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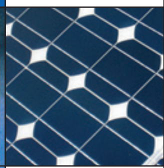

NO. 23 / FEBRUARY 2016

ENERGIE-SPIEGEL

FACTS FOR THE ENERGY DECISIONS OF TOMORROW

Carbon Dioxide: Taking care of the climate problem underground?

In spite of all warnings about the consequences of climate change, and unaffected by political declarations: Global carbon dioxide emissions continue to climb. Coal and natural gas power plants to cover the increasing demand for electricity are mainly responsible. Is it possible to store these CO_2 emissions permanently in the ground, instead of burdening the atmosphere and climate? And would this also be of interest in Switzerland? PSI attempts to answer these questions together with national research partners.*

Electricity generation from fossil fuels like coal and natural gas, as well as cement and steel production, release large amounts of carbon dioxide (CO_2), raising the CO_2 concentration in the atmosphere. This leads to global warming by the greenhouse effect. Capturing the CO_2 emissions and storing them in deep geological formations could be an appropriate countermeasure. The "Carbon Capture and Storage" process (abbreviated CCS) is not only suitable for new plants, but also for the retrofit of existing power plants and industries.

In countries like China and India at least one new coal power plant is connected to the grid each week. That will not change quickly, because the addition of photovoltaic, nuclear, wind and hydropower plants will not suffice to cover the quickly growing electricity demand in a climate-friendly way for the foreseeable future. So CCS is more or less a "must" to achieve the international climate target of a maximum global warming of 2 degrees Celsius. And Switzerland could also benefit from CCS – gas power plants with CCS could under some circumstances be a low CO_2 electricity source for the future.

However, CCS is not free. The use of fossil resources is increasing and electricity prices are climbing significantly. The separation and storage of CO_2 will only be profitable when the CO_2 producers must pay enough for their emissions. And the central question is still open – where and in how large quantities can the CO_2 be stored safely and permanently?

* Research project „CARMA“: http://www.carma.ethz.ch/

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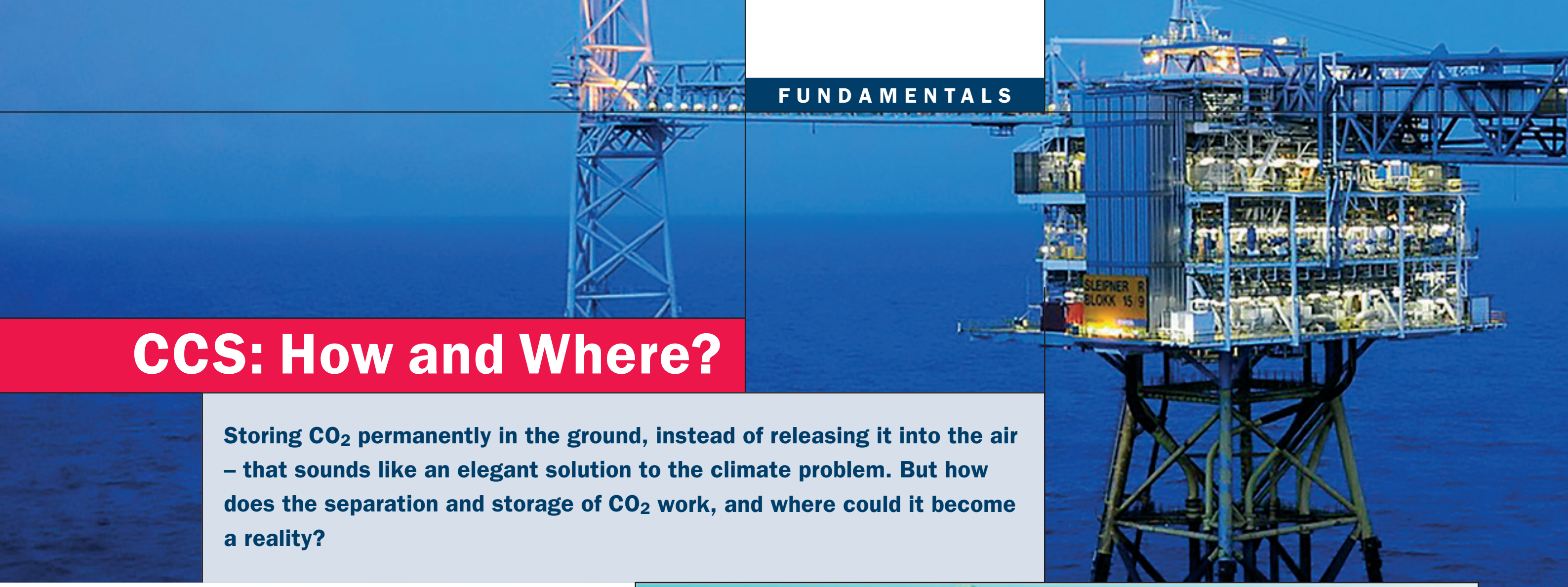

