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CO_2-Sequestration in Switzerland?

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Abstract

This short review summarizes the role of CCS (Carbon Capture Storage) in the Swiss energy strategy and the current activities concerning research, estimation of subsurface storage potential and plans for pilot injection tests.

Several measures applied in the last years aiming to reduce the greenhouse gas emission of Switzerland (target is 20% less in 2020 than 1990) were already able to stabilize the total national output at a level of 1990. The new proposal to exit at the same time from nuclear energy to supply electric power, poses however, new challenges to meet these objectives. If gas-fired power generation is chosen as bridge to a fully renewable energy supply system of the future, the CCS technology might be an interesting option to compensate for the additional greenhouse gas emissions.

In 2010 a first study demonstrated that several saline aquifers in the Swiss Molasse Basin have a combined theoretical storage capacity of ~2,700 million tons of CO_2. Although these estimates are based on a rather sparse data set, they indicate substantial potential that merits further investigations. Recently the CARMA research project presented a roadmap for a CCS pilot test that has the objective to demonstrate that CO_2 can be permanently stored in a safe way in the Swiss subsurface and that CCS is an economic option on the way to a renewable energy era.

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1 Introduction

The fundamental role of anthropogenic greenhouse gas emissions in the evolution of the Earth's climate and the impact on human society and wellbeing has received wide-spread attention of virtually everyone notably by the efforts of the Intergovernmental Panel on Climate Change.

While Switzerland's original equipment manufacturers (OEMs) are very well established in various segments of the technological CCS (Carbon Capture Storage) value chain and participate successfully in the market place, national knowledge about the applicability of CCS in Switzerland is very low. In 2005 an American gas exploration company developed an enhanced coal bed methane (ECBM) gas production project from deep coal beds in northeastern Switzerland, linked to a gas fired power plant. The idea was to capture CO_2 from the flue gases in the power plant, liquefy and reinject it into the coals to enhance methane production and to sequester at the same time the greenhouse gas. The application for a sequestration permit was rejected by the authorities mainly because of lack of knowledge about the CCS technology and questions concerning safety issues.

Three years later Swiss parliament was informed that there was very low potential for CO_2 storage in Switzerland's deep subsurface, despite strong indications for deep saline aquifers in the Swiss Molasse Basin. Only in 2010 a study by a group of geologists headed by Geological Institute of Bern University arrived after reviewing available, albeit sparse, subsurface data that there exists a theoretical storage capacity of about 2.7 × 109 tons of CO_2 in the most promising regions of the Swiss Molasse Basin, two to three orders of magnitude larger than Switzerland's annual greenhouse gas emissions. However, it has to be kept in mind that there is still insufficient knowledge of the real subsurface characteristics to make reliable predictions for the actual storage capacity and hence the value of new information will be very high to further refine the CCS option value to the Swiss energy system.

Meanwhile extensive research programs have been launched in Switzerland (e.g. CARMA at ETH-Z, Mt. Terri research laboratory by Swisstopo and the Carbon Storage Chair at EPFL) to produce better knowledge of specific topics of the CCS technology.

2 CCS – A Component of the Swiss Energy Strategy

Many governments face the daunting task of providing a framework for managing the consequences of rising greenhouse gas concentration in the atmosphere. During the last few decades the focus has been to lower anthropogenic emissions of greenhouse gas emissions to minimize or mitigate climate change via a host of policy measures (http://www.bafu.admin.ch/klima/12325/index.html?lang=de). Facing innumerous obstacles when attempting to lower greenhouse gas emissions, governments have also had to start acting in the field of adaptation (Swiss Federal Office of the Environment 2012) to the increasingly inevitable climate change. Needless to say, climate change is reflected on primarily through its impact on human society and human condition. Earth throughout its history has of course experienced much more dramatic variations (Hoffman & Schrag 2002).

