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sweet swiss energy research for the energy transition

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Abstract

Starting point As part of the SWEET EDGE programme funded by the SFOE, the Laveba Cooperative in Wittenbach is planning to build a biogas plant which employs innovative technologies. The biogas from the agricultural plant is to be processed into biomethane and fed into the gas network. As biogas contains approx. 40% CO_2 by volume and the biomethane fed into the gas network may contain a maximum of 4%, the CO_2 is to be separated by means of a membrane separation process. Instead of releasing this CO_2 into the atmosphere, it could be utilised, e.g. for the production of synthetic fuels, or permanently stored. The latter would lead to negative emissions.

In Wittenbach, the biogas plant will produce around 1,200 tonnes of CO_2 per year. Compared to most biogas plants in Switzerland and Europe that feed biomethane into the gas grid, this amount is low. The processing of CO_2 (purification and liquefaction) poses an economic challenge due to the lack of economies of scale, especially for small quantities.

Objective This report examines ecological and economic possibilities for the recycling or permanent storage of CO_2 from a biogas plant. The evaluation will be carried out on the basis of the biogas plant planned in Wittenbach. Various options are considered, such as use as 'air fertiliser' in a greenhouse or use for carbon dioxide production for beverage manufacturers, as well as permanent storage in geological deposits or in demolition concrete.

Recommendations For the planned biogas plant in Wittenbach, it is recommended that the majority of the CO_2 produced during biogas processing is transferred to concrete recycling plants for permanent storage of the CO_2 (bioenergy with carbon capture and storage, BECCS).

For utilisation in the food and beverage industry (carbon capture and usage CCU), the CO_2 would have to be processed for food quality and the quality would have to be checked at great expense. Without subsidies, quality control for the small quantity cannot be carried out economically. Although subsidisation would be possible through the sale of climate protection certificates, from today's perspective, the climate protection effect of utilisation is rather low: the biogenic CO_2 captured in the biogas plant would mainly replace CO_2 on the Swiss and European CO_2 market, which is produced as a 'waste product' in the chemical industry (e.g. ammonia production). The effect would be greater if geogenic or fossil CO_2 were to be replaced on the market. Potentially, some of the CO_2 could be supplied to vegetable growers to fertilise the air in their greenhouses. No elaborate quality control is required for this application, but logistical challenges would have to be overcome as, depending on the season, greenhouse demands for CO_2 fluctuates greatly.

Legislators are recommended to examine a ban on the import of CO_2 from geogenic sources for Switzerland. Throughout Europe, projects are being developed at great expense and effort to store CO_2 underground (CCS). It would be a paradox if it remained legal to drill for geogenic CO_2 at other locations and import it into Switzerland. For biogas plants feeding into the grid, it is recommended that an obligation to recycle or permanently store CO_2 be examined. In addition, a legal framework should be created to efficiently allocate the limited CO_2 storage sites to the various CO_2 sources.

Glossary

Fossil emissions	are produced by the combustion of fuels such as coal, natural gas or oil, which originate from a geological time far in the past.
Geogenic Emissions	are emissions caused by the release of CO_2 from rocks or natural carbon dioxide, e.g. in the vicinity of volcanoes. Differentiation from fossil CO_2: Fossil fuels are formed from organic material under the influence of increased pressure and temperature. In the case of geogenic CO_2, there was no conversion to a hydrocarbon compound or to elemental coal.
Biogenic Emissions	are produced by the combustion or microbial degradation of organic material. Biogenic emissions were defined as climate-neutral in the Kyoto Protocol, and consequently also by the Federal Office for the Environment (FOEN), because the combustion of organic material or biomethane only emits as much CO_2 as the plants have absorbed while growing. The CO_2 captured during the processing of raw biogas is also described as biogenic and its emission into the atmosphere as climate neutral.
Negative Emissions	refers to the targeted and permanent removal of CO_2 from the atmosphere through human activity, i.e. the removal that takes place in addition to natural carbon cycle processes. An example of such a technology is filtering CO_2 from the air and then storing it permanently underground, for example in the supercritical state or as solidified rock. The targeted afforestation of forests also leads to negative emissions, as tree growth removes CO_2 from the atmosphere. The CO_2 remains stored in trees, in the ground or in lumber for a longer period of time.

List of Abbreviations

FOEN	Federal Office for the Environment (Switzerland)
BECCS	Bioenergy with carbon capture and storage - Energiegewinnung aus Biomasse inklusive CO_2-Abscheideung und -Speicherung
SFOE	Swiss Federal Office of Energy (Switzerland)
CA	Controlled atmosphere
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
DACCS	Direct air carbon capturing and storage
EBA	European Biogas Association
eFuels	Synthetic fuels produced from water and CO_2 using electrical energy
EIGA	European Industrial Gases Association
EOR/EGR	Enhanced Oil/Gas Recovery
EWF	Emission Weight Factor
GWP	Global Warming Potential
LHV	Lower heating value (LHV) - also called lower calorific value
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MSWI	Municipal solid waste incineration plant
Klik	Foundation for Climate Protection and CO_2 Offset
LCO_2	Liquid CO_2
LNG	Liquified natural gas
N_2	Nitrogen
NH_3	Ammonia
N_2O	Nitrous oxide
NET	Negative emission technologies
O_2	Oxygen
PV	Photovoltaic systems
RFI	Radiative Forcing Index
SUVA	Swiss accident insurance
TRL	Technology Readiness Level
WWTP	Waste Water Treatment Plant

1 Introduction

Governments around the world are working on climate strategies to stop or at least slow down the progression of global warming. At the heart of many climate strategies is a reduction pathway that specifies how quickly and in which sectors greenhouse gas emissions are to be reduced. We are still only at the beginning of the road to a climate-neutral economy, both in Switzerland and throughout Europe. Carbon dioxide (CO_2) is - in terms of its overall impact[1] on the climate - the greenhouse gas that drives global warming the most.

Figure 1 shows how the problem of the constantly rising concentration of CO_2 in the atmosphere could theoretically be solved. Almost all sectors can be decarbonised quickly with technical measures. Only a few industrial processes (for example, cement production) will still produce fossil or geogenic CO_2 in the future. This CO_2 - and/or an equivalent amount of CO_2 from the air or biogenic sources - could be utilised physically, materially or as an energy source in the future (see Figure 1). The 'permanent storage' branch in Figure 1, circled in red, is only shown after the utilisation options, but is also an option after the sources or at the 'end of life' stage. If the CO_2 is captured from industrial processes, waste incineration or cement production, this process is called carbon capture and storage (CCS).

If biogenic CO_2 - e.g. from biogas plants - is captured, this is referred to as bioenergy with carbon capture and storage (BECCS). To ensure that the cycle does not actually generate any additional fossil CO_2, all conversion steps must be powered by renewable energy (wind, photovoltaics (PV), hydropower).

[1] The total climate impact of a greenhouse gas is the product of its global warming potential (GWP) and the amount in the atmosphere.

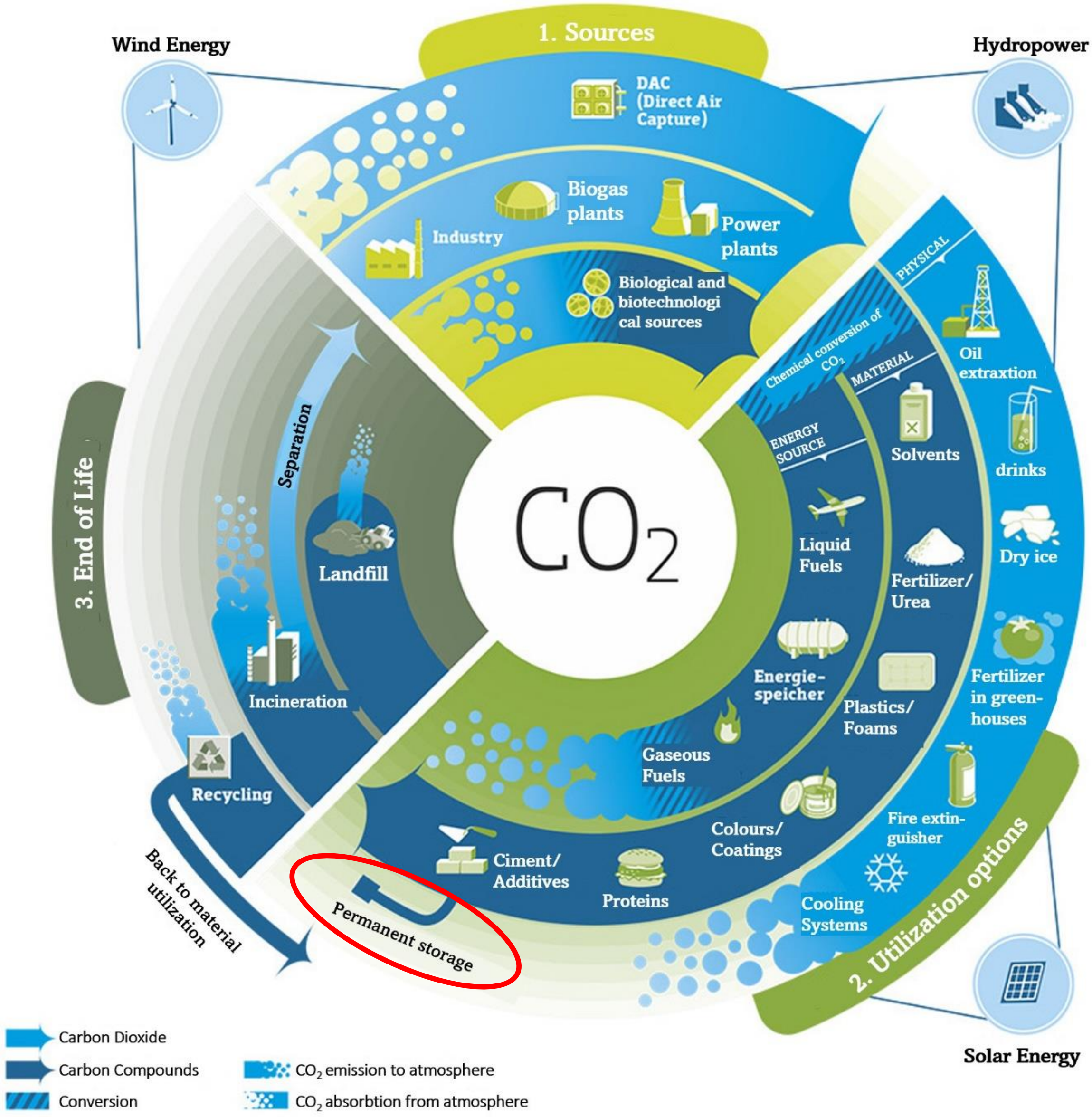

Figure 1 Infographic on carbon utilisation and storage (called ‘permanent storage’ in the graphic; Mensch, 2022).

1.1 Role of negative emissions in the Swiss climate strategy

In 2021, Switzerland emitted 46 million tonnes of CO_2eq, not including international air traffic. Figure 2 shows the current and expected future Swiss greenhouse gas emissions per sector. Fossil and geogenic emissions from the industrial sector are expected to be the most difficult to reduce. Large quantities are produced nowadays, for example, in the manufacture of cement or chemicals (e.g. acetylene or ethylene; see Section 2.2.1).

In European industry, large quantities of CO_2 are produced as a by-product of ammonia production. In order to produce ammonia (NH_3), hydrogen is required, which today is mainly obtained from fossil natural gas by means of methane reforming. CO_2 is a by-product of this process. The resulting CO_2 is often captured and processed to provide it for various applications (see Figure 1).

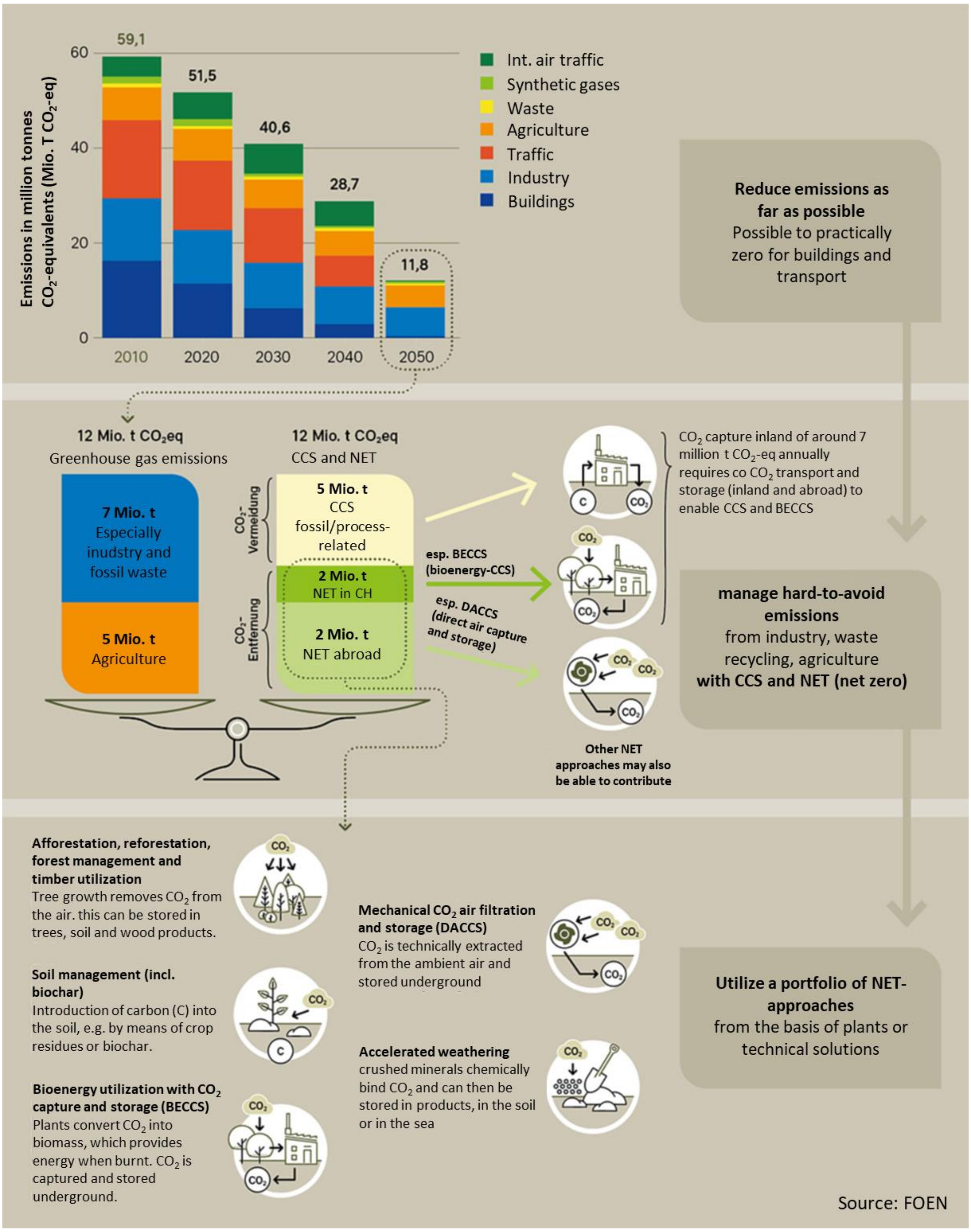

Figure 2 Visualisation of the Federal Council's long-term climate strategy of 2021 and the role of the various negative emission technologies (NET) according to FOEN (2022b).

The Federal Council's climate strategy (Figure 2)[2] stipulates that Switzerland should emit net-zero greenhouse gases by 2050 at the latest (The Federal Council, 2021; Der Bundesrat, 2021). In order to achieve that goal, it is a top priority to reduce both fossil and geogenic CO_2, methane (CH_4) and nitrous oxide (N_2O) emissions. It is difficult to reduce certain emissions, such as methane emissions from cattle farming or geogenic CO_2 emissions from cement production, without changing consumption habits and lifestyles. In its strategy, the Federal Council assumes that the annual residual emissions[3] of 7 million tonnes of CO_2 (Federal Council, 2021), which can only be reduced with difficulty[3], will be offset by *negative emissions* (Figure 2).

A general description of negative emission technologies (NET) is as follows: the technical or nature-based extraction of greenhouse gases from the atmosphere and permanent[4] storage in geological reservoirs, humus, buildings or particularly durable consumer goods. The Swiss Federal Council (or the Federal Office for the Environment, FOEN) sees great potential in two processes (see Figure 2): firstly in DACCS (direct air carbon capture and storage, which describes the capture of CO_2 from the air and subsequent permanent storage), and secondly in BECCS. According to the Federal Council's long-term climate strategy, 2 million tonnes of CO_2 are to be removed from the atmosphere each year in Switzerland, partly with the help of BECCS, while the remaining 5 million tonnes of CO_2 are to be removed from the atmosphere abroad, mainly by DACCs and permanently stored in suitable geological repositories. In addition, from 2050 at the latest, 5 million tonnes of CO_2 from cement production and waste incineration plants are to be avoided annually with CCS, and the CO_2 is to be permanently stored in geological repositories in Switzerland or abroad.

Various processes are grouped under BECCS. For the 'CO_2 capture from biomass' part, there is CO_2 capture during biomethane production on the one hand and CO_2 capture from the exhaust gas of waste incineration plants[5], wood incineration plants, wood gas incineration plants after wood pyrolysis and from the exhaust gas of combined heat and power plants (CHP) after biogas incineration on the other.

When wood is burned, CO_2 only accounts for about 13% of the exhaust mixture. Even after the combustion of biogas in a CHP unit, the CO_2 in the exhaust gas is diluted. The separation process from the flue gas of wood combustion plants or CHP units requires more energy compared to the separation of CO_2 from raw biogas. During biomethane production, CO_2 must be captured so that the biomethane can be fed into the natural gas grid. After the separation process, the CO_2 is almost pure. CO_2 separation from raw biogas is the only BECCS process that has been used in Switzerland so far (see Section 6.1). The biomass (e.g. sewage sludge, farmyard manure, green waste and food waste) is fermented into raw biogas and the CO_2 is separated in the biogas upgrading process and liquefied for transport to the site of permanent storage.

Raw biogas consists of 40 – 75 % methane; the remaining gas consists mainly of CO_2 and small amounts of other gases (including water vapour, nitrogen, oxygen, hydrogen and ammonia; Energie Systeme der Zukunft & BMVIT, 2014). Biogas plants that feed methane into the natural gas grid instead of producing electricity locally by burning the raw biogas must first process the raw biogas. Various separation processes are used to separate the CO_2 and the other gases from the raw biogas. To date, the captured CO_2 is released into the atmosphere in most cases. As BECCS is expected to play an important role in the future according to Switzerland's climate strategy, it can be assumed that the CO_2 from the processing of raw biogas will be captured and liquefied in the future so that it can be transported

[2] Emissions from international air traffic are calculated based on fuel sales at Swiss airports and without considering the Radiative Forcing Index (RFI factor) or Emission Weighting Factor (EWF). These factors indicate how much higher the warming effect of the various greenhouse gases and soot is at high altitudes than CO_2 emissions alone. According to Spirig et al. (2022), an EWF of 3 should be used. With an increasing share of sustainable aviation fuels, the EWF should decrease.

[3] The Federal Council's figures on residual emissions and the contribution of individual NET to achieving the net-zero target are based on assumptions that are subject to considerable uncertainty and political debate. Appropriate legislation and financial incentives could, for example, reduce the number of cattle in Switzerland, reduce the living space per person or increase the use of wood instead of concrete in construction. Such measures would reduce residual emissions.

[4] Experts do not agree on the minimum length of time that permanent storage must take place to effectively stop or slow down global warming. Some experts advocate storage sites with only 100 years of safe storage, others speak of at least 1,000 years.

[5] According to a survey with random samples, the proportion of biogenic waste amounted to 52 % of Swiss waste in 2022 (FOEN, 2023a).

to suitable underground storage sites or to concrete recycling plants. The injection of CO_2 into the pores of suitable underground rock or the mineralisation of CO_2 in the pores of demolition concrete are the two most common methods for permanent storage (see Section 6).

Another BECCS process would be the pyrolysis of biomethane. This produces hydrogen, which is used, for example, as an energy source or for the synthesis of ammonia and elemental carbon. This is used in the manufacture of many products such as tyres or electrodes for batteries. However, most of these products have too short a life cycle and can therefore not serve as permanent storage for the CO_2, but only as an interim storage site. For negative emissions to be possible, the CO_2 would have to be collected at the end of the life cycle of these products (e.g. from waste incineration) and transported to a permanent storage site.

1.2 Current Swiss biomethane production and sustainable potential

According to the SFOE (2023), Swiss biogas and sewage gas plants fed 423 GWh of biomethane into the natural gas grid in 2022 and generated 410 GWh of electricity with combined heat and power plants. Agricultural biogas plants fed 11 GWh of biomethane into the natural gas grid and produced 196 GWh of electricity with combined heat and power plants (SFOE, 2023b). Combined with the amount of biomethane imported (2.1 TWh), around 8% of Swiss gas consumption was covered by biomethane (Association of the Swiss Gas Industry [VSG], 2023)

The Zero Basis scenario of the Energy Perspectives 2050+ envisages biomethane covering the entire gas consumption of 15.3 TWh in 2050, whereby a large proportion of the biomethane would be imported (SOFE, 2021). According to a study by the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), the sustainable potential for the production of Swiss biomethane from non-woody biomass is 5.7 TWh per year (Thees et al., 2017). Since only about 2/3 of the generation takes place closer than 5 km to the existing gas network, the SFOE estimates the potential of Swiss biomethane that can be fed into the gas network at 3.5 TWh per year (SOFE, 2021).

Assuming that an average of 0.136 t CO_2/MWh is produced when raw biogas is processed into biomethane, the existing biomethane-feeding plants in Switzerland could currently collect and store or reuse around 57,000 t CO_2 per year. If the annual feed-in target of 3.5 TWh of Swiss biogas is achieved by 2050, this corresponds to a potential of up to 476,000 tonnes of CO_2 that could be used for BECCS.

1.3 Research question

This report uses the case study of a biogas plant planned in Wittenbach to analyse which options for using the CO_2 produced make ecological and economic sense from today's and future perspectives. The focus is on utilisation and permanent storage.

The biogas plant planned by the Laveba Cooperative will produce around 1,200 tonnes of CO_2 per year, a smaller amount than average plants in Europe.

2 CO_2 market

As illustrated in Figure 1, CO_2 is not only a waste product from combustion and undesirable as a greenhouse gas, but for certain industries is a sought-after raw material for materials and products, such as carbonated beverages. The following section describes the current market situation.

2.1 Current CO_2 requirements

According to the assumptions of the International Energy Agency (IEA), at present just over 250 million tonnes of CO_2 are used worldwide every year (IEA, 2019). The breakdown of demand by different utilisation purposes is shown in Figure 3. More than half is used for urea[6] production, around a third for enhanced oil recovery (EOR) and the remaining 10 % in the food and beverage sector and for other applications (see Figure 3). The food sector requires CO_2 to produce carbonic acid for the beverage industry as well as for the packaging and transport of food. As no EOR projects are operated in Europe apart from an oil field in Hungary (Global CCS Institute, 2022), the proportion of CO_2 used for the food industry is higher here than the global average and amounted to around 50 % in 2021 (Fact.MR, 2022). The German food industry requires around 1 million tonnes of CO_2 per year (Schaller, 2023). At around a quarter, Germany has the largest share of the European CO_2 market (Fact.MR, 2022).

