, as one can see in Fig. 2.5. In particular, the anthropogenic carbon cycle becomes significantly more complex than in absence of CCUS.

In Fig. 2.5, the carbon fluxes between the three main natural reservoirs (the atmosphere, the terrestrial Biosphere and the oceans) are represented by arrows and occur:

- between the terrestrial Biosphere and the atmosphere: E_{df} (CO_2 emissions due to deforestation and changing land use), E_{od} (CO_2 emissions due to decomposition of organic matter), E_{re} (CO_2 emissions due to respiration of the land biota), U_{ph} (CO_2 uptake due to the photosynthesis of the land biota), U_{ew} (CO_2 uptake due to enhanced weathering on land), U_{cm} (CO_2 uptake due to soil and land carbon management);
- between the oceans and the atmosphere: E_{oc} (CO_2 emissions by the oceans), U_{oc} (CO_2 uptake by the oceans).

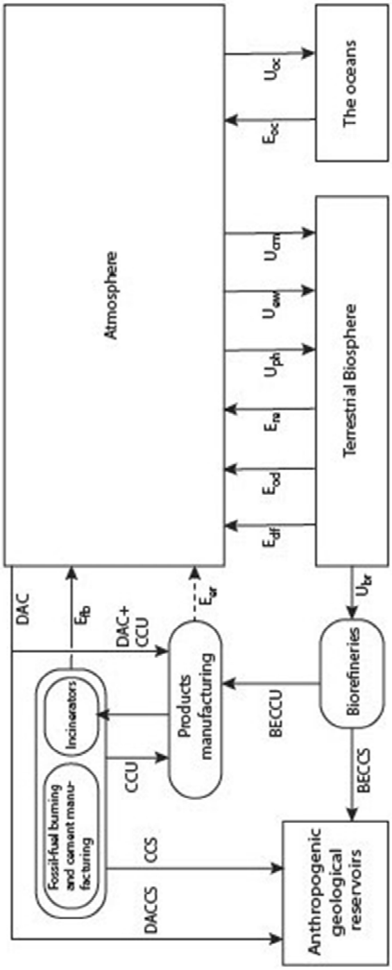

Figure 2.5: Diagram of the global carbon cycle with schematic representation of CCUS processes.
Source: by the author.

In a rough first approximation, the right-hand side of Fig. 2.5 represents the natural carbon cycle whereas the left-hand side represents the anthropogenic carbon cycle. However, the term E_{df} represents CO_2 emissions due to deforestation and changing land use: it is therefore part of the Anthroposphere and humans can intervene on the magnitude of this term, e.g. increasing or decreasing the deforestation rate. We can also represent the possible large-scale deployment of a number of negative emissions (or carbon dioxide removal) technologies (NETs, or CDR), cf. appendix A. Possible such NETs are (Keller et al. 2018):

- afforestation/reforestation, which consists in planting or restoring forests to increase carbon dioxide uptake (via primary production) and storage in biomass and soils, and which can affect the terms E_{re} and U_{ph} in the carbon cycle;
- soil and land carbon management (U_{cm}), which consists in employing management practices, such as irrigation, cover crops, soil and compost amendments (e.g. biochar[11]), wetland restoration, and fire management, to increase carbon retention and storage in agricultural soils or managed natural lands;
- enhanced weathering on land (U_{ew}), which consists in spreading alkaline minerals on land to chemically remove carbon dioxide from the atmosphere in reactions that form ions eventually transported to the ocean, or in some cases solid minerals (geological sequestration); it may also enhance vegetation productivity and subsequently soil carbon storage.

Moreover, the flux U_{oc} can also be enhanced by carbon dioxide removal methods such as (Keller et al. 2018):

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[11] *Biochar results from biomass that has been converted to decomposition-resistant charcoal. It is created when biomass is pyrolyzed (cf. section 3.1.3). Biochar added to soils can store carbon for thousands of years and also improves soil fertility properties (Creating Negative Emissions 2018; IPCC 2018).*

- ocean alkalinization, which consists in increasing the alkalinity of the upper ocean to chemically increase the carbon storage capacity of seawater and hence, also increase carbon dioxide uptake;
- ocean fertilization, which consists in adding micronutrients like iron or macronutrients like nitrogen and phosphorus to increase phytoplankton growth (CO_2 fixation) and ocean carbon storage via the biological pump (the transport of this fixed carbon into the deep ocean).

On the left-hand side of Fig. 2.5, rounded rectangles represent the main industrial processes in the CCUS chain (fossil-fuel burning and cement manufacturing, waste incineration, products manufacturing from captured CO_2, and biorefineries) whereas squared rectangles represent reservoirs, as before (in this case, anthropogenic geological reservoirs[12]).

The direct extraction of carbon dioxide from the atmosphere is called DAC (direct air capture). The CO_2 can then either be stored in anthropogenic geological reservoirs (DAC with carbon storage, or DACCS) or be used in different valorization paths, mainly to manufacture different products which request carbon for their fabrication, such as chemicals, biofuels, etc. (DAC with carbon utilization, or DACCU).

According to the definition given in IEA Bioenergy 2014, biorefineries are refineries that convert biomass to energy (fuels, power, heat) and other marketable products (food, feed, chemicals, etc.), cf. Fig. 2.6. The carbon stored in the biomass is processed in the biorefineries through the flux U_{br} which represents the uptake of CO_2 from the terrestrial Biosphere by the biorefineries. Carbon dioxide which is produced during the biorefinery processes and then captured can be either stored (bio-energy with carbon capture and storage, or BECCS) or bounded in marketable products through valorization processes (bio-energy with carbon capture and utilization, or BECCU). At the end of its lifetime, the product can be

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[12] *Rock formations where carbon dioxide can be trapped are "anthropogenic" geological reservoirs in the sense that their specific utilization in the CCS chain is of anthropic origin.*

burned in waste incinerators (and therefore the bounded CO_2 can be released into the atmosphere via the flux term E_{fb}). Alternatively, the bounded CO_2 is released into the atmosphere at the end of the residence time of carbon in that product, through the flux term E_{er}.

The residence time, that is, the period of time in which CO_2 is bounded in the product and removed from the atmosphere, varies greatly among different products created through CCU technologies: some uses, such as the use of carbon dioxide as a fuel precursor are very short term (days to months), whereas others have a longer duration. In fact, the latter case may result in the CO_2 being fixed away from the atmosphere for a period of time up to centuries and can therefore be considered a form of storage (SAM 2018).

In fact, CCU can mitigate climate change in two ways: (1) by reducing the total amount of GHG emissions through the capture of CO_2 and the substitution of fossil fuel-based products with CCU-based products, and (2) by temporarily storing CO_2 in such products. Delayed GHG emissions are beneficial compared to early GHG emissions for two reasons: first, early GHG emissions might cause irreversible impacts if large amounts are released in a short period of time; second, early GHG emissions remain longer in the atmosphere within a given time horizon than later ones and therefore they absorb more radiation and have a higher contribution to global warming. Accordingly, Life Cycle Assessment (LCA) methods to assess the total environmental impact of a product should also take into account the delay of GHG emissions by CCU technologies. The emissions’ point of time and thus the CO_2 storage duration are not reflected in current LCA practice: instead, the CO_2 storage duration is frequently used as separate metric alongside the carbon footprint. However, both metrics assess impacts on global warming and hence it would be more accurate to combine the conventional carbon footprint with the CO_2 storage duration in a new metric for global warming impacts (Assen 2015).

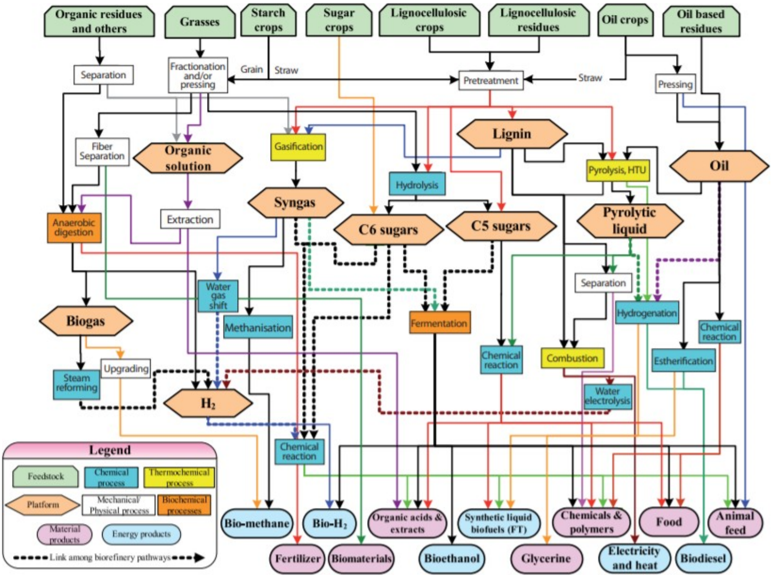

Figure 2.6: Schematic visualization of the concept of 'biorefinery': the processing of biomass into a spectrum of marketable products and energy.
Source: IEA Bioenergy 2014.

The traditional global warming potentials which are used for the various GHGs take into account any radiation which is absorbed within a chosen time horizon *TH* and neglect any absorbed radiation beyond *TH*. The choice of an adequate time horizon is difficult: on one side, a too-short time horizon disregards climate impacts for future generations; on the other side, a too-long time horizon ignores the urgency of climate mitigation. The usual time horizon in current LCA practice for global warming impacts is *TH* = 100 years, but this is "a subjective, policy-driven choice" (Brandão et al. 2012). To be consistent with the neglect of impacts beyond the time horizon, delayed GHG emissions should only be evaluated within the chosen time horizon. For example, for *TH* = 100 years, a GHG emission released today is considered to absorb radiation for the entire duration of 100 years, whereas a delayed GHG emission released 30 years later should be considered to absorb radiation only for the following 70 years. The global warming impacts should therefore be measured not only in equivalents of CO_2 emissions, but in equivalents of CO_2 emissions released at time $t = 0$ (Assen 2015).

Therefore, the arrow which represents the flux term Eer is dashed to signal that the passage of CO_2 from the manufactured product to the atmosphere does not necessarily occur within the time horizon considered, which is usually taken to be 100 years in the specialized literature.

If the bounded carbon has a residence time in the manufactured product shorter than *TH*, then it is considered to be released into the atmosphere at the end of this time, but its effect on global warming is delayed according to the discussion above. This occurs, for example, if the manufactured product is methanol and we take *TH* = 100 years, since the residence time of carbon in methanol is only of a few months.

If, on the other hand, the bounded carbon has a residence time in the manufactured product which is longer than *TH*, then it is considered to be virtually stored into the product for all practical purposes involved in the climate change mitigation approach consistent with that choice of *TH*.

2.3 CCUS IN THE POLITICAL DEBATE

From a political point of view, CCUS is a subject that lays at the intersection of a number of very important policies, such as environmental, energy, industrial, economic, fiscal and technology policies. The complexity of the policy design that is therefore necessary for the large-scale deployment of CCUS technologies and their integration with the rest of the industry and energy complex, coupled with the sense of urgency that the issue of global warming conveys, feeds the debate around the role that these technologies should play in the mitigation of climate change alongside more traditional instruments such as renewable energies deployment and fossil fuel phase-out, energy efficiency measures, emissions limit values or the electrification of mobility.

However, to this day, a number of arguments are usually brought up as signs of concern towards CCUS technologies:

1. CCUS deployment could delay a full transition of our energy system to a low- or zero-carbon emissions system; for example, CCUS could play a role in delaying the fossil fuel phase-out when fossil fuel power plants are equipped with such technologies, therefore complying with carbon dioxide emissions limits, whereas in absence of such technologies they should shutdown and be replaced with low- or zero-carbon emitting power plants
2. CCUS technologies are not always perceived as effective NETs (as already mentioned in section 2.1)
3. CCUS development will require important funding and resources which would otherwise be available for renewable energy development or other energy transition initiatives.

The respective counter-arguments that are generally given by proponents of CCUS are the following:

1. To this day, fossil fuels remain by far the main source of primary energy worldwide. In 2017, the share of oil in global primary energy consumption was 34%, the share of coal was 27.6% and the share of natural gas was 23.4%, whereas renewable energy amounted only to 3.6% (BP 2018). Even if the forecasts for future renewable energy growth are promising, fossil fuels still play a dominant role worldwide in every foreseeable scenario up to 2050. For example, a 2013 study by the World Energy Council examines two different 2050 world energy scenarios, one in which the world attempts to orchestrate climate change mitigation with a global, coordinated government lead (the so-called "Symphony" scenario), and one in which the focus is on adaptation and on market-driven growth (the so-called "Jazz" scenario). The future primary energy mix in 2050 shows that, even if growth rates will be highest for renewable energy sources, still, in absolute terms, fossil fuels (coal, oil, gas) will remain dominant, up to

and including 2050. “The share of fossil fuels will be 77% in the Jazz scenario and 59% in the Symphony scenario – compared to 79% in 2010. The share of renewable energy sources will increase from around 15% in 2010 to almost 20% in Jazz in 2050 and almost 30% in Symphony in 2050. Nuclear energy will contribute approximately 4% of total primary energy supply in Jazz in 2050 and 11% in Symphony globally – compared to 6% in 2010” (WEC 2013). According to this study, “the hard truth is that, in both worlds we seem unable to mitigate the climate challenge in time to the extent our scientists believe is necessary to avoid the risk of dramatic climate effects” (WEC 2013).

Since the currently slow pace of the energy transition seems to make it inadequate as the only response to climate change, in order to meet the goals of the Paris Agreement it is essential to introduce new public policies to steer the deployment of innovative technologies addressing climate change. According to the same World Energy Council study, “CC(U)S is a suitable technology (in addition to renewable electricity generation) to reduce CO_2 emissions. Given a CO_2 price signal, CC(U)S can play an important role after 2030 as a cost-efficient CO_2 mitigation option. Such a price for CO_2 has to be high enough to create the right signals to provide an adequate incentive for CO_2 reduction” (WEC 2013). The issue of the complementarity of CCUS with the energy transition cited in section 2.1 can be addressed by public policies which are adequately planned and well coordinated, for example by requesting the electricity powering CCUS technologies to be 100% from renewable or low-carbon emissions power, a goal less difficult to achieve in a country like Switzerland with its large hydroelectric and nuclear power generation than in other countries more heavily dependent on fossil resources.

Moreover, in a country like Switzerland the possibility for CCUS to consistently delay the fossil fuel phase-out in the power generation sector is excluded since currently only a tiny fraction (less than 3%) of the electricity produced in Switzerland comes from fossil fuels

(Swiss Confederation 2017). On the other hand, in case it were not possible to replace timely the nuclear power which is supposed to be phased-out in the next decades with renewable energy, it would be necessary to build “up to seven natural gas combined cycle (NGCC) power plants in order to bridge the power gap at acceptable costs”, according to a 2013 report commissioned by the Swiss Federal Office of Energy (SFOE 2013). Furthermore, the deployment of CCUS would allow to store or recycle most of the carbon dioxide produced by these NGCC power plants and therefore would help Switzerland to keep on track with the goals of the Paris Agreement which would otherwise be much more difficult to reach. In fact, according to the same report, “While the current electricity mix is virtually free of CO_2 emissions, a single 400 MW NGCC plant would emit about 1 Mt of CO_2 per year, corresponding to a 2.5% increase in Switzerland’s current total CO_2 emissions” (SFOE 2013).

It should also be noted that many industrial process (e.g. cement manufacturing) inevitably emit CO_2 as a byproduct. Hence, retrofitting these processes with CCUS technologies not only does not threaten the decarbonization of the economy, but also allows to decrease CO_2 emissions in a way that no other currently known techniques do. Besides, CCU enables the development of a circular carbon economy which allows to use recycled carbon dioxide in place of traditional fossil resources. This is a major paradigm shift with respect to the current economy, mostly based on the usual extraction and processing of fossil resources, which is an unsustainable process in the long term since it leads to both the depletion of these resources and an important increase in CO_2 concentration in the atmosphere, as discussed in UNEP 2019.

Finally, the two most controversial CCS techniques are unlikely to undergo a large-scale development in the Swiss context due to the lack of adequate conditions for their deployment. These techniques are enhanced oil recovery (EOR) with CO_2 and bioenergy with carbon capture and storage (BECCS). EOR with CO_2 is the process of increasing the amount of oil that can be recovered from an oil reservoir by injecting compressed carbon dioxide into an existing oil well: CO_2 acts like a solvent, and causes the oil to expand and flow more easily to production wells.

On the other hand, BECCS is a particular NET which consists in capturing CO_2 from bioenergy applications (e.g. ethanol production or burning biomass for electricity) and subsequently sequestering that carbon dioxide through CCS. The argument for this technique is that the carbon captured in the biomass by way of the photosynthesis during growth will be captured again after the combustion of the biomass in the power plant and sequestered in underground geological formations, the net result being that CO_2 is removed from the atmosphere.