It is the remit of the Swiss Federal Office of the Environment to address greenhouse gas emissions, develop policies to lower greenhouse gas emissions, and to develop strategies and implement plans to adapt the country to climate change. Besides binding targets for CO_2 emissions as described in Switzerland's CO_2-Act, a wide range of policy instruments, rules and regulations have been developed.

As of 1 January 2013 the target is to reduce greenhouse gas emissions (the exact definition of what constitutes greenhouse gases is detailed in the CO_2-ordinance) by 20% with respect to 1990 by 2020. Policy instruments include a CO_2-levy, establishment of an emissions trading system, a program to promote the deployment of low emission energy technologies in buildings, CO_2 emission targets for cars, mandatory compensation of CO_2 emissions from transport fuels and fossil fuels for (combined heat and) power generation, measures related to education, information and advisory services, and a low carbon emission technology fund.

The impact has been substantial (Fig. 1) – particularly in the overall stabilization of greenhouse gas emissions over the last 25 years. Detailed trends are mixed however, for example CO_2 emissions from private households continue to decline while transport related emissions (fossil fuels) has been rising.

Greenhouse gas emissions from energy conversion to heat and power – while only a small contribution in absolute terms (around 10% or ~ 4 million tons of CO_{2eq} per year) of Switzerland's greenhouse gas emissions – have been growing at an compound annual growth rate of ~ 2.5% since 1990. To a large part this owes to Switzerland's energy supply being dominated by nuclear and hydro power, and only a small contribution from combined heat and power plants (~ 60% non-renewable (fossil) energy sources and 40% from renewables or (short-term) biogenic sources, Swiss Federal Office of Energy 2013).

In response to the major incident at the Fukushima Daiichi Nuclear Power Station in

March 2011, the substantial reduction in the leveled cost of electricity and clear identification for credible paths to commerciality for new renewable energy sources such as photovoltaics and wind achieved in the 1990s and 2000s, and finally political instabilities in North Africa and the Middle East (a major supplier of fossil fuels to Switzerland), the Federal Council of Switzerland along with both chambers of Swiss Parliament have proposed a phased exit from nuclear energy for the supply of power.

During the years 2011–2013 a detailed energy strategy has been developed by the Swiss Federal Office of Energy, and as a critical first step a completely revised Energy Act has been submitted by the Swiss federal government for consideration to parliament in September 2013. The Energy Act would enshrine binding targets, guiding principles for energy supply, energy transport and distribution, the role of renewable energy and ways to enable financing of the transition to widespread deployment of renewables, the role of energy efficiency, the role of support policies, and a range of other enabling features to implement the energy strategy.

The requisite holistic approach to describing, studying and analyzing Switzerland's energy system opens up new avenues for fertile and highly useful research. Research results lay the foundation for evaluating technology options – options that may appear counterintuitive when viewed in isolation but when viewed from a system level may yield a greater amount of flexibility in achieving both, first an affordable, readily available, secure and safe energy supply while secondly neither compromising on environmental goals nor on continued economic growth and well-being.

For example, the commercial viable potential for the deployment of new renewables such as photovoltaics, wind, bioenergy, geothermal energy has been subject to (generally downward) revisions as the reality of deployment sets in. Also, the transition from being only a marginal to a major contributor

