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CO_2 capture and use or storage options for the Swiss Waste-to-Energy plants

Summary of main results and input from stakeholder consultation workshop
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Global and Swiss context

The latest IPCC report urges to limit warming to 1.5 degrees. This both to avoid systematic consequence and reduce the risk of tipping the planet into a "hothouse state"

- Human-induced warming reached approximately 1°C (likely between 0.8°C and 1.2°C) above pre-industrial levels in 2017, increasing at 0.2°C per decade[1]
- With the Paris agreement, the world aligned on the objective to "limit the rise in global temperatures to well below 2˚C and as close as possible to 1.5˚C above pre-industrial levels"
- 1.5 degrees will significantly reduce the impact of climate change – but more importantly, every 0.1 degree more warming increases the risk of reaching "tipping points"[2] and scientists urge that 2 degrees cannot be considered safe

Staying below 1.5 degrees means a drastic turnaround/ acceleration of decarbonization over the next decade and until 2050 – including addressing "hard to decarbonize sectors" like cement, steel, heavy industry, and heavy transport

- The latest United Nations IPCC report clarifies the reductions needed for 1.5 degrees: 50% until ~2030 and to zero by 2050. This would give a 50% chance of not exceeding 1.5 degrees by 2100
- These targets mean in particular that we need to decarbonize "hard to decarbonize sectors" like cement (both highly energy intensive and emitting CO2 from the chemical process), steel (energy), plastics (carbon released through burning at end of life), and fuels for transport that can not easily be electrified (heavy road transport, shipping and aviation)
- These sectors represent 10 GT of emissions today (30%) and are set to grow to 16 GT until 2050

Switzerland will need to reach unprecedented reductions of CO2 emissions– e.g., 1.5 degrees means ~50% reduction of CO2 emissions until 2030 with the remaining 50% to be neutralized over the following 20 years to reach zero carbon emissions at around 2050

- Currently, the national climate policy post-2020 is being debated in the national parliament. The parliament is expected to release a new CO2-law by the end of the year. In addition, negotiations on a new agreement between WtE plants and the national government regarding integration of the WtE plants in the post-2020 national climate policy are due to start soon
- At the same time, Switzerland is undertaking a challenging transition in its energy system - nuclear phase-out will start this year with the permanent shut down of the Mühleberg power plant. The complete nuclear phase-out will significantly reduce the availability of low-carbon electricity

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[1] "IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty" and headline statements" https://www.ipcc.ch/site/assets/uploads/sites/2/2018/07/sr15_headline_statements.pdf

[2] Will Steffen el al., "Trajectories of the Earth System in the Anthropocene," *PNAS* (2018). www.pnas.org/cgi/doi/10.1073/pnas.1810141115

Decarbonization of the waste sector will need to come from capturing CO_2 emissions at WtE plants, as the total quantity of waste for incineration is not expected to go down materially until 2050

- Investment decisions for WtE plants are currently being made, impacting the next 50 years
- Waste for incineration is expected to increase by 10-36% until 2050. The most optimistic scenario of a strongly developing circular economy would only reduce waste for incineration by 11%
- VBSA expects the waste composition to shift toward less plastic waste and more biogenic waste. Thus, the fossil-based CO_2 emissions will probably decrease to a certain extent, but the overall CO_2 emissions from WtE-plants will most likely rise

Swiss WtE plants are already embedded in the energy system and could help enable the transition to renewables

- Most of the Swiss WtE plants are strategically located at the intersection of three energy distribution grids: gas, electricity and district heating grids. Because of this location at the grid nodes, WtE plants are ideally suitable for energy storage and energy conversion. A growing number of plants already operate large power-to-heat facilities, taking off excess electricity from the grid and converting it to useful heat for district heating
- Conversion of excess renewable electricity to methane (process referred to as power to eMethane hereafter) — requires large amount of electricity to produce hydrogen, but also a large source of CO_2. Electricity and CO_2 are both available onsite in large quantities at every WtE plant
- Other forms of energy storage, like large batteries or simply seasonal storage of waste, are also possible and are currently being investigated (battery storage) or implemented (seasonal waste storage). Seasonal energy storage is recognized to be a key component of a future energy system based on renewables