EOR is controversial because of the risk of leakages of the CO_2 injected into the well and because the enhancement in oil production caused by this technique actually increases the dependence of the economy on fossil fuels, undermining the energy transition. BECCS is controversial because, according to its opponents, there is simply not enough sustainable biomass available on our planet to support a large-scale deployment of this technology. Also the energy penalty associated with CCS will apply to BECCS, meaning that it will require additionally 25-40% biomass to run the operation, which represents an extraordinary demand on a resource that is already under pressure (de la Plaza et al. 2017).

However, Switzerland does not present the ideal conditions to deploy these two specific technologies on a large, and therefore critical, scale: EOR (or its equivalent enhanced gas recovery, EGR) because of the geological and seismic risks connected with oil and gas exploration (Leu 2012) and because of the many current legal limitations on oil and gas extraction in many cantons of Switzerland[13] (Hünerwadel, Speck, and Tschudin 2016), and BECCS because of the limited

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[13] *Switzerland relies fully on import of oil and gas for its current oil and gas needs.*

amount of biomass which would be theoretically available for such process.

2. It is true that most CCU techniques cannot be classified as NETs (cf. appendix A), since they do not store carbon dioxide away for a period of time long enough to be considered virtually removed from the carbon cycle. Usually it is assumed that this happens when the storage time is longer than a time horizon *TH* conventionally taken to be e.g. *TH* = 100 years, cf. section 2.2. However, as already seen in section 2.2, even delayed carbon emissions can have a positive impact on climate change mitigation, although smaller than avoided ones. Furthermore, we can include CCS (also in its variants DACCS and BECCS) in the NETs class (Minx et al. 2018); additionally, a few CCU technologies, mainly carbon mineralization technologies (cf. section 3.4.2) but also the production of some polycarbonates with long bounding times of the molecules of CO_2 and the chemical recycling of plastics polymers, can be considered NETs inside a time period $t = TH$, consistent with the time horizon of climate change mitigation in the current policy framework. A graphic representation of the relationship existing between CCS, CCU and NETs, with their respective overlaps, is provided in Fig. 2.7.

   In particular,

   - DACCU and BECCU technologies whose final products result in permanent storage of the recycled CO_2 are at the same time NETs, CCU and CCS technologies, since the final products permanently store carbon dioxide (as in CCS), are marketable (as in CCU) and result in net negative carbon emissions since the carbon dioxide which is recycled is not of fossil origin but is either extracted from the atmosphere (in DACCU) or captured from the combustion of biomass (in BECCU);
   - other CCU technologies with permanent CO_2 storage (and therefore similar to CCS) in which the recycled carbon dioxide is of fossil origin are not NETs;

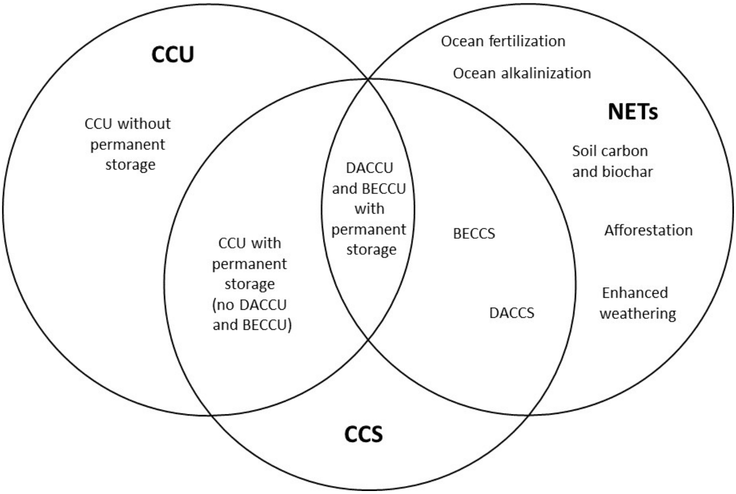

Figure 2.7: Schematic representation of the mutual relationships between CCS, CCU and NETs systems.
Source: by the author.

- CCS processes with geological storage of carbon dioxide which is either extracted from the atmosphere (DACCS) or captured from the combustion of biomass (BECCS) are also NETs.

3. The issue of the allocation of the resources available in the context of such deep changes in the economic, industrial and energy landscape is a complex one. In the absence of a public policy on CCUS, the climate change mitigation strategy of the Federal Council has been centered so far on the two great axes of the energy transition, namely the defossilization of the energy sector (through the development of renewable energies) and the improvement of energy efficiency (*CO_2 Act* 2011). However, as the current policy measures in all likelihood will be proven inadequate to meet the goal of the 20% reduction in carbon dioxide emissions by 2020 contained in the CO_2 Act (*CO_2 Act* 2011) according to the evolution of GHG emissions in Switzerland in the last years (*Dispatch on the complete revision of the CO_2 Act for the period after 2020* 2017), it becomes urgent to expand the scope of

the governmental action to achieve the goals of the Paris Agreement. Hence, it seems politically sound to implement the next steps suggested by the IPCC aside from the energy transition, mainly the development of CCUS. As indicated in the IPCC Special Report *Global Warming of 1.5°C*, "electrification, hydrogen, bio-based feedstocks and substitution, and, in several cases, carbon dioxide capture, utilization and storage (CCUS) would lead to the deep emissions reductions required in energy-intensive industries to limit warming to 1.5°C. However, those options are limited by institutional, economic and technical constraints, which increase financial risks to many incumbent firms (medium evidence, high agreement). Energy efficiency in industry is more economically feasible and helps enable industrial system transitions but would have to be complemented with greenhouse gas (GHG)-neutral processes or carbon dioxide removal (CDR) to make energy-intensive industries consistent with 1.5°C (high confidence)" (IPCC 2018).

Energy transition and deployment of CCUS should therefore be regarded as complementary since each of them appears to be inadequate if implemented alone, looking at the current trends in GHG emissions. The issue of funding should also be considered in this larger framework: in particular, the expansion of scope of the federal climate change strategy should be adequately reflected in the expansion of the financial means allocated to it, to develop CCUS technologies without undermining the energy transition goals. In the design of the public policies implementing CCUS in the context of the broader climate change mitigation strategy which includes the energy transition, the Federal Council should be wary to avoid the pitfalls which could potentially undermine the effectiveness and the efficiency of its climate change strategy. For example, as mentioned above, the goal to get 100% renewable energy to power CCUS processes can be achieved by the Federal Council (as well as the other institutional bodies in charge of the application of the strategy) with a careful planning and an adequate coordination of the different policies involved in the strategy.

Moreover, at the current level of technological development, a certain number of industrial processes, such as cement production, cannot significantly decrease their carbon emissions unless carbon capture methods are implemented. Therefore, renewable energy development would not address the issue of GHG emissions coming from these sectors.

2.4 CONCLUSIVE REMARKS

This chapter has shown that CCUS processes bring profound changes to the usual representation of the global carbon cycle, by adding a number of additional CO_2 fluxes between the Biosphere and the Anthroposphere, as well as between various elements of the Anthroposphere itself, cf. Fig. 2.5. It shows that the establishment of a “circular economy of carbon” based not on the extraction of fossil resources from the underground, but on the recycling of carbon atoms already present in the Atmosphere, Biosphere and Anthroposphere, not only can offer a supplementary instrument to mitigate climate change, but also profoundly modifies some traditional views about sinks and sources of carbon dioxide, according to which the activities in the Anthroposphere can only emit CO_2.

The novelty of this shift is at the origin of an intense, ongoing public debate around CCUS (cf. section 2.3), which takes place not only in the scientific community and which concerns the possible role played by CCUS in climate change mitigation. As we have seen, CCUS technologies can reduce the dependence of our current economic system on the extraction of fossil resources and some of them can be effective NETs, thus efficaciously complementing the contribution of renewable energy development to the decrease in carbon dioxide concentration in the atmosphere.

3 DESCRIPTION OF CCUS PROCESSES

In order to investigate the main issues regarding public policies, use rights and regulations involved in CCUS deployment, we first describe the ensemble of the CCUS processes which could be relevant for the case of Switzerland. This ensemble of processes can be sequentialized in three main parts: CO_2 capture, CO_2 storage (or sequestration) and CO_2 utilization. Every process can therefore be decomposed in a first part (capture) which is common to all processes, and a second part which, depending on the specific process considered, is either storage or utilization (Meylan, Moreau, and Erkman 2015). Of course, utilization is more consistent with the ecological principle of attempting to close material cycles than storage, but both technologies can be important instruments for the mitigation of climate change. A schematic representation of the concept of CCUS is presented in Fig. 3.1.

At the end of most sections in this chapter, we also present a synthetic list of the main policy and legal issues, as well as the policy actors involved, related to the content of each section. Such lists will guide the investigation of these topics and its items will be explored in detail in the following chapters.

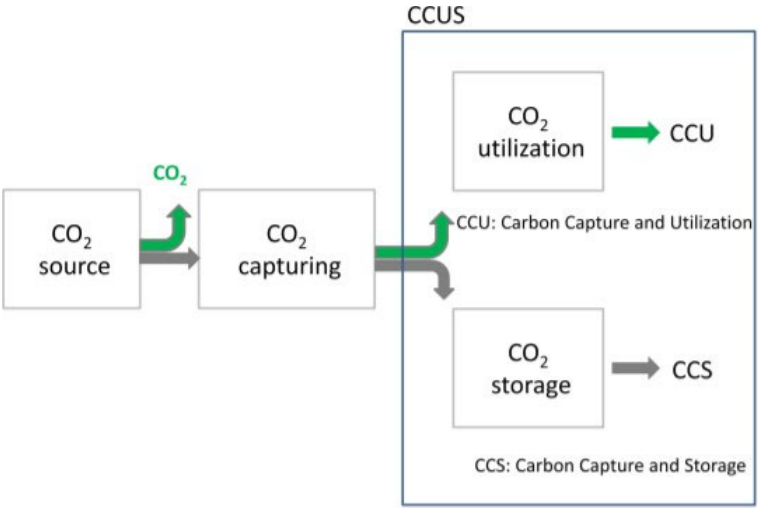

Figure 3.1**:** Schematic representation of the concept of CCUS.
Source: Alper and Orhan 2017.

3.1 CO_2 CAPTURE

3.1.1 CAPTURE AT LARGE POINT SOURCES

By “capture at large point sources” we mean the extraction of carbon dioxide from the flue gases of industrial sources such as fossil fuel power stations, cement or steel factories. This is particularly advantageous since the concentration of CO_2 in flue gases is higher than in ambient air. Carbon dioxide concentration in flue gases depends on the fuel such as coal (12–15% CO_2) and natural gas (3-4% CO_2), whereas in petroleum and other industrial plants, CO_2 concentration in exhaust stream depends on the process such as oil refining (8-9% CO_2), production of cement (14–33% CO_2) and production of iron and steel (20–44% CO_2)[14] (Mondal,

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[14] *A technical summary which explains gas concentration units is provided in appendix B.*

Balsora, and Varshney 2012; Songolzadeh et al. 2014). By comparison, the average CO_2 concentration in the atmosphere is much lower, currently around 415 ppm or 0.04% CO_2.

There are currently three main approaches to capture CO_2 at large point sources: post-combustion capture, oxy-fuel combustion and pre-combustion capture, cf. fig. 3.2**.**

In post-combustion capture, the flue gas which is produced by combustion, instead of being discharged directly to the atmosphere, is passed through equipment which separates and captures most of the CO_2.

In oxy-fuel combustion, instead of ambient air, nearly pure oxygen is used for combustion, which results in a flue gas that is mainly CO_2 and H_2O, which are separated by condensing water.

Finally, in pre-combustion capture, a fuel reacts with oxygen or air and in some cases steam to produce a gas, known as “synthesis gas” (or “syngas”), which is mainly composed of carbon monoxide and hydrogen: the carbon monoxide is reacted with steam in a catalytic reactor, called a shift converter, to give CO_2 and more hydrogen. Carbon dioxide is then separated, resulting in a hydrogen-rich fuel which can be used in many applications, such as furnaces, gas turbines, engines and fuel cells (Thiruvenkatachari et al. 2009; Songolzadeh et al. 2014).

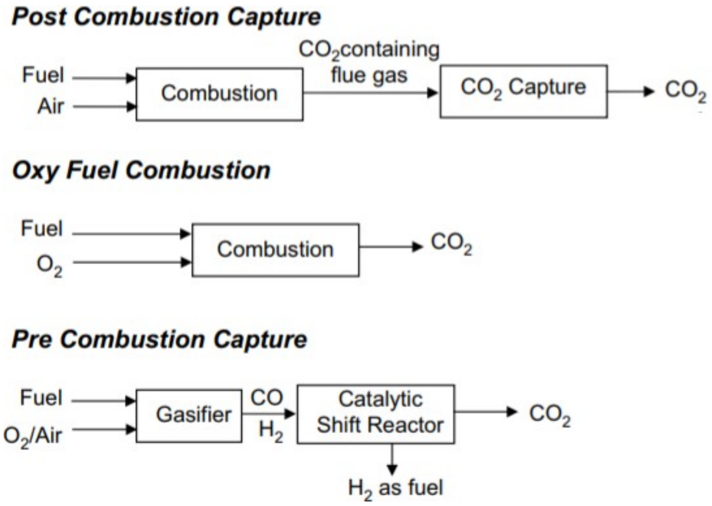

Figure 3.2: The three major approaches for CO_2 capture from flue gases at large point sources.
Source: adapted from Thiruvenkatachari et al. 2009.

3.1.2 DIRECT AIR CAPTURE

Description. DAC, that is, the capture of carbon dioxide from ambient air, presents, over the capture at large point sources, the disadvantages of the low atmospheric concentration of carbon dioxide which makes this procedure more energy-consuming than capturing CO_2 in flue gases and of the necessity to process considerable larger volumes of air (typically 2600 mol of air per mole of CO_2 captured, cf. (Gebald et al. 2011)). However, it also presents the considerable advantage to decouple the geographic location of such an installation from the presence of an industrial source of carbon dioxide in order to operate. To be environmentally sustainable, the energy source to power the process should be renewable or rely on heat which would otherwise be wasted (e.g. industrial waste heat). Two main DAC processes which could be used are adsorption with anion exchange resin (Lackner 2009) and with immobilized amines (Wurzbacher et al. 2012; the latter is used e.g. at the Climeworks plant, which is discussed below).

Outside of academic research, only a few start-ups are testing the concept of DAC. However, DAC is facing increasing attention due to technological developments and diminishing costs. In Switzerland, the company Climeworks opened a plant near Zürich in 2017 that is capable of capturing 900 tonnes of carbon dioxide in a year directly from the air. The captured CO_2 is subsequently used to grow vegetables in a nearby greenhouse. In 2018, Climeworks stated that it costs around 600 US$ to capture one tonne of CO_2 from the air (Tollefson 2018). The same year, Harvard professor David Keith and his colleagues estimated that their company, Carbon Engineering, could capture CO_2 for between 94 US$ and 232 US$ per metric ton (Keith et al. 2018). In either case, the cost is many times the cost of CCS applied on coal or biomass power plants. But the DAC technology has the advantage that it does not need to be located where the CO_2 is produced. Instead, it could be placed where the CO_2 is to be injected (Rathi 2018), thereby reducing transportation costs.

Policy outline.

- *Policy actors.* DAC companies - Public authorities (for land use planning, delivery of building permits and of licenses to operate) - NGOs (Non-governmental organizations) - Electric power utilities.
- *Legal issues and policy rules.* Use and property rights concerning the CO_2 captured from ambient air with the DAC installation - Delivery of permits to build DAC installations - Economic and fiscal incentives for DAC - CO_2 reduction goals coming from climate change mitigation policies and other environmental policies - Rules about power production and utilization - Rules about land use planning and building permits.

3.1.3 BIOENERGY WITH CARBON CAPTURE

Description. The general process of capturing the CO_2 emitted by bioenergy production is called *bioenergy with carbon capture and storage*

(BECCS). The carbon dioxide can also be reused for chemical, biological or physical purposes, in which case we have *bioenergy with carbon capture and utilization (BECCU)*. A schematic diagram representing the concepts of BECCS and BECCU is shown in Fig. 3.3. Processes which capture carbon dioxide emitted by bioenergy production are:

- The capture of CO_2 produced during ethanol fermentation, very concentrated and cheap;
- The extraction of CO_2 resulting from the so-called “biogas upgrading”, that is, the process of concentrating the methane in a biogas to increase its energy content by removing carbon dioxide and other contaminants from the biogas (Petersson and Wellinger 2009);
- The capture of carbon dioxide released as a by-product of the combustion of biomass or biofuel to generate electricity with steam or gas powered generators;
- The capture of carbon dioxide released as a by-product of the combustion of biofuel for heat generation;
- Pyrogenic carbon capture, that is, the capture of a portion of the carbon bounded in the biomass during the thermal treatment of such biomass at 350°C–900°C in an oxygen-deficient atmosphere, a process called “pyrolysis” (Werner et al. 2018).