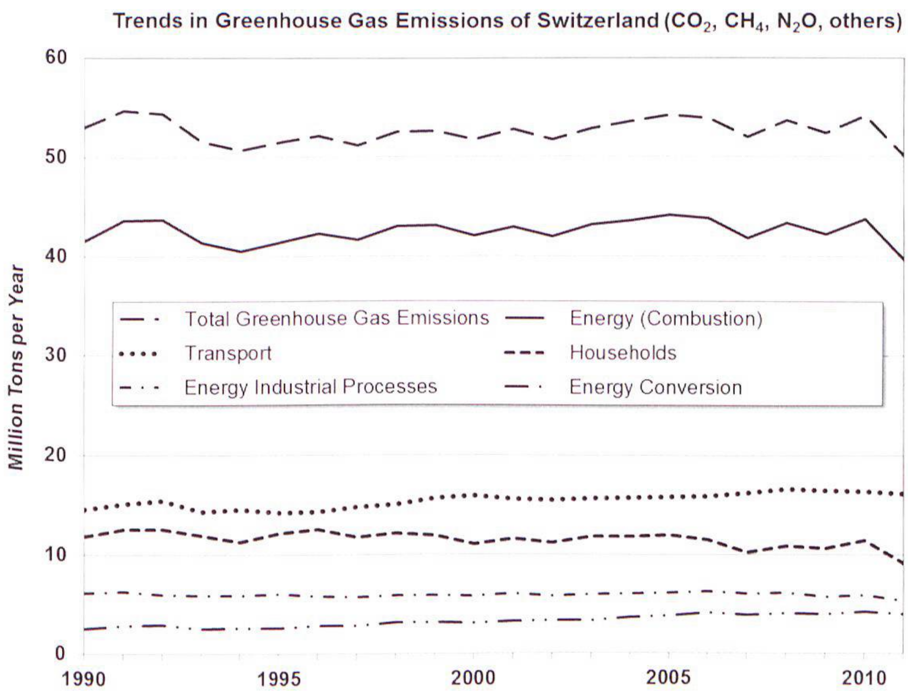

Fig. 1: Greenhouse gas emissions have stabilized since 1990. Notable is the steady rise in emissions from the transport sector and energy conversion which is partly offset by reduction of emission in households. Future power generation from fossil fuels (e.g. a gas-fired combined cycle scheme of 400 MW_{el} installed capacity may cause a rise of around 1 million tons per year) would need to compensate its emissions to not adversely affect the evolution. (Data Source: Swiss Federal Office of the Environment http://www.bafu.admin.ch/klima/09570/09574/index.html?lang=de&download=NHzLpZeg7t,lnp6I0NTU042l2Z6ln1acy4Zn4Z2qZpnO2Yuq2Z6gpJCFd39,gmym162epYbg2c_JjKbNoKSn6A--).

to the supply side of the energy sector often reveals unforeseen challenges – as is manifested in, for example, Germany.

In the face of unavoidable uncertainty, Switzerland's utilities may face the seemingly paradox choice for Switzerland's hitherto virtually CO_2 emission-free electricity supply of deploying gas fired power generation capacity to meet market demand. A wide range of stakeholders perceive such a deployment as a retrograde step for the future of Switzerland's energy supply in view of greenhouse gas emission targets.

Yet, policy makers impose strict compensation rules for emissions which may – in future – be achievable via the option of deployment of Carbon Capture and Storage (CCS) in Switzerland. CCS, a technology package, comprises capture of CO_2 from the flue gas stream of processes (such as combustion of fossil fuels), compression to transition CO_2 from the gas to the liquid phase, and finally transporting the liquefied CO_2 for injection into deep geological horizons for storage and (over geological time scales eventually) mineral precipitation.

Energy system research suggests that CCS is a highly attractive technology package if nuclear energy will be phased out and if climate targets remain stringent. CCS has the potential for major effects on end-use sectors, such as residential heating by way of today's perceived desirable electrification of the energy system enabling the deployment of cost-efficient heat pumps and decreasing the pressure on progressively expensive saving measures. CCS would also offer an attractive option for widespread decarbonisation of the electricity sector again with the added benefit of less pressure for some of the more costly efficiency measures and allowing for a less disruptive transition away from combustion based automotive systems. Finally CCS may ultimately yield significantly lower total system cost in the face of a nuclear phase-out and if climate targets are rigorously adhered to. Hence, CCS is an option which may prove to be of very high value to Switzerland's energy system. But, for this option to be realized a few key elements have to be established first.