Findings on capture and use or storage

CO2 capture is a commercially available technology starting at a cost of CHF 68 per ton of CO2 excl. cost of purification and liquefaction

- Amine-based CO_2 capture at point sources with flue gases similar to WtE flue gases is a commercially available technology that can be implemented at scale at WtE plants with a CO_2 capture efficiency of about 90%
- Based on indicative quotes, we estimate the costs of CO_2 capture at 22 CHF per ton of CO_2 excl. thermal energy. If purification and liquefaction are included, the cost rises to CHF 56 per ton of CO_2
- CO_2 capture requires substantial amount of thermal energy. This thermal energy could be converted to electricity, so using it for CO_2 capture has an opportunity cost for power generation of approximately CHF 46 per ton of CO_2 captured[3] rising to CHF 75 if the energy-intensive steps of purification and liquefaction[4] are included. Hence, the total cost of CO_2 capture will be about CHF 68 per ton of CO_2, rising to about 131 CHF per ton of CO_2 with purification and liquefaction

[3] 0.8 MWh per t/CO_2 of thermal energy converted assuming 66% electric conversion efficiency and electricity sales price of rp 8.7/kWh

[4] 1.3 MWh per t/CO_2 of thermal energy converted assuming 66% electric conversion efficiency and electricity sales price of rp 8.7/kWh

- Furthermore, a recent IEAGHG study[5] suggests that increasing CO_2 capture rate to 99% could be achieved at an 8% cost increase
- Capturing CO_2 from WtE flue gases (CO_2 concentration ~9%) is 2-3 times more energy efficient than capturing directly from the air (CO2 concentration <0.1%)

We scanned three broad options to deal with the captured CO2: *Utilization for generation of eMethane, eMethanol; Carbonation and deep geological storage as gas*

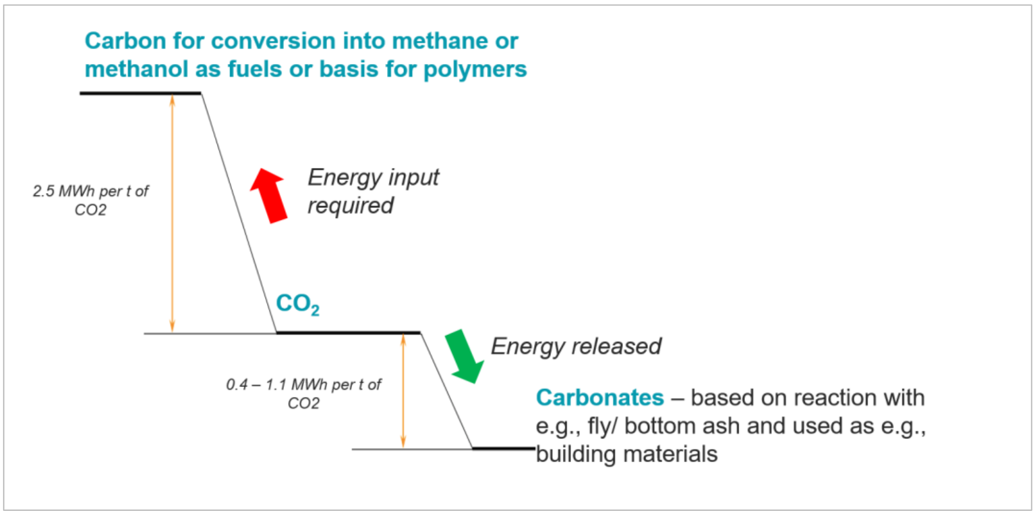

Figure 1 Energy requirements for CO2 conversion

Conversion to eMethane and eMethanol are not feasible at the required scale due to energy requirements and temporary nature of CO2 storage