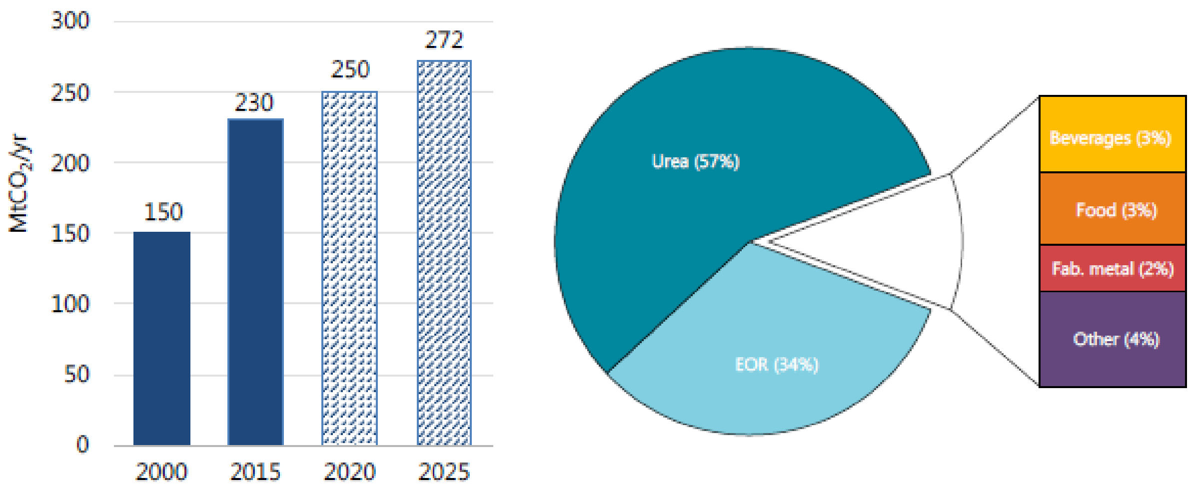

Figure 3 Situation for the years 2000 and 2015, and forecast[7] for global demand for CO_2 up to 2025 and breakdown by use for 2015 (IEA, 2019).

There are three major gas providers in Switzerland: Linde Gas Schweiz AG (formerly PanGas), Carbagas AG (Air Liquide Group) and Messer Schweiz AG. The majority of Switzerland's CO_2 requirements are covered by these three traders, with Carbagas having a significant market share. Overall, the Swiss gas industry sells around 60,000 - 70,000 tons of CO_2 per year. According to Simon Staufer (Neustark AG), the demand from the food industry (mainly for the carbonation of beverages) in Switzerland is likely to be around 50,000 tons of CO_2 per year. The annual CO_2 demand to produce dry ice for cooling food and other products is around 10,000 tonnes of liquid CO_2.

In the coming years, the need for CO_2 for air fertilisation in greenhouses is also likely to become relevant for the CO_2 market. Until now, most vegetable growing companies with greenhouses have used the CO_2 from the exhaust gases from combustion heating systems for air fertilisation. With the switch to renewable heating systems, heat pumps are increasingly being used instead of fossil-fuelled burners. If the ventilation systems of the greenhouses are not optimised on a large scale in the future (e.g. by reducing the amount of fresh air by circulating the air with integrated dehumidification instead of the complete air

[6] Urea is mainly used in agriculture in nitrogen fertilizers and as an animal feed additive, for exhaust gas aftertreatment of combustion engines (AdBlue) and in the chemical industry as a starting material for many manufacturing processes (URACA GmbH & Co. KG, n. d.)

[7] The IEA assumes an annual growth of 1.7% in global CO_2 demand. The CO_2 demand for EOR will fall as fossil oil production decreases. It is expected that the demand for CO_2 for the production of synthetic fuels will increase.

changes that are common today), an annual CO_2 requirement of over 25,000 tonnes of CO_2 could arise for air fertilisation in the future (see Section 5.3).

2.2 Current CO_2 production

There are four different ways of extracting CO_2 for the liquid CO_2 and dry ice markets. These are described in more detail below.

2.2.1 Fossil CO_2 as a by-product of the chemical industry

The production of ammonia, ethylene, methanol, propylene and other chemicals produces CO_2 emissions as a by-product. In Europe, the production of ammonia, which is mainly produced for fertilisers, is one of the most important sources of CO_2. The synthesis of ammonia requires hydrogen. This is largely obtained from natural gas by means of steam reforming, which produces almost pure CO_2 as a by-product. In 2018, ammonia production generated globally 500 million tonnes of CO_2, or around 1.4 % of global CO_2 emissions (The Royal Society, 2020). For use as a fertiliser, ammonia is often processed into urea in a further synthesis step, which in turn requires CO_2. Annually, this amounts to around 140 million tonnes of CO_2 worldwide (seeFigure 3). If all of the CO_2 produced during ammonia production were captured and made available for further utilisation, today's global demand could be covered twice over. In Europe, there are several ammonia plants which, due to rising natural gas prices from the end of 2021, have partially reduced or completely stopped the production of ammonia and thus also CO_2 as a by-product. In addition, plants usually shut down for maintenance in summer, while demand for CO_2 from the food industry is at its highest in summer. These two factors led to a shortage of CO_2 on the European market in summer 2022.

2.2.2 Biogenic CO_2 as a by-product of bioethanol production

In bioethanol plants, CO_2 is produced by breaking down sugar into ethanol and CO_2 during the alcoholic fermentation processes (Demirbas, 2007). In Germany, this quantity is relevant to the market because German petrol must contain at least 10 % bioethanol, which requires a correspondingly high level of production. However, the production of bioethanol for use as a fuel additive is the subject of controversial debate in view of the competition for land use and space for food production (Air Liquide, 2019).

2.2.3 Fossil CO_2 from the combustion of fossil fuels with CO_2 as the main product

CO_2 is also produced by burning fossil fuels such as natural gas, oil or coal. In Europe and America, this type of production is unlikely to play a significant role, as sufficient CO_2 is available almost everywhere as a by-product from industry or carbon dioxide from natural underground sources (see section 2.2.3) in the vicinity of processes which require it. In Asia and Africa, however, there are cases where the consumer is far away from the producer, and production by burning fossil fuels is the most cost-effective way of extracting CO_2. In India, for example, CO_2 production plants can be purchased that produce CO_2 from the combustion of natural gas, diesel or coal (Ashirwad Carbonics, n. d.).

2.2.4 'Natural' geogenic CO_2 from source fields

'Natural' carbon dioxide from source fields is mainly produced in the area of extinct or active volcanoes. To extract the gas, wells are drilled at depths of 100 to 3000 metres and the raw gas which is extracted is either within natural mineral water or is in a moisture-saturated gas state. A few years ago in Germany and Italy, geogenic CO_2 from source fields accounted for around a quarter of all CO_2 produced and liquefied in these countries (Air Liquide, 2019; TPI Tecno Project Industriale, 2020). The 'natural' carbon dioxide is relevant for the climate as soon as the product, for whose production the geogenic CO_2 is used, is consumed or incinerated in a waste incineration plant. For example, when carbonated drinks are consumed, the CO_2 is released into the atmosphere, where it is a burden on the climate in the same way as fossil CO_2. Nevertheless, German food and beverage manufacturers (e.g. Gerolsteiner, n. d.) advertise that they use residue-free 'natural' carbon dioxide and even claim that this is climate-neutral because the CO_2 would escape into the atmosphere anyway (Rapunzel, 2022). However, this is unlikely to be the case in most cases. For example, wells for 'natural' CO_2 are being drilled in the German region of Vulkaneifel in order to tap into source fields (Carbo, n. d.).

Not only this report, but also countless other Swiss and European research papers have dealt with the topic of CCUS (IEA, 2019; Cames et al., 2023; DemoUpCARMA, 2021; ECCSL, 2020). The Swiss Federal Council has only recently created the necessary conditions to allow CO_2 to be stored in the seabed and to connect Switzerland to the CO_2 pipelines that are currently being planned throughout Europe to transport CO_2 to suitable storage sites (see Section 6).

In view of these developments, the question arises as to why it is not yet prohibited to extract climate-relevant CO_2 directly from underground and sell it on the European market if at the same time, CO_2 has to be captured, transported and stored at great effort and expense. Representatives of the gas industry share this opinion. For example, Ansgar Rinklake (2020) from Air Liquide said in an interview: "From our point of view, it no longer makes sense to extract this CO_2 today, especially as many organisations are currently working on projects to remove CO_2 from the atmosphere and inject it into the ground. It is simply absurd to drill for it elsewhere and extract it again." In a press release in April 2019, Air Liquide announced that the company will no longer use CO_2 from drilled sources in future and will focus on recycling the by-product CO_2 from industrial processes (Air Liquide, 2019). However, it is not yet clear how long it will take until this goal will be reached or if it is already reached. There are no studies that show how much CO_2 is currently being extracted from natural sources worldwide. In 2012, 45 million tonnes of CO_2 were extracted from the ground and used for EOR in the USA alone (Naims, 2016). By comparison, in 2022 there were CCS plants worldwide, i.e. CO_2 capture plants for industrial sources that were built specifically to extract CO_2 for EOR or permanent underground storage, with a maximum capacity of 40 million tonnes of CO_2 per year (Global CCS Institute, 2022).

2.2.5 CO_2 production for the Swiss market

The potentially largest Swiss production plant for liquid CO_2 is probably the one installed at Arxada (formerly Lonza) in Visp. CO_2 is a by-product of the cracking of natural gas for acetylene and ethylene production. Between 0.9 and 1.8 tonnes of CO_2 are produced per tonne of ethylene, of which 90 % of the CO_2 can be recovered (S&P Global, 2022). With an annual ethylene production of 25,000 tonnes (MRC, 2020), between 19,000 and 40,500 tonnes of CO_2 are therefore generated. According to Heinz Peyer (Air Liquid), who was involved in the engineering of the CO_2 liquefaction plant in Visp in the early 1990s, the plant was designed for the production of 50,000 tonnes of liquid CO_2 (LCO_2) per year.

Not all of the CO_2 used in Switzerland comes from Switzerland. The CO_2 source at Arxada in Visp produces exclusively for Air Liquide/Carbagas. Carbagas and other Swiss gas companies also import CO_2 from abroad. The ammonia plant in Ottmarsheim in France or BASF's ammonia plant in Ludwigshafen, for example, are foreign sources of CO_2 for Switzerland (Jürg Stalder, personal communication, 2.11.2023). Geogenic CO_2 (natural carbon dioxide) may also be extracted from the ground through boreholes for import into Switzerland.

2.2.6 Possible future CO_2 production from raw biogas processing in Europe and Switzerland

If all the raw biogas produced in Europe had been processed into biomethane in 2020, 18 billion m³ of biomethane could have been produced and 24 million tonnes of CO_2 could have been captured (European Biogas Association [EBA], 2021). Just under half of this potential could have been utilised in Germany. The EBA estimates that annual biomethane production in the EU will be around 35 billion m³ by 2030. This suggests a potential of around 50 million tonnes of CO_2 per year which could be recovered for BECCS or utilisation. According to a rough estimate by Manuel Maciejczyk, Managing Director of the German Biogas Association, the German food industry could already cover the entire annual CO_2 demand of around 1 million tonnes of CO_2 with biogenic CO_2 if all existing German biogas injection plants were to capture and liquefy the CO_2 produced during raw biogas processing (Schaller, 2023). A study commissioned by the German Bioenergy Association calculated an annual CO_2 capture potential of 1.5 million tonnes of CO_2 (Steindamm, 2023). The situation is likely to be similar in Switzerland. A rough estimate by the authors of this report shows that Swiss biogas plants, which currently feed 423 GWh of biomethane into the grid annually (SFOE, 2023), could liquefy up to 57,000 tonnes of CO_2, with a CO_2

capture rate of 136 tonnes of CO_2 per GWh of biomethane fed in (see Section 1.2). This amount would cover a large part of Switzerland's current annual demand of 60,000 to 70,000 tonnes of CO_2.

2.3 CO_2 market price

The price of CO_2 traded on the market is made up of the costs of the various process steps involved in capturing the CO_2 (capture from combustion gases, liquefaction and, if necessary, purification), storage and transport. As described in Section 2.2, a large proportion of European and Swiss CO_2 comes from ammonia, bioethanol or ethylene production. Since CO_2 has to be captured in these processes anyway and the concentration after the capture process is high (98 – 100 %), the capture costs consist only of the costs for purification and liquefaction and are correspondingly low (Table 1). They are mainly dependent on the electricity price at the production plant site and the size of the plant. The capture costs in Table 1 were estimated by the IEA in 2019. Increased natural gas and electricity costs are currently leading to higher capture costs at most European locations. Assuming an electricity consumption for liquefaction of 200 kWh/t CO_2 (see Table 3) and electricity costs of 20 Rp/kWh, the minimum costs for liquefaction are CHF 40/t CO_2. In addition, the cost allocation between the main product and the waste product CO_2 is difficult. This makes it difficult to compare the capture costs for different CO_2 sources.

Table 1 Capture costs for CO_2 for various industrial processes (IEA, 2019). The exchange rate in 2019 was assumed to be 1 CHF = 1 USD.

CO_2 source	**CO_2 concentration**	**Capture costs**
	[%]	[CHF/t CO_2]
Natural gas processing	96 - 100	15 - 25
Coal to chemicals (gasification)	98 - 100	15 - 25
Ammonia	98 - 100	25 - 35
Bioethanol	98 - 100	25 - 35
Ethylene oxide	98 - 100	25 - 35
Hydrogen (steam reforming)	30 - 100	15 - 60
Iron and steel	21 - 27	60 - 100
Cement	15 - 30	60 - 120

According to Henning Dicks, co-founder of agriportance GmbH, biogas producers in Germany only receive 20 – 50 Euros per tonne of liquid CO_2 (Schaller, 2023). Presumably, this price is below the production costs for liquid CO_2 for most plants (see electricity costs for liquefaction in Figure 7). Nevertheless, CO_2 liquefaction and purification can be operated economically in many cases because the biomethane (or certificates) from plants with CO_2 utilisation can be sold to the fuel sector at a lower greenhouse gas quota and thus at a higher price. It is also possible to certify biogenic LCO_2 and achieve a higher price on the market compared to LCO_2, which is a by-product of the chemical industry. Biogas plant operators who buy CO_2 recovery plants from Comtecswiss LTD often sell the biogenic CO_2 certified as $BioLCO_2$ (Cockerill, 2022).

CO_2 Energie AG operates a biogas plant in Nesselnbach, Switzerland, which produces up to 3,500 tonnes of CO_2 per year (Regionalwerke Baden, 2023). Thanks to the sale of CO_2 reduction certificates to the Swiss Climate Protection Foundation (Klik), the CO_2 liquefaction plant and quality control can be operated economically (Regionalwerke Baden & Neosys AG, 2021). According to the project description, the liquid CO_2 with verified food quality was sold to Messer Schweiz AG in 2021 for 60 CHF /t LCO_2 (Regionalwerke Baden, 2022). However, this price is below the cost of production. The sale of reduction certificates (see Section 7.2) can generate additional revenue of up to 160 CHF/t LCO_2 (maximum price for reduction certificates from KliK).

The end customer pays between 300 – 600 CHF/t CO_2 (including transport and possibly tank rental) for larger deliveries (e.g., 20-tonne tank) in Switzerland. The market price for CO_2, which gas traders obtain from large point sources, is therefore lower by a factor of 5 – 10. The large difference is probably due to long transport distances and thus high transport costs as well as the traders' margin, storage costs, tank fillings and maintenance. Due to the rise in the price of natural gas as a result of Russia's war of aggression against Ukraine, many ammonia plants in Europe have ceased production and consequently there has been and still is a CO_2 shortage in certain regions, which has led to higher CO_2 prices. For example, in the UK in 2022, the price increased by a factor 30 (£3000/t CO_2 in 2022 compared to £100/t CO_2 in 2021).

2.4 CCUS at biogas plants in Europe and Switzerland

The capture and subsequent liquefaction of CO_2 from raw biogas has been established in Europe for some time. Zoltan Elek, Managing Director of Landwärme GmbH, said in an interview with the Biogas Journal that there are already a good two dozen biogas plants with CO_2 liquefaction in Europe and that every new construction project currently being planned includes CO_2 liquefaction (Bensmann, 2022). For example, Landwärme GmbH is planning a CO_2 liquefaction facility at a biogas plant in Remlingen, Bavaria, which will liquefy 10,000 tonnes of CO_2 annually (Fischer, 2022; Gaz Energie, 2022). In Friesoythe in Lower Saxony, one of the largest biogas plants in Europe is currently being built (Revis bioenergy GmbH, 2023). Only farmyard manure will be used as the substrate. Raw biogas processing will generate more than 100,000 tons of CO_2 annually, which will be liquefied with screw compressors and partially processed into dry ice at the site. In addition, the construction of a plant for the production of synthetic fuels is planned (Schaller, 2023). Existing CO_2 liquefaction plants have been installed in England, the Netherlands, Italy, Germany and Switzerland. In Lombardy (Italy), the organic portion of household waste is fermented and produces 7,000 tonnes of food-grade CO_2 per year (Esposito et al., 2019). Examples from Germany include AVA Abfallverwertung Augsburg and EGK Entsorgungsgesellschaft Krefeld GmbH & Co KG. Both liquefy the CO_2 produced during the fermentation of sewage sludge and have been selling 4,500 t LCO_2 – 7,700 t LCO_2 annually with industrial grade (for cleaning with dry ice or as coolant for air conditioning systems) to a gas trader since 2020 and 2022, respectively (Wraneschitz, 2022; Schaller, 2023). In both projects, the gas is used for technical purposes, although it is of food quality (99.9 % purity). The reason for this is discussed in more detail Section 5.2. Zoltan Elek mentioned in the interview that the substrate for fermentation plays an important role in the intended use of the captured CO_2 as it can have an influence on the quality. He pointed out that waste-based biomethane plants (wastewater treatment plants or fermentation of liquid manure) cannot provide high-purity CO_2: "You can't guarantee that it won't contain any trace or odour substances. The CO_2 probably won't be used in the beverage industry. This is less of a problem for a system based purely on renewable raw materials[8]. If the CO_2 is only used in greenhouses, for example, then the origin of the slurry or manure does not interfere (Bensmann, 2022, p. 68)."

Compared to the typically larger biogas plants in neighbouring European countries, Swiss biogas plants usually produce less raw biogas and thus less CO_2, which is why the operating conditions are somewhat different to the rest of Europe. The first CO_2 liquefaction facility at a Swiss biogas plant was put into action by ARA Region Bern AG at a wastewater treatment plant in Bern in 2021. The CO_2 is delivered to Neustark AG for storage in demolition concrete (ARA Region Bern AG, 2021). In April 2023, a second biogas plant opened a CO_2 liquefaction plant in Nesselnbach (Regionalwerke Baden, 2023). Here, food waste is fermented into biogas in one of the largest biogas plants in Switzerland and partially purified into biomethane for feeding into the natural gas grid. The amount of CO_2 liquefied annually (food quality) will be around 3,500 tonnes. From the beginning of 2024, Biopower Nordwestschweiz AG in Pratteln will provide Neustark AG with space for a liquefaction plant. Neustark AG will liquefy 1,500 tonnes of CO_2 per year from raw biogas processing and then transport it to a concrete recycling plant, where it will be used to treat the demolition concrete with CO_2 and thus store it permanently (see Section 6.1).

[8] Renewable raw materials, such as biogas and ethanol production from maize or similar.

3 Description of the planned biogas plant in Wittenbach

The plant will use farmyard manure from neighbouring dairy cattle and individual breeding/fattening farms, as well as whey and green waste as the fermentation substrate. The plant is a type C[9] agricultural fermentation plant. The raw biogas is to be processed and biomethane fed into the gas grid. The raw biogas will be processed in two stages. The first stage is gas purification, in which the gas is dehumidified and the sulphur is largely removed. In the second stage, CO_2 and other foreign gases (water vapour, nitrogen, ammonia) are separated. The processes and facilities of the planned biogas plant in Wittenbach are shown schematically in Figure 4.

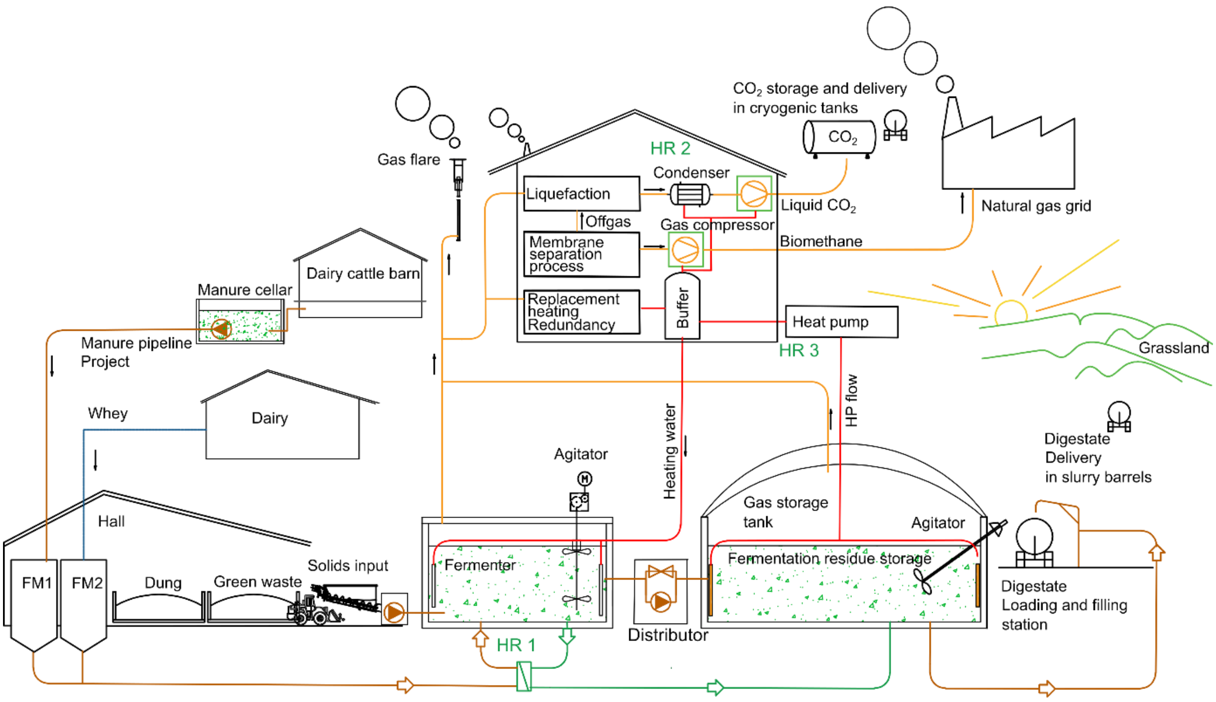

Figure 4 Schematic representation of the processes and plants in the planned biogas plant in Wittenbach (drawing: Mátyás Scheibler, EnergieWenden).

The feasibility study carried out by Laveba in 2022 on behalf of the municipality of Wittenbach sets out the key figures shown in

Table 2 for the biogas plant in Wittenbach (Keel & Scheibler, 2022). One tonne of biomass produces 43 m^3 of raw biogas (raw gas yield). The proportion of biomethane yield in the raw gas yield is approximately 58 %. The raw gas consists of 38 % CO_2 and 3 % accompanying gases. This means that approx. 17 m^3 of CO_2 can be captured per tonne of biomass. The amount of CO_2 that is captured annually and the mass flow is 1,232 t CO_2 (density CO_2 = 1,976 kg/ m^3).

[9] Permissible source material for type C: Farmyard manure plus other material of agricultural origin (from own or third-party farms) and > 20 % to a maximum of 50 % material of non-agricultural origin. (Federal Office for Agriculture, 2021)

Table 2 Energy balance biogas plant Wittenbach, basic variant B from feasibility study by Keel & Scheibler (2022).

Input/Output	Unit	Amount
Annual quantity of biomass	t	39,806
Raw gas yield	Nm^3/a	1,582,000
Raw gas yield 8760h/a	Nm^3/h	181
Biomethane yield	Nm^3/a	911,122
Biomethane yield 8760h/a	Nm^3/h	104
Annual yield biomethane	MWh	9,082
Annual quantity of CO_2	t	1,232
Mass flow CO_2	kg/h	141

4 Capture, liquefaction and transport of CO_2 from biogas plants

CO_2 must be separated from the raw biogas, liquefied and transported both for utilisation and permanent storage. These process steps are described in the following section in general and in relation to the planned biogas plant in Wittenbach.