Capture, compression and transport of CO_2 streams (including minor, less than about 5% of other species) is a routine, many decades old, safe and reliable operation in many parts of the world and in a number of industries, notably food and gas processing. In recent years additional applications of CO_2 capture have found their way into the power generation and industrial (cement and steel) sectors, in parts by being large stationary point sources of CO_2 and by a rather slow realization that there is value associated with avoiding CO_2 emissions. While Switzerland does not have many large stationary point sources of CO_2 and other greenhouse gas emissions, the introduction of gas-fired power generation may introduce new ones. Such power projects will be subject to stringent compensation measures for their potential greenhouse gas emissions. Similarly for other point sources again, CCS may prove to be a highly cost-effective option.

In short, with uncertainty in the market place with respect to the value of greenhouse gas emissions, with downward cost trends in many segments of the CCS value chain and with a lack of knowledge regarding Switzerland specific features of CCS deployment, research and development are well advised to continue working towards an improved understanding of the option to apply CCS in Switzerland.

3 First Estimates of the CO_2 Storage Potential in the Swiss Subsurface

In 2008 the Swiss Federal Office of Energy initiated a first study on the geological potential for the sequestration of waste CO_2 in the deep subsurface of Switzerland. The objectives of the assessment were to gather some basic technical knowledge for future storage projects and to characterize qualitatively

and quantitatively the sequestration potential of Switzerland compared to other geological areas and countries.
The study was based on a thorough evaluation of published literature and existing seismic and well data from the petroleum industry, nuclear waste disposal and deep geothermal projects. We present here a short summary of the main findings published in detail by Chevalier et al. 2010 and Diamond et al. 2010.

For Switzerland the following four options for CO_2 sequestration have to be considered when assessing the technical storage potential:

- Mineral carbonation
- Unmineable coal beds
- Depleted natural gas/oil fields
- Deep saline aquifers

3.1 Mineral carbonation

Mineral carbonation is the in-situ formation of carbonate minerals when injected CO_2 reacts at temperatures above 150 °C with porous rocks that have high Mg, Ca and Fe content (e.g. basalt or serpentinite). In the Swiss Alps such rocks at high enough temperatures occur only at too great depth and are highly metamorphosed and hence not permeable enough for an efficient injection rate. In-situ carbonation appears therefore not to be a potential primary mechanism for CO_2 sequestration in Switzerland.

3.2 Unmineable coal beds

Unmineable coal beds that are too deep (> 800 m), too thin or have a too high sulphur content for an economic direct coal production have been proposed for permanent geological storage of CO_2. Carbon dioxide injected into coal will fill the available fracture (cleat) and micro-pore volume, as well as being adsorbed into the coal matrix. Primary methane production (CBM) via wells from coal beds can be enhanced by CO_2 injection with a second well (ECBM). Additional methane is desorbed and displaced by CO_2 that is permanently adsorbed. The cost of CO_2 storage is lowered by the added value of the recovered methane.
In northern Switzerland adequate coal seams within the Carboniferous sediments at depth between 1,400–1,800 m have been proven by Nagra's well Weiach-1 and in 2000 by a second gas exploration well Weiach-2. In the early 1990's first investigations showed already that a coal bed methane production in this area would most likely not be economic because of the rather great depth and costly formation water disposal. More recently, a study by Pini (2009) that was based on adsorption capacity measurements on core samples indicated that the main coal seam of the greater Weiach area alone could have a theoretical storage potential of 3–12 million tons CO_2. These volumes are very small compared to estimates of other options in Switzerland (saline aquifers, see below). More detailed investigations, including a pilot injection project in the vicinity of Weiach would be necessary to delineate the actual storage potential in more detail.