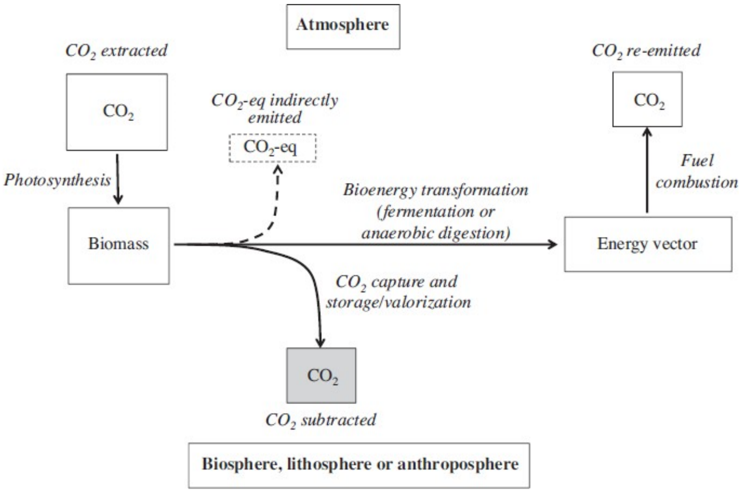

Figure 3.3: Schematic representation of the concepts of BECCS and BECCU.
Source: Meylan, Moreau, and Erkman 2015.

Policy outline.

- *Policy actors*. Bioenergy companies and producers - Future industrial users of the CO_2 captured at the bioenergy plant - Electric power utilities - Public authorities (for land use planning, delivery of building permits and of licenses to operate) - NGOs (Non-governmental organizations).
- *Legal issues and policy rules*. Delivery of permits to build carbon capture installations - Economic and fiscal incentives for carbon capture - CO_2 reduction goals coming from climate change mitigation policies and other environmental policies - Rules about power production and utilization - Rules about land use planning and building permits, especially in agricultural or forested areas.

3.2 CO_2 TRANSPORT

In case the point-of-capture site and the storage or utilization site are far away, carbon dioxide needs to be transported to the new location. Transport of captured carbon dioxide can essentially occur in four ways: through pipelines, motor trucks, ships and rail. CO_2 can be transported in gaseous, liquid or, more rarely, solid phase. Pipelines constitute the dominant mode of transporting large quantities of CO_2: in fact, they can deliver a constant and steady supply of carbon dioxide with no need to have temporary CO_2 storage along the transmission pathway. Concerning transport by ship, it may be appropriate in case of overseas delivery: however, "the location of anthropogenic CO_2 sources and suitable sinks is typically away from navigable waterways, so such scheme would still most likely require pipeline construction between CO_2 sources and port terminals" (Serpa, Morbee, and Tzimas 2011).

3.3 CO_2 STORAGE: GEOLOGICAL STORAGE

Description. Geological carbon storage involves injecting the CO_2 captured from industrial processes into rock formations deep underground. The formations are selected for their huge capacity to store and retain the injected greenhouse gases indefinitely: in this way, the CO_2 is effectively removed and isolated from the atmosphere. Moreover, in some cases the low purity of CO_2 can be detrimental for certain processes of valorization and therefore CCS could constitute a valid alternative to CCU.

A short description of the mechanisms trapping carbon dioxide in geological reservoirs can be found on p. 46.

In 2005, the IPCC released a Special Report on Carbon Dioxide Capture and Storage, summarizing the existing scientific findings on the role which could be played by CCS in the mitigation of climate change (IPCC 2005). This report states that the risks of geological CO_2 storage on human health and the environment, mainly related to the issue of potential CO_2

leakages in the atmosphere, are actually comparable to the risks arising from other current activities such as EOR, natural gas storage, and deep underground disposal of acid gas. Moreover, it is suggested that the fraction of carbon dioxide retained in geological reservoirs which are selected and managed in an appropriate manner "is very likely to exceed 99% over 100 years and is likely to exceed 99% over 1,000 years" (IPCC 2005; WRI 2008).

Policy outline.

- *Policy actors*. Companies and producers of the CO_2 captured (by DAC or other means) - Landowners of the terrain where the installation for CO_2 storage is built - Public authorities - NGOs (Non-governmental organizations).
- *Legal issues and policy rules*. Use and property rights of the surface terrain (where the installation for CO_2 storage is built) and underground (where the carbon dioxide is stored), cf. art. 655 ff. of the Swiss Civil Code concerning real rights in immovable property - Liability rules about possible leakages or earthquakes caused by the storage of carbon dioxide - Procedures of delivery of acts of authorization or concession agreements (with payment of a royalty) by the local public authority (e.g. for the use of the public domain to store CO_2) - Legal regime applicable to waste, according to art. 30 ff. EPA - Economic and fiscal incentives for CCS - CO_2 reduction goals coming from climate change mitigation policies.

Trapping mechanisms of CO_2 in geological reservoirs

Several mechanisms work in combination to ensure that CO_2 remains in the storage reservoir. Supercritical CO_2 is buoyant, and will migrate upward. This migration can be prevented by a confining zone overlying the injection formation. Storage through this physical trapping contains very high fractions of CO_2, and acts immediately to limit vertical CO_2 migration. Capillary trapping can immobilize a substantial fraction of CO_2. This mechanism also acts immediately and is sustained over long time scales. CO_2 trapped this way may be considered permanently trapped. A fraction of the CO_2 will dissolve into other pore fluids, including hydrocarbons (oil and gas) or brines. Depending on the fluid composition and reservoir condition, this may occur rapidly (seconds to minutes) or over a period of tens to hundreds of years. Over very long time scales, much of the dissolved CO_2 may react with minerals in the rock volume to dissolve or precipitate new carbonate minerals, often called mineral trapping. Precipitation of carbonate minerals permanently binds CO_2 in the subsurface; dissolution of minerals generally neutralizes carbonic acid species and increases local pH, buffering the solutions and trapping CO_2 as an ionic species (usually bicarbonate) in the pore volume. Source: WRI 2008.

3.4 CO_2 UTILIZATION

Carbon utilization is an attractive option to sequester CO_2 because the value of the products created can in principle improve the overall economics of the entire carbon capture and sequestration process. While in the context of flue gases CO_2 is seen as a waste product, in CCU carbon dioxide is considered as a valuable commodity. A wide range of potential products can be derived from carbon dioxide. However, the challenge is that CO_2 is a stable compound and thus it is potentially energy-intensive to get CO_2 to react with other substances.[15] In an ideal case, in order to

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[15] *It is however worth noticing that some of such reactions do not require vast amounts of energy to take place, for instance the reaction of mineral carbonation is exothermic, that is, it can theoretically yield energy instead of requiring it (cf. chapter 7 of IPCC 2005).*

match the climate change mitigation level of carbon storage options, any utilization option should be net CO_2-negative or neutral all along the life cycle of the product. This means that the energy required for the CO_2 utilization should come from a source that emits less carbon dioxide than the amount of CO_2 which is being converted in the utilization process and the product of this utilization should not release the CO_2 back into the atmosphere during its life cycle (National Climate Change Secretariat and National Research Foundation of Singapore 2011). As we will discuss in the next sections, this is not always the case: in fact, many utilization options release the recycled CO_2 after a certain amount of time which can sometimes be very short (days to months, as in the case of urea yield boosting). Conversely, some utilizations (such as carbon mineralization or enhanced oil recovery) are similar to CCS in the sense that the time during which the carbon dioxide is bounded (stored) inside the final product is permanent on any relevant climate change time scale (leakages aside). These utilization processes are therefore more significant as climate change mitigation options.

Table 1 shows the main CCU technologies with potential for commercial viability which are discussed in the literature. In this table, these technologies are classified according to the pathways of the recycled carbon dioxide, as explained in the next paragraphs.

In the context of CCU, the captured CO_2 is valorized in different manners. We can distinguish two main pathways for CCU: conversion uses of CO_2 and non-conversion uses (i.e. direct physical uses) of CO_2. Each of these pathways can then be further divided in two sectors, according to whether the storage of the CO_2 is permanent or non-permanent:

- *Conversion - Non-permanent storage*. The situation in which the CO_2 is subject to conversion or incorporation processes. During these processes, the CO_2 endures chemical reactions which typically break its chemical bonds to form new ones and the carbon atoms are recycled into new, useful products. For example, in a CCU process known as “algae cultivation” CO_2 is absorbed by microalgae which can then be used to manufacture proteins, fertilizers and biofuels.

- *Non-conversion - Permanent storage*. The situation in which the CO_2 is not chemically converted and therefore the carbon atom remains bounded into the CO_2 compound after the process. For instance, in Enhanced Oil Recovery (EOR) processes, the captured carbon dioxide is injected in a liquid-like state into an existing oil well reducing the viscosity of the oil, therefore increasing the amount of oil that can be produced from the well. Most of the CO_2 injected into the well becomes trapped in the rock and is permanently stored in the pore spaces, whereas the portion of the injected CO_2 which is recovered with the oil is immediately separated and combined with CO_2 arriving from the original source for re-injection into the formation. Ultimately, all the CO_2 injected in the well will be permanently stored in the formation.
- *Conversion - Permanent storage*. In mineralization processes, e.g. carbon mineralization, carbon dioxide chemically reacts with other compounds, generally calcium- or magnesium-containing minerals, to produce new compounds which can be used e.g. as a construction material. In this case, the carbon atom is permanently stored in this new material.
- *Non-conversion - Non-permanent storage*. This is the case of desalination processes, which do not appear in the list of Table 1. In desalination processes, CO_2, mixed with H2O brine at high pressure and low temperature, forms a hydrate of CO_2 surrounded by H2O molecules. The hydrate is removed and rinsed, and then goes through multiple stages to remove dissolved solids in the brine, resulting in an exhaust stream of potable water (Nemitallah, Habib, and Badr 2019). The brine is then disposed.

The last column of Table 1 refers to the categories of CO_2 emissions or CO_2 sinks in which the CCU technologies listed in the table can be included. These categories are defined according to the criteria outlined in art. 4, par. 1, sec. d of the United Nations Framework Convention on Climate Change (UNFCCC) of 9 May 1992 (UNFCCC 1992), whose goal is to "stabilize [...] the concentrations of greenhouse gases (GHGs) in the atmosphere at a level that prevents dangerous anthropogenic interference with the climate system" (art. 2 UNFCCC 1992). The Convention defines a "reservoir" as "a component or components of the climate system where a greenhouse gas or a precursor of a greenhouse gas is stored" and a "sink" as "any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas from the atmosphere" (art. 1 of UNFCCC 1992), cf. also appendix A. In the perspective of the goal previously mentioned, States Parties are invited to take measures to reduce GHG emissions, but also to conserve and reinforce GHG sinks in accordance with art. 4, par. 1, sec. d of the Convention[16] (UNFCCC 1992).

Moreover, art. 4, par. 2, sec. a of the Convention stipulates that each of these States Parties "shall adopt national policies and take corresponding measures on the mitigation of climate change, by limiting its anthropogenic emissions of greenhouse gases and protecting and enhancing its greenhouse gas sinks and reservoirs" (UNFCCC 1992). This paragraph is written in a broad enough way to allow for the inclusion of anthropogenic geological reservoirs in the "GHG sinks and reservoirs" considered. Therefore, it provides a legal basis for CCS development as a way to mitigate global warming.

More in detail, GHG emissions (including CO_2 emissions) can be divided into the two categories of (1) natural GHG emissions and (2) anthropogenic GHG emissions; GHG sinks (including CO_2 sinks) can analogously be separated into two groups, (3) natural sinks and (4) artificial (or anthropogenic) sinks. The Convention on Climate Change calls for a stabilization of the concentration of GHGs in the atmosphere and therefore for a balance between the emissions of GHGs and the uptake

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[16] *"All Parties […] shall […] promote sustainable management, and promote and cooperate in the conservation and enhancement, as appropriate, of sinks and reservoirs of all greenhouse gases not controlled by the Montreal Protocol, including biomass, forests and oceans as well as other terrestrial, coastal and marine ecosystems [. . .]".*

of GHGs by the sinks. One can get this either reducing GHG emissions in category 2 (natural GHG emissions) or increasing GHG sinks in category 4 (artificial sinks) while protecting the existing sinks in category 3 (natural sinks). Before the introduction of CCUS technologies, only category 3 appeared on the ‘sink’ side of the balance, hence narrowing the 2 and reforestation in category 3. The technologies of CCUS not only increase the number of options available in category 2[17], but also introduces the option of anthropogenic sinks, i.e. category 4. Some NETs such as ocean fertilization, large-scale afforestation or enhanced weathering, on the other hand, enhance the uptake of carbon dioxide by natural sinks and could therefore be included in category 3.

As a consequence, we can assign each CCU method to the category 2 whenever the recycling of CO_2 replaces the utilization of fossil resources, the category 4 whenever the CCU technique allows to store the carbon dioxide in a permanent way, or both. The result, as already said, is shown in the last column of Table 1.

Classification of the main CCU technologies		*Technology*	*Description*	*Residence time of CO_2*	*Categorization*
Conversion	*Mineralization*	Carbon mineralization	Mildly concentrated CO_2 (e.g. power station flue gas) is contacted with mineral-loaded alkaline brine (in mineral or industrial waste products). The CO_2 present in the gas precipitates out as mineral carbonates (limestone / dolomite equivalent precipitates). The resulting product can be further processed to form an aggregate equivalent product for the construction industry, which can potentially substitute a portion of Portland Cement in concrete and therefore decrease the carbon emissions in the sector of cement production.	Permanent	Substitution (cat. 2), storage (cat. 4)

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[17] *By replacing fossil resources for the manufacture of marketable products such as some chemicals.*

Classification of the main CCU technologies		*Technology*	*Description*	*Residence time of CO_2*	*Categorization*
Conversion	*Mineralization*	Concrete curing	Waste CO_2 flue gas stream is used to cure precast concrete, limiting the need for heat and steam in the curing process. CO_2 is therefore stored as an unreactive limestone within the concrete. The use of CO_2 could result in an accelerated curing process. Moreover, there is a net effect of substitution of CO_2-emitting processes (e.g. for heat production).	Permanent	Substitution (cat. 2), storage (cat. 4)
		Bauxite residue carbonation	The extraction of alumina from bauxite ore results in a highly alkaline bauxite residue slurry known as 'red mud'. Concentrated CO_2 can be injected into the red mud slurry to partially neutralise the product, improving its manageability, reducing its disposal costs and limiting its potential environmental impacts. In the neutralisation process, the CO_2 is converted to mineral form (typically carbonates), which can be used as construction materials (cement, bricks, tiles, aggregate blocks and wood substitute). Also, this technology reduces the cost of red mud disposal.	Permanent	Storage (cat. 4)
	Biological	Algae cultivation	Microalgae absorb CO_2 and then can be converted for example into proteins, fertilizers and biomass for biofuels, thereby replacing fossil resources. Some possible utilization avenues can also lead to semi-permanent storage of CO_2. However, the high surface requirement for cultivation may reduce the commercial viability of this technology in areas where land prices are high.	Non-permanent	Substitution (cat. 2)

Classification of the main CCU technologies		*Technology*	*Description*	*Residence time of CO_2*	*Categori-zation*
Conver-sion	*Biological*	Greenhouse enrichment	Various systems have been proposed to increase food productivity while sequestrating CO_2 from ambient air by enriching the air in a greenhouse with captured CO_2, cf. Bao et al. 2018.	Non-permanent	Substitution (cat. 2)
		Succinic acid biosynthesis	Captured CO_2 can be used for succinic acid production in a few biochemical processes (cf. Cheng et al. 2012), whereas today succinic acid is mainly produced from fossil resources (through maleic acid hydrogenation).	Non-permanent	Substitution (cat. 2)
	Chemical	Power-to-fuel (or power-to-X)	CO_2 is electro-chemically converted into gaseous or liquid energy carriers or industrial feedstocks.	Non-permanent	Substitution (cat. 2)
		Formic acid synthesis	CO_2 is electro-chemically converted in water to produce formic acid, replacing the use of fossil fuel as raw material (cf. Pérez-Fortes et al. 2016).	Non-permanent	Substitution (cat. 2)
		Polymers / chemical feedstock	CO_2 is transformed into polycarbonates and other chemicals.	Non-permanent	Substitution (cat. 2)
		Urea yield boosting	Ammonia and CO_2 are converted to urea fertilizer, thereby replacing fossil fuels that are typically used in urea production plants.	Non-permanent	Substitution (cat. 2)
Non conversion		Enhanced oil/gas recovery	CO_2 is injected into an existing oil or gas well to increase pressure and reduce the viscosity of the substance, increasing the amount of the substance that can be recovered. This technology is considered a commercially mature technology, having first been deployed in the 1970's.	Permanent	Storage (cat. 4)

Classification of the main CCU technologies	*Technology*	*Description*	*Residence time of CO_2*	*Categorization*
Non conversion	Enhanced geothermal systems	Supercritical CO_2 transfers geothermal heat or generates power directly through a supercritical CO_2 turbine. This would achieve geologic storage of CO_2 as an ancillary benefit. However, this technology is still in a pre-commercial phase.	Permanent	Substitution (cat. 2), storage (cat. 4)
	Enhanced coal bed methane	CO_2 is injected into partially depleted coal seams, where it's absorbed by coal, in turn displacing methane to the surface for it to be captured and consumed as fuel.	Permanent	Storage (cat. 4)

Table 1: List of the main CCU technologies classified according to the pathways of the recycled carbon dioxide.
Source: derived from Global CCS Institute 2011.