CCS: How and Where?

Storing CO_2 permanently in the ground, instead of releasing it into the air – that sounds like an elegant solution to the climate problem. But how does the separation and storage of CO_2 work, and where could it become a reality?

About half of the global CO_2 emissions today come from coal, gas and oil power plants, as well as from the steel and cement industries. These are exactly the large "point sources" that are suited for filtering out CO_2 from the exhaust gases. There are three different processes for the separation: before burning the fuel ("pre-combustion"), or afterwards using two processes ("oxy-fuel combustion" or "post-combustion", the process used today). The CO_2 is then compressed, transported (preferably by pipeline), and injected into appropriate geological storage. Permanent CO_2 repositories may include unusable coal deposits, exhausted oil or gas fields, or so-called "saline acquifers" (Figure 1). These porous sandstone layers that contain salty water exhibit the largest storage potential. If they are at a depth of more than 800 meters and below impermeable rocks, physical barriers and geochemical processes prevent CO_2 from escaping to the surface finally resulting in transformation to carbonate rock.

Large storage, large uncertainties

How much CO_2 can finally be rendered harmless with this process is difficult to estimate. One must assume that sufficient, suitable geological formations are available to store the global CO_2 emissions for many decades. The largest potentials are assumed to be in Asia and the Middle East (Figure 2).

In Switzerland, CCS could be interesting today for cement plants, as well as in the future for natural gas power plants, if these are needed for electricity supply. The separated CO_2 must no doubt be stored within Switzerland. The Swiss midlands between Freiburg and Baden are the most suitable area (Figure 3). The storage potential is not yet exactly known, but one current estimate is that there is enough storage in Switzerland for many decades.

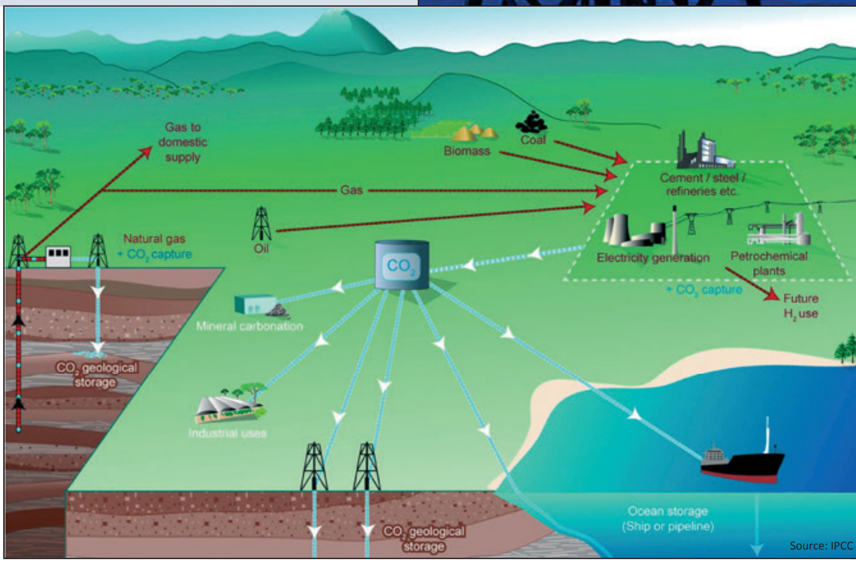

Figure 1: How CO_2 separation and storage works.