3.3 Depleted natural gas/oil fields

Depleted natural gas and oil fields are a well proven option for CO_2 sequestration. Once the hydrocarbons have been produced CO_2 can be injected into the porous reservoir rocks, where it will be stored over geological time scales. The fact that the hydrocarbons remained in the structures for millions of years is a clear indication that the structures are closed and have a high sealing efficiency that prevents the gases to leak to the surface. In some cases CO_2 is injected into oil fields to keep up reservoir pressure and enhance production rates (EOR).
During the last hundred years ~ 45 deep wells have been drilled in the Swiss Molasse Basin in the search for domestic oil/gas

resources, geothermal energy or nuclear waste repositories. To date only one semi-commercial gas field has been discovered: Entlebuch-1 produced from karstified upper Jurassic limestones at a depth of over 4 km some 74 Mio. m^3 of gas and some condensate. Unfortunately these depth are greater than what is today considered to be the commercial floor for a CO_2 sequestration. Today's exploration for gas in Switzerland aims mainly at unconventional gas reservoirs in a variety of lithologies that are clearly too tight for CO_2 storage (Leu 2012). Also the search for shallower Tertiary clastic units in the Molasse, that are porous and permeable enough to be suitable for seasonal gas storage projects, was without success (Leu 2003).

3.4 Deep saline aquifers

The most efficient storage option for waste CO_2 seems to be the storage in deep saline aquifers. The porous reservoir units should ideally be structures that are sealed by impermeable rocks and/or have very slow flow fluid rates (e.g. several cm per year). The CO_2 must be pressurized for injection and forms a fluid plume in a supercritical liquid-like phase that displaces the formation brine. Over decades or centuries the fluid CO_2 will dissolve in the formation water. Solubility is highest in low salinities and in the temperature range of 80–100 °C. The dissolved CO_2 may react chemically with the reservoir rock where either carbonate minerals are precipitated in the pore space or the acidified formation water increases porosity by partial dissolution. Maximum storage capacity in a low-salinity aquifer is reached in the depth interval of 800–2,500 m, mainly depending on the geothermal gradient.

For Switzerland the following aquifers have been evaluated for the area north of the Alpine chain in the Molasse Basin and the Jura mountains (Chevalier et al. 2010):

- *Upper Marine Molasse* sandstones, sealed by Upper Freshwater Molasse marls/mudstones.
- *Upper Malm-Lower Cretaceous* limestones, sealed by Lower Freshwater Molasse marls and mudstones.
- *Hauptrogenstein* limestones, sealed by Effingen Member calcareous mudstones.
- *Upper Muschelkalk* dolomites, sealed by Gipskeuper evaporites.
- *Buntsandstein* and fractured basement, sealed by Anhydrite Group evaporites.

In a first step the suitability for CO_2 sequestration of the entire sediment stack was calculated applying 9 evaluation criteria (existence of aquifer-caprock pair in depth window 800–2,500 m, thickness, geothermal gradient, hydrogeology, exploration maturity, seismicity, fault occurrence, structural trap system and stress regime). All criteria were mapped in a resolution of several km^2 and then combined with a scoring/weighting scheme. The resulting map (Fig. 2) shows the distribution of the calculated potentials with clear patterns across the basin. The total area with a potential greater than 0.6 covers ~ 5,000 km^2, with the highest potentials for CO_2 sequestration in the central Plateau (Fribourg-Bienne-Baden-Lucerne).

In a second step the same evaluation scheme was applied for each individual aquifer unit (see above). Four of the five aquifers exhibit locally good to very good potential, whereas the Buntsandstein aquifer has only moderate to poor sequestration potential.

The actual storage capacity in million tons CO_2 can be calculated by combining the volume of the aquifer, its mean effective porosity, the density of CO_2 and a storage coefficient (reduction of theoretical storage capacity due to capillary effects and limited reservoir accessibility by injection wells). This total theoretical storage capacity for all considered aquifers with a potential greater than 0.6 (Fig. 2) amounts to ~ 2,680 million tons of CO_2. Although the data base for this estimate has low spatial density and limits the accuracy of the calculations, the storage capacity is at least two orders of magnitude greater than the annual greenhouse gas emission of Switzerland (Fig. 1). If in the future gas fired power stations should be built in Switzerland, one 400 MW_{el} combined cycle station would contribute 0.7–1.0 million tons of additional CO_2 per year, if run at full load.