4.1 CO_2 capture process and methane in off-gas[10]

There are various processes for separating CO_2 from raw gas, which have different advantages and disadvantages in terms of methane slip, costs, space and electricity requirements (Gkotsis et al., 2023; Struk et al., 2020). Since no process for CO_2 capture is 100 % 'leak proof' for methane molecules, a certain amount of CH_4 will be found in the CO_2 off-gas stream regardless of the process. If the CO_2 was not further utilised or stored after capture but released into the atmosphere, the CH_4 would also enter the atmosphere (methane slip). Due to the high *global warming potential (GWP)* of CH_4, methane slip must be prevented. Over a period of 100 years, the GWP is 27 ± 11 (GWP100). Since the half-life of CH_4 in the atmosphere is only 12 years, the GWP is much higher over a 20-year period (GWP20) and amounts to 80 ± 25 (Intergovernmental Panel on Climate Change (IPCC), 2023). According to the enforcement aid for the Ordinance on Air Pollution Control, the methane slip in Switzerland can be reduced to a maximum of 0.5 % with regard to methane in the raw biogas using the state-of-the-art technology (Cercl'Air, 2022). This means that the methane slip causes 30 g CO_2eq/kWh biomethane (calculated with the GWP20). In other words, methane slip increases CO_2 emissions from the combustion of methane from biogas plants by up to 15 %. However, while the emissions from the combustion of methane (202 g CO_2eq/kWh) are not climate-relevant because this CO_2 is biogenic and was removed from the atmosphere only a few months to years before the combustion, the methane slip is climate-relevant because it would not have reached the atmosphere, or at least not to this extent, without fermentation. The direct spreading of fertiliser on the field or composting of biomass would also produce methane and nitrous oxide emissions, which would escape into the atmosphere. This argument is often used to emphasise the climate friendliness of biomethane from farmyard manure. On the other hand, methane slip emissions from biomethane production are additional climate-relevant emissions that need to be prevented, even if more emissions would be produced in a different scenario.

When separating the CO_2, it is possible to prevent the CH_4 in the off-gas stream from escaping into the atmosphere, regardless of the separation method selected. For this purpose, the CO_2 is liquefied and then the gases that do not condense during CO_2 liquefaction (oxygen, nitrogen and methane) are separated using the stripper process (see Figure 6) and fed back into the fermenter. In this way, the methane slip can be reduced to almost 0 %. The process is described in more detail in the next subsection

[10] The gas separated from the methane, which mainly consists of CO_2, is referred to as off-gas in the language of process engineers and is released into the atmosphere by default. In the case of Wittenbach, the CO_2 is not to be released into the atmosphere as off-gas, but the standard term is still used here.

(4.2). If the CO_2 is liquefied after separation and a stripper process is installed, the choice of the separation process does not play a role in the methane slip quantities, as this is eliminated to 0 %.

In Switzerland, 30 out of 50 plants upgrading raw gas use the membrane separation process, 9 plants use chemical absorption scrubbing and 5 use pressure swing adsorption (Nägele, 2023). Across Europe, the membrane separation process is used in 39 % of the raw biogas processing plants. The use of the membrane separation process is also planned for the biogas plant in Wittenbach.

4.2 CO_2 liquefaction

In addition to reducing methane slip, the liquefaction of CO_2 is also necessary for transport in pipelines or trucks, whereby the supercritical state is more advantageous for transport over very long distances in pipelines (seeFigure 5). Thanks to the high density, a high throughput through the pipelines is possible (EnArgus, 2023b). For the liquefaction of gaseous CO_2, the gas is cooled and compressed. The phase diagram in Figure 5 shows possible combinations of temperature and pressure that lead to liquefaction. Most manufacturers of liquefaction plants liquefy CO_2 at -24 C (249 K) and at a suitable pressure (seeFigure 5). Pentair, for example, compresses the CO_2 in two stages to 18 bar (Pentair, 2021). Hitachi Zosen Inova planned the plant in Nesselnbach (HZ-Inova, 2023) and Asco (subsidiary of Messer AG) supplied the plant (ASCO, 2023). According to the project description for a project to reduce emissions in Switzerland by the Foundation for Climate Protection and Carbon Offset (KliK), CO_2 is also liquefied in Nesselnbach at -24 C (249 K) and 18 bar (Regionalwerke Baden & Neosys AG, 2021).

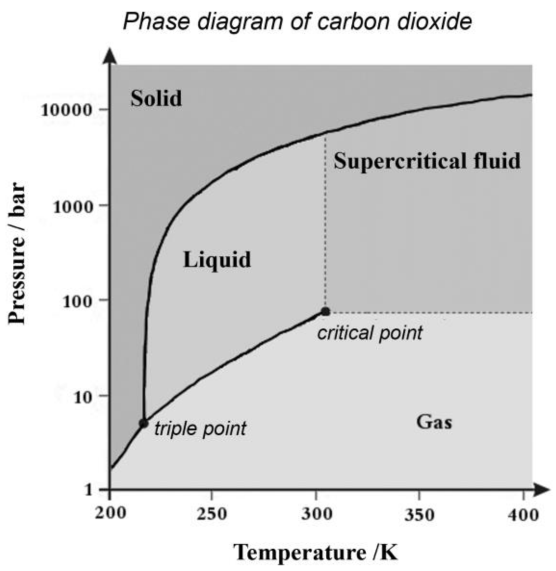

Figure 5 Phase diagram of carbon dioxide. PictureSaperaud (2005) by Saperaud (2005).

CO_2 liquefaction is a technologically advanced process. Various established manufacturers on the market offer the compressors or cryostats required for liquefaction. Some manufacturers also offer combined systems for biomethane processing and CO_2 liquefaction. Schaller (2023) names the following European companies with comparatively extensive experience (several plants realised in recent years): Pentair, ETW Energietechnik, Krieg & Fischer and Hitachi Zosen Inova (Schaller, 2023). In addition, Bright renewables and Comtecswiss realized also several liquefaction plants in the last years. As can be seen in Table 3, however, the minimum CO_2 liquefaction capacities for these plants are significantly higher than the amount of CO_2 that will be produced by the one planned in Wittenbach (approx. 140 kg CO_2/h). In contrast, Hypro Ingenieure Pvt. GmbH from India, offers liquefaction plants for small quantities and the Swiss company Comtecswiss LTD is currently developing a liquefaction plant for CO_2 quantities of 160 kg CO_2 /h (Mario Principe, personal communication, 01.12.2023).

Table 3 Suppliers of liquefaction systems and their minimum capacities

Company	Electricity consumption [kWh/kg CO_2]	min. Capacity [kg CO_2/h]	Comment
ASCO	0.21	500	Additional capacities on request
Bright renewables		300	
Comtecswiss	0.2 – 0.24	200	Capacity between 200 and 5000 kg CO_2/h
ETW Energie	0.15	630	850 Nm^3/h raw biogas
Hitachi Zosen Inova		250	Operation of the smallest system (500 kg CO_2/h) with 50 % of nominal capacity
Hypro	0.25	6	
Pentair Südmo		500	

4.2.1 Description of process

Figure 6 shows a process diagram for CO_2 liquefaction and purification for the modular system *Performance Drive* from Comtecswiss (Comtecswiss, 2022). The model has the same main components that Pentair (2021) describes in detail in the schematic illustration of their facilities.

(1) The CO_2 from biogas processing is temporarily stored in a storage balloon.

(2) The low-pressure CO_2 is compressed to 18 bar in two steps. Between the compression stages, the CO_2 is cooled in each case by the intercooler or the aftercooler. The operation of the compressor is controlled via the intake pressure. The CO_2, which is still moist, is then cooled further, causing water to condense, thereby reducing the load on the dryer and increasing the effectiveness of the activated carbon filter.

(3) The CO_2 is then purified and odour-neutralised via a dual adsorber system, each with one activated carbon filter, and dried to the dew point by a dryer each. If the CO_2 is not dried, unwanted ice crystals can form during liquefaction. The two adsorber systems are operated intermittently. The inactive group is regenerated by flushing particles out of the filter with a small CO_2 stream and heating the filters at the same time. In addition to the activated carbon filter, further dual filter systems (e.g. for removing H_2S) can be integrated depending on the gas composition and cleaning requirements.

(4) In this module block, the CO_2 is cooled until it reaches approx. -24 C and 18 bar. This occurs via a heat exchanger, whereby heat is extracted from the CO_2 up to the condensation point via a refrigerant (e.g. NH_3) and a compressor for the refrigerant. A considerable proportion of the non-condensable gases (CH_4, N_2 and O_2) is dissolved in the liquid CO_2. The portion that is not dissolved in the liquid CO_2 can be extracted at the top of the condenser and fed back into the fermenter of the biogas plant. This slightly reduces the methane slip[11].

(5) The CO_2 is fed in gaseous form into the stripper/reboiler module. The liquefied CO_2 is heated again in the reboiler with the compressor waste heat of the liquefaction, whereby the non-condensable gases (CH_4, N_2 and O_2), which are dissolved in the CO_2, rise into the stripper where they are finally separated from CO_2 and returned to the fermenter. This almost completely prevents methane slip.

(6) The CO_2 is finally filled into special cryogenic tanks and can be vaporised again at the consumer's site when required.

[11] In a liquefaction plant operated by Neustark AG, which liquefies CO_2 with a CH_4 content of 1.3%, the proportion of CH_4 dissolved in the liquid CO_2 is 89% (Helena Wiemeyer, personal communication, 22 December 2023)

Comtecswiss plants have a modular design so that certain modules can be omitted, depending on the initial substrate for fermentation, and the quality and odour requirements. For example, if the quality requirement is low, it is possible to omit the filter system for removing H_2S and/or the stripper/reboiler module.

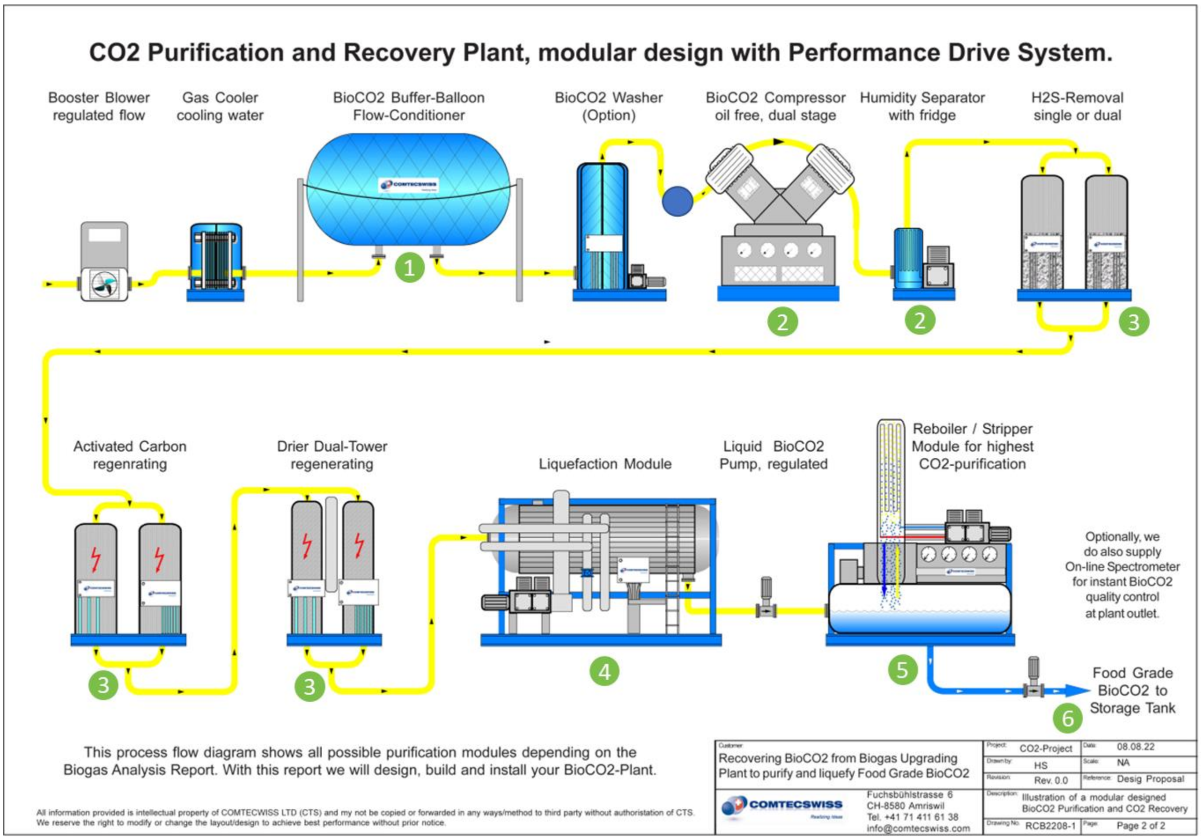

Figure 6 Process diagram of CO_2 liquefaction and purification of the *Performance Drive* model from Comtecswiss (Comtecswiss, 2022)

4.2.2 Investment costs and space requirements

An investment of CHF 500,000 is to be expected for a liquefaction plant with the appropriate capacity for the biogas facility in Wittenbach. In order to fulfil the requirements for purity and maximum concentrations of the various gas components, in most cases the CO_2 liquefaction facilities are equipped with a stripper/reboiler unit. Industry experts estimate the cost of purchasing such a unit at CHF 30,000 – 40,000. The liquefaction plant and accessories are expected to fit in a standard 20ft container.

4.2.3 Electricity requirements and costs

The liquefaction plants have a high electrical energy demand. 150 – 250 kWh of electricity is consumed per tonne of liquefied gas (Casaretto & Casaretto, 2023; ETW Energietechnik, n. d.). According to Heinz Peyer's experience, small plants are less efficient than large plants (personal communication, 13.11.2023). In Nesselnbach, the electricity consumption is 210 kWh per tonne of liquefied CO_2. The electricity requirement of the compressor is 130 kWh/t CO_2 and that of the cooling is 80 kWh/t CO_2 (Regionalwerke Baden & Neosys AG, 2021). Due to the lower capacity, it can be assumed that the efficiency of a liquefaction plant in Wittenbach will be rather lower than that in Nesselnbach.

The energy costs for liquefaction as a function of electricity costs are shown in Figure 7, assuming that 250 kWh must be used per tonne of liquefied CO_2. The annual electric energy demand for liquefaction in Wittenbach is approximately 310 MWh. This corresponds to about 3.4 % of the energy generated by the biogas plant. The annual energy yield in the form of biomethane amounts to 9,082 MWh.

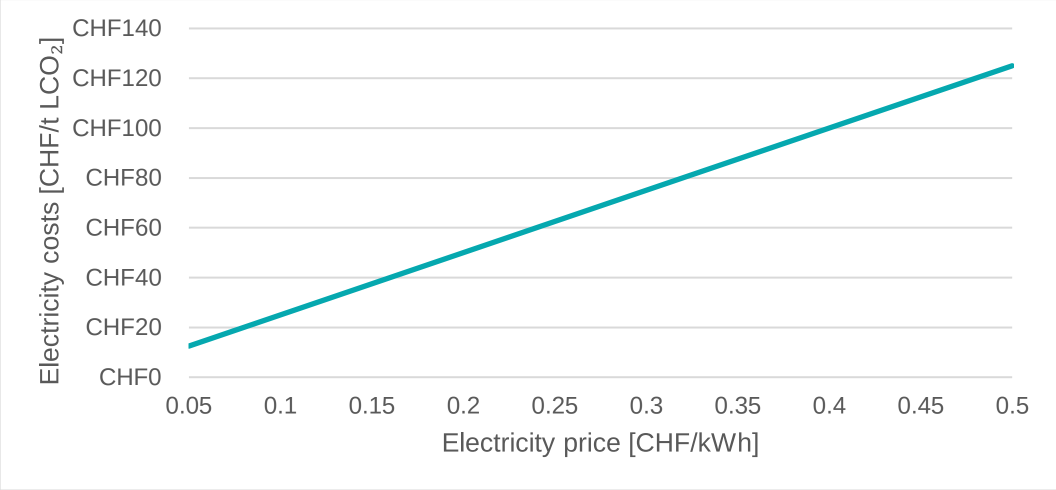

Figure 7 Electricity costs per tonne of liquid CO_2 (LCO_2) depending on the electricity price.

In Switzerland, electricity is generated almost free of fossil fuels and the Swiss production mix was therefore low in emissions in 2018 at 30 g CO_2 eq/kWh compared to other countries (Krebs & Frischknecht, 2018). The value also includes the indirect greenhouse gas emissions generated during the construction of the infrastructure for electricity production and distribution. However, the production mix does not take imports into account. If these are taken into account, this is the consumer mix. At 128 g CO_2 eq/kWh, the emission factor for the Swiss consumer mix in 2018 was higher by more than a factor of 4 compared to the production mix, due to the import of electricity from the EU, some of which was produced using gas or coal (Krebs & Frischknecht, 2018). Table 4 shows the greenhouse gas emissions that occur with the Swiss electricity mix during electricity production for CO_2 liquefaction. Depending on the electricity mix, this is 0.6 – 2.7% compared to the amount of CO_2 liquefied.

Table 4 Greenhouse gas emissions (CO_2eq) of electricity production for CO_2 liquefaction. These correspond to 0.6 – 2.7% compared to the amount of CO_2 that is liquefied.

	Emission factor electricity [g CO_2eq/kWh]	**Emissions electric energy consumption liquefaction [kg CO_2eq/t LCO_2]**
Production mix CH, 2018	30	6
Consumer mix CH, 2018	128	27

4.3 CO_2 transportation

CO_2 can generally be transported in all states, i.e. gaseous, liquid, in the supercritical state or as dry ice[12]. In Switzerland, trucks and pipelines are considered as transport options, although trucks are better suited for small amounts of CO_2 (EnArgus, 2023b).

For reasons of space, CO_2 is usually highly compressed and cooled for transport, which is why the transportation media must be able to withstand corresponding pressures and temperatures. Otherwise, temperature or pressure fluctuations can lead to changes in aggregate state and volume. If transportation containers are damaged, health risks arise because CO_2 as a gas displaces oxygen or as a solid (dry ice) in contact with the skin can lead to frostbite (Industriegasverband Schweiz [IGS], n. d.).

[12] Dry ice is used in medicine and biotechnology, as well as in the food industry for cooling. Dry ice is produced by expanding liquid CO_2 and is more energy-intensive than the production of liquid CO_2, because when the CO_2 solidifies, part of it changes into a gaseous state and has to be recovered and liquefied again (ASCO, n. d.).

4.3.1 CO_2 transportation by truck

Transportation of CO_2 by truck usually takes place in the liquid state. Compared to the gaseous state, the volume is significantly reduced, which is why fewer truckloads are needed for the same quantity. To transport the 1,232 t of CO_2 produced annually by the biogas plant in Wittenbach for example, 51 truckloads of ASCO CO_2 Semi-Trailer 25 m^3 PUR type (ASCO, 2021) are required, assuming that the liquid CO_2 is stored at a temperature of -15 to -18°C and a pressure of approx. 22 bar (ASCO, n. d.; Babel, n. d.). For the same amount of CO_2 in the gas state compressed to 22 bar, 1,161 truckloads per year would be required for transportation at room temperature (25°C). For the transportation of dry ice blocks (600 kg) in the form currently sold by PanGas (Marianna, 2021), the requirement of 63 trucks per year is only slightly higher than for liquid transport, assuming that a load weight of 25 t per truck must not be exceeded.

Transport with diesel-powered trucks produces CO_2 emissions. For a Euro 6 emission standard truck with a load weight of 25.2 t/LCO_2, the emissions are 33.2 g CO_2eq/tkm and thus 836 g CO_2eq/km (Verein mobitool, 2023). Assuming that the truck would only travel back and forth between the biogas plant and the customer, the emissions per kilometre are 0.06 kg CO_2eq/t LCO_2. At a distance of 100 km, the transportation, including the return journey of the empty truck, causes around 12 kg CO_2eq/t LCO_2. At a distance of 100 km, the transport emissions are thus around 1.2 % of the transported LCO_2.

4.3.2 Pipeline transportation

According to Simon Staufer (Neustark AG), the transportation of comparatively small amounts of gaseous CO_2 via pipelines is only economically advantageous compared to truck transport at distances of a maximum of 300 meters (personal communication, 09.08.2023). For transport of large quantities of CO_2 via longer pipelines, the CO_2 needs to be liquefied or compressed to the supercritical state so that the pipe diameter can be kept small. Worldwide, CO_2 pipelines amount to a total length of more than 6,500 km. Most of these are operated in the US for EOR projects (Bui et al., 2018). For example, since the year 2000, CO_2 has been transported via a 320 km long pipeline from the North Dakota Beulah synfuels plant in North Dakota (USA) to the Weyburn oil field in Saskatchewan (Canada). The lifespan of this oil field can be extended by more than 25 years with CCS-EOR and it is expected that 40 million tonnes of CO_2 will be transported over its lifetime (Bui et al., 2018).

In the future, a CO_2 pipeline network for CCS applications is to be created in Europe. There are concrete plans for various storage sites in several European countries.

5 Utilisation options for CO_2

A market for CO_2 utilisation already exists due to demand from various industries. In the chemical industry, CO_2 serves as a raw material for syntheses. In the food industry, high purity CO_2 (food quality) is mainly used as carbon dioxide for drinks, but also for packaging products in a protective atmosphere. Other industries that require high-quality CO_2 include research & development and the storage of fruit and berries. Lower quality CO_2 (industrial grade) is used in greenhouses for 'air fertilisation' to increase vegetable growth, or as a coolant (R744) for refrigerators or heat pumps, for water treatment in wastewater treatment plants, as an inert gas for laser cutting and welding, or as dry ice for cooling (food industry, chemical industry or medical technology). It is also conceivable that in the future, large quantities of synthetic fuels will be used in Switzerland for aviation or high-temperature processes, for example. CO_2 is used as a raw material in almost all synthesis routes. Another option for using CO_2 would be not to burn synthetically produced hydrocarbons, but to use carbon for the manufacture of products such as outdoor clothing, toothbrushes or car tyres.

5.1 Is the utilisation of biogenic CO_2 a climate protection measure?

In Switzerland, around 60,000 – 70,000 tonnes of CO_2 are used annually, around 80 % of which is used in the beverage industry (see Section 2.1). When CO_2 is recycled, it returns to the atmosphere after use.

When biogenic CO_2 is utilised, a CO_2-neutral activity can - in the best case - be achieved[13]. Negative emissions, on the other hand, are not possible through utilisation, only permanent storage allows the permanent removal of CO_2 from the atmosphere.

Looking at the system as a whole, the question arises as to whether the utilisation of biogenic CO_2 actually leads to fewer climate-relevant CO_2 emissions globally. To answer this question, the current and future supply chains of CO_2 must be considered. The use of biogenic CO_2 instead of fossil or geogenic CO_2 only leads to a reduction in climate-relevant CO_2 emissions if fossil or geogenic CO_2 is produced or extracted specifically for one activity (e.g. carbonation of sweet drinks). In Switzerland, most of the CO_2 used is a by-product of ethylene or ammonia production. In most cases, the hydrogen for ammonia production is obtained by reforming natural gas, which produces CO_2 as a by-product (see Section 2).

Replacing fossil CO_2 from natural gas reforming with biogenic CO_2 does not necessarily lead to fewer fossil CO_2 emissions. If the ammonia industry no longer has any customers for its by-product, it could simply release it unused into the atmosphere. This risk is referred to as *leakage* when it comes to projects to reduce emissions with certificates (see Section 7.2). Nevertheless, various expected developments in terms of supply and demand for biogenic CO_2 indicate that purified and liquefied biogenic CO_2 from biogas plants could become a sought-after raw material in Europe in the future. For example, since the rise in natural gas prices as a result of the Russian war of aggression against Ukraine, the European ammonia industry has been producing less ammonia and therefore less CO_2. On the other hand, a large supply of biogenic CO_2 could also arise in the future if waste incineration plants begin to capture their CO_2 emissions. The material burned in waste incineration plants is considered 50 % biogenic and consequently 50 % of the CO_2 is also considered biogenic.