We focus our following analysis on the utilization options that are among the most relevant ones in the case of Switzerland (cf. chapter 4), such as fuel synthesis (or "power-to-fuel"), mineralization, synthesis of polycarbonates, and biological utilization.

3.4.1 POWER-TO-X

Description. In the process called "power-to-fuel"[18], or (more broadly) "power-to-X", where X stands for various fuels and chemicals (hydrogen, methane, methanol, ethylene, . . .), the captured CO_2 is used to create products such as (i) gaseous or liquid energy carriers which can be mainly used for transportation or heating, or (ii) chemicals for the industry sector, by conversion of electrical energy to chemical energy.

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[18] *This process is also called sometimes "CO_2-to-fuel" in the literature (Smit, Park, and Gadikota 2014).*

Power-to-X processes, which are represented in Fig. 3.4, are made of three basic steps (Kober et al. 2019):

- the first step consists in the electrolysis of water, namely splitting water into hydrogen and oxygen using electricity to power the process. Depending on the end-use application, hydrogen can then be used directly, for example for transportation, or it can in turn be used for the synthesis of other energy carriers;
- the second step involves a set of additional reactions, in which the hydrogen previously yielded reacts with the captured CO_2 to produce gaseous or liquid hydrocarbons such as methane, methanol, other liquid fuels, or ammonia;
- the third step involves the possible upgrading and conditioning of these substances to get the final products for further usage, such as diesel or kerosene[19].

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[19] *On the other hand, methane can directly be fed into the gas network, without further chemical processing.*

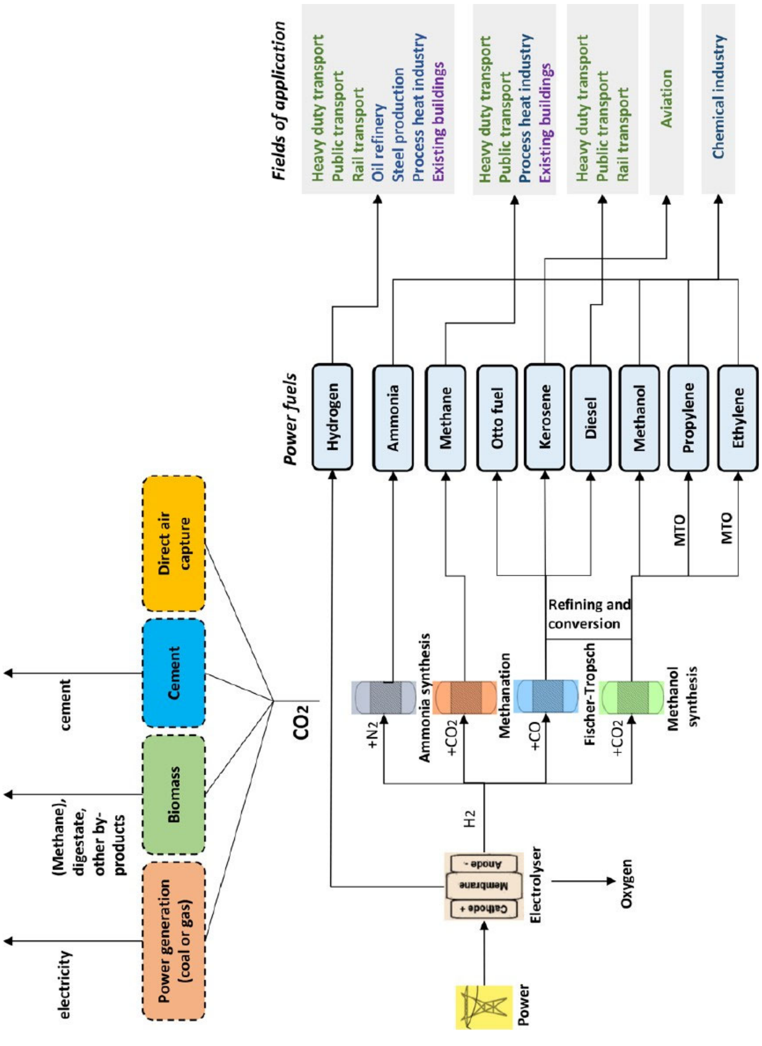

Figure 3.4: Scheme of the different power-to-X pathways with technology alternatives. Source: Kober et al. 2019.

The whole pathway is environmentally more sustainable when solar energy or other renewable energies are used as sources of power for such conversions. In particular, the use of surpluses of electricity caused by a high penetration of renewables has been proposed. In fact, in the electricity sector, intermittent renewables such as wind or solar energy may cause temporary surpluses of production, which will be curtailed unless effective storage solutions are developed. In combination with other storage technologies, power-to-X could be a relevant option to absorb the surpluses of renewable electricity when the share of renewable energy reaches 80% (Pleßmann et al. 2014). Predicting the amount of surpluses that would be curtailed in high RE scenarios is difficult because it depends on a large number of parameters, especially the future capacity of the electricity transmission grid. It has been estimated that, in a European scenario in which the share of renewable energy is 80%, more than 100 TWh would be wasted by 2050, despite a projected increase in electricity transmission capacity (Meylan, Piguet, and Erkman 2017).

Policy outline.

- *Policy actors*. Companies involved in the production or capture (by DAC or other means) of the CO_2-feedstock - Producers of the fuel - Electric power utilities - Public authorities (e.g. the Federal Electricity Commission, ElCom) - NGOs (Non-governmental organizations).
- *Legal issues and policy rules*. Upgrade of the legal status of CO_2 as a resource, in order eventually to develop a legal regime of resources - Policy goals and rules for CCU - Economic and fiscal incentives for CCU - CO_2 reduction goals coming from climate change mitigation policies - Rules about power production and utilization - Rules about fuels and transportation.

3.4.2 MINERALIZATION (PRODUCTION OF CARBONATES)

Description. Carbon mineralization (or mineral carbonation) is a chemical process in which CO_2 reacts with a metal oxide such as magnesium or calcium to form carbonate minerals[20]. The resulting new compound can be used in construction, as a consumer product or an alternative to CCS. The main advantage of mineral carbonation is that the carbonates thus formed are very stable, therefore capable of storing CO_2 in a permanent way, without the risk of CO_2 leakage as in conventional CCS systems (Cuéllar-Franca and Azapagic 2015).

Policy outline.

- *Policy actors*. Companies involved in the production or capture (by DAC or other means) of the CO_2-feedstock - Producers of the carbonates - Electric power utilities - Public authorities - NGOs (Non-governmental organizations).
- *Legal issues and policy rules*. Upgrade of the legal status of CO_2 as a resource, in order eventually to develop a legal regime of resources - Policy goals and rules for CCU - Economic and fiscal incentives for CCU - CO_2 reduction goals coming from climate change mitigation policies - Rules about power production and utilization - Rules about construction products (certification, marketing, . . .)[21].

3.4.3 SYNTHESIS OF POLYCARBONATES

Description. Polycarbonates are a group of macromolecules containing carbonate groups which are used extensively in construction materials in place of glass and in security and personal protection products due to its high strength and impact resistance while being extremely light and moldable (Henrickson 2005). The worldwide production of polycarbonates is about 4 Mt/yr and the conventional synthetic route utilizes phosgene, a chemical compound with the formula $COCl_2$. However, a considerable effort towards the direct synthesis of the

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[20] *Carbonate minerals, or carbonates, are those minerals containing the carbonate ion,* CO_3^{2-}.

[21] *For instance, the Federal Act and the Ordinance on Construction Products (*Federal Act on Construction Products 2014; Ordinance on Construction Products 2014*). An adaptation of the technical standards of the SIA (the Swiss Society of Engineers and Architects) to regulate the use of the new constructionmaterials which can be created by recycling* CO_2 *should also be possible.*

polymers from carbon dioxide is emerging. Replacing phosgene with CO_2 is also more consistent with the principles of green chemistry[22] (Meylan, Piguet, and Erkman 2017).

Policy outline.

- *Policy actors*. Companies involved in the production or capture (by DAC or other means) of the CO_2-feedstock - Producers of the carbonates - Electric power utilities - Public authorities - NGOs (Non-governmental organizations).
- *Legal issues and policy rules*. Upgrade of the legal status of CO_2 as a resource, in order eventually to develop a legal regime of resources - Policy goals and rules for CCU - Economic and fiscal incentives for CCU - CO_2 reduction goals coming from climate change mitigation policies - Rules about power utilization - Rules about plastics production and recycling.

3.4.4 BIOLOGICAL UTILIZATION

Description. There are a number of pathways of biological utilization of CO_2, for example (Meylan, Piguet, and Erkman 2017):

- Carbon dioxide can be used to enrich the atmosphere of a greenhouse, for boosting plant growth.
- Carbon dioxide can be used to cultivate microalgae used for the production of biofuels. Microalgae have the ability to fix CO_2 directly from waste streams such as the flue gases of power plants and other industrial plants. Cultivation of microalgae can be carried out in open raceway ponds and photo-bioreactors (flat-plate, annular or tubular) (Cuéllar-Franca and Azapagic 2015). It has been reported that microalgae can accommodate wastewater: this avenue potentially reduces the consumption of fresh water and fertilizers and provides

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[22] *Green chemistry "is the design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances. Green chemistry applies across the life cycle of a chemical product, including its design, manufacture, use, and ultimate disposal. Green chemistry is also known as sustainable chemistry" (US EPA 2019).*

two environmental services (carbon fixation and wastewater treatment) (Meylan, Piguet, and Erkman 2017). In addition, biofuels are not the only possible final product: the biological utilization system could also use crude algal oil in the production of plastics, useful nutraceuticals can also be extracted and used in food supplements and the algal biomass which remains after extraction may then be used to make animal feed, fertiliser, biochar or to produce biogas by anaerobical digestion. The attractiveness of some of these pathways is that they will result in semi-permanent storage of carbon dioxide, while also having an indirect mitigation effect when displacing fossil fuel utilization (Global CCS Institute 2011).

- Finally, a few biochemical processes such as succinic acid production incorporate CO_2. Succinic acid has multiple practical applications. Bio-based succinic acid is a potential substitute for current industrial succinic acid which is produced from oil (Cheng et al. 2012).

Policy outline.

- *Policy actors*. Companies involved in the production or capture (by DAC or other means) of the CO_2-feedstock - Greenhouses owners, microalgae crops and succinic acid producers - Public authorities - NGOs (Non-governmental organizations) - Electric power utilities.
- *Legal issues and policy rules*. Upgrade of the legal status of CO_2 as a resource, in order eventually to develop a legal regime of resources - Some biological uses of CO_2 (not just some of those listed in this section but also biochar, ocean fertilization, etc.) involve carbon enrichment of soil and water and as such could be interested by the norms of the Environmental Protection Act (EPA) concerning waste deposit or soil pollution (cf. art. 30 ff. *EPA* 1983) - Policy goals and rules for CCU - Economic and fiscal incentives for CCU - CO_2 reduction goals coming from climate change mitigation policies - Rules about power utilization.

3.5 CONCLUSIVE REMARKS

The description of the main CCUS processes conducted in this chapter has clearly shown the richness of these opportunities to tackle anthropogenic climate change. While some of these options are still to be tested on a large scale, others are already commercially viable and a few (most notably, geological storage and EOR) have even been in operation since a few decades.

4 THE TECHNICAL POTENTIAL OF CCUS IN SWITZERLAND

In this chapter we investigate the role that CCUS facilities could play given the opportunities and the possible drawbacks present in Switzerland for CCUS development for what concerns industrial production, power generation, geological conditions of the deep underground, and other technical aspects that can affect capture, storage and valorization of CO_2. In the first section, we compare the current state of electricity production in Switzerland with the forecasted future generation as a consequence of the Swiss Energy Strategy, in order to investigate possible opportunities for CCUS in this area. In the second section, we break down the carbon dioxide emissions in Switzerland by economic sector, in order to identify the most promising sectors for CO_2 capture. Finally, in the last two sections, we investigate the opportunities for CO_2 storage and for CO_2 utilization, respectively, which can be found in the current industrial situation.

4.1 CURRENT AND FUTURE ENERGY LANDSCAPE

According to 2014 data, in Switzerland electricity generation is based on hydropower (54%) and nuclear power (39%), with a very little share of fossil fuel power[23] (Redondo and Vliet 2015), therefore in the Swiss electricity system the opportunity for the application of CCUS technologies is smaller than in other countries with a larger share of fossil fuel power.

However, this situation is going to change drastically in the near future. The *Energy Act* 2016, also known as the "Energy Strategy 2050", outlines the future of the energy system in Switzerland at the horizon 2050. It promotes three strategic objectives: the development of renewable energies (such as hydropower, wind, solar, and biomass), the increase of

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[23] Fossil electricity sources include: combined cycle gas turbine (CCGT), combined heat and power (CHP), open cycle gas turbine (steam turbine, combustion turbine).

energy efficiency and the exit from nuclear energy through the refusal to grant new general licenses for the construction of nuclear reactors and a step-by-step withdrawal of the existing nuclear plants (with safety as the sole criterion). Concerning the first objective, intermediate goals of 4400 GWh of renewable energy production (excluding hydroelectric power) by 2020 and 11400 GWh at least by 2035 are required, whereas the average energy consumption per person and per year is set to decrease by 16% up to 2020 and by 43% up to 2035. According to a recent assessment by the Swiss Federal Office of Energy (SFOE), the first goal is within reach whereas the second one has even been surpassed (SFOE 2020).

Unfortunately, the Energy Act merely provides the absolute figures for the renewable energy production targets and not the percentages of the forecasted generation of renewable energy compared to the total energy production. However, a 2015 academic paper has analyzed the feasibility of future electricity scenarios drawn in the Swiss Energy Strategy 2050. The conclusions are harsh: in the words of the authors, in the electricity sector "results show that it will be impossible to cover future demand only with domestic production, even if Switzerland reduces the consumption as envisaged. The daily profile of solar and limited capacity of wind lead to scenarios with maximum generation during peak hours. Moreover, we find a need to rearrange generation by flexible technologies to cover future demand"[24] (Redondo and Vliet 2015). As it is showed in Fig. 4.1, this is primarily a consequence of the decision of the Federal Council to phase out nuclear power, an important baseload technology, which by 2035 will lead to a large deficit in national power generation. According to the model used in the research, in fact, 30% of the power will need to be imported from abroad in 2035, whereas currently Switzerland enjoys on average a net balance between imports and exports of electricity,

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[24] *However, it is worth noticing that this paper does not consider battery storage as an option to store surpluses of electricity generated during peak hours by technologies such as solar, which could provide some additional flexibility to cover the high levels of imports needed during the night and during winter, when renewable energy generation is at its lowest (Redondo and Vliet 2015).*

although with some seasonal variability and important annual fluctuations.

Technologies	2014	2035	2050
Nuclear	0.39	0.00	0.00
Hydro	0.54	0.79	0.67
Fossil	0.06	0.08	0.06
Solar	0.01	0.09	0.19
Wind	0.00	0.04	0.07
Total generated	1.00	0.70	0.85

Figure 4.1: Share of the different sources of electricity production in Switzerland in the 2035 and 2050 Energy Strategy scenarios, in reference to 2014.
In 2014 Switzerland generated about 4,000 GWh more than consumed: this allowed the country to cover all the demand with almost no imports of electricity except in the winter months. By 2035 instead, 30% of the electricity consumed will need to be imported, since the large share of nuclear power (39% in 2014) is destined to disappear and the growth in hydropower generation (from 54% in 2014 to 79% in 2035), in solar power generation (from 1% to 9%) and in wind power generation (up to 4% in 2035) are not enough to compensate for it, despite the planned reduction in energy consumption. Source: Redondo and Vliet 2015.