4 Next steps for a CO_2 Capture and Geological Storage Test in Switzerland

The CARMA project has clearly demonstrated that the CO_2 capture technologies to separate the greenhouse gases in natural gas fired power plants are ready to be built (Mazzotti et al. 2013). The largest uncertainties in an economic assessment of a CCS project in Switzerland are, however, related to the technical and commercial feasibility of the storage of the CO_2 in the subsurface in Switzerland. Although the theoretical storage capacity is impressive, there remain questions concerning potential conflicts with other subsurface resources (engineering projects in sealing formations, nuclear waste disposal, geothermal energy, natural gas storage, hydrocarbon and mineral resources), surface restrictions by sensitive areas (protected habitats, population centers etc.) or environmental hazards and safety issues. Any initial site selection would have to address the following main topics concerning hazards and safety:

- Induced seismicity and risk of triggered earthquakes while injecting CO_2.
- Leakage of CO_2 from the target reservoir unit upwards into shallower aquifers.

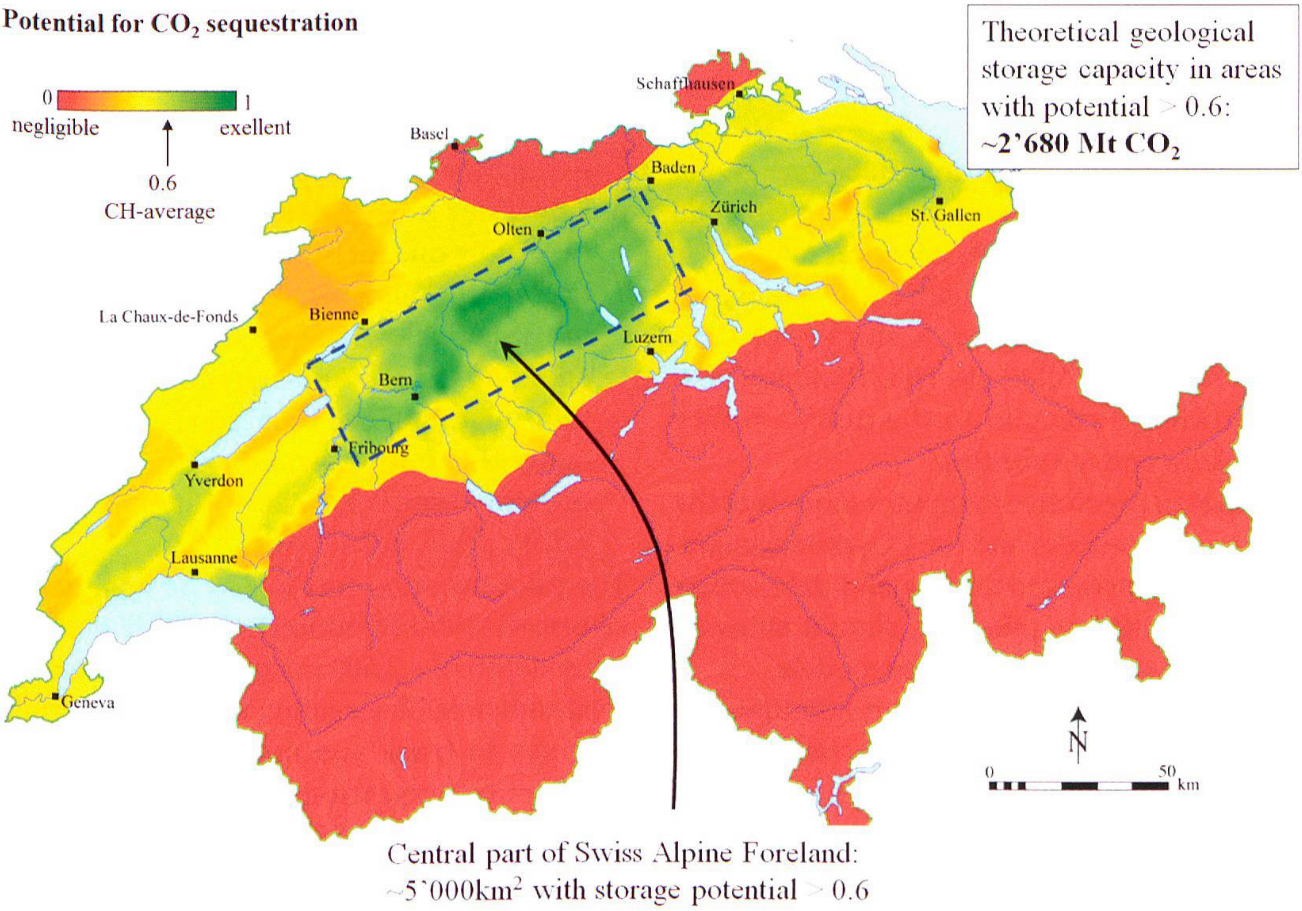

Fig. 2: Technical geological potential for CO_2 sequestration in deep saline aquifers of Switzerland. The combined storage capacity of the four main aquifers with a potential of › 0.6 amounts to a total of ~ 2,670 million tons of CO_2 and is concentrated mainly in the central part of the Alpine Foreland south of the Jura (modified from Diamond et al. 2010).

- Displacement of saline formation water into producing freshwater aquifers.
- Dispersed leakage to the to surface (influence on ecosystem, hazardous to humans).

During the final phase of the CARMA project a roadmap for a capture and storage pilot test was developed (Mazzotti et al. 2013). We present here a brief summary.
The roadmap defines the next steps and necessary financial resources for:
a. Necessary research clusters for capture and storage.
b. CO_2 capture pilot project in a test Combined Cycle Power Plant.
c. CO_2 storage pilot project.

Besides an analysis of the existing legal framework, that located substantial gaps for a CCS deployment in Switzerland, the roadmap postulates an overall budget for a 15 years program of 100–150 Mio. CHF including suitable organization and financial structures.
The main objectives of a pilot injection test are:
- Assess if the Swiss subsurface has geological formations with adequate storage potential for high CO_2 injection rates.