5.2 Utilisation in the food industry

As already mentioned in Section 2.1, the food industry in Switzerland is the most important consumer of CO_2 and the CO_2 must be of high quality. The quality standards and requirements for verification are defined by the European Industrial Gases Association (EIGA, 2017). At Linde Gas GmbH, for example, CO_2 can be obtained from biogenic sources that meet the EIGA standards. The information on the maximum concentrations of the various components of this product is shown in Table 5. The purity must be at least 99.9 %.

[13] Only in a completely decarbonised economic system is it possible to carry out activities in a completely CO_2-neutral way. In the current system, indirect CO_2 emissions always occur in the upstream or downstream value chain, e.g. for the construction of machines or for the production of electricity for liquefaction of CO_2.

Table 5 Minor components BIOGON ® C, E290 liquid (EIGA / ISBT), **ppm** from (Linde Gas GmbH, 2023)

CO	≤ 10
Methanol	≤ 10
Total sulphur	≤ 0.1
Phosphine	≤ 0.3
Taste and odour in water	≤ no foreign taste or odour detectable
H_2O	≤ 20
NH_3	≤ 2.5
NO	≤ 2.5
NO_2	≤ 2.5
non-volatile components	≤ 10 mg/kg
non-volatile organic components	≤ 5 mg/kg
volatile C_nH_m (calculated as methane)	≤ 50 ppm, of which<20 ppm is not methane KW
acetaldehyde	≤ 0.2
benzene	≤ 0.02

Leading food and beverage producers will only accept liquefied CO_2 from a source that they have analysed themselves (European Biogas Association [EBA], 2021). Before accepting a supply of liquid biogenic CO_2 from anaerobic digestion, they assess the risks associated with the source (i.e. fluctuations in feedstock supply and the risks of unknown components). It is therefore more difficult for a biogas plant to qualify than a source based on chemical processes or a bioethanol plant with a relatively constant feedstock. An anaerobic digestion plant should aim to maintain a stable mixture of feedstock over a year and ensure that the purification process is designed for a wide range of different impurities. The EBA also refers to the EIGA specific guidelines for the 'source qualification' of liquefied CO_2 from biogas sources (EBA, 2021):

1. A risk analysis must be carried out to consider all chemical and biological health risks that affect both the feedstock and the fermentation process itself. For biogas plants fuelled exclusively by plants and their residues, the same criteria apply as for 'yeast-based fermentation sources' (as in the case of bioethanol plants), which are a widely accepted source of food- and beverage-grade CO_2 worldwide. Biogas plants using waste or a mixture of plants and waste must carry out a more detailed risk analysis.
2. Each batch of liquefied CO_2 must be analysed with regard to the minimum requirements already mentioned.
3. Any change to the feedstock requires authorisation and revision of the risk assessment.
4. The biogas plant and its feedstock must comply with the European Implementing Regulation 142/2011 on CO_2 quality for the food and beverage sector.

The EBA also strongly recommends setting up a food safety management system (e.g. ISO 22000) in the anaerobic digestion plant.

5.2.1 Quality control challenge

Unisensor Sensorsysteme GmbH and Comtecswiss LTD sell analysers that use optical absorption spectroscopy to determine the amount and type of contamination. The quality requirements of the International Society of Beverage Technologists (ISBT) can be met based on the analysis results from these devices. The various devices measure a different number of different substances as standard: there are 16 for the smaller carboscan150 device from Unisensor, 22 for the larger carboscan300 device and 20 for the CARBONIC 4401 device from Comtecswiss LTD. The investment costs are around CHF 250,000 – 350,000. In recent years, Unisensor has supplied carboscan300 to several European biogas plants, which liquefy CO_2 and sell it to gas traders. For the operators oft the biogas plant in Wittenbach, it might be an option to procure and operate one of these analysers in the future. Nevertheless, for safety reasons, the gas should only be sold to gas traders who also carry out their own more comprehensive quality control or the gas could be supplied to customers with lower quality requirements. In order for gas traders to be willing to transport CO_2, a minimum quality control requirement is usually set, as the risk of contamination of tanks for transport by truck due to contaminated CO_2 represents a major business risk. However, the procurement costs for the analyser are only one challenge. If the aim were to carry out comprehensive quality control in Wittenbach itself, trained personnel would have to be employed for this purpose.

So far, Swiss gas traders have hardly any experience with CO_2 from biogas plants and are therefore sceptical when it comes to quality until they have carried out their own in-depth risk analysis. An additional challenge in quality control is the fact that those substances that are expected to be contaminants are measured. If a new impurity suddenly appears, it is recognised under normal circumstances that an unknown substance is present. To find out which substance it is, a sample must be sent to the laboratory and analysed using sensitive methods such as mass spectrometers. It may take several weeks for a substance to be identified and the CO_2 may not be able to be sold during this time. From today's perspective, it seems unlikely that CO_2 with EIGA quality will soon be sold in Wittenbach due to the high costs of investing in and operating the analyser.

5.2.2 Controlled atmosphere for fruit and berry storage

In fruit and berries storage, CO_2 is not added to the food as it is in the beverage industry. Nevertheless, the quality requirements for CO_2 in this application also fulfil EIGA standards, as the food comes into direct contact with highly concentrated CO_2. A controlled atmosphere is required for the optimal storage of fruit over a longer period of time. For optimum colour and flavour intensity, soft fruit should only be harvested when it is ready to eat as it does not continue to ripen after harvesting, unlike apples or bananas, for example. The controlled atmosphere of soft fruit is therefore defined by lower temperatures and an increased CO_2 content in the air, which slows down the metabolism and thus the decay of the berries while also reducing the risk of fungal infections. The optimum CO_2 content in the gas mixture for the controlled atmosphere for storage is between 10 % and 20 %, depending on the berry (Neuwald & Klein, 2017).

The demand for CO_2 from soft fruit producers near Wittenbach (such as Tobi Seeobst AG) is subject to strong seasonal fluctuations. At Tobi Seeobst AG, demand totals 20 tonnes of CO_2 for the period from mid-May to November. To distribute the total amount of CO_2 produced by the Wittenbach biogas plant, it would therefore be necessary to be able to supply around 75 soft fruit producers of the same size as Tobi Seeobst AG. In addition, high storage capacities would be required to temporarily store the CO_2 quantities produced by the biogas plant in winter (approx. 120 tonnes of CO_2 per month).

5.3 CO_2 fertilisation in greenhouses for vegetable production

Many vegetable farms 'fertilise' the air in their greenhouses with CO_2 to optimise plant growth. This can increase plant growth by 15 % to 40 % (EBA, 2021). The Netherlands is currently the leader in CO_2 fertilisation, where around 500,000 tonnes of CO_2 per year were purchased on the market for fertilisation in greenhouses in 2015 (Alberici et al., 2017). Vermeulen (2015) estimates that, including exhaust gases from heating systems, around 5 million tonnes of CO_2 were used and that the demand for CO_2 could even amount to up to 10 million tonnes of CO_2 per year if CO_2 were available in these quantities at low cost. In the Netherlands, the CO_2 concentration in the greenhouse is kept at 400 – 800 ppm in winter and at 50 – 100 ppm above the 'natural' CO_2 concentration in the air of 400 ppm in summer (Vermeulen, 2015). In summer, the CO_2 concentration is lower because the windows of the greenhouses have to be open so that it does not get too hot.

In contrast to the food industry, there are still no quality standards for CO_2 fertilisation in Switzerland. Therefore, CO_2 of 'industrial grade' quality could be supplied to greenhouses, meaning quality controls could be dispensed with. What must be taken into account, however, are the SUVA emission limits for ensuring workplace safety (SUVA, 2023a, 2023b). The limit value in the case of carbon monoxide (CO) is 30 ppm or 35 mg/m^3. The exact composition of raw biogas and therefore also of the off-gas stream varies depending on the source substrate and fermentation process. Raw biogas from agricultural residues contains a maximum of 1 % CO (Chen et al., 2015). It is therefore important to measure the CO concentration in the greenhouse and, for example, ensure that it is diluted by ventilation before the limit value is exceeded.

The authors are not aware of any estimates of today's CO_2 requirements for greenhouses in Switzerland. As most vegetable farms have heated their greenhouses with gas heating systems up to now, the exhaust gas from the heating system could be fed into the greenhouse for air fertilisation. However, from 2026 at the latest, Migros will oblige vegetable growers to only heat greenhouses using renewable energy and not to use fossil CO_2 for air fertilisation (Steiger, 2021). Companies that have switched to heat pumps or are in the process of doing so will not have their own CO_2 for air fertilisation. Daniel Stüssi, energy consultant at the Competence Centre for Renewable Energy Systems Thurgau (KEEST), estimates that around half of the 450 hectares of greenhouses in Switzerland will have to rely on purchased CO_2 for air fertilisation in the future and that 100 tonnes of CO_2 will have to be purchased per hectare per year. On this basis, he assumes an additional Swiss CO_2 requirement of around 23,000 tonnes of CO_2 per year (Daniel Stüssi, personal communication, 14.11.2023).

In order to find interested customers for the biogas plant planned in Wittenbach, contact was made with vegetable farms within a radius of approx. 100 km from Wittenbach. Hans Ott's vegetable farm and other farms in the cantons of Thurgau and St. Gallen are potentially interested in purchasing the biogenic CO_2. With an estimated annual requirement of 400 tonnes of LCO_2, the Ott vegetable farm would in principle be an interesting customer and its demand is therefore analysed below as an example for vegetable farms, as the challenge in supplying vegetable farms is the seasonal fluctuation in demand (Figure 8). April is the only month in which demand accounts for more than 80 % of Wittenbach's production. In May, the value falls to 60 % and then remains at around one third from June to the end of October. From November to February, the Ott vegetable farm has no demand. In contrast, the production of CO_2 from the biogas plant in Wittenbach hardly fluctuates. Only very small seasonal fluctuations in the raw biogas yield and therefore CO_2 production are expected due to fluctuations in the composition of the biomass substrate.

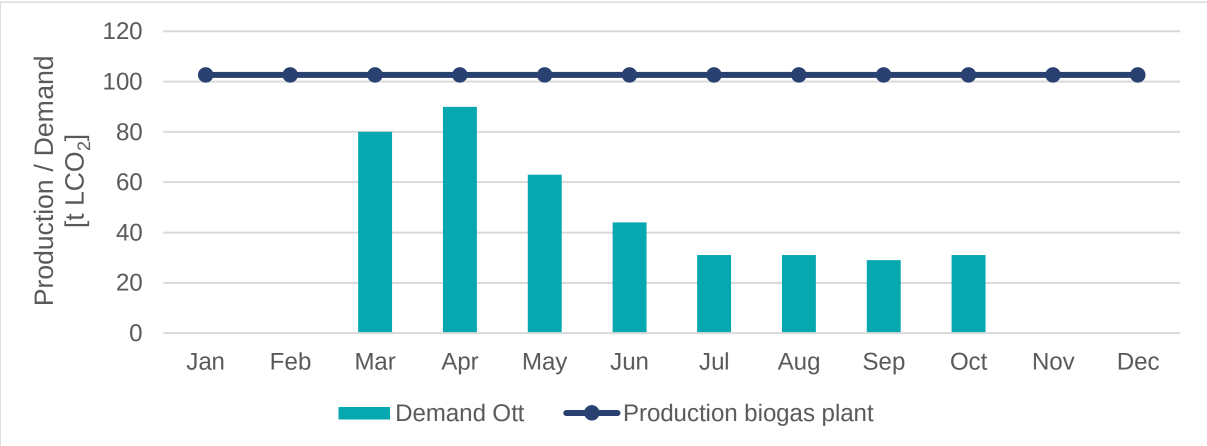

Figure 8 Monthly demand for liquid CO_2 of the Ott vegetable farm compared to the expected CO_2 production in Wittenbach.

If two more vegetable farms with a similar CO_2 requirement to the Ott vegetable farm were found, the entire annual amount of CO_2 produced in Wittenbach could theoretically be sold directly to the vegetable farms without involving gas traders. However, due to the strong seasonal fluctuations, storage capacities of up to 280 tonnes of LCO_2 would be required. Standard tanks (30 t LCO_2 or 300 t LCO_2) can be provided by gas suppliers for CHF 100,000 or CHF 500,000 per tank (Heinz Peyer, personal communication, 13.11.2023). These prices include the infrastructure costs and the costs for the filling station for trucks. In addition to the investment costs, the space required for the tanks would be a further challenge for biogas plant operators or vegetable growers. Moreover, it would hardly be possible to match demand precisely to production. If the production from Wittenbach were not able to not cover the entire demand, the vegetable farms would have to purchase small quantities of CO_2 on the market, which could also pose a challenge under certain circumstances.

The direct supply of vegetable farms would be less problematic if it were combined with other customers whose CO_2 consumption peaks are in winter or who can flexibly purchase CO_2 from various suppliers. From today's perspective, however, it would also be difficult to find such customers in the vicinity of Wittenbach. Most companies have either a constant or an increased demand in spring and summer and are currently only supplied by one provider.

5.4 Synthetic fuels

Synthetic fuels (also known as eFuels) are interesting for CO_2 utilisation because they can be introduced directly into a market with an existing infrastructure (Bazzanella & Krämer, 2017). Most fuels are synthesized via the intermediate step of methane, syngas or methanol (Figure 9). The direct hydrogenation of CO_2 to CH_4 (methane) is the most widely used technology worldwide to produce synthetic methane. Large quantities of hydrogen are required for the reactions. 'Green' hydrogen is produced by electrolysis. For the process to be truly 'green' (climate-friendly), the electricity for electrolysis must come from renewable sources. This could make sense for the entire Swiss energy system if surplus electricity from renewable energy sources could be used (Schemme et al., 2020). In none of the projects realised in Switzerland to date has the electrolysis for hydrogen production been operated solely with 'surplus' renewable electricity. In most cases, electrolysis draws its electricity from a run-of-river power plant (e.g. the Eniwa AG project on the River Aare). This is also due to the fact that few projects have currently been realised in this field and the capacity utilisation of electrolysis devices would often not be sufficiently high for economic operation if only 'surplus' renewable electricity were to be used (Sperr & Rohrer, 2018).

Currently, the final costs for the production of synthetic fuels are still too high to be competitive (Biollaz et al., 2017; Glenk et al., 2023).

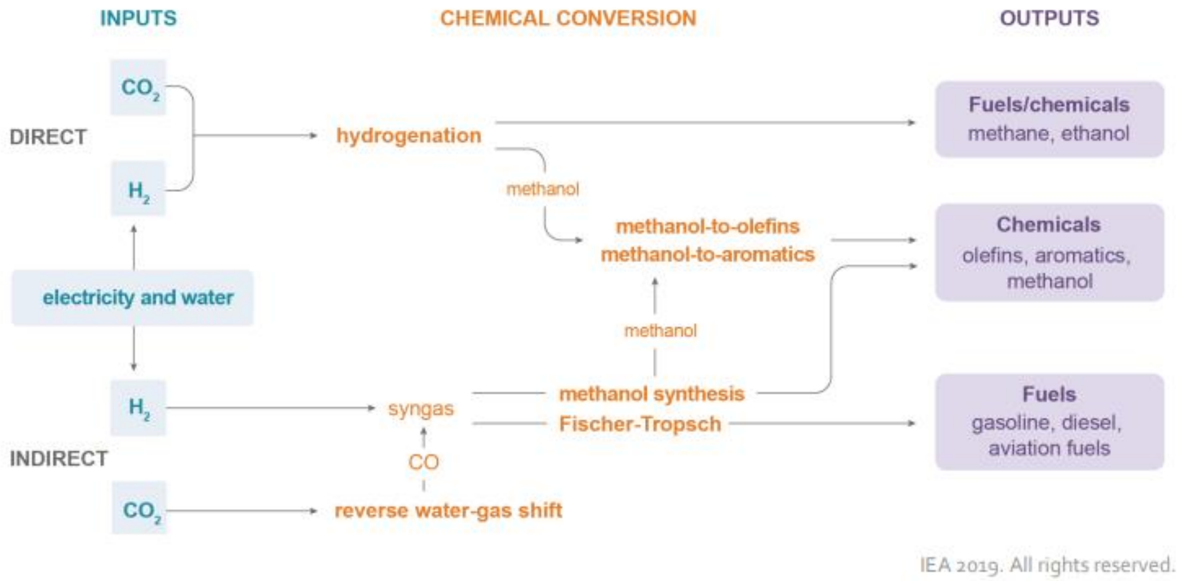

Figure 9 Various synthesis routes for synthetic fuels (IEA, 2019).

The direct hydrogenation of CO_2 is already being used in some projects in Switzerland. At the sewage sludge fermentation plant of the Limeco WWTP (Dietikon) the CO_2 from the sewage gas, which consists of approx. two thirds methane and one third CO_2, is hydrogenated to produce synthetic methane. This means that 18 GWh of biomethane and synthetic methane are fed into the gas network every year (Limeco, 2023). For methane synthesis, CO_2 and hydrogen from electrolysis are converted in a bioreactor. As methanisation takes place in a closed system, emission-free operation can be guaranteed.

Based on an assumed price of 10 to 12 Rp/kWh for biomethane that can be fed into the grid, the maximum electricity costs must not exceed 3.5 to 4.5 Rp/kWh (including grid fees and taxes) so that electrolysis for hydrogen production can be operated economically (Biollaz et al., 2017; Witte et al., 2018). Although current biogas prices are higher than in 2017 and 2018, electricity prices have also risen. Limeco uses electricity from the waste incineration plant for electrolysis, where steam turbines are driven by heat from waste incineration. This type of electricity generation is not CO_2-neutral according to the *Greenhouse Gas Protocol* standard, unless CCS systems are installed at the MSWI plant (Alig et al., 2017). The synthetic biomethane produced by Limeco in Dietikon is therefore not CO_2-neutral. The influence of the origin of the electricity on the greenhouse gas balance of the hydrogen produced by electrolysis is discussed in the next subsection.

In the future, the method the start-up Methanology uses for producing methanol, which electrochemically reduces CO_2 and water directly to methanol using biocatalysts, could be of interest (Schlager et al., 2016). The efficiency is currently only at 20 %. According to the start-up, the efficiency could be massively increased (up to 80 %) with more research and development in the coming years. If this were successful, this type of methanol production would be more efficient than the production of hydrogen for methane production or the production of methanol via the intermediate step of synthesis gas (syngas).

5.4.1 Comparison of GHG emissions of synthetic methane and natural gas

No fossil GHG emissions are produced during the combustion of synthetic methane. The emission factor for fossil methane consists of the CO_2 emissions resulting from combustion (direct CO_2 emissions 202 t CO_2eq/GWh LHV) and indirect methane emissions from the upstream value chain, which amount to 12 t CO_2eq/GWh for natural gas from Norway, 90 t CO_2eq/GWh for natural gas from Russia and 97 t CO_2eq/GWh for liquefied natural gas (LNG) from Algeria, calculated with a GWP over 100 years. With a GWP over 20 years (see Section 4.1), indirect emissions are much higher, for example for LNG from Algeria, at 158 t CO_2eq/GWh (Baumann & Schuller, 2021; Münter & Liebich, 2023). The potential to reduce fossil GHG emissions by substituting 1 GWh of fossil natural gas with synthetic gas is therefore a maximum of 214 t CO_2eq to 360 t CO_2eq, depending on the origin of the natural gas and the time horizon considered (GWP100 or GWP20).

With an emission factor for the Swiss consumer electricity mix of 0.128 t CO_2eq/MWh (Krebs & Frischknecht, 2018), on the other hand, around 204 t CO_2eq/GWh of indirect emissions result from the provision of electricity for electrolysis. The comparison of CO_2 emissions per GWh (LHV) in Figure 10 shows that substituting natural gas with synthetic methane only contributes to decarbonisation if only renewable electricity is used for electrolysis, such as PV electricity with an emission factor of 42 t CO_2eq/GWh (Krebs & Frischknecht, 2018) or fossil gas with very high indirect emissions, such as LNG from Algeria or pipeline gas from Russia, is replaced.

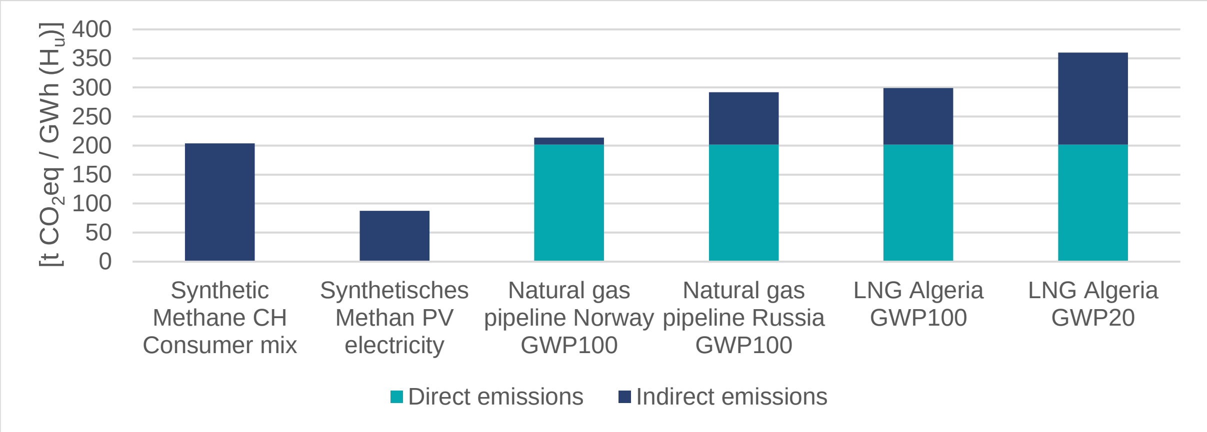

Figure 10 Comparison of GHG emissions in t CO_2eq for the provision and combustion of 1 GWh of synthetic methane or natural gas. The Swiss consumer electricity mix and electricity from photovoltaics (PV) were used to calculate the indirect emissions from electricity production for electrolysis for hydrogen production, which is required for methane synthesis. For the indirect emissions of fossil gas, values from a study by Münter and Liebich (2023) are given with GWP100 in each case. The last column also shows GWP20 for LNG from Algeria for comparison.

5.4.2 Potential to produce synthetic fuels in Wittenbach

Electrolysis to produce the required hydrogen would consume 12.6 GWh of electricity annually and the additional synthetic methane yield would be around 6 GWh (LHV) annually[14]. This corresponds to 0.02 % of the average annual Swiss natural gas imports over the last 10 years[15]. The synthetic gas could be fed into the natural gas grid in addition to the biomethane produced in the fermentation process of around 9 GWh. The efficiency in terms of electricity consumption of 13 GWh of electricity to 6 GWh of synthetic methane would be 47 %. Since no large quantities of 'excess' renewable electricity are expected in Wittenbach in the next few years (Stocker et al., 2023), it does not seem to make much sense from today's perspective to produce synthetic methane in Wittenbach.

5.4.3 Production and use of synthetic fuels in Switzerland

The potential of synthetic fuels to decarbonise Switzerland should not be overestimated. The use of synthetic fuels makes sense for high-temperature processes and air traffic, as these areas are difficult to electrify. Using synthetic fuels for motorised private transport or heating buildings would make little sense due to their poor energy efficiency. This is illustrated by the following figures: in 2021, according to the Swiss Greenhouse Gas Inventory published by the Federal Office for the Environment, Switzerland produced CO_2 emissions from the combustion of fossil fuels amounting to around 34 million tonnes of CO_2 (FOEN, 2023b). Averaged over the last 10 years, the import too Switzerland of oil amounted to 110 TWh and the import of natural gas to 34 TWh (SFOE, 2023a).