4.2 BREAKDOWN OF CO_2 EMISSIONS IN SWITZERLAND: THE OPPORTUNITIES FOR CARBON CAPTURE

Apart from the Energy Act, the other centerpiece of the Swiss legislation which can play an important role in promoting CCUS development is the *CO_2 Act* 2011, which constitutes a revision of the original 1999 CO_2 Act and whose provisions were then further detailed in the *CO_2 Ordinance* 2012. The Act is being revised once more by the Federal Assembly at the time of the writing of this work. A more comprehensive discussion on the content of this legislation will be given in volume 2, chapter 5 of this work. For the purpose of the present volume, we expose here only the fundamental points of the CO_2 Act, as of 2019:

- a CO_2 levy on GHG emissions for heating, industrial process, and transportation fuels;
- a system of trade of emission allowances, which are tradable rights to emit GHGs allocated or recognized by the Confederation;
- the obligation to partially compensate GHG emissions from motor fuels;
- the reduction of CO_2 emissions from new passenger cars;
- the reduction obligation, i.e. the possibility to refund the CO_2 levy to companies which are officially committed to reduce GHG emissions by a specific amount by the year 2020;
- the obligation for fossil-fuel thermal power plants and for motor fuels producers to compensate (in full or partially) for the emissions caused.

This Act governs the climate policy of the Confederation and is the main instrument to reduce GHG emissions over time. In this section, we are going to unravel the amount of such emissions in Switzerland, particularly by economic sector.

In 2016, Switzerland emitted 39.2 millions tons of CO_2 overall, as can be seen from Fig. 4.3. This is slightly more than 38.8 millions tons of CO_2 in 2015 (FOEN 2017). A large part of these 39.2 millions tons are concerned by either the CO_2 levy or by the obligation to (partially) compensate the emissions outlined in the CO_2 Act, as it is illustrated in Fig. 4.2.

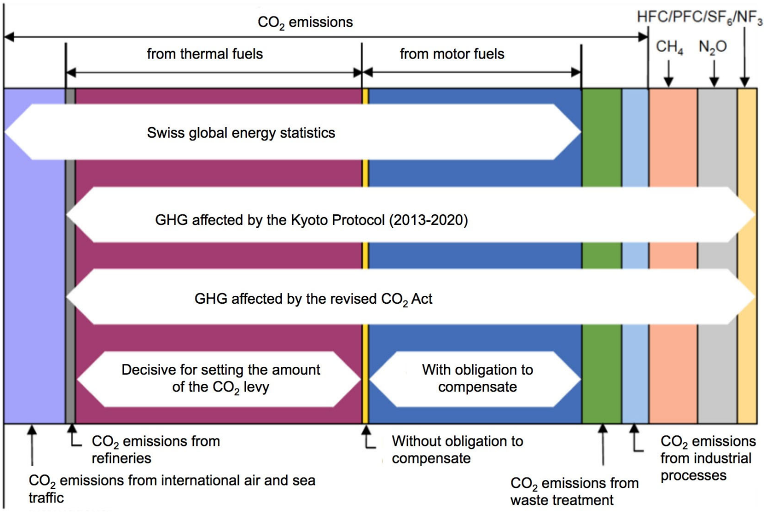
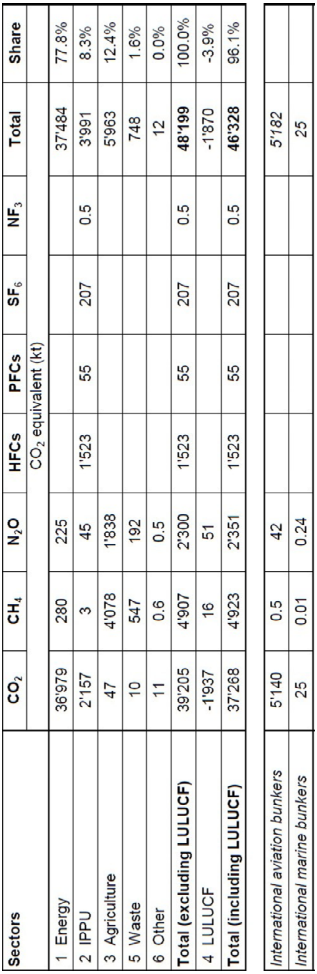


Figure 4.2: Schematic representation of the main relationships between the global energy statistics and the GHG emissions covered by the Kyoto Protocol (2nd commitment period) and the revised CO_2 Act in Switzerland.
CO_2 emissions related to thermal fuels, which are decisive for setting the amount of the CO_2 levy, are corrected for climatic variations exclusively for this purpose. CO_2 emissions related to motor fuels, instead, are not subject to the CO_2 levy but have to be partially compensated, according to art. 26 of the *CO_2 Act* 2011. CO_2 emissions from potential future gas-fired combined-cycle power plants will be taken into account neither for the setting of the amount of the CO_2 levy, nor for the objectives under the revised CO_2 Act, but they will have to be fully offset (cf. art. 22 ff. of the *CO_2 Act* 2011). The emissions from these plants (and the corresponding compensation) must nevertheless be taken into account under the UNFCCC. It should be noted that the GHG balance of the forests is not represented. Source: adapted from FOEN 2016.



Sectors	CO_2	CH_4	N_2O	HFCs	PFCs	SF_6	NF_3	Total	Share
				CO_2 equivalent (kt)					
1 Energy	36'979	280	225					37'484	77.8%
2 IPPU	2'157	3	45	1'523	55	207	0.5	3'991	8.3%
3 Agriculture	47	4'078	1'838					5'963	12.4%
5 Waste	10	547	192					748	1.6%
6 Other	11	0.6	0.5					12	0.0%
Total (excluding LULUCF)	39'205	4'907	2'300	1'523	55	207	0.5	**48'199**	100.0%
4 LULUCF	-1'937	16	51					-1'870	-3.9%
Total (including LULUCF)	37'268	4'923	2'351	1'523	55	207	0.5	**46'328**	96.1%
International aviation bunkers	5'140	0.5	42					5'182	
International marine bunkers	25	0.01	0.24					25	

Figure 4.3: GHG emissions by sector and gas in Switzerland in 2016.
IPPU stands for 'Ìndustrial Processes and Product Use' and LULUCF stands for 'Land use, land-use change and forestry'. A more detailed and explanatory breakdown of the CO_2 emissions is provided in appendix C. Source: FOEN 2018b.

Fig. 4.3 shows the emissions of all greenhouse gases (GHGs) in 2016 for each category and (in the last column) the relative shares of the different categories. Furthermore, emission data on international aviation and marine bunkers are provided. One can see that CO_2 is the main contributor to total GHG emissions followed by CH_4, N_2O and F-gases. The Energy category is the main source concerning climate-related emissions followed by Agriculture, IPPU (Ìndustrial Processes and Product Use) and Waste. In contrast, the LULUCF (land use, land-use change and forestry) category is a net sink regarding GHG emissions, since it absorbs more GHGs from the atmosphere than it emits. A more articulated breakdown of the CO_2 emissions is provided in appendix C.

Breaking down the Swiss CO_2 emissions by category allows to single out the most convenient sources of emissions to target for potential future CCUS applications. The *energy* category is by far the most significant source of CO_2 emissions in Switzerland and section C.2, where this category is broken down into smaller sectors, allows us to rank these sectors according to their share of emissions[25]:

1. The road transportation sector accounts for 33.22% of emissions and is therefore the main source of emissions in the energy category. However, this sector is made up of small mobile sources, which prevents CO_2 capture with current techniques. The solution will probably lie in the electrification of the vehicles fleet, according to the most recent trends and policies in this domain[26].
2. The second most relevant sector is the residential sector (19.79% of total gross CO_2 emissions), that is, the emissions from fuel combustion in households. Decarbonization will therefore be achieved by improving energy efficiency and by switching to alternative, low-carbon or neutral heat sources (heat pumps, pellets, geothermal heating, remote heating from renewable sources or waste, biogas). One

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[25] *The detailed descriptions of the various kinds of emission sources in the energy sector can be found in section* C.2.1.

[26] *However, it is worth noticing that there is some ongoing research about capturing and storing CO_2 emitted by vehicles on board, cf. e.g. Sharma and Maréchal 2019.*

could then apply CCS or CCU technologies to some of these heat sources which are still CO_2-emitting, such as biogas.

3. Manufacturing industries and construction is the third sector for total amount of carbon dioxide emissions (11.14%). The reduction of these emissions can have an impact in certain cases where the sources are large (at least a few tens of thousands of tonnes of CO_2 per year). It will also include process improvement and energy efficiency measures. However, the capture of CO_2 can also definitely play a role in the decarbonization of such large point sources.

4. The fourth most relevant sector is the commercial/institutional sector (9.64% of total gross CO_2 emissions), that is, the emissions from fuel combustion in commercial/institutional buildings. Decarbonization will therefore be achieved in the same way as in the residential sector seen above.

5. Public electricity and heat production accounts for 6.74% of total gross CO_2 emissions. Although far smaller than in the majority of the other industrialized countries, this share is still relevant enough to be a possible target for CCUS applications, especially if new NGCC power plants will be needed in the near future to bridge the Swiss electricity system towards a fully renewable one while at the same time still decreasing the GHG emissions.

6. Cement production represents 4% of total gross CO_2 emissions and therefore it could be a sector where CCUS application makes sense.

7. Finally, petroleum refining, incineration and open burning of waste represent in Switzerland only a very small fraction (0.81% and 0.02%, respectively) of the total gross CO_2 emissions. However, some of the installations for these sectors such as the Crissier (NE) refinery (which supplies a quarter of the fuel requirements of Switzerland) or the Hagenholz (ZH) incineration plant are concentrated point sources which are important enough to be likely worth being retrofitted with CCS or CCU technologies.

In conclusion, the main candidates for CO_2 capture in Switzerland are:

- the industrial plants emitting large amounts of concentrated carbon dioxide in specific point sources;
- thermal power plants, included biomass power plants and waste-to-energy plants, as well as possible future gas-fired power stations;
- cement plants;
- petroleum refineries;
- waste incineration plants.

In addition, since concentrated point sources are less widespread in Switzerland compared to the majority of the other industrialized countries, direct air capture (DAC) is set to play a significant role in the Swiss strategy, also considering that Switzerland is already at the cutting edge of this technology, e.g. with a company like ClimeWorks.

4.3 THE OPPORTUNITIES FOR CO_2 STORAGE

The provision of the CO_2 Act requiring fossil-fuel thermal power plants to compensate (in full or partially) for the emissions caused (cf. section 4.2) could prove to be a gateway for CCUS in Switzerland in association with a possible future deployment of gas-fired power plants. In fact, in order to reduce the foreseeable future deficit in national electricity generation, as explained in section 4.1, it will be crucial to find alternative low-carbon electricity sources to transform the Swiss energy system in a more sustainable way. In this framework, natural gas combined cycle plants with CCS or CCU could potentially provide a large-scale source of low-carbon electricity. Therefore, if gas-fired power is chosen as a bridge to a fully renewable energy system of the future, CCUS technologies might be an interesting option to compensate for the additional GHG emissions coming from the natural gas power plants[27] .

In this regard, one of the advantages of CCS compared to CCU is that in CCS the CO_2 is permanently stored (assuming that leakages can be avoided or strongly limited), whereas many CCU applications release the CO_2 at the end of the life cycle of the product. Other than by possibly avoiding, or consistently reducing, GHG emissions at gas-fired power plants built to bridge the gap in national energy supply caused by the phase out of nuclear power plants, another relevant role that CCS could play in the perspective of the Swiss Energy Strategy concerns bioenergy. In fact, in the context of bioenergy with carbon capture and storage (BECCS, cf. section 3.1.3), CCS would allow to increase the sustainability of the bioenergy sector.

4.3.1 POSSIBILITY OF GEOLOGICAL STORAGE IN SWITZERLAND

Contrary to CCU, the potential role of CCS in Switzerland has been examined in recent times, albeit to a lesser extent than in the U. S. or in the EU.

While Switzerland has established itself as a global leader in various segments of the technological CCS value chain and has participated successfully in the marketplace, only recently the applicability of CCS in Switzerland was investigated. In 2010, a study by a group of geologists headed by Geological Institute of Bern University demonstrated that several saline aquifers in the Swiss Molasse Basin have a combined theoretical storage capacity of about 2680 million tons of CO_2 (Chevalier, Diamond, and Leu 2010, Leu and Siddiqi 2013): “considering that a 400 MW gas-fired power plant at full load produces about 1 million tons of CO_2 per year, such a capacity would be sufficient in principle to store the CO_2 produced by ten such power plants in the course of two to three

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[27] *These additional GHG emissions would be indeed considerable: up to seven natural gas combined cycle (NGCC) power plants will be needed in the next years in order to bridge the power gap at acceptable costs and a single 400 MW NGCC plant would emit about 1 Mt of CO_2 per year, corresponding to a 2.5% increase in Switzerland’s current total CO_2 emissions (SFOE 2013).*

hundred years" (SFOE 2013). The CARMA[28] research project (2009-2012) also presented a roadmap for a CCS pilot test with the objective to demonstrate that CO_2 can be permanently stored in a safe way in the Swiss subsurface. It also showed that gas-fired power plants can be built already today in a "capture-ready" configuration, i.e. in such a way that their extension to incorporate the CO_2 capture equipment is from a technical point of view straightforward (SFOE 2013).

4.4 THE OPPORTUNITIES FOR CO_2 UTILIZATION

As we said before, carbon dioxide valorization represents a whole set of new industrial processes which would contribute to a general shift towards a circular economy while at the same time increasing the number and reach of the instruments available for climate change mitigation purposes.

The current state of the Swiss manufacturing industry is summarized in Fig. 4.4, which shows that the mechanical engineering, electrical engineering and metalworking (MEM) industry represents the largest industrial sector in the Confederation, measured by gross value added, and it constitutes almost half of the Swissmanufacturing industry (Deloitte 2013). If we analyze this diagram in the light of the description of CCU processes contained in section 3.4, we can see that there is a number of CCU opportunities for some relevant industrial sectors.

For instance, a sector as important as construction could benefit from carbon mineralization processes (cf. section 3.4.2) in two manners. As we have already seen in section 4.2, cement production was the sector of industrial processes which accounted in 2016 for the largest percentage value (around 4.3%) of total CO_2 emissions in Switzerland. Thus, it represents an area where it is especially important to intervene in order to lower Swiss carbon emissions in a sizeable manner. This can be done not only by capturing the carbon dioxide emitted by a cement plant (cf.

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[28] *CARbon dioxide MAnagement in power generation. See https://www.psi.ch/eem/carma (visited the 26.11.2018).*

section 4.2), but also by substituting fossil resources with recycled CO_2 as a feedstock material.

In the sectors of plastics and chemicals, synthesis of polycarbonates from captured carbon dioxide (cf. section 3.4.3) is another promising road to produce commodity plastics, synthetic fabrics, rubbers, etc., while at the same time reducing the utilization of petroleum-based feedstock for their fabrication. Another CCU application, formic acid synthesis from captured carbon dioxide (cf. Table 1), could become relevant for various industries such as chemical, food products, textile, and others.

Some CO_2 utilization processes can also play a role in regards to the Energy Strategy landscape depicted in section 4.1. The most important of such processes are:

- power-to-gas, or power-to-fuel (cf. section 3.4.1), which is a mechanism allowing to use water, carbon dioxide and intermittent renewable electricity that cannot be fed into the grid (and therefore would normally be curtailed) to produce synthetic natural gas (SNG), through a chemical reaction called “methanation”. SNG is a mixture of methane, hydrogen and carbon dioxide. From a chemical point of view, this mixture has a strong resemblance to natural gas and it can therefore be distributed using the existing pipeline infrastructure. It is perfectly suited to heat homes or as fuel in cars (with a NG-adapted combustion engine), just like conventional natural gas. Power-to-gas is therefore a technology which is particularly interesting in a situation with a large penetration of renewables in the energy mix. In fact, not only it allows to reduce the curtailment from intermittent energy sources but also it creates a valid substitute of natural gas in the process. Moreover, the final product can be stored efficiently in enormous amounts, in contrast with the storage of electricity which requires batteries;

- cultivation of microalgae for the production of biofuel (cf. section 3.4.4), which allows to produce a substitute for fossil fuels.