- Demonstrate and ensure the safety of injection and long-term storage of CO_2, including a full-cycle risk dialogue and knowledge transfer to the public, policy makers and authorities.
- Develop predictive computer models of the injection process and the CO_2 plume migration. Extensive monitoring and data collection during the pilot test should allow an optimal calibration of these models.
- Provide data that allows an adequate up scaling of the results for an economic full-scale CCS project.

The roadmap defines further in detail the project constraints for a pilot test (valid trap vs. open hydraulic system, possible injection rates, regulatory and economic) and the site selection criteria following international standards (infrastructure, geology, environment and safety).
It is proposed to carry out the test within the zone of highest storage potential delineated by Chevalier et al. 2010, unless the full site selection process and seismic exploration would indicate another site location. Ideally the pilot test should be placed in an area where several potential aquifers are stacked up (e.g. Malm, Hauptrogenstein, Muschelkalk and Buntsandstein). It should be possible to test with a single well all these aquifers that have a maximum depth separation of ~ 700 m. Related to limited volumes of CO_2 available for the scaled down pilot test it is proposed to carry out several pulsed high rate injections.

For the pilot project two potential test scenarios are possible:
a. Explore for the test a valid closed and fully sealed structure (new or already partially explored, like Hermrigen, Tschugg or Ruppoldsried) to inject and monitor the CO_2. This would demonstrate the feasibility of a full-cycle CO_2 storage project in the Swiss subsurface.
b. Select for the injection test a dipping reservoir unit with a predictable migration path. This scenario would cost less but would allow quickly to gather experience and process-understanding for injection, migration and retention issues. Obviously this option would never be a permanent storage because of its field laboratory scale and set-up.

The pilot injection test would be composed of one vertical injection well with a maximum depth of ~ 2,500 m and at least two vertical slim hole observation wells. Monitoring systems to track and measure micro-seismicity, CO_2 migration and environmental impact would be installed before, during and after the actual injection phases.

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