Emissions from international air traffic are not included in the 34 Mio. t CO_2 mentioned above. In the greenhouse gas inventory, these emissions are calculated on the basis of fuel sales at Swiss airports. For 2019, emissions of 5.9 million tonnes of CO_2 from kerosene refuelled in Switzerland were reported in the Swiss greenhouse gas inventory. This corresponds to a kerosene volume of 22.5 TWh (SFOE, 2020). The CO_2 emissions were calculated using the emission factor for the combustion of the kerosene without multiplying by the *Radiative Forcing Index (RFI)* or *Emission Weighting Factor (EWF).* As mentioned in the footnote on page 10, the 5.9 million tonnes of CO_2 would actually have to be multiplied by a factor of 3, which means that the climate-relevant figure for the total greenhouse gas emissions from air traffic is around 18 million tonnes of CO_2 eq. By replacing fossil fuels with synthetic fuels for air traffic, there is potential that the RFI factor could also be reduced (less soot is emitted and therefore less

[14] With an efficiency of 70 % in relation to the lower calorific value (LHV) of H_2.

[15] Between 2012 and 2022, Switzerland imported an average of 33.6 TWh of natural gas per year.

aerosol formation is expected). However, an RFI factor of 1 is not to be expected. Therefore, synthetic fuels alone are not a sufficient measure for climate-neutral air traffic.

As described in Section 1.2, the sustainable potential for the production of Swiss biomethane from non-wooded biomass is 5.7 TWh per year (Thees et al., 2017). When kerosene is produced on the basis of biomethane, there are conversion losses. Switzerland's total sustainable biomethane potential would therefore not be sufficient to meet the fuel needs of air traffic if this were to rise again in the longer term to or above the level before the coronavirus pandemic in 2019.

In order to achieve Switzerland's net-zero target, a reduction in energy and material consumption should be sought wherever possible through efficiency and/or sufficiency measures and electrification. Replacing the amounts of fossil fuels used today with synthetic gases is unrealistic for reasons of land availability and cost. If the average annual import of natural gas of 34 TWh were replaced by synthetic methane, a simplified calculation indicates that 7 million tonnes of CO_2 would have to be captured annually from biomass or from the air and made available to produce synthetic fuels. This is around 6,000 times more than the CO_2 that is expected to be produced annually in the planned biogas plant in Wittenbach. This calculation does not consider the amount of CO_2 required, in case also imported oil was replaced with synthetic fuels.

5.5 Concluding remarks on utilisation of CO_2 from the planned biogas plant in Wittenbach

The main exclusion criterion for the option of purifying the CO_2 to food quality and selling it to gas traders with appropriate quality control is the lack of economic viability. In addition to the liquefaction plant, this option would require investment in and the operation of an analyser to monitor the remaining impurities. The labour and investment required to carry out quality control in accordance with food industry standards makes this option uneconomical for the comparatively small quantities (1,230 tonnes of CO_2/year). Alternatively, comprehensive quality control could be dispensed with and the CO_2 could be sold to gas traders with industrial grade. Today, however, there are only a few gas traders who have their own logistics for industrial grade CO_2. Carbagas AG, for example, only has logistics for food-grade CO_2. There is a risk of contamination when filling truck tanks with low-quality CO_2.

Even without investing in and operating an analyser, the production costs at the Wittenbach site are CHF 100 – 150 per tonne of liquid CO_2 (see Figure 12). These costs are higher than the Swiss market price for liquid CO_2 in recent years (60 – 80 CHF/t LCO_2). The sale of climate protection certificates could possibly generate additional income. However, this would only be advisable if the benefit for the climate from the utilisation of biogenic CO_2 could be clearly quantified. If biogenic CO_2 were to replace geogenic CO_2 from source fields, climate-relevant emissions could be reduced. However, since it can be assumed that geogenic CO_2 accounts for only a small proportion of the Swiss CO_2 market, the climate impact of the CO_2 utilisation variant is estimated to be low (see Sections 2.2.4, 0 and 7.2). Therefore, it is not recommended to pursue a climate protection project for the utilisation of CO_2.

In the spring and summer months, it is possible to sell some of the CO_2 to vegetable growers for air fertilisation of the greenhouses. For this application, there are currently no quality requirements for CO_2 in Switzerland, which is why there is no need for an analyser for quality control. Demand from vegetable growers varies seasonally (see Figure 8). Due to seasonality, this solution of CO_2 utilisation would have to be combined with another flexible CO_2 demand or a certain CO_2 storage capacity would have to be installed. The former could be associated with a lower purchase price, the latter with additional costs for storage. Provided that the vegetable growers are willing to either invest in storage themselves or pay a price that either covers the storage costs or compensates for the shortfall in revenue from the combination with another flexible demand, some or all of the CO_2 could be sold to vegetable growers.

The production of synthetic fuels from the CO_2 produced in Wittenbach is not economically feasible from today's perspective and does not make sense from an ecological point of view, as there is no 'excess' renewable electricity available.

Instead of utilisation, permanent storage of the CO_2 is also possible either in demolition concrete or in underground geological deposits. These possibilities are described and discussed in the following section.

6 Permanent storage of CO_2

An alternative to the utilisation of biogenic CO_2 is to store it as permanently as possible over a period of at least several hundred years. In this way, CO_2 can be removed from the atmosphere (negative emission). The process is known as BECCS (see Section 1.1). In Europe today, there are two main options for permanent storage: one, the mineralisation and thus permanent binding of CO_2 in demolition concrete, and two, CO_2 can be stored underground in the rock. These two options are described below.

6.1 Permanent storage in demolition concrete

The cement and concrete industry causes high greenhouse gas emissions and will not be able to prevent these completely. Cement production requires the burning of clinker, which releases geogenic CO_2 (FOEN, 2022b). One solution to achieve a better CO_2 balance in this sector in the long term is the implementation of CCS. One of the options is to store CO_2 in demolition concrete.

Each concrete is made from a mixture of water, cement, and aggregates in different fractions. The aggregates can consist of primary raw materials (gravel and sand) or secondary raw materials, so-called recycled aggregates. Recycled aggregates for use in high-quality types of concrete are predominantly made from demolition concrete. The demolition concrete is prepared for this purpose, i.e. crushed and sieved into the various fractions (Robineck et al., 2023).

When the cement is mixed with water and sand or gravel, the cement components react to form calcium silicate hydrate, calcium hydroxide and ettringite, among other things, which cause the concrete to harden. These substances can absorb CO_2 from the air and store it in the form of calcium carbonate (limestone, $CaCO_3$). Under normal conditions, this process takes place over years. As a result, 10 to 15 % of the CO_2 emissions caused by cement production can be bound again over the lifetime of the concrete (Cames et al., 2023). In order to increase the amount of CO_2 stored in concrete and to accelerate the carbonation process, concentrated CO_2 can be sprayed onto dry demolition concrete granules in a technically sealed system. With this process, the demolition concrete can bind up to 30 % of the CO_2 emissions generated during cement production for this amount of concrete from the combustion of fuels and during calcination (Leemann & Nygaard, 2012).

CO_2 that mineralises to $CaCO_3$ is considered permanently stored. As the CO_2 undergoes a chemical reaction and is fixed as a $CaCO_3$ mineral, the concrete can be fed into further recycling cycles or landfilled without releasing the bound CO_2 into the atmosphere (Tiefenthaler et al., 2021). Through mineralisation, the CO_2 is permanently and irreversibly bound under normal conditions of use. Furthermore, the addition of recycled demolition concrete in the production of new concrete can lead to a reduction in the amount of cement used, which can improve the carbon footprint of the concrete (Tiefenthaler et al., 2021).

Tiefenthaler et al. (2021) estimate that, based on the 5 million tonnes of concrete demolition waste generated in Switzerland in 2021 and a recovery rate of 85%, a storage potential of 0.035 million tonnes of CO_2 could be technically tapped. Tiefenthaler et al. (2021) also estimate that the amount of demolished concrete in Switzerland will increase linearly to 40 million tonnes by 2050. This corresponds to a storage potential of 0.560 million tonnes of CO_2 in 2050. The estimate is based on the assumption that concrete structures have a service life of 80 years. The amount of concrete used in recent years was determined on the basis of the historical geogenic emissions from Swiss cement production. The annual geogenic emissions of cement production amounted to 2.63 million tonnes of CO_2 in 2019 (cemsuisse, 2021). If they remain constant until 2050, around 20 % could then be bound in demolition concrete.

In addition to demolition concrete, other mineral waste streams (e.g. slags) with high oxide contents are also suitable for the permanent binding of CO_2 by mineralisation. Before the maximum storage capacity for these further waste streams can be estimated, more data on their life cycle and chemical properties must be collected (Simon Staufer, personal communication, 07.09.2023).

6.1.1 Active Swiss companies in the field of permanent CO_2 storage in demolition concrete

In Switzerland, Neustark AG, Zirkulit AG and Sika Schweiz AG are currently developing business models to utilise the CO_2 sink capacity of processing demolition concrete with CO_2.

Neustark AG's strategy is to equip (semi-) stationary concrete recycling plants with its CO_2 technology and at the same time to find a suitable supplier for biogenic CO_2 for each recycling plant. Neustark AG takes care of the transport and provision of the liquefaction plant and the intermediate storage facility, if required by the operator of the biogas plant. The CO_2-enriched concrete granules can be used, for example, as loose ballast material or in recycled concrete. The carbonation technology of Neustark AG can store around 10 kg of CO_2 per tonne of concrete granules (Neustark AG, n. d.). Neustark AG currently obtains CO_2 in Switzerland from the WWTP Region Bern biogas plant and supplies 11 Swiss CO_2 storage facilities (Neustark AG, 2023). Liquefaction facilities are planned for two other biogas plants in Switzerland. Biopower Nordwestschweiz AG in Pratteln will offer Neustark AG space for a liquefaction facility and the CO_2 from the stack (Biopower Nordwestschweiz AG, 2023). Construction is planned for the beginning of 2024 and 1,500 tonnes of CO_2 are to be liquefied annually. Another plant is planned at the Winterthur compogas facility. With its CO_2 storage technology, Neustark AG wants to permanently store 1 million tonnes of CO_2 in concrete worldwide in 2030 (Neustark AG, 2023).

Zirkulit AG uses its technology to enrich its own recycled concrete products with CO_2. At least 6.5 kg of CO_2 can be stored per tonne of concrete granules (Stiftung Klimarappen, 2023; Zirkulit Beton AG, n. d.). Zirkulit AG has been sourcing CO_2 from a biogas plant in Switzerland since 2022 and has previously partially imported biogenic CO_2 from Germany (Robineck et al., 2023).

Sika Schweiz AG also manufactures its own concrete products using the material used to bind CO_2. In the process, the demolition concrete granulate is broken down into the constituent parts of silica, sand and mineral materials (see Figure 11) and CO_2 is bound in the powdered limestone by means of a chemical additive material, which can be used to produce concrete (Müller, 2021; Stiftung Klimarappen, 2023). With this technology, approx. 60 kg of CO_2 can be bound per tonne of crushed concrete demolition material (Sika Schweiz AG, 2021).

Figure 11 Schematic representation of Sika's recycling and CO_2 enrichment process (Sika Schweiz AG, 2021)

The storage of biogenic CO_2 from biogas plants in demolition concrete does not require cost-intensive quality controls of the CO_2, as would be the case with the supply to the food industry. From today's perspective, this option is therefore very interesting for operators of biogas plants. However, the question arises as to whether it will be possible in the long term to release CO_2 from an industry that itself has high CO_2 emissions, which could also be captured and bound in demolition concrete. In view of Switzerland's net-zero target, it is very likely that the cement industry will be legally obliged to capture and permanently store CO_2 (CCS) generated during cement production in the coming decades. It seems obvious that the cement industry itself will utilise the sink potential of demolition concrete for this purpose. As shown in Section 6.1, the cement industry could thus permanently store around 20 % of its annual geogenic emissions.

6.1.2 Potential consumers of CO_2 from the biogas plant in Wittenbach

Discussions have been held with Neustark AG and Zirkulit AG. Both companies are interested in taking the CO_2 from the biogas plant in Wittenbach. Both customers take the CO_2 either in the gaseous state directly from the stack or in liquid form. The price for the purchase in the gaseous state is lower, since the cost of CO_2 liquefaction would be borne by the buyers (see Table 6). Biogas plant operators are essentially compensated with the price of gaseous CO_2 for providing space for the liquefaction plant. Both Neustark AG and Zirkulit AG raised the prospect of an electricity price clause in the purchase agreement, which means that the purchase price for the liquid CO_2 would be adjusted to fluctuations in the electricity price. However, the underlying assumptions for the electricity price were not communicated.

Table 6 Potential purchase prices for CO_2 from Neustark AG and Zirkulit AG for gaseous or liquid CO_2 (Simon Staufer, personal communication, 07.09.2023, Reto Märki, Zirkulit AG, personal communication, 14.09.2023)

Customer	Annual minimum quantity desired	Price gaseous CO_2	Price liquid CO_2
	[t CO_2/a]	[CHF/t CO_2]	[CHF/t CO_2]
Neustark AG	1,000	15	80 – 120
Zirkulit AG	1,500	5	100 - 150

Laveba has carried out an economic calculation for the installation and operation of a CO_2 liquefaction plant. As high quality is not required for storage in demolition concrete, there is no need to invest in a cleaning unit (stripper/reboiler) or an analyser for quality control. Furthermore, there are no operating and maintenance costs for quality control. Based on Laveba's assumptions about the investment and operating costs of the CO_2 liquefaction plant, the production costs for liquid CO_2 shown in Figure 12, depending on the electricity price. It is assumed that the investment costs are CHF 610,000 and the electricity consumption of the liquefaction plant is 250 kWh/LCO_2.

Based on the information on the potential purchase prices in the discussions with Neustark AG and Zirkulit AG (see Table 6), it can be assumed that both companies could very probably agree with Laveba on a price that would enable the CO_2 liquefaction plant to be operated economically.

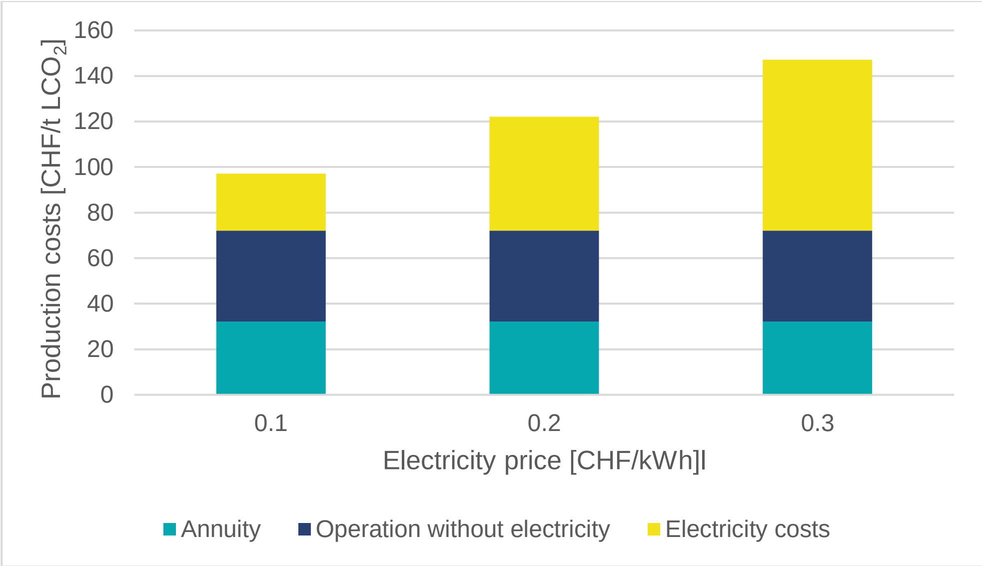

Figure 12 Production costs per tonne of liquid CO_2 (LCO_2) depending on the electricity price for the liquefaction.

Sensitivity analyses for the parameters 'investment costs' and 'electricity consumption per liquefied tonne of CO_2' are shown in Figure 13 and Figure 14. It can be seen that only a combination of the most important parameters that is very unfavourable for Laveba would leave no margin between the production costs and the purchase price range of Neustark AG or Zirkulit AG. If, for example, at an investment cost of CHF 610,000, the electricity price were 30 Rp/kWh or more and the electricity consumption of the condensing plant were 300 kWh/t LCO_2 instead of the expected 250 kWh/t LCO_2, a higher purchase price would have to be negotiated. The same applies in the event that, in combination with a high electricity price, the investment costs were to deviate by more than 50 % from the assumed CHF 610,000.

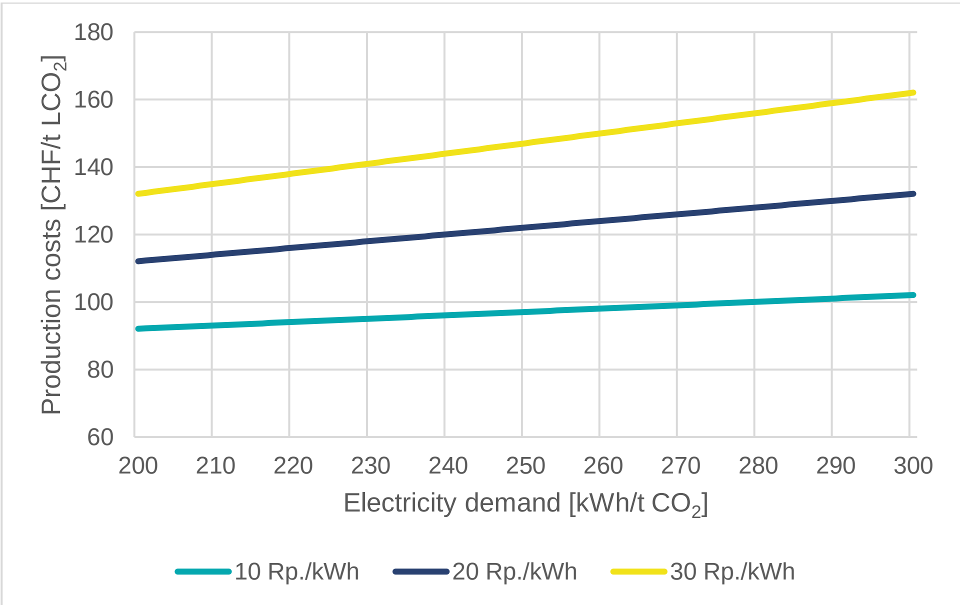

Figure 13 Sensitivity analysis for the production costs per tonne of liquid CO_2 (LCO_2) depending on the electricity consumption per liquefied tonne of CO_2 at an investment cost of CHF 610,000.

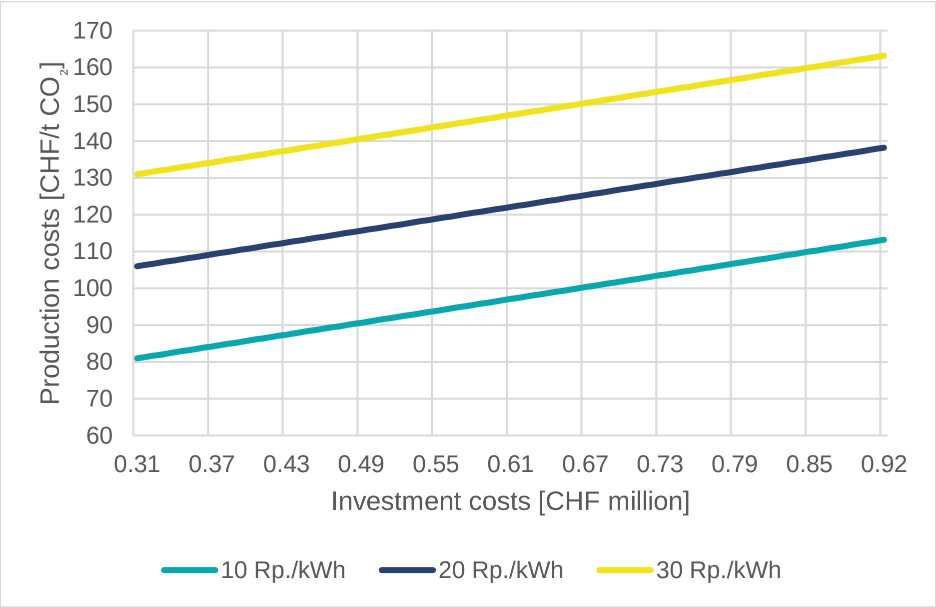

Figure 14 Sensitivity analysis for the production costs per tonne of liquid CO_2 (LCO_2) depending on the investment costs for the liquefaction plant at an electricity consumption of 250 kWh/t LCO_2.

6.2 Geological storage sites for CO_2

Another possibility for the permanent storage of CO_2 is the storage of captured CO_2 in rock layers (CCS). According to Kühn (2011), the following types of geological repositories, which can occur onshore and offshore, are suitable for geological storage:

- **Saline aquifers**: Saline aquifers are porous salt water-bearing rock layers. Due to the high salt and mineral content, the water from these rock layers is unsuitable for use as a source of drinking water. Deep aquifers are separated from the surface by an impermeable layer, which is why the gaseous CO_2 or CO_2 dissolved in water does not escape or escapes only very slowly.
- **Depleted oil and gas deposits**: Emptied natural gas and petroleum fields are also suitable CO_2 storage sites. The underground temporary storage of natural gas has already been tested and suggests that this is also possible for other gases in a supercritical state as long as the storage facility is leak-proof (EnArgus, 2023a).
- **Enhanced Oil/Gas Recovery (EOR/EGR)**: The injection of CO_2 into oil production sites means that more oil can be produced. This technology is mature (TLR of 9). The injection of CO_2 into natural gas production sites for the increased production of natural gas is not yet mature (Bui et al., 2018).

Other storage types such as coal seams, basalt rocks, oil- or gas-rich shale, salt caverns or abandoned mines are also suitable for the geological storage of CO_2 (Benson et al., 2005). In 2022, around 80 % of the capacity of all global CCS projects related to the extraction of CO_2 were operated for EOR (Global CCS Institute, 2022). Around 80 % of the CCS projects planned by 2030 envisage the permanent storage of CO_2 in the subsurface without EOR (IEA, 2023). Permanent storage in saline aquifers has the greatest potential worldwide (Benson et al., 2005; Global CCS Institute, 2022).

One point that has not yet been conclusively clarified with regard to underground CO_2 storage is the durability of the storage as well as the long-term effects of CO_2 on the rock and pore water (Benson et al., 2005). The risk of large amounts of CO_2 escaping from geological repositories in a short period of time is considered to be low. Storage locations are carefully selected on the basis of geological factors, such as impermeable cover layers as well as low temperatures and geothermal gradients. Under these conditions, CO_2 is in the supercritical state. In this state, CO_2 is the densest and can most effectively fill the pore spaces of the reservoir. Some of the CO_2 can be trapped by capillary forces. In the supercritical state, CO_2 also has a low buoyancy force, which increases storage safety (Bachu, 2003; Benson et al., 2005)

Furthermore, the risk of escaping CO_2 in saline aquifers decreases over time because CO_2 dissolves at a given salinity and corresponding temperatures and pressures, thus eliminating the buoyancy force (Benson et al., 2005). If the conditions for the carbonation process are present, under which a part of the CO_2 undergoes a mineral binding process over a time scale of a thousand years, the outer part of a CO_2 bubble is mineralised. As a result, some of the CO_2 inside the bubble is trapped and thus also immobilised (Cohen & Rothman, 2015; Kühn & Clauser, 2006). For CO_2 dissolved in water in basalt rocks, carbonation is faster and 95% of the CO_2 injected can be mineralised within 2 years (Gislason et al., 2014; Sigfússon et al., 2018). But as long as the CO_2 is not fully carbonated or trapped, there is a risk of leakage. This residual risk also applies to depleted or still operating gas deposits, in which CO_2 can either escape abruptly through leaking boreholes or successively through natural, fine cracks or fractures in the rock (Kühn, 2011). The amount of gas escaping per leaking well is currently estimated at 0.1 – 0.2% of the stored gas volume (Anthonsen & Christensen, 2021).