- Electricity requirements for CO_2 conversion to eMethane and eMethanol are prohibitive - converting all 4.4 million tons of CO_2 to methane would increase the total Swiss electric consumption in 2018 by 56%[6], slightly less (49%[7]) if converted to methanol instead of methane
- From a CO_2 perspective, the process only makes sense if clean renewable electricity is used
- In addition, CO_2 is emitted back into the air as soon as the eMethane or eMethanol is used (i.e. oxidized)
- Economically, even under optimistic assumptions, converting all CO_2 emitted by WtE plants to eMethane and assuming it could be sold as biogas would result in a net loss of CHF 1.2 billion per annum while converting all CO_2 to eMethanol would give an annual loss of CHF 1.96 billion. The main cost driver is the price of electricity for the water electrolysis/ hydrogen production. Due to temporality of the storage, economic benefits from carbon credits are unlikely – for eMethane the

[5] Technical report «Towards zero emissions CCS in power plants using higher capture rates or biomass» by the International Energy Agency Greenhouse Gas R&D Programme (IEAGHG), 2019

[6] The resulting eMethane would cover 64% of Swiss annual natural gas consumption

[7] The resulting eMethanol would cover almost 27% of Western Europe's annual methanol demand

required carbon credit per ton of CO_2 would be CHF 265 assuming that eMethane can be sold as biogas or CHF 646 assuming that it is sold as fossil methane

Large-scale carbonation of CO_2 was not found to be practicable in Switzerland

- Carbonation refers to a process where a (mineral) carbonation basis[8] reacts with CO_2 to form stable carbonates that can later be used as natural aggregates in construction or stored
- Theoretically, carbonation process may be attractive as it is exothermic, i.e., releasing, rather than requiring energy, and the carbonated minerals are very stable, providing long-term CO_2 storage
- However, none of the typical "carbonation" materials or processes such as fly ash, bottom ash, steel slag, accelerated concrete curing, rocks and minerals – were found to be available in relevant quantities

Geological storage of CO_2 in Switzerland is unlikely to become available over the next 10-20 years

- Switzerland's[9] CO_2 storage potential is estimated at up to 70 years of current emissions
- However, no actual exploration has been done so far to understand feasibility at a large scale and long-term testing would be required
- In particular, there is currently very limited knowledge about several essential factors that suggest appropriate CO_2 storage sites. These factors include knowledge about the exact location of reservoir rocks (saline aquifers) that are coupled to impermeable rock strata that act as seals, at depths between 800 and 2,500 m. Also, CO_2 storage in saline aquifers is best done at low temperatures at the 800-2,500 m depth window, which makes low geothermal gradients (i.e., degrees per km of depth) preferable. High geothermal gradients would result in exploitable geothermal energy resources instead, although hybrid developments are possible
- There is an opportunity to investigate the suitability of Switzerland's subsurface for CO2 storage in conjunction with the current subsidy programs intended to characterize the subsurface for geothermal energy utilization

As an alternative to storage in Switzerland, northern European offshore storage projects might become an option within the next few years

- Norway is planning to open up their offshore geological reservoirs to all European CO_2 emitters by 2024 (tbc over the coming years). The Norwegian Parliament will make an investment decision for the project in 2020/2021. The project will then be able to commence operations in 2023/2024 with a planned capacity of approximately 5 million tons of CO_2 per year. The timeline for making larger storage capacity available to CO_2 emitters outside of Norway will depend on the interest from other countries and industry
- Norwegian offshore CO_2 storage capacity estimated at 70 Gt – providing space for 20 years of EU 28 direct CO_2 emissions

[8] Metal hydroxide or metal oxides - .e.g, CaO or MgO

[9] Based on current estimates, theoretical (unproven) storage capacity in Swiss deep porous geological formations may be up to 2.6 Gt of CO_2 (equivalent to storing app. 70 years' worth of Swiss CO_2 emissions)