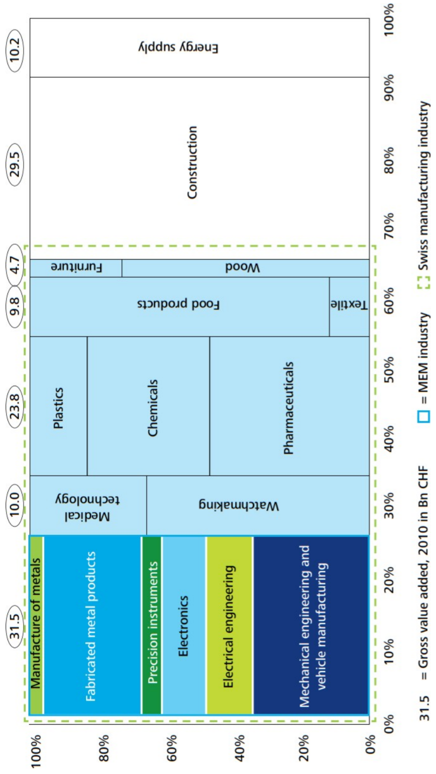

Figure 4.4: Breakdown of the Swiss industrial sector by gross value added for the year 2010.
MEM stands for "mechanical engineering, electrical engineering and metalworking industry" and represents the largest manufacturing sector. Source: Deloitte 2013.

Ultimately, the development of CCU constitutes a great occasion to promote a greater symbiosis between CO_2-emitting and CO_2-consuming industrial facilities as an additional step towards a circular economy, although the establishment of clusters of industries with such synergies currently seems to be much easier to obtain in developing countries in Africa or Asia, where new industries can be installed from scratch following the principles of a recycling economy (including carbon dioxide), than in a country like Switzerland where the industrialization process has already happened. The creation of such integrated clusters is therefore to be intended as a long-term target in the case of Switzerland.

4.5 CONCLUSIVE REMARKS

Our analysis shows that both CCS and CCU seem to have an untapped technical potential for development in Switzerland, at least on a theoretical level. This potential could be exploited on both an environmental and an economic ground, especially for what concerns CCU. In fact, it would provide additional technological instruments in fundamental parts which constitute CCUS (cf. also chapter 3). We have therefore broken down the carbon dioxide emissions by economic sector, in order to identify the most emitting ones and thereby the most favorable ones for CO_2 capture: i.e., large industrial power plants, cement plants, petroleum refineries, and waste incinerators. Fossil power plants could become a relevant option for CO_2 capture in case they were needed to fill in the gap in power generation caused by the foreseeable shutdown of the existing nuclear power plants, in connection with the Energy Act. We have then summarized the opportunities which exist in Switzerland for CO_2 storage, with particular emphasis on the theoretical geological potential for carbon dioxide sequestration in deep saline aquifers, estimated in Chevalier, Diamond, and Leu 2010 and in Leu and Siddiqi 2013 to be of about 2680 million tons of CO_2. Finally, we have identified the main manufacturing sectors which could benefit the most from the introduction of carbon valorization applications: construction industry in association with carbon mineralization, plastics and chemical industry in association with the synthesis of polymers, and the energy supply industry in association with power-to-fuel processes and cultivation of microalgae.

While a more comprehensive quantification of the technical potential for CCUS is beyond the scope of this chapter, we believe that our analysis offers nevertheless a compelling argument for the advantages of introducing and developing CCUS facilities in Switzerland.

CONCLUSIONS

The work conducted in this volume has mainly consisted in a broad review of the specialized literature on the natural science aspects and on the technical aspects of CCUS processes. This has included:

- the physical and chemical processes at the basis of the global carbon cycle and anthropogenic climate change (in chapter 1);
- a description of impacts of a possible large-scale development of CCUS on the global carbon cycle (in chapter 2);
- an outline of the main CCUS technologies (in chapter 3);
- a description of the technical potential offered in Switzerland either by the geological conditions of the deep underground (for what concerns CCS) or by the current state of the manufacturing industry (in chapter 4).

This volume does not contain a fully detailed evaluation of the possible CCUS scenarios in Switzerland from a quantitative perspective, since it would have required thorough analysis of a vast number of chemical engineering processes as well as inquiries on the complex economic issues underlying CCUS development. However, our study clearly shows that these technologies have an important role to play in the domain of climate change mitigation. For instance, while total CO_2 emissions in Switzerland in 2016 amounted to 39.2 millions tons, we have seen that geological storage capacity in the Swiss Molasse Basin has been estimated to be about 2680 million tons of CO_2, cf. section 4.3.1. Although this is just an approximate theoretical estimation, possibly subject to additional limitations such as economic constraints or subsequent, less favorable geological investigations, it is still significant that this potential is two orders of magnitude bigger than the total yearly carbon dioxide emissions in Switzerland.

As we have seen in chapter 4, the electricity sector in Switzerland is already largely defossilized. Instead, the two main sources of emissions are industry and transportation, which are more difficult to defossilize than the power sector. Hence, it is precisely in these sectors that the greatest opportunities for CCUS development are concentrated. In particular, as seen in section 3.4, there is a number of CCU processes that can be applied to industrial plants in order either to recycle their carbon dioxide emissions, or to use recycled CO_2 to manufacture their products, or both. Life-cycle transportation emissions could also be reduced by CCUS as in biofuels from BECCS, power-to-fuel technologies, etc.

This volume, with its depiction of the foundations of CCUS and the context within which CCUS is slated to develop, constitutes a groundwork for a full comprehension of the analysis of the institutional and legal framework of CCUS which takes place in Volume 2.

ACKNOWLEDGMENTS

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APPENDICES

A1 TECHNICAL DEFINITIONS AND ACRONYMS

Atmospheric CO_2 adjustment (or equilibration) time. By adding a certain amount of anthropogenic CO_2 to the atmosphere at a certain time, the concentration of CO_2 will increase suddenly and then fall off following a complicated function that depends on the response of the various active carbon reservoirs (surface ocean, intermediate and deep ocean, marine sediments, terrestrial biosphere). The time connected to such a relaxation in atmospheric CO_2 concentration is the adjustment (or equilibration) time (Köhler et al. 2018).

Atmospheric CO_2 residence time. The residence time of carbon dioxide in the atmosphere is the average length of time for which an individual molecule of CO_2 remains in the atmosphere before being taken up by the ocean or terrestrial biosphere (Köhler et al. 2018). The actual value of this residence time is still debated in the scientific community: however, according to the mainstream view backed by the IPCC reports the residence time of carbon dioxide in the atmosphere is currently estimated to be around 100-150 years (IPCC 2007).

Bioenergy with Carbon Capture and Storage (BECCS). BECCS is identical to CCS, except that the CO_2 is released from biomass.

Carbon Capture and Storage (CCS). CCS consists in capturing, transporting, and finally injecting the CO_2 emitted by large emission sources (e.g. power plant, cement plant, incinerator) in suited geological formation.

Carbon Capture and Utilization (CCU). CCU considers CO_2 as a resource, which can be transformed to create marketable products (e.g. fuels, polymers), or directly used (e.g. fire extinguisher). By extension, the terms BECCU (Bioenergy with Carbon Capture and Utilization) and DACU (Direct Air Capture and Utilization) can also be used.

Carbon Capture, Utilization and Storage (CCUS). CCUS is a term which includes both CCS and CCU processes.

Carbon dioxide equivalent (CO_2-eq). A carbon dioxide equivalent, or CO_2 equivalent (abbreviated as CO_2-eq), is a widely used metric measure to report the emissions of various GHGs on the basis of their GWP. Any amount of a given GHG can be expressed in CO_2-eq, to represent the amount of CO_2 which would warm the Earth as much as that amount of that gas. Carbon dioxide equivalents are usually expressed as metric tonnes of CO_2-eq. The carbon dioxide equivalent of any amount of a given GHG can be found by multiplying the tonnes of the gas by the associated GWP.

Carbon footprint. The carbon footprint is an environmental indicator of the contribution to anthropogenic climate change of a process, product, activity or population. As such, it is difficult to be exactly calculated, especially because of our incomplete knowledge of necessary data and the complexity of interactions between the various contributing processes. For this reason, L. Wright, S. Kemp and I. Williams have proposed to define it as “a measure of the total amount of CO_2 and CH_4 emissions of a defined population, system or activity, considering all relevant sources, sinks and storage within the spatial and temporal boundary of the population, system or activity of interest. Calculated as CO_2-eq using the relevant 100-year global warming potential (GWP100)” (Wright, Kemp, and Williams 2011). In fact, CO_2 and CH_4 are the most important GHGs and the data regarding these emissions are usually available or can be easily gathered, whereas accurate data on the emissions of other GHGs are more difficult to find.

Carbon neutrality. Carbon neutrality, or having a net zero carbon footprint, refers to achieving net zero carbon dioxide emissions by compensating carbon emissions with carbon removal (often through carbon offsetting), or simply eliminating carbon emissions altogether.

Carbon offset. Carbon offset refers to reduction in emissions of carbon dioxide or other greenhouse gases made in order to compensate for emissions made elsewhere. Carbon offsets are measured in tonnes of carbon dioxide-equivalent (CO_2-eq). One tonne of carbon offset represents the reduction of one tonne of carbon dioxide or its equivalent in other greenhouse gases.

Direct Air Capture (DAC). DAC aims at extracting CO_2 from ambient air through physico-chemical methods.

DACCS. Direct Air Carbon Capture and Storage.

DACCU. Direct Air Carbon Capture and Utilization.

GHG(s). Greenhouse gas(es).

Global Warming Potential (GWP). The global warming potential of a certain GHG is a measure of its impact on global warming in the atmosphere. It represents the heat absorbed by 1 ton of a given GHG in the atmosphere, with respect to the heat absorbed by 1 ton of atmospheric CO_2 over the same period of time. For example, methane has been estimated to have a GWP of 28-36 over a 100-year period, i.e. a GWP which is approximately 32 times higher than the GWP of carbon dioxide.

Negative Emissions Technologies (NETs). The term "negative emissions technologies" denotes a range of techniques for removing carbon dioxide from the atmosphere, thereby repaying the world's carbon debt—with interest. These technologies are also called Carbon Dioxide Removal (CDR) technologies. According to the IPCC, the world would need to rely significantly on these techniques to avoid increasing Earth's temperatures above 1.5 degrees Celsius, or 2.7 degrees Fahrenheit, compared to pre-industrial levels (IPCC 2018). The portfolio of NETs includes afforestation and reforestation, BECCS, DAC, soil carbon, biochar, enhanced weathering (Minx et al. 2018).

Reservoirs, sources and sinks. According to the IPCC guidelines (IPCC 2008), we consider that a reservoir is a "system which has the capacity to accumulate or release carbon". A reservoir becomes a source when more carbon is released than accumulated. Inversely, a reservoir is considered a sink when the amount of immobilized carbon increases.

A2 UNITED STATES GOVERNMENT: AGENCIES AND DEPARTMENTS

US EPA. United States Environmental Protection Agency.

US DoE. United States Department of Energy.

A3 SWISS GOVERNMENT: OFFICES AND DEPARTMENTS

DETEC. Federal Department of the Environment, Transport, Energy and Communication.

FOEN. Federal Office for the Environment. It is the Swiss federal government’s centre of environmental expertise and is currently part of the DETEC.

SFOE. Swiss Federal Office of Energy. It is the country’s competence centre for issues relating to energy supply and energy use at the DETEC.

B GAS CONCENTRATION UNITS

There are a number of ways to define the concentration of a gas in a mixture. These are typically given either in terms of partial pressure, or in terms of the ratios of the number of particles or number of moles like mole fraction or mole percent. For very small concentrations, we tend to use measures like parts-per-million (ppm) or parts-per-billion (ppb) (Henrickson 2005).

- The partial pressure of a constituent gas in a mixture of gases is the notional pressure of that constituent gas if it alone occupied the entire volume of the original mixture at the same temperature. The total pressure of an ideal gas mixture is the sum of the partial pressures of the gases in the mixture.

- The mole fraction, or molar fraction, is defined as the amount of a constituent (expressed in moles), n_i, divided by the total amount of all constituents in a mixture (also expressed in moles), n_{tot}:

$$x_i = \frac{n_i}{n_{tot}}$$

The sum of all the mole fractions is equal to 1:

$$\sum_{i=1}^{N} n_i = n_{tot}; \sum_{i=1}^{N} x_i = 1$$

- Multiplying mole fraction by 100 gives the mole percent or molar percentage or molar proportion (mol%).

- Parts-per-million (abbreviated ppm) or parts-per-billion (ppb) is the ratio of the number of molecules of a constituent gas to the mixture of gases. For example, 1,000 ppm of CO_2 means that if one could count a million gas molecules in the mixture of gases considered, 1,000 of them would be of carbon dioxide and 999,000 molecules would be some other gases.

- When one starts counting over 10,000 ppm, most scientists typically change from ppm to percent concentration. So instead of describing, for example, a 10,000 ppm CO_2 sensor, one talks about a 1% CO_2 sensor. Namely, $10{,}000 \text{ ppm} = \frac{10{,}000}{1{,}000{,}000} = 0.01 = 1\%$ gas.

C CO$_2$ EMISSIONS IN SWITZERLAND

In this appendix, we present an exhaustive inventory of the CO$_2$ emissions in Switzerland in the year 2016, built upon the official data disclosed in the Switzerland's National Greenhouse Gas Inventory Report, an official report of the Climate Division of the Federal Office for the Environment (FOEN). This report has been submitted every year since 2004 under the UNFCCC; it was implemented as a consequence of the ratification by the Swiss Confederation of the Kyoto Protocol and it is currently based on the 2006 IPCC Guidelines (IPCC 2006). The 2018 inventory submission under the UNFCCC and under the Kyoto Protocol, which shows emissions data up to the year 2016 and on which we rely for the data presented here, includes the National Inventory Report (FOEN 2018b), the greenhouse gas inventory 1990–2016 including also the Kyoto Protocol LULUCF[29] tables 2008–2016 in the Common Reporting Format (FOEN 2018a).

In section C.1 we present the total amount of carbon dioxide emissions in 2016, divided by category and subcategory. We report both the total gross carbon dioxide emissions (excluded LULUCF data) and the total net carbon dioxide emissions (that is, included LULUCF sinks and sources). Data on international bunkers[30] are reported separately from the other sectors and activities since, according to the IPCC guidelines, they are not normally included in the national total emissions from the energy sector. Amounts of biomass used as fuel are included in the national energy consumption but the corresponding CO$_2$ emissions are not included in the national total as it is assumed that the biomass is produced in a sustainable manner. If the biomass is harvested at an unsustainable rate, net CO$_2$ emissions are accounted for as a loss of biomass stocks in the LULUCF sector.