Because long-term monitoring and experience over several hundred or thousand years is still lacking, these reservoirs must be monitored via a complex measurement network, and escaping CO_2 must be measured (EnArgus, 2023a; SFOE, Energia plus, 2023; Fibbi et al., 2023). There are therefore also many critical voices. According to a report by the Center for International Environmental Law (CIEL), there is a risk that the release of CO_2 through leaks could lead to acidification of the oceans and harmful effects on ecosystems (Bund für Naturschutz und Umwelt Deutschland, 2023; Fendt et al., 2023). It should also be noted that previous CCS projects have repeatedly failed to meet their CO_2 capture rate targets and have faced financial and technical problems, raising doubts about their feasibility and safety (Bund für Naturschutz und Umwelt Deutschland, 2023; Fendt et al., 2023; Hauber, 2023; Rempel et al., 2023). The two Norwegian projects Sleipner and Snøhvit are often cited as examples of the feasibility of the technology. However, studies have shown that these projects cannot serve as models for the future of CCS due to unexpected geological circumstances (Hauber, 2023). The effect of regulations to monitor CO_2 injections is still untested and there are doubts about the long-term technical and financial feasibility of underground carbon storage The question of who bears the long-term risk of CO_2 storage is complex and depends on the regulatory framework and the responsibilities of the actors involved. In the case of CO_2 leaks, the costs of repairs and any damage during the entire storage period must be clarified.

For the CO_2 from the biogas plant planned in Wittenbach, underground storage would be referred to as BECCS (negative emissions). If, on the other hand, fossil CO_2 is captured from point sources (industry, cement works or waste incineration plants), this is referred to as CCS (avoidance of emissions). CCS is generally criticised because the technology is used as an excuse to postpone emission reductions into the future and to continue to adhere to fossil business models. Moreover, the high project costs are largely borne by the public, e.g. through tax credits and loan guarantees (Bund für Naturschutz und Umwelt Deutschland, 2023; Fendt et al., 2023).

The following sub-sections discuss specific storage sites and their potential in Switzerland and other European countries. This is particularly relevant with regard to Switzerland's climate strategy. This anticipates negative emissions of 2 million tonnes of CO_2 in Switzerland and 5 million tonnes of CO_2 abroad will be necessary in the future.

6.2.1 Current situation in Switzerland

Saline aquifers in the sedimentary layers of the Central Plateau have been investigated over several years for their CO_2 storage potential (Chevalier et al., 2010; Diamond, 2019). The so-called Upper Shell Limestone lies at depths of 60 to 6000 m below the entire Swiss Plateau and is generally well suited for the mineral binding of CO_2 thanks to its high limestone and dolomite content. Initial estimates by Chevalier et al. (2010) assumed a storage potential of 2,500 million tonnes of CO_2 (red area in Figure 15). However, this has been reduced by criteria such as a minimum depth of the aquifers of 800 m or the minimum porosity so that CO_2 can be injected efficiently into the aquifers (Driesner et al., 2021). Estimates according to Diamond (2019) assume a storage potential of around 52 million tonnes of CO_2 (green area in Figure 15).

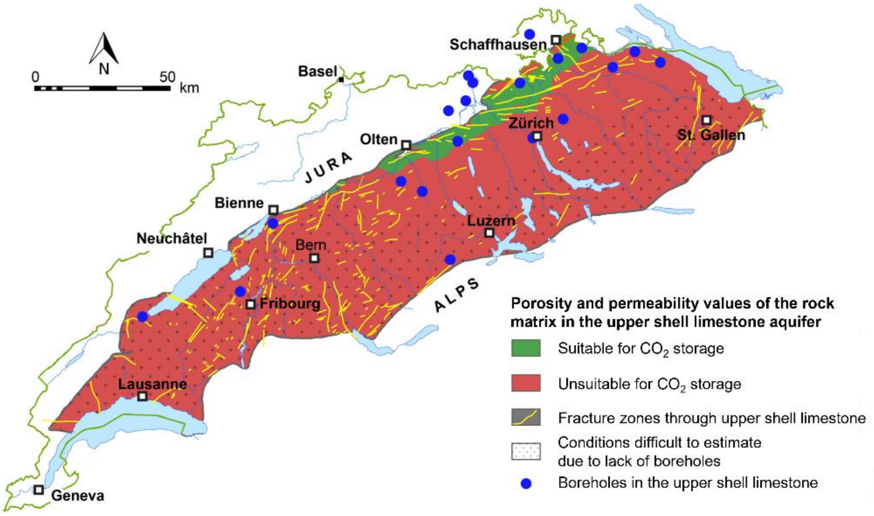

Figure 15 Suitability of the Upper Shell Limestone rock strata for the geological storage of CO_2 (Diamond, 2019)

According to the Federal Council's climate strategy, 2 million tonnes of CO_2 are to be stored annually in Switzerland in the future (see Figure 2). If this quantity is assumed, the storage capacity would be depleted after 27 years. If the entire 12 million tonnes of CO_2eq that the Federal Council's climate strategy (see Figure 2) could generate with CCS and negative emissions (without taking into account nature-based processes such as reforestation or biochar) were to be stored domestically, this would only be possible over a period of just over 4 years. In the long term, Switzerland therefore has too little CO_2 storage potential of its own to permanently store the quantities of 'unavoidable' CO_2 emissions envisaged in the climate strategy in Switzerland alone. In addition, the geological storage options in Switzerland have not yet been sufficiently explored or developed (The Federal Council, 2020). Geological repositories abroad are therefore also being considered (The Federal Council, 2022a). In November 2023, the Federal Council created the legal basis for CO_2 to be exported and stored in the seabed in the future (EDA, 2023). It also held informal talks with Germany about a connection to the planned European CO_2 pipeline network (Häne, 2023).

6.2.2 Current situation abroad

Analyses indicate that the estimated geological storage capacities of 482 Gt CO_2 in Europe would be sufficient to store the EU's total annual CO_2 emissions of approx. 66 Gt CO_2 (as of 2022) for just over 7 years (Anthonsen & Christensen, 2021; European Environment Agency, 2023; Grove, 2021). The greatest storage potential lies in saline aquifers in northern Europe as well as in used and decommissioned oil and gas fields in the North Sea (see Figure 16).

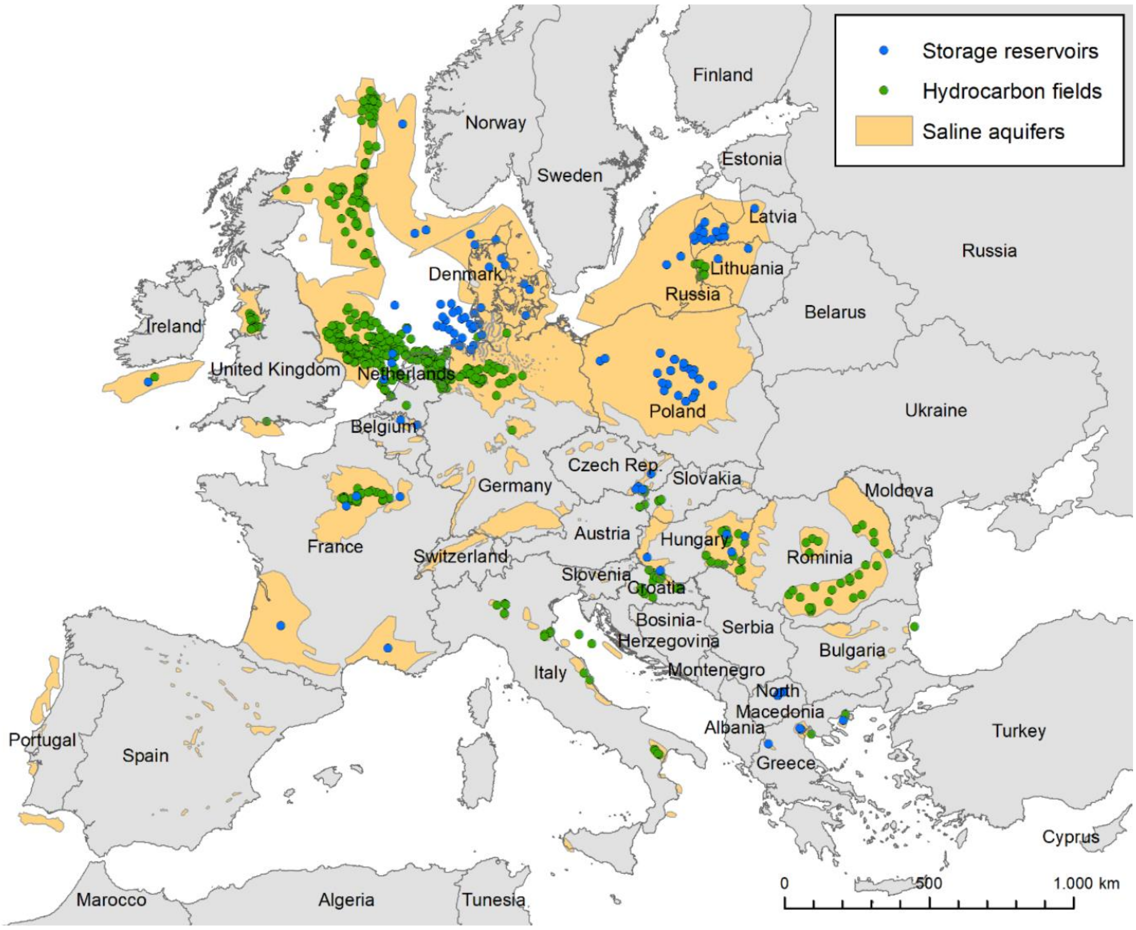

Figure 16 Saline aquifers, oil and natural gas fields (hydrocarbon fields) and other geological storage reservoirs available in Europe for potential CO_2 storage (Anthonsen & Christensen, 2021)

The aforementioned capacity estimates of 482 Gt CO_2 for Europe may be too optimistic. Anthonsen & Christensen (2021), for example, used an outdated value of 3,000 million tonnes of CO_2 instead of 52 million tonnes of CO_2 for the potential of saline aquifers in Switzerland (Driesner et al., 2021).

In Europe, there are several projects for the geological storage of CO_2, some of which have already been in operation for several years. In Norway, for example, the Sleipner and Snøhvit projects have been in operation since 1996 and 2006, respectively. In both projects, CO_2 that is captured during natural gas extraction and processing is injected into submarine aquifers, whereby around 1.7 million tonnes of CO_2 are stored and avoided each year (Benson et al., 2005; Schmidt-Hattenberger, 2018). However, as already mentioned in Section 6.2, these projects cannot serve as models for CCS[16]. Carbfix has been dissolving CO_2 in seawater in Iceland since 2014 (Carbfix hf., n. d.). The dissolved CO_2 is then stored in deep, basalt-containing rock, whereby the CO_2 is permanently stored in the rock layer within 2 years due to carbonation. In Switzerland, a pilot project was launched in collaboration with Carbfix (DemoUpCARMA, 2021), which, among other things, is investigating the upscaling of CO_2 storage abroad. The first load of CO_2 has already been transported to Iceland by truck, rail and ship and stored. The resulting CO_2 emissions reduce the effectiveness of this negative emission, so that only 750 – 800 kg of CO_2 are saved net per tonne of CO_2 stored (SFOE, Energia plus, 2023).

Other pilot projects, such as CO_2 storage in an exploited natural gas field in France (*Lacq-Rousse project*), an aquifer storage facility in Germany (Ketzin) or in carbonate rock in Spain (*Hontomin project*) are investigating the durability of the various storage types (Schmidt-Hattenberger, 2018).

[16] For criticism of these projects, see Section 6.2 on page 37.

6.3 Concluding remarks on permanent storage

The permanent storage of biogenic CO_2 in concrete or underground are both approaches to negative emissions that are not (yet) utilised on a large scale in Switzerland. The potential for storing CO_2 underground in Switzerland is low (52 million tonnes of CO_2) and would be depleted after a few years. Transporting CO_2 by truck, rail and ship to suitable storage sites abroad is very energy-intensive and currently still CO_2-intensive. If Switzerland were to be connected to European pipelines for CO_2 in the future, CO_2 emissions from transport could be reduced. While CO_2 is directly mineralised and permanently bound in demolition concrete, this only takes place in underground storage facilities within a few years if CO_2 is dissolved in water and stored in certain rock types (e.g. basalt). In other rock types, mineralisation takes place over a very long period of time (thousands of years) or indeed not at all. CO_2 leaks can therefore not be ruled out. This is a disadvantage for underground storage compared to storage in demolition concrete.

The use of demolition concrete as storage for CO_2 from biogas plants is already being successfully utilised in several projects in Switzerland. Neustark AG and Zirkulit AG transport the CO_2 to the concrete recycling plants and market the sink capacity. In order to be able to sell certificates for negative emissions, they are dependent on biogenic CO_2 and would accordingly purchase the CO_2 at a price at which the liquefaction plant can be operated economically by Laveba. For the biogas plant planned in Wittenbach, it is therefore recommended that CO_2 storage in demolition concrete be pursued further with one of the Swiss companies.

At present, hardly any CO_2 is captured and stored in the cement industry and waste incineration plants (MSWI plants) in Switzerland. Depending on the development of the legal and economic framework conditions, however, it is conceivable that investments in the corresponding plants and their operation will be worthwhile for cement manufacturers and MSWI operators and that competition for the limited resource of demolition concrete and thus storage capacity for CO_2 could therefore arise in the future. Current project developments, e.g. at MSWI Linth in Switzerland, point to this development (KVA Linth, 2020). With their large CO_2 point sources in terms of volume, they are likely to have a better market position than biogas plant operators with comparatively small quantities of CO_2 and thus compete for sales to treat demolition concrete. For the operators of the biogas plant in Wittenbach, this means that a long-term contract with a company in the concrete recycling business could be sought to secure the future economic purchase of CO_2.

With an ambitious Swiss climate policy, the focus in future could mainly be on reducing emissions and negative emissions could also be promoted so that in the long term not only the climate target of *net zero* but also *net negative* is achieved. With a strong focus on reduction, for example, reducing the amount of concrete used or waste produced could also be a goal. This can be achieved, for example, by increasing the use of wood instead of concrete for building. Wood, with its low specific greenhouse gas emissions, has great potential to contribute to the goal of net zero greenhouse gas emissions in the construction industry. This effect would also be amplified if building components were used for longer (renovation instead of new construction or circular economy; Frischknecht & Pfäffli, 2023). In the long term, the demand for recycled concrete could be reduced. In this scenario, some of the demolition concrete treated with CO_2 would therefore be stored in landfills if demolition concrete were only used to a limited extent as a raw material for new concrete. As long as the mineralisation of CO_2 in the pores of demolition concrete can be sold as a negative emission via certificates, it presumably plays a subordinate role for the economic viability and availability of this option whether the demolition concrete is subsequently used for the production of new concrete or stored in a landfill.

A detailed comparison of all climate impact variants described in Sections 5 and 6 can be found in the next section.

7 Climate protection impact of the various options and certificate trading

In this report, the most sensible options for the utilisation or permanent storage of CO_2 from the planned biogas plant in Wittenbach from today's perspective were developed (Table 7). Synthetic fuels cannot currently be produced economically as there is no cheap 'surplus' renewable electricity available for electrolysis (hydrogen production). Geological storage in Switzerland is only being investigated in small pilot projects and the Swiss storage potential is small (52 million tonnes of CO_2). Storage abroad currently involves high CO_2 emissions for transport and therefore makes little sense as a climate protection measure from today's perspective. The main criterion for ruling out the option of purifying the CO_2 to food quality and supplying it to gas traders with appropriate quality control is the lack of economic viability. The additional sale of climate protection certificates could generate extra income. Due to the uncertainty about the climate impact (see Section 7.2), it seems to make little sense to aim for a climate protection project for the use of CO_2. Direct delivery to greenhouses (with industrial grade) could only be realised economically if an alternative customer were found in winter or if a certain CO_2 storage capacity were installed. However, both options pose logistical challenges that are difficult to solve from today's perspective. Permanent storage in demolition concrete, on the other hand, is already economically feasible from today's perspective and makes sense from a climate protection perspective. The differences in terms of climate impact and opportunities for certificate trading for the two most promising options are therefore discussed in more detail in the following sections.

Table 7 Overview of the possibilities considered in this report for use or permanent storage of the CO_2 from the planned biogas plant in Wittenbach. The measures are listed in the table in descending order of their potential for effective and economical climate protection measures.

	Measure	
1	Demolition concrete	Permanent storage
2	Air fertilisation in greenhouses (direct supply with industrial grade)	Utilisation
3	Food quality or with industrial grade to gas traders	Utilisation
4	Synthetic fuels	Utilisation
4	Geological storage	Permanent storage

7.1 Climate protection effect of the measures 'permanent storage in demolition concrete' and 'utilisation in greenhouses for air fertilisation'

Table 8 shows a comparison of the climate impact of the measures 'CO_2 liquefaction and permanent storage in demolition concrete' and 'CO_2 liquefaction and utilisation in greenhouses for air fertilisation' with the reference scenario, in which the CO_2 from the raw biogas upgrading would be released into the atmosphere. Indirect CO_2eq emissions, such as those resulting from the production of electricity for the operation of the liquefaction plant, are taken into account.

The climate impact of these two variants differs, as already mentioned, in that storage in demolition concrete provides an effective sink, while utilisation can only mean a reduction in climate-relevant CO_2 emissions under certain circumstances:

- The option of permanent storage in demolition concrete brings added value for the climate as the biogenic CO_2, which would be released into the atmosphere in the reference case, is permanently stored in the demolition concrete and thus enables negative emissions.
- Vegetable growers who switch to heat pumps to heat their greenhouses as part of a decarbonisation strategy will have to buy CO_2 on the market for air fertilisation in future (see Section 5.3). In this case, no negative emissions are possible, as the CO_2 is released back into the atmosphere after utilisation (for example, after consuming vegetables from the greenhouse or after ventilating the greenhouse). However, a reduction in emissions of climate-relevant greenhouse gases compared to today would be possible if it were clear that the CO_2 for utilisation had been

procured without the project from a geogenic source (natural carbon dioxide) or extra fossil fuels had been burned to produce it. If, on the other hand, the CO_2 for utilisation is a by-product from the chemical industry or if it is separated from the exhaust gas from combustion processes (e.g. to provide process heat), then the use of biogenic CO_2 for utilisation cannot lead to a reduction in greenhouse gas emissions.

The purity of the CO_2 is sufficient for utilisation in greenhouses and storage in demolition concrete without additional purification with a stripper/reboiler module. However, by omitting this module, the methane slip cannot be reduced to 0 % (see Section 4.2.1). From a climate perspective, there is an interest in minimising methane slip during biogas processing. So far, however, the methane slip from CO_2 capture has not been included in the life cycle analysis for calculating the amount of negative emissions for treating demolition concrete with CO_2 (Tiefenthaler et al., 2021; Robineck et al., 2023) and therefore there is no financial incentive to eliminate the methane slip in this case. If the system boundaries for the life cycle analysis are adjusted in the future and methane slip is taken into account, it should be possible to generate a financial incentive for investing in and operating a stripper/reboiler module. The climate impact of methane slip (see Table 8) was calculated with the GWP100, because this corresponds to the current requirements of international climate policy. The United Nations Framework Convention on Climate Change (UNFCCC) has adopted the GWP100 for international reporting under the Paris Agreement and mandates the use of the 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines (UNFCC, 2019). However, the GWP20 would be a better method to capture the climate impact of methane over the coming decades relevant to achieving the net zero target and temperature targets (e.g. 1.5°C).

Table 8 Comparison of the climate impact of the measures 'CO_2 liquefaction and utilisation for air fertilisation in a greenhouse' and 'CO_2 liquefaction and permanent storage in demolition concrete' with the reference scenario in which the CO_2 from the raw biogas treatment would be released into the atmosphere. Indirect CO_2eq emissions, such as those resulting from the production of electricity for the operation of the liquefaction plant, are taken into account. Liquefaction and subsequent transport are the first steps both for utilisation and for storage in demolition concrete. The purity of the CO_2 is sufficient for utilisation in greenhouses and storage in demolition concrete without additional purification with a stripper/reboiler module. Without this module, the methane slip cannot be reduced to 0 %. Another measure would therefore be to invest in and operate a stripper/reboiler module.

	Measure			Reference			Net	Emissions prevented	Negative emissions
		Assumption	**[kgCO_2 eq/ t LCO_2]**	**Assumptions**		**[kgCO_2eq/ t CO_2]**	**[kgCO_2eq/ t LCO_2]**	**[kgCO_2eq/ t LCO_2]**	**[kgCO_2eq/ t LCO_2]**
Liquefaction	Electricity requirement Liquefaction	Consumer mix (EF =128 gCO_2eq/kWh)	27				27		
Liquefaction	Coolant leak Liquefaction	Glycol[17]	8				8		
Transport	Transport	100 km of	12				12		
						Total	**47**		
Depositing in demolition concrete	CO_2 permanently stored No biogenic CO_2 escapes into the atmosphere	Assumption: All liquefied CO_2 can be stored in concrete (Negative emission)	0	CO_2 from raw biogas escapes into the atmosphere		1,000	-1,000 (NET)	**0**	**953**
Utilisation in a greenhouse for air fertilisation	Biogenic CO_2 escapes into the atmosphere after utilisation		1,000	CO_2 from raw biogas and CO_2 by-product from chemical industry or natural carbon dioxide escapes into the atmosphere partly with or without recycling	Proportion of natural carbon dioxide = 10 %	1,100	-100	**53**	**0**
Prevent methane slip[18]	Stripper/Reboiler Module	Methane slip can be reduced to 0 %.	0	No CO_2 liquefaction and therefore no stripper/reboiler	Methane slip 0.45 % based on methane content in the raw biogas	75	-75	**75**	**0**

[17] Alternatively, ammonia or CO_2 could also be used as coolants. CO_2 has a GWP100 of 1 and ammonia a GWP100 of 0.

[18] The CO_2eq emissions of the methane slip were converted into CO_2eq based on its climate impact over 100 years (GWP100 = 28 g CO_2eq/g CH4 (IPCC, 2013)).

7.2 CO_2 certificate trading

CO_2 certificate trading - like all trading - basically consists of selling and buying parties. The selling parties invest in measures that reduce greenhouse gas emissions. One certificate is generated for every tonne of CO_2eq saved by the measure compared to the reference scenario without the measure. The certificates are generally traded on two different markets in Switzerland. On the one hand, there is the so-called 'mandatory' market, in which only buyers who are obliged by law to offset a certain proportion of their business's greenhouse gas emissions participate. In Switzerland, for example, these are fuel importers who are obliged by the CO_2 Act to offset a certain proportion[19] of CO_2 emissions from the combustion of imported petrol and diesel by purchasing certificates. The Swiss Climate Protection and CO_2 Compensation Foundation (KliK) buys certificates issued by the Federal Office for the Environment from operators of climate protection projects and sells them to fuel importers. Swiss climate protection projects that sell certificates on the mandatory market will receive an average of 125 CHF/ t CO_2 from KliK in the years 2025 – 2030 (KliK, 2023). For certain projects, up to 160 CHF/ t CO_2 will be paid (KliK, 2022). On the other hand, foundations and companies such as MyClimate, Swissclimate or SouthPole sell certificates from climate protection projects on the voluntary market to buyers who are not legally obliged to offset. These can be private individuals or companies who want to support climate protection financially out of conviction or for marketing purposes.

Currently, according to the CO_2 Act, climate protection projects (The Federal Council, 2022b) – apart from CO_2 sequestration in wood products – cannot claim any sink capacity. For this reason, the sink capacity of CO_2 sequestration (BECCS or DACCS) is currently still being sold to companies and private individuals on the voluntary market and not via KliK. An important funding criterion for all climate protection projects, whether for the voluntary market or for KliK, is the lack of economic viability. In each case, proof must be provided that projects would not be economically viable without additional funding (i.e. revenue from the sale of certificates).