- Equinor[10] has been testing a similar concept for 20 years at Sleipner project, located offshore Norway, since1996, with a total of 15.5 Mt CO_2 (0.9 Mtpa) already injected in deep saline aquifers 800- 1000 m below the seabed and no signs of leakage observed
- Opportunities for offshore geological storage of CO_2 are also considered in other European countries, with the Netherlands and UK being at a most advanced state following Norway

Costs are expected to be high in the beginning and need further investigation

- Current very rough estimates indicate the cost for CO_2 capture, transport[11], injection and monitoring costs of around CHF 340 per ton of CO_2[12] with the expectation to go down to CHF 110 per ton of CO_2 in the next 10 years (amounting to CHF 1.3 and 0.4 billion, respectively, in annual costs for all Swiss WtE CO_2)
- No CO_2 credits were considered in the calculations, but given the permanence of storage, the process could potentially benefit from them in the future. Different CO2 markets/ incentive schemes with different price levels exists – so determining the possible eligibility will be crucial
- Pipeline or other transport infrastructure to connect Switzerland to offshore geological CO_2 storage would be needed – currently real industry cost data is scare and will need to be collected

In addition, concerns of the public around safety and permanence, as well as regulatory questions will need to be considered

- Many decades of injecting CO_2 in deep underground formations worldwide, and in the context of CCS for the last 20 years, have led practitioners and regulators to the conclusion that CO_2 storage is a safe operation as long as storage sites are properly selected, characterized and managed
- A number of regulatory frameworks (the EU directive on the geological storage of CO_2, the so-called "CCS Directive") as well as industry standards (ISO/TC 265 - Carbon dioxide capture, transportation, and geological storage) exist

If implemented, CCS on waste-to-energy plants could unlock faster pathways to a carbon neutral future for other sectors like cement, heavy transport and heat

- Permanent storage of all the CO_2 emitted by WtE plants would be an opportunity for the WtE plants to become carbon-negative (52% of the WtE CO_2 emissions are considered biogenic) and thus contribute to national Swiss targets
- Building a CCS infrastructure would allow cutting of emissions for other hard-to-decarbonize sectors like cement production, where at least 50% of emission are inherent in the chemical process
- Lastly, CCS would expand the portfolio of decarbonization options and pathways in industry, transport and heating, specifically by enabling hydrogen, as CCS would allow creating "blue hydrogen", where natural gas is converted to hydrogen and CO2, which is stored underground. This could be seen as a transition technology to allow for large quantities of CO2 free hydrogen while until sufficient hydrogen directly from renewables will be available

[10] Previously called Statoil

[11] Assuming transport by train/ship to Norway in the current price scenario and a hypothetical CO_2 pipeline to Norway in the scenario referring to the 10 years in the future

[12] These costs estimates are significantly higher than some of the quotes in the literature due to the first-of-a-kind premium

In conclusion: The most promising path to drastically reduce CO_2 emissions from Swiss WtE plants appears to be capturing CO_2, enabling its transport to northern Europe and storing it permanently in suitable geological formations.

This approach should be extended to other large point sources in Switzerland, like cement production and other "hard to decarbonise" large CO_2 point sources.

Who we are

VBSA represents all 30 waste-to-energy (WtE) plants currently in operation in Switzerland. Together, these 30 WtE plants emit a total of approximately 4.4 million tons of CO_2 per year - about half of these emissions are fossil-based, and the other half biogenic. More information on https://vbsa.ch/.

The Sustainability in Business Lab (sus.lab) is an initiative of the Chair for Sustainability and Technology at ETH Zurich. More on www.suslab.ch.

Results were validated in a stakeholder workshop with participants from industry, academia and other organizations, including, ETH, Industrielle Werke Basel, IET Institut für Energietechnik, Swiss RE, Limeco, WWF, Rytec AG, BAFU