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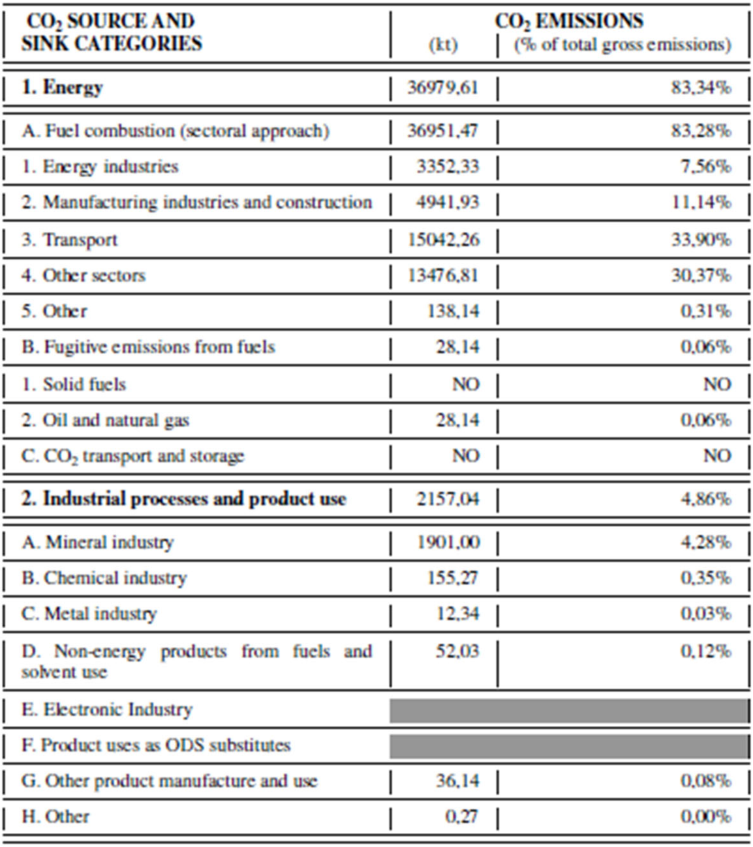
[29] *Land use, land-use change and forestry.*

[30] *In energy statistics, marine bunkers and aviation bunkers are the energy consumption of ships and aircraft.*

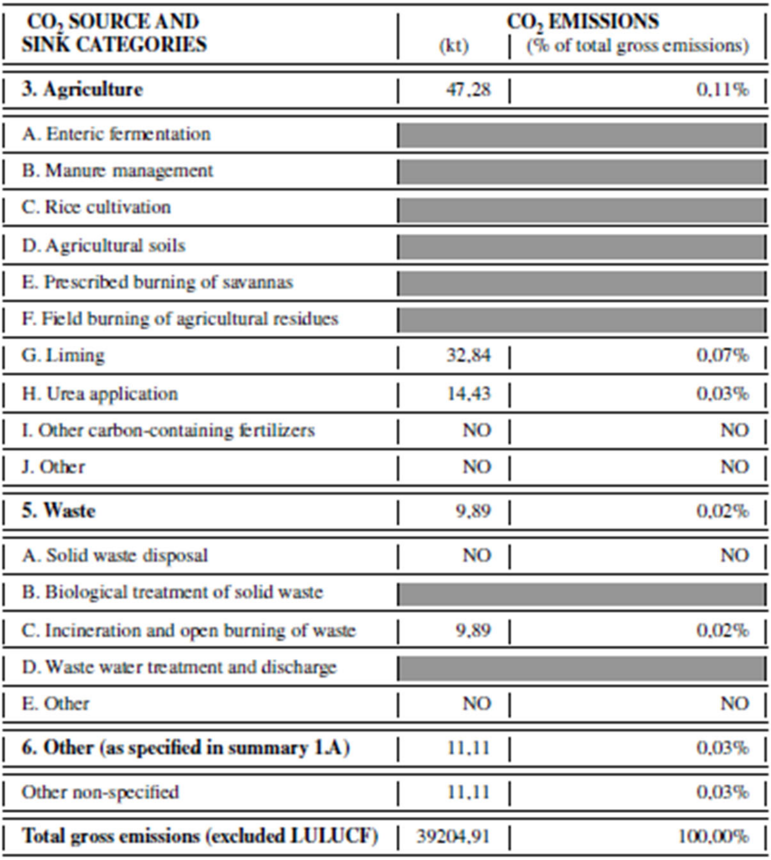
Finally, the tables in section C.2 and section C.3 articulate in more detail the carbon dioxide emissions in the Energy sector and in the Industrial Processes sector following the IPCC guidelines. The exact definitions of the subsectors which constitute the different emissions sector can be found in these guidelines (IPCC 2006).

C.1 CO_2 EMISSIONS IN SWITZERLAND IN 2016 BY SECTOR

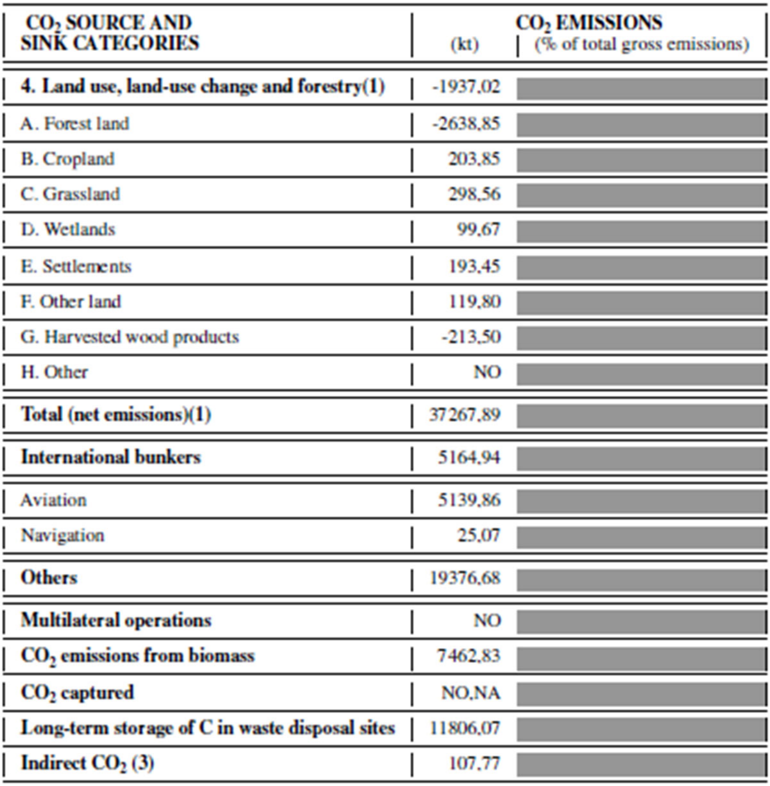


CO_2 SOURCE AND SINK CATEGORIES	CO_2 EMISSIONS (kt)	(% of total gross emissions)
1. Energy	36979,61	83,34%
A. Fuel combustion (sectoral approach)	36951,47	83,28%
1. Energy industries	3352,33	7,56%
2. Manufacturing industries and construction	4941,93	11,14%
3. Transport	15042,26	33,90%
4. Other sectors	13476,81	30,37%
5. Other	138,14	0,31%
B. Fugitive emissions from fuels	28,14	0,06%
1. Solid fuels	NO	NO
2. Oil and natural gas	28,14	0,06%
C. CO_2 transport and storage	NO	NO
2. Industrial processes and product use	2157,04	4,86%
A. Mineral industry	1901,00	4,28%
B. Chemical industry	155,27	0,35%
C. Metal industry	12,34	0,03%
D. Non-energy products from fuels and solvent use	52,03	0,12%
E. Electronic Industry	▨	▨
F. Product uses as ODS substitutes	▨	▨
G. Other product manufacture and use	36,14	0,08%
H. Other	0,27	0,00%

Table 2: Inventory of the CO_2 emissions in Switzerland for the year 2016.
Source: adapted from FOEN 2018a.

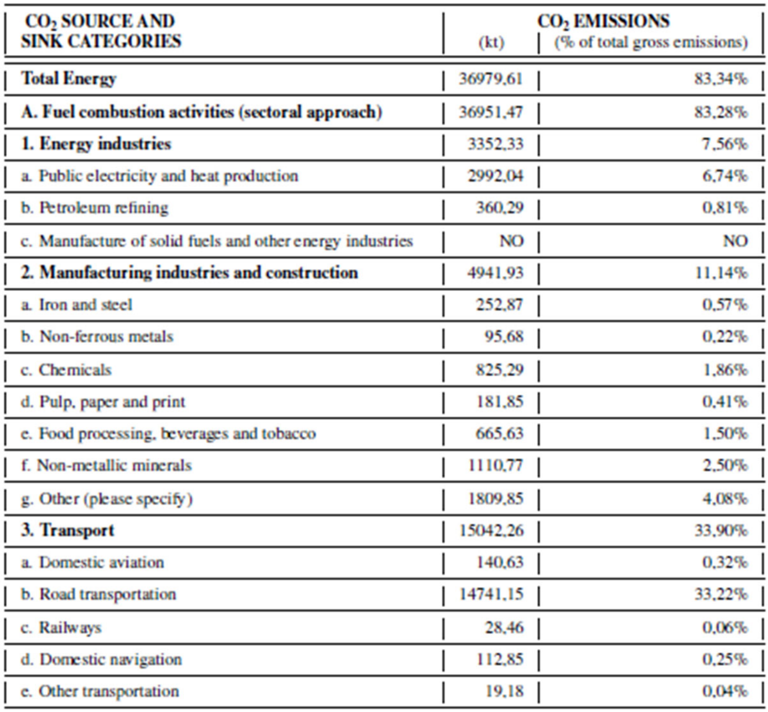


CO_2 SOURCE AND SINK CATEGORIES	CO_2 EMISSIONS (kt)	(% of total gross emissions)
3. Agriculture	47,28	0,11%
A. Enteric fermentation		
B. Manure management		
C. Rice cultivation		
D. Agricultural soils		
E. Prescribed burning of savannas		
F. Field burning of agricultural residues		
G. Liming	32,84	0,07%
H. Urea application	14,43	0,03%
I. Other carbon-containing fertilizers	NO	NO
J. Other	NO	NO
5. Waste	9,89	0,02%
A. Solid waste disposal	NO	NO
B. Biological treatment of solid waste		
C. Incineration and open burning of waste	9,89	0,02%
D. Waste water treatment and discharge		
E. Other	NO	NO
6. Other (as specified in summary 1.A)	11,11	0,03%
Other non-specified	11,11	0,03%
Total gross emissions (excluded LULUCF)	39204,91	100,00%



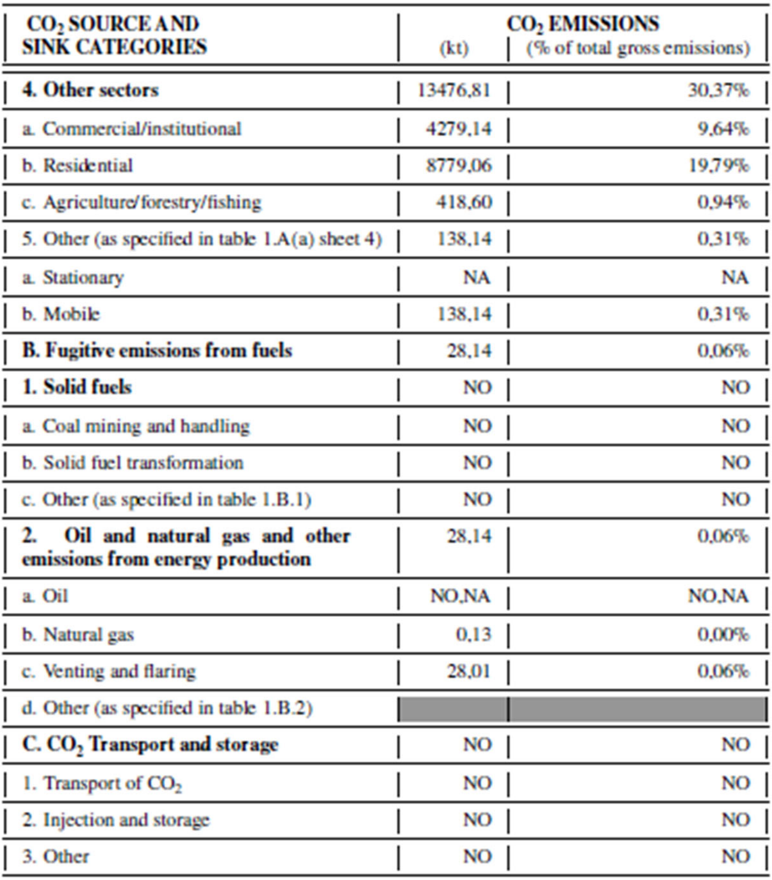
CO_2 SOURCE AND SINK CATEGORIES	CO_2 EMISSIONS	
	(kt)	(% of total gross emissions)
4. Land use, land-use change and forestry(1)	-1937,02	
A. Forest land	-2638,85	
B. Cropland	203,85	
C. Grassland	298,56	
D. Wetlands	99,67	
E. Settlements	193,45	
F. Other land	119,80	
G. Harvested wood products	-213,50	
H. Other	NO	
Total (net emissions)(1)	37267,89	
International bunkers	5164,94	
Aviation	5139,86	
Navigation	25,07	
Others	19376,68	
Multilateral operations	NO	
CO_2 emissions from biomass	7462,83	
CO_2 captured	NO,NA	
Long-term storage of C in waste disposal sites	11806,07	
Indirect CO_2 (3)	107,77	

C.2 CO_2 EMISSIONS IN SWITZERLAND IN 2016 – ENERGY SECTORIAL REPORT



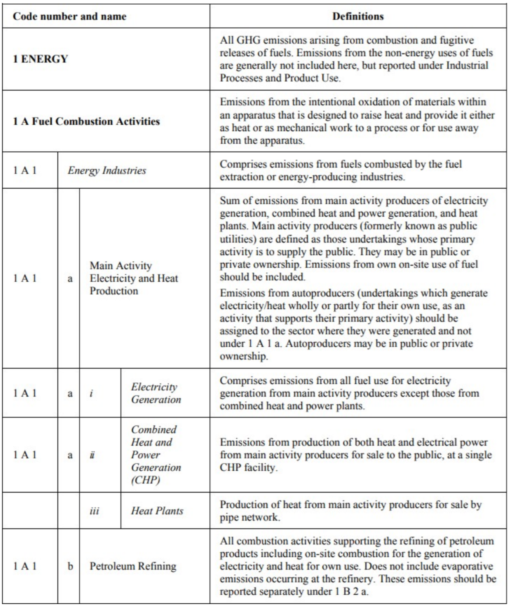
CO_2 SOURCE AND SINK CATEGORIES	CO_2 EMISSIONS (kt)	(% of total gross emissions)
Total Energy	36979,61	83,34%
A. Fuel combustion activities (sectoral approach)	36951,47	83,28%
1. Energy industries	3352,33	7,56%
a. Public electricity and heat production	2992,04	6,74%
b. Petroleum refining	360,29	0,81%
c. Manufacture of solid fuels and other energy industries	NO	NO
2. Manufacturing industries and construction	4941,93	11,14%
a. Iron and steel	252,87	0,57%
b. Non-ferrous metals	95,68	0,22%
c. Chemicals	825,29	1,86%
d. Pulp, paper and print	181,85	0,41%
e. Food processing, beverages and tobacco	665,63	1,50%
f. Non-metallic minerals	1110,77	2,50%
g. Other (please specify)	1809,85	4,08%
3. Transport	15042,26	33,90%
a. Domestic aviation	140,63	0,32%
b. Road transportation	14741,15	33,22%
c. Railways	28,46	0,06%
d. Domestic navigation	112,85	0,25%
e. Other transportation	19,18	0,04%

Table 3: Breakdown of the CO_2 emissions in Switzerland for the year 2016 in the energy sector.
Source: adapted from FOEN 2018a.



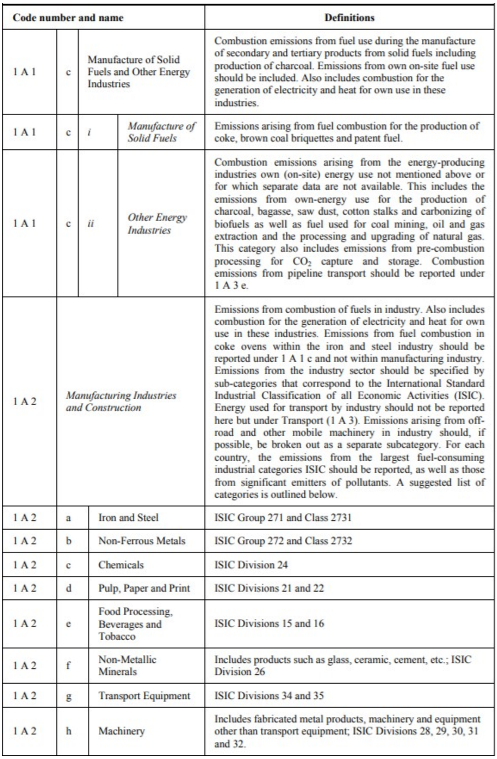
CO_2 SOURCE AND SINK CATEGORIES	CO_2 EMISSIONS (kt)	(% of total gross emissions)
4. Other sectors	13476,81	30,37%
a. Commercial/institutional	4279,14	9,64%
b. Residential	8779,06	19,79%
c. Agriculture/forestry/fishing	418,60	0,94%
5. Other (as specified in table 1.A(a) sheet 4)	138,14	0,31%
a. Stationary	NA	NA
b. Mobile	138,14	0,31%
B. Fugitive emissions from fuels	28,14	0,06%
1. Solid fuels	NO	NO
a. Coal mining and handling	NO	NO
b. Solid fuel transformation	NO	NO
c. Other (as specified in table 1.B.1)	NO	NO
2. Oil and natural gas and other emissions from energy production	28,14	0,06%
a. Oil	NO,NA	NO,NA
b. Natural gas	0,13	0,00%
c. Venting and flaring	28,01	0,06%
d. Other (as specified in table 1.B.2)	▨	▨
C. CO_2 Transport and storage	NO	NO
1. Transport of CO_2	NO	NO
2. Injection and storage	NO	NO
3. Other	NO	NO

C.2.1 DESCRIPTION OF SOURCES OF CO_2 EMISSIONS IN THE ENERGY SECTOR

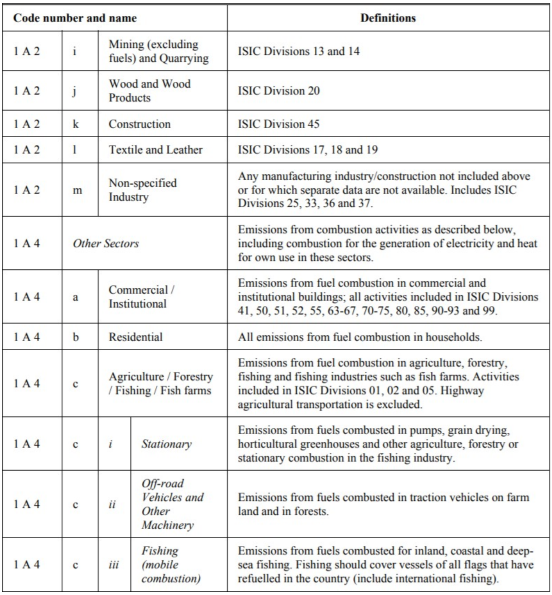


Code number and name				**Definitions**
1 ENERGY				All GHG emissions arising from combustion and fugitive releases of fuels. Emissions from the non-energy uses of fuels are generally not included here, but reported under Industrial Processes and Product Use.
1 A Fuel Combustion Activities				Emissions from the intentional oxidation of materials within an apparatus that is designed to raise heat and provide it either as heat or as mechanical work to a process or for use away from the apparatus.
1 A 1	*Energy Industries*			Comprises emissions from fuels combusted by the fuel extraction or energy-producing industries.
1 A 1	a	Main Activity Electricity and Heat Production		Sum of emissions from main activity producers of electricity generation, combined heat and power generation, and heat plants. Main activity producers (formerly known as public utilities) are defined as those undertakings whose primary activity is to supply the public. They may be in public or private ownership. Emissions from own on-site use of fuel should be included. Emissions from autoproducers (undertakings which generate electricity/heat wholly or partly for their own use, as an activity that supports their primary activity) should be assigned to the sector where they were generated and not under 1 A 1 a. Autoproducers may be in public or private ownership.
1 A 1	a	*i*	*Electricity Generation*	Comprises emissions from all fuel use for electricity generation from main activity producers except those from combined heat and power plants.
1 A 1	a	*ii*	*Combined Heat and Power Generation (CHP)*	Emissions from production of both heat and electrical power from main activity producers for sale to the public, at a single CHP facility.
		iii	*Heat Plants*	Production of heat from main activity producers for sale by pipe network.
1 A 1	b	Petroleum Refining		All combustion activities supporting the refining of petroleum products including on-site combustion for the generation of electricity and heat for own use. Does not include evaporative emissions occurring at the refinery. These emissions should be reported separately under 1 B 2 a.