Every emission of greenhouse gases contributes to global warming and causes economic damage due to the negative consequences of global warming, such as heavy precipitation events, storms, drought and heat, which can lead to crop failures, damage to infrastructure and direct and indirect negative effects on health. Viewed over a somewhat longer period of time, most climate protection measures are therefore likely to be worthwhile from an economic perspective. However, if limited capital is available for investment in climate protection, this capital should be used as efficiently as possible. This also applies in particular to the use of subsidies. In order to assess the climate protection impact of a measure or project, the project case is compared with a plausible reference scenario. Depending on the assumptions regarding the development in the reference case and the system limits, the calculated climate impact may be lower or higher. This is illustrated by the following practical example:

The FOEN has issued CO_2 reduction certificates for the climate protection project at the biogas plant in Nesselnbach, which are sold to KliK. For the reference scenario it is in this case assumed that natural carbon dioxide from a geogenic source would have been procured without the biogenic CO_2 from Nesselnbach. According to the publicly available project description and validation report, a letter from a gas trader confirming this, was sufficient to validate the reference scenario (Regionalwerke Baden & Neosys AG, 2021). The company that validated the project did not carry out a market analysis for CO_2 in Switzerland or Europe.

As part of this study, discussions were held with various representatives of the gas industry, and a literature and internet search was carried out on the subject of the CO_2 market. The statements made by the interviewees and information from various publications and websites indicate that hardly any carbon dioxide from geogenic sources is currently imported into Switzerland from abroad. According to their press release Air Liquide (2019), for example, no longer produces geogenic carbon dioxide and imports CO_2 for the Swiss market from the ammonia plant in Ottmarsheim (France). Ethylene production in Visp (formerly Lonza) also produces enough CO_2 to cover a large part of Switzerland's demand for

[19] From 2024, the proportion of CO_2 emissions from transport to be offset (offset rate) will be 24% (FOEN, 2022a)

CO_2. However, it is likely that not the entire quantity from Visp is sold on the Swiss market, but a certain proportion is exported to Italy. Of course, it can happen from time to time that individual gas traders resort to natural carbon dioxide from geogenic sources in the event of a CO_2 shortage. However, it is questionable whether this leads permanently to a high share of geogenic CO_2 in the Swiss market.

The adoption of the geogenic CO_2 share in the Swiss market is central to the calculation of revenues from certificates in order to be able to realise the investment and operation of a liquefaction plant economically. For the calculations in Table 8 it was assumed that only about 10 % of the imported CO_2 currently comes from a geogenic source (natural carbon dioxide) and is therefore harmful to the climate. On this assumption, only 53 kg CO_2eq of climate-relevant emissions per tonne of utilised biogenic CO_2 can be avoided. With a certificate price of CHF 160 per tonne of avoided CO_2, revenues of CHF 8.60 per tonne of liquid CO_2 produced could thus be generated. If, on the other hand, it is assumed that 100 % geogenic carbon dioxide can be replaced, then additional revenue of CHF 152 per tonne of liquid CO_2 produced could be generated from the sale of certificates. Paid market studies, such as those offered by S&P Global, could probably provide a more detailed insight. In any case, it would be desirable to create a fair reference scenario for all gas traders in future for the supply of biogenic CO_2 to gas suppliers who sell it on for utilisation.

However, a more effective way of avoiding the import of geogenic carbon dioxide than incentivising it through certificate trading for biogenic CO_2 would be a ban. The current legal and political situation is contradictory: on the one hand, negative emissions projects are being promoted and the Federal Council is creating conditions that will allow Swiss CO_2 to be stored underground abroad in the future. At the same time, however, it is legal to continue extracting geogenic and therefore climate-relevant CO_2 from boreholes abroad and importing it into Switzerland. In the event of a ban, supply may become scarcer in the short term and the price would rise as a result. A moderate price increase would enable the economical operation of liquefaction plants for larger biogas plants and possibly other CO_2 point sources without climate protection projects. A major price increase could also allow small biogas plants to liquefy and purify economically. On the other hand, the price of products containing CO_2 (e.g. carbonated drinks) would probably rise. In this case, the additional costs would be borne by consumers in accordance with the polluter pays principle.

The assessment of climate impact is the most important criterion for our recommendations for the planned biogas plant in Wittenbach in the following section.

8 Recommendations

The results of this report from Sections 5 to 7 form a solid basis for formulating recommendations. These are aimed firstly at the operators of the planned biogas plant in Wittenbach and secondly at Swiss politicians.

8.1 Recommendations for the planned biogas plant in Wittenbach

For the planned biogas plant in Wittenbach, it is recommended, for the reasons set out in Sections 5 to 7, that the majority of the CO_2 produced during raw biogas processing be transferred to demolition concrete plants for the permanent storage of CO_2 and that a climate protection project with KliK for the utilisation of CO_2 be dispensed with due to the lack of clearly verifiable climate protection effects. Looking ahead to the next few years, it can be assumed that competition for permanent CO_2 storage sites will increase due to CO_2 from the cement industry and waste incineration plants. Against this background, it is recommended that purchase agreements with fixed purchase prices and quantities over a longer period of time should be sought, thus favouring security over flexibility.

Potentially, some of the CO_2 could be supplied to vegetable growers to fertilise the air in their greenhouses. However, the climate protection effect of this option is not significant from today's perspective (see Table 8 and Section 7.2). If direct deliveries from the biogas plant to the vegetable farms could be organised, potential customers would probably be prepared to pay a higher price than gas traders. Regional deliveries to direct customers could save transport costs (see Section 2.3). Vegetable growers might also be prepared to pay a surcharge for biogenic CO_2 as part of holistic decarbonisation strategies. However, in order to supply the entire amount of CO_2 produced in Wittenbach directly to vegetable farms without gas traders, large storage tanks would probably be necessary.

8.2 Recommendations for policymakers

Based on the results from Sections 5 to 7, the following recommendations are made to policymakers on the topics of CO_2 utilisation, synthetic fuels and the permanent storage of CO_2.

8.2.1 Import ban on CO_2 from geogenic sources

Today, around 60,000 - 70,000 tonnes of CO_2 are used in Switzerland every year, most of it for the carbonation of carbonated drinks. Greenhouses require CO_2 for air fertilisation in order to increase vegetable growth. Until now, many vegetable growers have used the exhaust gases from fossil fuelled heating systems. Under pressure from their customers, many vegetable growers will switch to fossil-free heating by the beginning of 2026. Many greenhouses will therefore be heated with heat pumps in future and will no longer be able to use the exhaust gases from the burners for CO_2 fertilisation. In the next few years, the demand for liquid CO_2 on the Swiss market could increase by up to 23,000 tonnes of CO_2 due to vegetable growing. Most of the CO_2 traded and used in Switzerland is a by-product of the chemical industry (e.g. ammonia or ethylene synthesis). In certain regions of Europe, however, geogenic CO_2 is extracted from underground. The so-called 'natural' carbon dioxide from geogenic sources (see Section 2.2.4) was formed millions of years ago and becomes climate-relevant as soon as the CO_2 is released into the atmosphere after utilisation.

A comparatively simple and cost-effective measure to reduce the emission of climate-relevant CO_2 would be to ban the import of CO_2 from geogenic sources. Some representatives of the gas industry, such as The French company Air Liquide, also find it absurd that many projects are currently being worked on to remove CO_2 from the atmosphere and inject it into the ground while drilling is carried out elsewhere to extract it again. Air Liquide and its Swiss subsidiary Carbagas are voluntarily refraining from extracting and importing geogenic carbon dioxide. Other gas traders do not voluntarily refrain from importing geogenic carbon dioxide, which is probably cheaper in certain cases. Messer Schweiz AG, for example, chose to forego geogenic carbon dioxide and was indirectly subsidised by KliK. Thanks to CO_2 reduction certificates issued by the FOEN and paid for by KliK (see Section 7.2), the operators of the biogas plant in Nesselnbach can sell CO_2 that is separated from the biogas to Messer Schweiz AG at low cost. In view of the fact that a large amount of taxpayers' money is being invested in research and the development of an infrastructure for negative emissions and CCS in Switzerland, we recommend introducing an import ban on geogenic CO_2 as part of upcoming legislative revisions in the area of climate and energy.

8.2.2 Mandatory use or permanent storage of captured CO_2

As the example of the planned biogas plant in Wittenbach shows, the utilisation of the captured CO_2 can be a challenge from an economic point of view. From a climate policy point of view, the CO_2 should not be released into the atmosphere unutilised.

It would therefore make sense, at least for new biogas plants feeding into the grid, to oblige operators to utilise or permanently store the CO_2. In principle, this obligation could be extended to cases where a certain minimum amount of CO_2 is separated from the biogas annually.

8.2.3 Actively directing the permanent storage of CO_2

It is likely that MSWI and cement plants will be legally obliged to capture and permanently store CO_2 emissions in the coming decades. Large producers often have better sales conditions for their product or disposal conditions for their waste. There is therefore a risk that large CO_2 producers will have easier access to the scarce Swiss CO_2 storage capacity than biogas plants. Connection to the planned CO_2

pipeline network is likely to be more efficient for larger CO_2 producers than for small biogas plants in most cases, both economically and from a climate protection perspective.

Criteria for the optimal allocation of CO_2 sources to the various storage sites should therefore be defined and anchored in the legal framework. Without legal control, the allocation is controlled by market mechanisms and the result does not necessarily make sense from an economic and climate policy perspective.

8.2.4 Realistically assessing synthetic fuels

If production facilities for renewable energy such as photovoltaics and wind were to be expanded on a large scale in Switzerland in the future, scenarios would be possible in which surplus electricity is available on sunny days, especially in summer. Hydrogen could be produced using electrolysis to utilize this surplus. CO_2, which is separated from biogas, could be used to produce synthetic fuels such as synthetic methane or methanol. As energy is 'lost' in the form of heat during the various conversions from electricity to hydrogen and from hydrogen to methane/methanol and is not available as fuel, the efficiency of these processes is low. In very few cases is it economical to operate an electrolysis plant with only 'surplus' renewable electricity in Switzerland.

If electrolysis is operated with electricity from hydroelectric power plants or waste incineration plants, this electricity is not available for other applications and more electricity must therefore be imported. As some electricity is produced in nearby European countries using coal or gas-fired power plants, the emission factor for the average Swiss electricity mix (including imports, known as the supply mix) is already not negligible at 128 g CO_2 / kWh. If more electricity had to be imported, there is a risk that the emission factor would increase.

If the carbon footprint of synthetic methane is calculated using the emission factor for the average Swiss electricity mix, it is evident that synthetic methane does not perform any better or only slightly better than natural gas imported from abroad in terms of greenhouse gas emissions (see Figure 10). For this reason, it would be important for Swiss energy and climate policy to consider the potential for Swiss production of synthetic fuels with low emissions realistically and in coordination with the potential for renewable electricity production and the electricity requirements of other applications. The impact on the demand for photovoltaic and wind power plants when using synthetic fuels on a large scale - such as for international aviation - should be communicated transparently.

8.2.5 Taking account of global warming potential over 20 years (GWP20)

When estimating the effect of measures to reduce emissions, Switzerland largely follows the recommendations of the IPCC and uses the 100-year global warming potential (GWP100). This does not adequately take into account the effect of emissions that are degraded in or removed from the atmosphere in less than 100 years. This applies in particular to methane emissions.

Emissions over the next 10 to 20 years are crucial for limiting global warming and for meeting the 1.5-degree target of the Paris Climate Agreement. It would therefore make a lot of sense to use a measure such as GWP20 in addition to GWP100, which takes better account of the effects over the critical period of the next 10 to 20 years.

This could ultimately also be beneficial for agriculture in specific, as the efforts to reduce methane emissions would become more visible.

8.2.6 Focus more on sufficiency and substitution measures

Capturing and transporting CO_2 is energy-intensive. For climate protection reasons, but also from an economic point of view, avoiding emissions is therefore preferable to NET and CCS.

The reduction of CO_2 emissions can be achieved efficiently and cost-effectively by reducing livestock numbers in agriculture, for example, or by reducing consumption in general. Such measures are often neglected in the discussion or labelled as unfeasible for reasons that are incomprehensible.

It is important to focus on those sufficiency measures that aim to reduce resource requirements. This can be achieved by promoting sustainable lifestyles, reducing waste and extending the lifespan of products.

Substitution measures are also of great importance. They aim to replace high-emitting resources with low-carbon or carbon-free alternatives. For example, agriculture could contribute to the reduction of greenhouse gas emissions through the increased use of precision agriculture and the cultivation of carbon sequestering plant species.

Bibliography

Air Liquide. (2019, April). *Klimafreundliche Erzeugung von CO_2 für Lebensmittel | Air Liquide*. https://de.airliquide.com/ueber-uns/medien/news/klimafreundliche-erzeugung-von-co2-fur-lebensmittel

Alberici, S., Noothout, P., Mir, G. U. R., Stork, M., & Wiersma, F. (2017). *Assessing the potential of CO2 utilisation in the UK*.

Alig, M., Tschümperlin, L., & Frischknecht, R. (2017). *Treibhausgasemissionen der Strom- und Fernwärmemixe der Schweiz gemäss GHG Protocol*. treeze. https://treeze.ch/fileadmin/user_upload/downloads/Publications/Case_Studies/Energy/619-GHG_Strom_Fernw%C3%A4rme_v3.0.pdf

Anthonsen, K. L., & Christensen, N. P. (2021). *EU Geological CO_2 storage summary*. https://cdn.catf.us/wp-content/uploads/2021/10/20183953/EU-CO2-storage-summary_GEUS-report-2021-34_Oct2021.pdf

ARA Region Bern AG. (2021). *Abwasser wird zu Energie.* https://www.arabern.ch/fileadmin/PDFs/Golden_Generation_Abwasser_wrid_zu_Energie__bmmedia_GG_2021-1_ara_def_.pdf

ASCO. (n. d.). *Allgemeine Informationen über CO_2 von ASCO*. Abgerufen 26. Oktober 2023, von https://www.ascoco2.com/co2-produktion-und-co2-rueckgewinnung/allgemeine-informationen-ueber-co2

ASCO. (2021, Januar). *ASCO CO_2 Tanks Transportabel / ASCO CO_2 Semi-Trailer*. https://www.ascoco2.com/fileadmin/PDF_Download/PDF_Produkte/PDF_CO2_und_Trockeneis_Zubehoer/CO2_Lagerung/de/ASCO_Transportable_CO2-Tanks.pdf

ASCO. (2022, Januar). *Rückgewinnungsanlagen für CO_2 als Nebenprodukt*. https://www.ascoco2.com/fileadmin/PDF_Download/PDF_Produkte/PDF_CO2_Produktion_und_Rueckgewinnung/de/ASCO_Rueckgewinnungsanlagen_fuer_CO2_als_Nebenprodukt.pdf

ASCO. (2023). *Regionalwerke Baden: «Das Pilotprojekt ist Türöffner für Schweizer Bioenergie mit CO2-Rückgewinnung («BECCUS»)*. https://www.ascoco2.com/ueber-uns/news/details/regionalwerke-baden-das-pilotprojekt-ist-tueroeffner-fuer-schwei-zer-bioenergie-mit-co2-rueckgewinnung-beccus

Ashirwad Carbonics. (n. d.). *CO_2 Production Plant—Ashirwad Carbonics (India) Pvt Ltd*. Abgerufen 21. November 2023, von https://www.ashirwadco2.com/co2-production-plant.html

Babel, O. (n. d.). *Kohlendioxid, Stoffdaten entlang der Dampfdruckkurve*. Abgerufen 26. Oktober 2023, von https://www.unternehmensberatung-babel.de/industriegase-lexikon/industriegase-lexikon-a-bis-m/kohlendioxid/kohlendioxid-stoffdaten.html

Bachu, S. (2003). Screening and ranking of sedimentary basins for sequestration of CO2 in geological media in response to climate change. *Environmental Geology*, *44*(3), 277–289. https://doi.org/10.1007/s00254-003-0762-9

Baumann, M. Dr., & Schuller, O. Dr. (2021). *Emissionsfaktoren der Stromerzeugung—Betrachtung der Vorkettenemissionen von Erdgas und Steinkohle*.

Bazzanella, A., & Krämer, D. (Hrsg.). (2017). *Technologien für Nachhaltigkeit und Klimaschutz - chemische Prozesse und stoffliche Nutzung von CO2: Ergebnisse der BMBF-Fördermaßnahme* (Datenstand: Juni 2017). DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V.

Bensmann. (2022). „Wir müssen künftig das in Biogasanlagen entstehende CO2 konsequent nutzen“. *Biogas Journal*, 64–68.

Benson, S., Anderson, J., Bradshaw, J., Deguchi, G., Gale, J., Heidug, W., Holloway, S., Keith, D., Lloyd, P., Thomson, J., Zarlenga, F., Zhou, D., Celia, M., Lombardi, S., Oldenburg, C., Stevens, S., Borm, G., & Hawkins, D. (2005). *Underground geological storage*. https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_chapter5-1.pdf

Biollaz, S. Dr., Calbry-Muzyka, A. Dr., Schildhauer, T. Dr., Witte, J., & Kunz, A. (2017). *Direct Methanation of Biogas*.

Biopower Nordwestschweiz AG. (2023, Juli). *AB 2024 PRODUZIERT BIOPOWER DEKARBONISIERTES BIOGAS*. https://www.bio-power.ch/Informationen/Medienmitteilungen/PobVw/

Bui, M., S. Adjiman, C., Bardow, A., J. Anthony, E., Boston, A., Brown, S., S. Fennell, P., Fuss, S., Galindo, A., A. Hackett, L., P. Hallett, J., J. Herzog, H., Jackson, G., Kemper, J., Krevor, S., C. Maitland, G., Matuszewski, M., S. Metcalfe, I., Petit, C., … Dowell, N. M. (2018). Carbon capture and storage

(CCS): The way forward. *Energy & Environmental Science*, *11*(5), 1062–1176. https://doi.org/10.1039/C7EE02342A

Bund für Naturschutz und Umwelt Deutschland. (2023, August). *CCS: Falsche Weichenstellung verhindern*. BUND - BUND für Naturschutz und Umwelt in Deutschland. https://www.bund.net/service/publikationen/detail/publication/ccs-falsche-weichenstellung-verhindern/

Bundesamt für Landwirtschaft. (2021). *Biogasanlagen in der Landwirtschaft*.

Cames, M., Mader, C., Hermann, A., Köhler, A. R., Malinverno, N., Möller, M., Niesen, B., Som, C., & Wäger, P. (2023). *Chancen und Risiken von Methoden zur Entnahme und Speicherung von CO2 aus der Atmosphäre: Empfehlungen aufgrund der Analyse des Wissensstandes und einer systematischen Befragung von Fachleuten in der Schweiz* (TA-SWISS, Hrsg.; 1. Aufl.). vdf Hochschulverlag AG an der ETH Zürich. https://doi.org/10.3218/4153-8

Carbfix hf. (n. d.). *Carbfix—How it works*. Abgerufen 17. November 2023, von https://www.carbfix.com/how-it-works

Carbo. (n. d.). *Unternehmen* | *CARBO Kohlensäurewerke GmbH & Co. KG*. Abgerufen 19. November 2023, von https://www.carbo.de/de/unternehmen

Casaretto, R., & Casaretto, R. (2023). *BIOMETHANPRODUKTION mit CO2 -Verflüssigung kalkulieren*. https://www.biogas-akademie.de/startseite/veroeffentlichungen?task=download.send&id=25:biomethan-mit-co2-verfluessigung&catid=2

cemsuisse. (2021). *Roadmap 2050*. https://www.cemsuisse.ch/app/uploads/2021/05/Cemsuisse_Roadmap_Stand-Mai.pdf

Cercl'Air. (2022). *Biogasanlagen—Hilfsmittel zum Vollzug der Luftreinhalte-Verordnung (LRV) bei stationären Anlagen*. https://cerclair.ch/assets/pdf/31q-2022-11-D-Biogasanlagen.pdf

Chen, X. Y., Vinh-Thang, H., Ramirez, A. A., Rodrigue, D., & Kaliaguine, S. (2015). Membrane gas separation technologies for biogas upgrading. *RSC Advances*, *5*(31), 24399–24448. https://doi.org/10.1039/C5RA00666J

Chevalier, G., Diamond, L. W., & Leu, W. (2010). Potential for deep geological sequestration of CO2 in Switzerland: A first appraisal. *Swiss Journal of Geosciences*, *103*(3), Article 3. https://doi.org/10.1007/s00015-010-0030-4

Cockerill, R. (2022). *Biogenic CO_2 - A CO_2 recovery plant success story*. Gasworld Magazine / UK. Februar 2022, Issue 202, 28-31.

Cohen, Y., & Rothman, D. H. (2015). Mechanisms for mechanical trapping of geologically sequestered carbon dioxide. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *471*(2175), 20140853. https://doi.org/10.1098/rspa.2014.0853

Comtecswiss. (2022). *Co2 recovery plant manufacturers,food cooling dry ice,co2 dry ice*. http://www.comtecswiss.com/en/equipment-and-plants/co2-recovery-plants-from-biogas/

Demirbas, A. (2007). Combustion of Biomass. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *29*(6), 549–561. https://doi.org/10.1080/009083190957694

DemoUpCARMA. (2021). *DemoUpCarma & Storage*. DemoUpCARMA and Storage. http://www.demoupcarma.ethz.ch/de/home/

Diamond, L. W. (2019). *Use hot water, store CO2 – the potential deep beneath our feet* | *National Research Programme Energy*. https://nfp-energie.ch/en/projects/960/

Driesner, T., Gischig, V., Hertrich, M., Loew, S., Maurer, H., Mazzotti, M., Saar, M. O., Wiemer, S., Zappone, A. S., Moscariello, A., Guglielmetti, L., Valley, B., Holliger, K., Laloui, L., Lecampion, B., Krause, R., Amann, F., Meier, P., Spada, M., & Lateltin, O. (2021). *Swiss Potential for Geothermal Energy and CO2 Storage: Synthesis Report* (S. 56 p.) [Application/pdf]. ETH Zurich. https://doi.org/10.3929/ETHZ-B-000518184

ECCSL. (2020). *European Research Infrastructure for CO2 Capture, Utilisation, Transport and Storage—ECCSL*. https://www.eccsel.org/

FDFA. (2023). *Der Bundesrat schafft die Grundlage für den Export von CO2 zur Speicherung im Meeresboden*. Federal Department of Foreign Affairs FDFA. https://www.admin.ch/gov/de/start/dokumentation/medienmitteilungen.msg-id-98800.html

EIGA. (2017). *CARBON DIOXIDE FOOD AND BEVERAGES GRADE, SOURCE QUALIFICATION, QUALITY STANDARDS AND VERIFICATION*. https://www.eiga.eu/uploads/documents/DOC070.pdf

EnArgus. (2023a). *CO2-Speicherung*. https://www.enargus.de/pub/bscw.cgi/d1927-2/*/co*/CO2-Speicherung.html?op=Wiki.getwiki

EnArgus. (2023b). *CO2-Transport*. https://www.enargus.de/pub/bscw.cgi/d1956-2/*/*/CO2-Transport.html?op=Wiki.getwiki&search=CCS

Energie Systeme der Zukunft, & BMVIT. (2014, Juli 4). *Biogas Netzeinspeisung: Zusammensetzung von Rohbiogas*. https://www.biogas-netzeinspeisung.at/technische-planung/funktionsprinzip-einer-biogasanlage/zusammensetzung-von-rohbiogas.html

Esposito, E., Dellamuzia, L., Moretti, U., Fuoco, A., Giorno, L., & Jansen, J. C. (2019). Simultaneous production of biomethane and food grade CO2 from biogas: An industrial case study. *Energy & Environmental Science*, *12*(1), 281–289. https://doi.org/10.1039/C8EE02897D

ETW Energietechnik. (n. d.). *CO2 Verflüssigung*. ETW Energietechnik. Abgerufen 12. Oktober 2023, von https://etw-energie.de/produkte/lco2/

European Biogas Association (EBA). (2021). *Biogenic CO2 from the biogas industry*. https://www.infothek-biomasse.ch/images//485_2022_EBA_Biogenes_CO2_aus_der_Biogasindustrie.pdf

European Environment Agency. (2023, Juli 27). *EU Emissions Trading System (ETS) data viewer* [Dashboard (Tableau)]. https://www.eea.europa.eu/data-and-maps/dashboards/emissions-trading-viewer-1

Fact.MR. (2022). *European Carbon Dixoide Market*. https://www.factmr.com/report/europe-carbon-dioxide-market

Fendt, L., Reisch, N., Feit, S., Fuhr, L., & Drugmand, D. (2023). *Deep Trouble—The Risks of Offshore Carbon Capture and Storage*. Center for International Environmental Law (CIEL).

Fibbi, G., Del Soldato, M., & Fanti, R. (2023). Review of the Monitoring Applications Involved in the Underground Storage of Natural Gas and CO2. *Energies*, *16*(1), Article 1. https://doi.org/10.3390/en16010012

Fischer. (2022, September 20). *Reverion gewinnt gemeinsam mit Landwärme den Innovationspreis der Deutschen Gaswirtschaft 2022*. Reverion. https://reverion.com/de/reverion-gewinnt-gemeinsam-mit-landwaerme-den-innovationspreis-der-deutschen-gaswirtschaft-2022/

FOEN, Federal Office for the Environment. (2022a). *Kompensationspflicht für Treibstoffimporteure*. https://www.bafu.admin.ch/bafu/de/home/themen/thema-klima/klimawandel-stoppen-und-folgen-meistern/schweizer-klimapolitik/kompensation-von-co2-emissionen/kompensation-von-co2-emissionen--treibstoffe.html

FOEN, Federal Office for the Environment. (2022b). *Wirtschaft: Die Ärmel hochkrempeln*. https://www.bafu.admin.ch/bafu/de/home/themen/thema-klima/klima--dossiers/magazin-2022-2-dossier/wirtschaft-die-aermel-hochkrempeln.html

FOEN, Federal Office for the Environment. (2022c, Juni 1). *Negativemissionstechnologien (NET): Notwendiges Standbein der Klimapolitik*. https://www.bafu.admin.ch/bafu/de/home/themen/thema-klima/klima--dossiers/magazin-2022-2-dossier/negativemissionstechnologien-notwendiges-standbein-der-klimapolitik.html

FOEN, Federal Office for the Environment. (2023a). *Bericht zur Erhebung der Kehrichtsackzusammensetzung 2022*. https://www.bafu.admin.ch/dam/bafu/de/dokumente/abfall/statistik/bericht_kehrichtsack-analyse_2022.pdf.download.pdf/bericht_kehrichtsackanalyse_2022.pdf

FOEN, Federal Office for the Environment. (2023b). *Treibhausgasinventar der Schweiz*. https://www.bafu.admin.ch/dam/bafu/de/dokumente/klima/fachinfo-daten/THG_Inventar_Daten.xlsx.download.xlsx/Entwicklung_THG_Emissionen_seit_1990_2023-04.xlsx

Frischknecht, R., & Pfäffli, K. (2023). *Bilanzierung von Negativemissionen (NET) im Bauwesen*.

gaz energie. (2022, Oktober 25). Bei Biogasherstellung aktiv CO2 senken. *CNG-Mobility*. https://www.cng-mobility.ch/beitrag/bei-biogasherstellung-aktiv-co2-senken/

Gerolsteiner. (n. d.). *Wie entsteht Kohlensäure?* Gerolsteiner Brunnen. Abgerufen 19. November 2023, von https://www.gerolsteiner.de/de/magazin/trinken/wasserarten/wie-entsteht-kohlensaeure/

Gislason, S. R., Broecker, W. S., Gunnlaugsson, E., Snæbjörnsdóttir, S., Mesfin, K. G., Alfredsson, H. A., Aradottir, E. S., Sigfusson, B., Gunnarsson, I., Stute, M., Matter, J. M., Arnarson, M. Th., Galeczka, I. M., Gudbrandsson, S., Stockman, G., Boenisch, D. W.-, Stefansson, A., Ragnheidardottir, E., Flaathen, T., … Oelkers, E. H. (2014). Rapid solubility and mineral storage of CO_2 in basalt. *Energy Procedia*, *63*, 4561–4574. https://doi.org/10.1016/j.egypro.2014.11.489

Gkotsis, P., Kougias, P., Mitrakas, M., & Zouboulis, A. (2023). Biogas upgrading technologies – Recent advances in membrane-based processes. *International Journal of Hydrogen Energy*, *48*(10), 3965–3993. https://doi.org/10.1016/j.ijhydene.2022.10.228

Glenk, G., Holler, P., & Reichelstein, S. (2023). Advances in power-to-gas technologies: Cost and conversion efficiency. *Energy & Environmental Science*. https://doi.org/10.1039/D3EE01208E

Global CCS Institute. (2022). *GLOBAL STATUS OF CCS 2022*. https://status22.globalccsinstitute.com/wp-content/uploads/2022/10/Global-Status-of-CCS-2022-Report-Final-compressed.pdf

Grove, B. (2021, Dezember 7). *Geologische Speicherung von Kohlendioxid in Europa: FAQ*. Clean Air Task Force. https://www.catf.us/de/2021/12/carbon-dioxide-storage-europe/

Häne, S. (2023). CO_2-Endlager in der Nordsee – Wie Schweizer Klima-gase im Meeres-boden eingebunkert werden. *Tages-Anzeiger*. https://www.tagesanzeiger.ch/co2-endlager-in-nordsee-landen-schweizer-klimagase-im-meeresboden-729346859933

Hauber, G. (2023). *Norway's Sleipner and Snøhvit CCS: Industry models or cautionary tales?* Institute for Energy Economics and Financial Analysis (IEEFA). https://ieefa.org/resources/norways-sleipner-and-snohvit-ccs-industry-models-or-cautionary-tales

HZ-Inova. (2023, Juli 5). CO2-Verflüssigung in Nesselnbach offiziell eröffnet. *Hitachi Zosen Inova*. https://www.hz-inova.com/de/co2-verflussigung-in-nesselnbach-offiziell-eroffnet/

IEA. (2019). *Putting CO2 to Use*. International Energy Agency. https://iea.blob.core.windows.net/assets/50652405-26db-4c41-82dc-c23657893059/Putting_CO2_to_Use.pdf

IEA. (2023). *CCUS Policies and Business Models: Building a Commercial Market*. International Energy Agency. https://doi.org/10.1787/6ef05538-en

Industriegasverband Schweiz (IGS). (n. d.). *A07 Umgang mit Kohlendioxid*. Abgerufen 26. Oktober 2023, von https://westfalen.com/fileadmin/user_upload/Website_Schweiz/Download/IGS-Sicherheits-empfehlungen/IGS-TS-A07-16-d_Umgang_mit_Kohlendioxid.pdf

Intergovernmental Panel on Climate Change (IPCC). (2023). *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. https://doi.org/10.1017/9781009157896

IPCC. (2013). *AR5 Climate Change 2013: The Physical Science Basis — IPCC*. https://www.ipcc.ch/report/ar5/wg1/

Keel, T., & Scheibler, M. (2022). *Machbarkeitsstudie Bioenergie Wittenbach* (unveröffentlicht). Energiewenden, Laveba.

KliK. (2022). *Erhöhung der Beitragssätze in vielen Kantonen*. https://www.klik.ch/news/news-article/erhoehung-der-beitragssaetze-in-vielen-kantonen

KliK. (2023). *Jahresbericht 2022*. Stiftung Klimaschutz und CO2-Kompensation. https://a.storyblok.com/f/230636/x/1c1d683800/klik_jahresbericht_2022_de.pdf

Krebs, L., & Frischknecht, R. (2018). *Umweltbilanz Strommixe Schweiz 2018* (S. 61). treeze Ltd., fair life cycle thinking. https://www.bafu.admin.ch/dam/bafu/de/dokumente/klima/fachinfo-daten/Umweltbilanz-Strommix-Schweiz-2018-v2.01.pdf.download.pdf/Umweltbilanz-Strommix-Schweiz-2018-v2.01.pdf

Kühn, M. (2011). CO2-Speicherung. Chancen und Risiken. *Chemie in unserer Zeit*, *45*(2), 126–138. https://doi.org/10.1002/ciuz.201100538

Kühn, M., & Clauser, C. (2006). Mineralische Bindung von CO2 bei der Speicherung im Untergrund in geothermischen Reservoiren. *Chemie Ingenieur Technik*, *78*(4), 425–434. https://doi.org/10.1002/cite.200600019

KVA Linth. (2020). *CO2-Abscheidung und -Speicherung: Chance für den Klimaschutz*. https://www.kva-linth.ch/fileadmin/user_upload/Factsheet_CCS.pdf

Leemann, A., & Nygaard, P. V. (2012). *Kohlendioxidaufnahme von Stahlbetonbauten durch Karbonatisierung*. EMPA. https://www.cemsuisse.ch/app/uploads/2020/04/2012_Kohlendioxidaufnahme-von-Stahlbetonbauten-durch-Karbonatisierung_Dr-Nygaard_Dr-Leemann.pdf

Limeco. (2023). *Erste industrielle Power-to-Gas-Anlage der Schweiz*. Limeco. https://www.limeco.ch/technologien/power-to-gas/ptg-kurz-erklaert/

Linde Gas GmbH. (2023). *BIOGON® C, E290 flüssig (EIGA / ISBT)*. https://produkte.linde-gas.at/lebensmittelgase/liq_biogas/biogon_c_fluessig.html

Marianna, F. (2021). *Trockeneis Block-Ware, CO2 (fest, tiefkalt)*.

Mensch, M. (2022). *CCU_PM-Magazin_MMensch-1.jpg (983×1203)*. https://www.mariomensch.de/wp-content/uploads/2022/11/CCU_PM-Magazin_MMensch-1.jpg

MRC. (2020, November 3). *Lonza new CEO takes over*. https://www.mrchub.com/news/378783-lonza-new-ceo-takes-over

Müller, G. V. (2021, Oktober 11). Sika scheint eine Lösung für das Betonproblem gefunden zu haben. *Neue Zürcher Zeitung*. https://www.nzz.ch/wirtschaft/sika-scheint-eine-loesung-fuer-das-betonproblem-gefunden-zu-haben-ld.1649459

Münter, D., & Liebich, A. (2023, Mai). *Analyse der Treibhausgasintensitäten von LNG-Importen nach Deutschland*. https://www.ifeu.de/fileadmin/uploads/Publikationen/Ressourcen/WPKS-Studie-CO2Bilanz_Analyse_der_Treibhausgasintensit%C3%A4ten_LNG.pdf

Nägele, H.-J. (2023). *Status quo and Perspectives of emissions from upgrading plants in Switzerland*.

Naims, H. (2016). Economics of carbon dioxide capture and utilization—A supply and demand perspective. *Environmental Science and Pollution Research*, *23*(22), 22226–22241. https://doi.org/10.1007/s11356-016-6810-2

Neustark AG. (.). *Wie unsere Lösung funktioniert*. Neustark DE. Abgerufen 10. Dezember 2023, von https://www.neustark.com/de/wie-unsere-lösung-funktioniert

Neustark AG. (2023). *Über neustark*. Neustark DE. https://www.neustark.com/de/über-neustark

Neuwald, D., & Klein, N. (2017). *Richtige Lagerung von Beerenobst*.

Pentair. (2021). *Process description CO2 recovery plant*. https://www.provincia.vicenza.it/doc-via/2021/A.%20F.%20BIOENERGIE%20S.R.L.%20-%20Impianto%20recupero%20rifiuti%20non%20pericolosi%20-%20BARBARANO%20MOSSANO/El._dep._/A1.4_rel_CO2.pdf

Rapunzel. (2022). *Nachhaltigkeitsbericht 2021*. https://www.rapunzel.de/epaper/nachhaltigkeitsbericht/2021/#102

Regionalwerke Baden. (2022, Februar 22). *Innovation in Nesselnbach*. https://www.regionalwerke.ch/privat-geschaeftskunden/ueber-uns/medien/mm/2022/co2energie-nesselnbach

Regionalwerke Baden. (2023, April 11). *Europaweit einzigartig: CO2-Verflüssigungsanlage in Nesselnbach*. https://www.regionalwerke.ch/privat-geschaeftskunden/ueber-uns/medien/mm/2023/nesselnbach-betrieb

Regionalwerke Baden, & Neosys AG. (2021). *Projektbeschrieb—Umbau der Biogas-Aufbereitungsanlage in Nesselnbach*. https://www.bafu.admin.ch/dam/bafu/de/dokumente/klima/klima-kop-ab-2022/00252%20Projektbeschreibung%20(2021%20%E2%80%93%202028).pdf.download.pdf/00252%20Projektbeschreibung%20(2021%20%E2%80%93%202028).pdf

Rempel, Cameron, L., & Bois von Kursk, O. (2023). *Unpacking Carbon Capture and Storage: The technology behind the promise*. International Institute for Sustainable Development (IISD). https://www.iisd.org/articles/insight/unpacking-carbon-capture-storage-technology

Revis bioenergy GmbH. (2023). *Biomethan-Werk im c-Port: Grüne Energie für die Klimawende*. https://www.revis-bioenergy.de/aktuelles/artikel/biomethan-werk-im-c-port-gruene-energie-fuer-die-klimawende/

Rinklake, A. (2020). *Verzicht auf Quellkohlensäure*. https://de.airliquide.com/statics/2021-05/verzicht_auf_quellkohlensaure_in_getranken_-_co2-emissionen_durch_richtiges_produktionsverfahren_einsparen.pdf?VersionId=p2ag6U4BxQwb0PJJnYxC8c7dg3h9lk23

Robineck, F., O'Connor, I., & Nesa, V. (2023). *Programmbeschreibung Dauerhafte CO2-Sequestrierung in Betongranulat*.

Saperaud. (2005). *Datei:Carbon dioxide pressure-temperature phase diagram deutsch.png – Wikipedia*. https://commons.wikimedia.org/wiki/File:Carbon_dioxide_pressure-temperature_phase_diagram_deutsch.png

Schaller, M.-L. (2023). Biogenes CO2 aus Biogas. *Biogas Journal*, *4*, 40–46.

Schemme, S., Breuer, J. L., Köller, M., Meschede, S., Walman, F., Samsun, R. C., Peters, R., & Stolten, D. (2020). H2-based synthetic fuels: A techno-economic comparison of alcohol, ether and hydrocarbon production. *International Journal of Hydrogen Energy*, *45*(8), 5395–5414. https://doi.org/10.1016/j.ijhydene.2019.05.028

Schlager, S., Dumitru, L. M., Haberbauer, M., Fuchsbauer, A., Neugebauer, H., Hiemetsberger, D., Wagner, A., Portenkirchner, E., & Sariciftci, N. S. (2016). Electrochemical Reduction of Carbon Dioxide to Methanol by Direct Injection of Electrons into Immobilized Enzymes on a Modified Electrode. *Chemsuschem*, *9*(6), 631–635. https://doi.org/10.1002/cssc.201501496

Schmidt-Hattenberger, C. (2018). *Globale Entwicklung der CCS-Technologie und ihre Rolle als mögliche Klimaschutzmaßnahme*.

Sigfússon, B., Arnarson, M. Þ., Snæbjörnsdóttir, S. Ó., Karlsdóttir, M. R., Aradóttir, E. S., & Gunnarsson, I. (2018). Reducing emissions of carbon dioxide and hydrogen sulphide at Hellisheidi power plant in 2014-2017 and the role of CarbFix in achieving the 2040 Iceland climate goals. *Energy Procedia*, *146*, 135–145. https://doi.org/10.1016/j.egypro.2018.07.018

Sika Schweiz AG. (2021, März 2). *RECO$_2$VER CONCRETE RECYCLING*. https://www.sika.com/en/knowledge-hub/reco2ver-concrete-recycling.html

SFOE. (2020). *Schweizerische Gesamtenergiestatistik 2019*. Swiss Federal Office of Energy (SFOE).

SFOE. (2021). *Energieperspektiven 2050+ Exkurs Biomasse: Potenziale und Einsatz in den Szenarien*. Swiss Federal Office of Energy (SFOE).

SFOE. (2023a). *Schweizerische Gesamtenergiestatistik 2022*. Swiss Federal Office of Energy (SFOE). https://www.bfe.admin.ch/bfe/de/home/versorgung/statistik-und-geodaten/energiestatistiken/gesamtenergiestatistik.html

SFOE. (2023b). *Schweizerische Statistik der erneuerbaren Energien—Ausgabe 2022*. Swiss Federal Office of Energy (SFOE). https://www.bfe.admin.ch/bfe/de/home/versorgung/statistik-und-geodaten/energiestatistiken/teilstatistiken.exturl.html/aHR0cHM6Ly9wdWJkYi5iZmUuYWRtaW4uY2gvZGUvcHVibGljYX/Rpb24vZG93bmxvYWQvMTE1MDk=.html

SFOE, Energia plus. (2023, November 7). *Von der Schweiz in den isländischen Boden: Wie CO2 gespeichert werden soll*. BFE-Magazine energeiaplus | Energy magazine of the Swiss Federal Office of Energy (SFOE). https://energeiaplus.com/2023/11/07/von-der-schweiz-in-den-islaendischen-boden-wie-co2-gespeichert-werden-soll/

S&P Global. (2022, März). *Net-zero carbon ethylene production via recovery of CO2 from cracking furnace flue gas*. S&P Global. https://www.spglobal.com/commodityinsights/en/ci/products/net-zero-carbon-ethylene-production.html

Sperr, N., & Rohrer, J. (2018). Die Perspektiven von Power to Gas in der Schweiz. *Schriftenreihe Erneuerbare Energien, Bodenökologie und Ökotechnologie, ZHAW Zürcher Hochschule für Angewandte Wissenschaften*. https://doi.org/10.21256/zhaw-4827

Spirig, C. (2022). *Overview of the impact of aviation on climate change and how this should be considered for air travel at ZHAW*.

Steiger. (2021). *Energetische Anforderungen an Gewächshäuser Analyse des Ist Zustandes*. DM Energieberatung AG. https://www.zh.ch/content/dam/zhweb/bilder-dokumente/themen/planen-bauen/bauvorschriften/bauvorschriften-im-energiebereich/energetische-bauvorschriften/merkblaetter/gewaechshausbau_uebersicht_zum_stand_der_technik.pdf

Steindamm. (2023). *CO2-Abscheidung: Potenzial aus Biomasseanlagen (Holzenergie-, Biogas- und Biokraftstoffanlagen) in Deutschland*. Erstellt für: Bundesverband Bioenergie e.V. (BBE).

Stiftung Klimarappen. (2023). *Negativemissionstechnologien*. https://www.klimarappen.ch/de/Negativemissionstechnologien-.1.html

Stocker, N., Wild, M., & Rohrer, J. (2023). *Need for energy balancing by region for renewable energy system scenarios of Switzerland (unveröffentlicht)* (SWEET Call 1-2020: EDGE) [Deliverable report]. Zürcher Hochschule für Angewandte Wissenschaften (ZHAW).

Struk, M., Kushkevych, I., & Vítězová, M. (2020). Biogas upgrading methods: Recent advancements and emerging technologies. *Reviews in Environmental Science and Bio/Technology*, *19*(3), 651–671. https://doi.org/10.1007/s11157-020-09539-9

SUVA. (2023a). *Aktuelle Grenzwerte*. www.suva.ch/grenzwerte

SUVA. (2023b). *Grenzwerte am Arbeitsplatz*. https://www.suva.ch/de-ch/download/richtlinien-und-gesetze/grenzwerte-am-arbeitsplatz/standard-variante--1903.D

The Federal Council. (2020). *Von welcher Bedeutung könnten negative CO2-Emissionen für die künftigen klimapolitischen Massnahmen der Schweiz sein?* https://www.bafu.admin.ch/dam/bafu/de/dokumente/klima/fachinfo-daten/bericht-br-2.09.20-postulat-18.4211-thorens-goumaz.pdf.download.pdf/01_d_Bericht_DE%20zu%20BRA%20UVEK%20202008xx.pdf

The Federal Council. (2021). *Langfristige Klimastrategie der Schweiz*. https://www.bafu.admin.ch/dam/bafu/de/dokumente/klima/fachinfo-daten/langfristige-klimastrategie-der-schweiz.pdf.download.pdf/Langfristige%20Klimastrategie%20der%20Schweiz.pdf

The Federal Council. (2022a, Mai 4). *AS 2022 311—Verordnung über die Reduktion der CO2-Emissionen (CO_2-Verordnung)*. https://www.fedlex.admin.ch/eli/oc/2022/311/de

The Federal Council. (2022b). *CO2-Abscheidung und Speicherung (CCS) und Negativemissionstechnologien (NET)*. https://www.bafu.admin.ch/dam/bafu/de/dokumente/klima/fachinfo-daten/br-bericht-zu-ccs-und-net.pdf.download.pdf/CO2-Abscheidung%20und%20Speicherung%20CCS%20und%20Negativemissionstechnologien%20NET.pdf

The Royal Society. (2020). *Ammonia: Zero-carbon fertiliser, fuel and energy store*.

Thees, O., Burg, V., Erni, M., Bowman, G., & Lemm, R. (2017). *Biomassenpotenziale der Schweiz für die energetische Nutzung* (57; WSL Berichte). Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft WSL.

Tiefenthaler, J., Braune, L., Bauer, C., Sacchi, R., & Mazzotti, M. (2021). Technological Demonstration and Life Cycle Assessment of a Negative Emission Value Chain in the Swiss Concrete Sector. *Frontiers in Climate*, *3*. https://www.frontiersin.org/articles/10.3389/fclim.2021.729259

TPI Tecno Project Industriale (Regisseur). (2020, Oktober 14). *Carbon Dioxide recovery and production plant*. https://www.youtube.com/watch?v=sokcauvChHM

UNFCC. (2019). *Report of the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement on the third part of its first session, held in Katowice from 3 to 14 December 2018. Addendum 2* (Annex II, Part D). United Nations Framework Convention on Climate Change. https://unfccc.int/sites/default/files/resource/cma2018_3_add2_new_advance.pdf#page=25

URACA GmbH & Co. KG. (.). *Harnstoffproduktion—Anwendungsbereiche der Harnstoffproduktion*. Abgerufen 7. Dezember 2023, von https://www.uraca.de/de-DE/anwendungen/harnstoffproduktion

Verband der Schweizerischen Gasindustrie (VSG). (2023, Juni). *Positionspapier Biogas und andere erneuerbare Gase*. https://gazenergie.ch/fileadmin/user_upload/e-paper/GE-Biogas/20230627-NL-TENE-23-103-DE-Positionspapier-Biogas.pdf

Verein mobitool, R. mobil G. (2023). *Mobitool-Faktoren v3.0*. mobitool-Faktoren v3.0. https://www.mobitool.ch/admin/data/files/marginal_download/file_de/26/mobitool-faktoren-v3.0.xlsx?lm=1683788409

Vermeulen, P. (2015). *Alternative sources of CO2 for the greenhouse horticulture*.

Witte, J., Kunz, A., Biollaz, S. M. A., & Schildhauer, T. J. (2018). Direct catalytic methanation of biogas – Part II: Techno-economic process assessment and feasibility reflections. *Energy Conversion and Management*, *178*, 26–43. https://doi.org/10.1016/j.enconman.2018.09.079

Wraneschitz. (2022). *Augsburg: CO2-Vermarktung aus Bioabfallvergärung* (Biogas Journal, S. 52–56).

Zirkulit Beton AG. (n. d.). *Zirkulärer Beton—Die neue Betongeneration*. Abgerufen 9. November 2023, von https://beton.zirkulit.ch/produkte

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