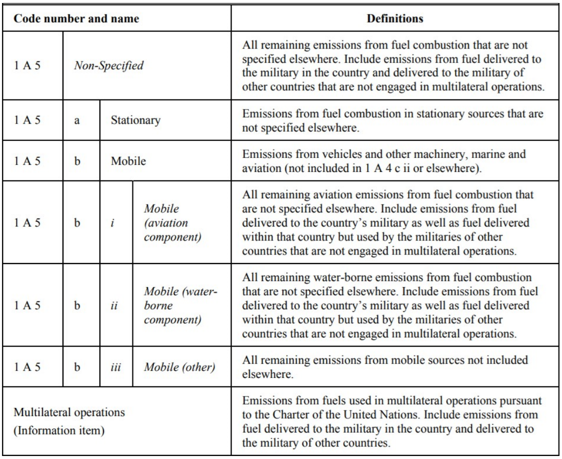
Table 4: In the sectoral approach, emissions from stationary combustion are specified for a number of societal and economic activities, defined within the IPCC sector 1A, Fuel Combustion Activities.
Source: IPCC 2006.



Code number and name				**Definitions**
1 A 1	c		Manufacture of Solid Fuels and Other Energy Industries	Combustion emissions from fuel use during the manufacture of secondary and tertiary products from solid fuels including production of charcoal. Emissions from own on-site fuel use should be included. Also includes combustion for the generation of electricity and heat for own use in these industries.
1 A 1	c	*i*	*Manufacture of Solid Fuels*	Emissions arising from fuel combustion for the production of coke, brown coal briquettes and patent fuel.
1 A 1	c	*ii*	*Other Energy Industries*	Combustion emissions arising from the energy-producing industries own (on-site) energy use not mentioned above or for which separate data are not available. This includes the emissions from own-energy use for the production of charcoal, bagasse, saw dust, cotton stalks and carbonizing of biofuels as well as fuel used for coal mining, oil and gas extraction and the processing and upgrading of natural gas. This category also includes emissions from pre-combustion processing for CO_2 capture and storage. Combustion emissions from pipeline transport should be reported under 1 A 3 e.
1 A 2			*Manufacturing Industries and Construction*	Emissions from combustion of fuels in industry. Also includes combustion for the generation of electricity and heat for own use in these industries. Emissions from fuel combustion in coke ovens within the iron and steel industry should be reported under 1 A 1 c and not within manufacturing industry. Emissions from the industry sector should be specified by sub-categories that correspond to the International Standard Industrial Classification of all Economic Activities (ISIC). Energy used for transport by industry should not be reported here but under Transport (1 A 3). Emissions arising from off-road and other mobile machinery in industry should, if possible, be broken out as a separate subcategory. For each country, the emissions from the largest fuel-consuming industrial categories ISIC should be reported, as well as those from significant emitters of pollutants. A suggested list of categories is outlined below.
1 A 2	a		Iron and Steel	ISIC Group 271 and Class 2731
1 A 2	b		Non-Ferrous Metals	ISIC Group 272 and Class 2732
1 A 2	c		Chemicals	ISIC Division 24
1 A 2	d		Pulp, Paper and Print	ISIC Divisions 21 and 22
1 A 2	e		Food Processing, Beverages and Tobacco	ISIC Divisions 15 and 16
1 A 2	f		Non-Metallic Minerals	Includes products such as glass, ceramic, cement, etc.; ISIC Division 26
1 A 2	g		Transport Equipment	ISIC Divisions 34 and 35
1 A 2	h		Machinery	Includes fabricated metal products, machinery and equipment other than transport equipment; ISIC Divisions 28, 29, 30, 31 and 32.

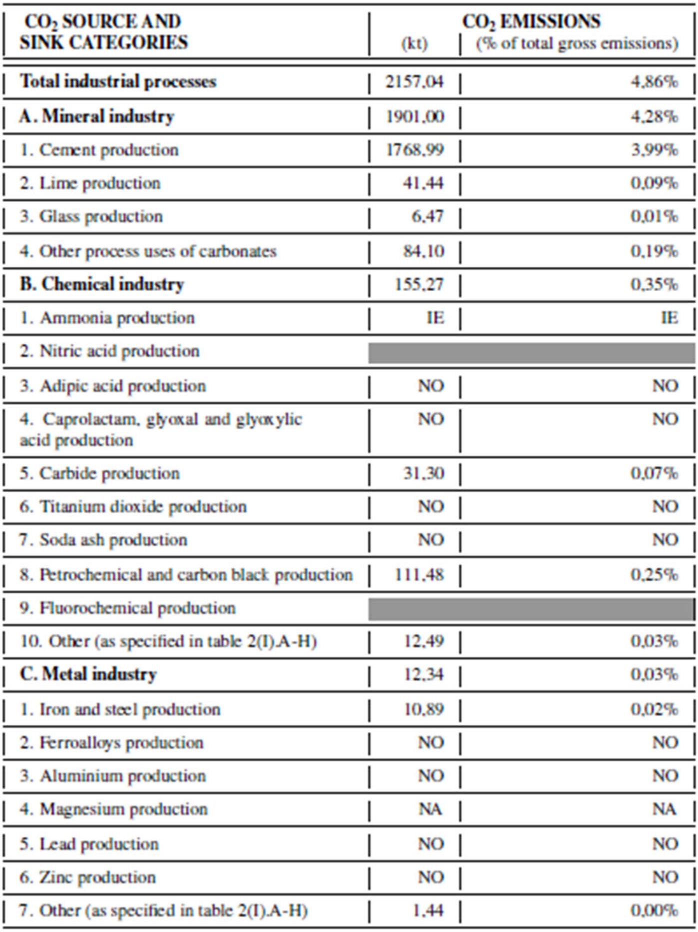


Code number and name				Definitions
1 A 2	i	Mining (excluding fuels) and Quarrying		ISIC Divisions 13 and 14
1 A 2	j	Wood and Wood Products		ISIC Division 20
1 A 2	k	Construction		ISIC Division 45
1 A 2	l	Textile and Leather		ISIC Divisions 17, 18 and 19
1 A 2	m	Non-specified Industry		Any manufacturing industry/construction not included above or for which separate data are not available. Includes ISIC Divisions 25, 33, 36 and 37.
1 A 4	*Other Sectors*			Emissions from combustion activities as described below, including combustion for the generation of electricity and heat for own use in these sectors.
1 A 4	a	Commercial / Institutional		Emissions from fuel combustion in commercial and institutional buildings; all activities included in ISIC Divisions 41, 50, 51, 52, 55, 63-67, 70-75, 80, 85, 90-93 and 99.
1 A 4	b	Residential		All emissions from fuel combustion in households.
1 A 4	c	Agriculture / Forestry / Fishing / Fish farms		Emissions from fuel combustion in agriculture, forestry, fishing and fishing industries such as fish farms. Activities included in ISIC Divisions 01, 02 and 05. Highway agricultural transportation is excluded.
1 A 4	c	*i*	*Stationary*	Emissions from fuels combusted in pumps, grain drying, horticultural greenhouses and other agriculture, forestry or stationary combustion in the fishing industry.
1 A 4	c	*ii*	*Off-road Vehicles and Other Machinery*	Emissions from fuels combusted in traction vehicles on farm land and in forests.
1 A 4	c	*iii*	*Fishing (mobile combustion)*	Emissions from fuels combusted for inland, coastal and deep-sea fishing. Fishing should cover vessels of all flags that have refuelled in the country (include international fishing).



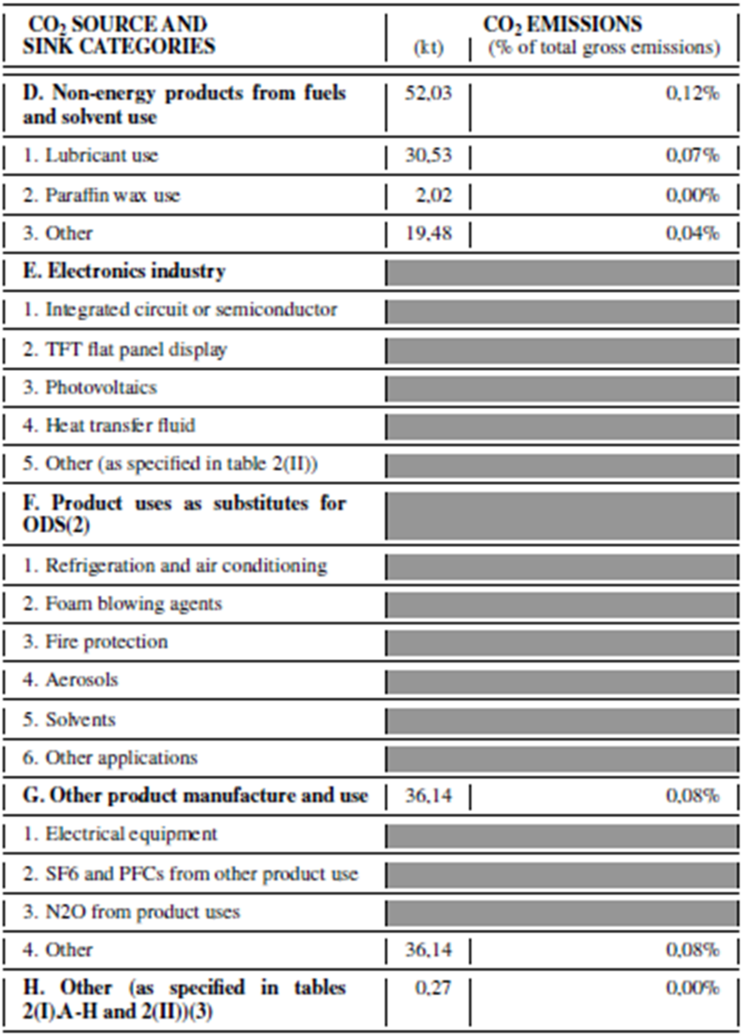
Code number and name				Definitions
1 A 5	*Non-Specified*			All remaining emissions from fuel combustion that are not specified elsewhere. Include emissions from fuel delivered to the military in the country and delivered to the military of other countries that are not engaged in multilateral operations.
1 A 5	a	Stationary		Emissions from fuel combustion in stationary sources that are not specified elsewhere.
1 A 5	b	Mobile		Emissions from vehicles and other machinery, marine and aviation (not included in 1 A 4 c ii or elsewhere).
1 A 5	b	*i*	*Mobile (aviation component)*	All remaining aviation emissions from fuel combustion that are not specified elsewhere. Include emissions from fuel delivered to the country's military as well as fuel delivered within that country but used by the militaries of other countries that are not engaged in multilateral operations.
1 A 5	b	*ii*	*Mobile (water-borne component)*	All remaining water-borne emissions from fuel combustion that are not specified elsewhere. Include emissions from fuel delivered to the country's military as well as fuel delivered within that country but used by the militaries of other countries that are not engaged in multilateral operations.
1 A 5	b	*iii*	*Mobile (other)*	All remaining emissions from mobile sources not included elsewhere.
Multilateral operations (Information item)				Emissions from fuels used in multilateral operations pursuant to the Charter of the United Nations. Include emissions from fuel delivered to the military in the country and delivered to the military of other countries.

C.3 CO_2 EMISSIONS IN SWITZERLAND IN 2016- INDUSTRIAL PROCESSES SECTORAL REPORT



CO_2 SOURCE AND SINK CATEGORIES	CO_2 EMISSIONS (kt)	(% of total gross emissions)
Total industrial processes	2157,04	4,86%
A. Mineral industry	1901,00	4,28%
1. Cement production	1768,99	3,99%
2. Lime production	41,44	0,09%
3. Glass production	6,47	0,01%
4. Other process uses of carbonates	84,10	0,19%
B. Chemical industry	155,27	0,35%
1. Ammonia production	IE	IE
2. Nitric acid production		
3. Adipic acid production	NO	NO
4. Caprolactam, glyoxal and glyoxylic acid production	NO	NO
5. Carbide production	31,30	0,07%
6. Titanium dioxide production	NO	NO
7. Soda ash production	NO	NO
8. Petrochemical and carbon black production	111,48	0,25%
9. Fluorochemical production		
10. Other (as specified in table 2(I).A-H)	12,49	0,03%
C. Metal industry	12,34	0,03%
1. Iron and steel production	10,89	0,02%
2. Ferroalloys production	NO	NO
3. Aluminium production	NO	NO
4. Magnesium production	NA	NA
5. Lead production	NO	NO
6. Zinc production	NO	NO
7. Other (as specified in table 2(I).A-H)	1,44	0,00%

Table 5: Breakdown of the CO_2 emissions in Switzerland for 2016 in the sector of industrial processes.
Source: adapted from FOEN 2018a.



CO$_2$ SOURCE AND SINK CATEGORIES	CO$_2$ EMISSIONS	
	(kt)	(% of total gross emissions)
D. Non-energy products from fuels and solvent use	52,03	0,12%
1. Lubricant use	30,53	0,07%
2. Paraffin wax use	2,02	0,00%
3. Other	19,48	0,04%
E. Electronics industry		
1. Integrated circuit or semiconductor		
2. TFT flat panel display		
3. Photovoltaics		
4. Heat transfer fluid		
5. Other (as specified in table 2(II))		
F. Product uses as substitutes for ODS(2)		
1. Refrigeration and air conditioning		
2. Foam blowing agents		
3. Fire protection		
4. Aerosols		
5. Solvents		
6. Other applications		
G. Other product manufacture and use	36,14	0,08%
1. Electrical equipment		
2. SF6 and PFCs from other product use		
3. N2O from product uses		
4. Other	36,14	0,08%
H. Other (as specified in tables 2(I).A-H and 2(II))(3)	0,27	0,00%

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Carbon capture, utilization and storage (CCUS) technologies have been proposed in recent times to mitigate anthropogenic climate change. Although already present in other Western countries, public policies regulating the deployment of CCUS facilities are still lacking in Switzerland.

In this first volume, we examine the technological and scientific conditions framing CCUS, in the perspective of its possible development in Switzerland.

Les technologies de capture, d'utilisation et de stockage du carbone (CUSC) ont été proposées ces derniers temps pour atténuer le changement climatique d'origine anthropique. Bien que déjà présentes dans d'autres pays occidentaux, les politiques publiques encadrant le déploiement des installations de type CUSC font encore défaut en Suisse.

Dans ce premier volume, nous examinons les conditions technologiques et scientifiques qui encadrent le CUSC, dans la perspective de son possible développement en Suisse.