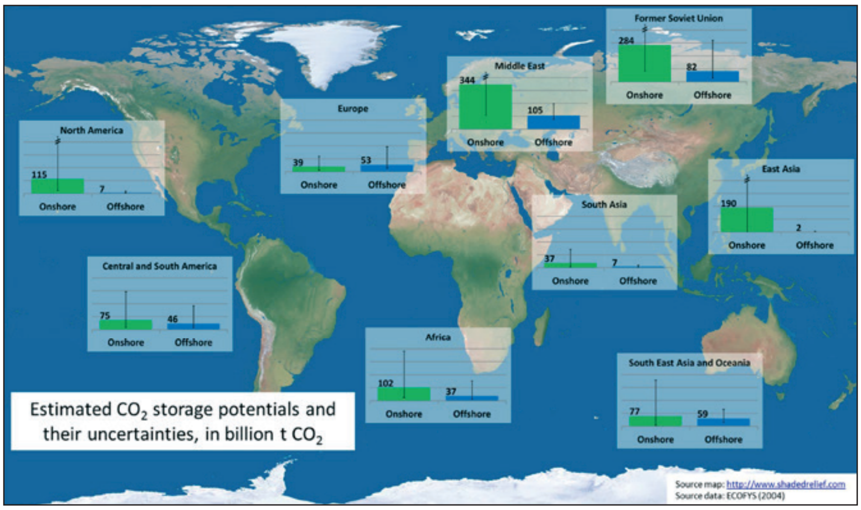

Figure 2: Assumed geological storage capacities for the different global regions. The vertical lines next to the numbers show the uncertainty of the estimates. For comparison: The CO_2 emissions from the electricity and industrial sectors are around 20 billion tons per year.

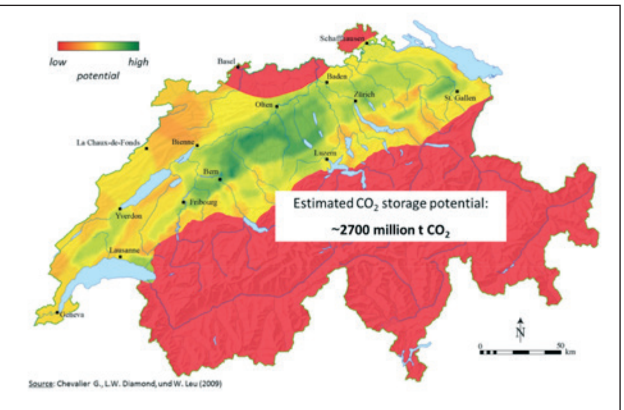

Figure 3: How well is the Swiss subsurface suited for geological CO_2 storage? Green-colored areas show the best conditions, red are unsuitable. For comparison: the total CO_2 emissions in Switzerland are around 43 million tons per year.

CCS: Costs and Benefits

CO_2 emissions cannot be completely eliminated with CCS. But the benefits for the climate are apparent, if one regards the full life cycle. However, everything comes at a price.

Around 90% of the CO_2 that results from burning coal and gas in power plants could be removed by CCS. The CO_2 reduction is actually somewhat less if one includes the entire energy chain from fuel production to waste disposal, lying somewhere between 70% and almost 90% (Figure 4). The greenhouse gas emissions from coal and gas plants with CCS lie in the range from 100 to 200 g CO_2 equivalent per kWh of electricity. This is certainly higher than emissions from renewable energy and nuclear power, but can still contribute to a climate-friendly electricity mix. Wood-fired power plants with CCS can even have negative CO_2 emissions – as long as the fuel they burn is replaced by growing new biomass. This is possible because the trees remove CO_2 from the atmosphere as they grow. The CO_2 from burning this wood is permanently removed by CCS from the atmosphere, and thus from the normal CO_2 cycle. This accounts for the "negative" emissions.

Because the CO_2 separation requires energy, a power plant with CCS uses up to about a quarter more fuel. The environmental burdens associated with the coal and gas production rise accordingly in comparison with power plants without CCS. But overall, this has only a small influence on the climate.

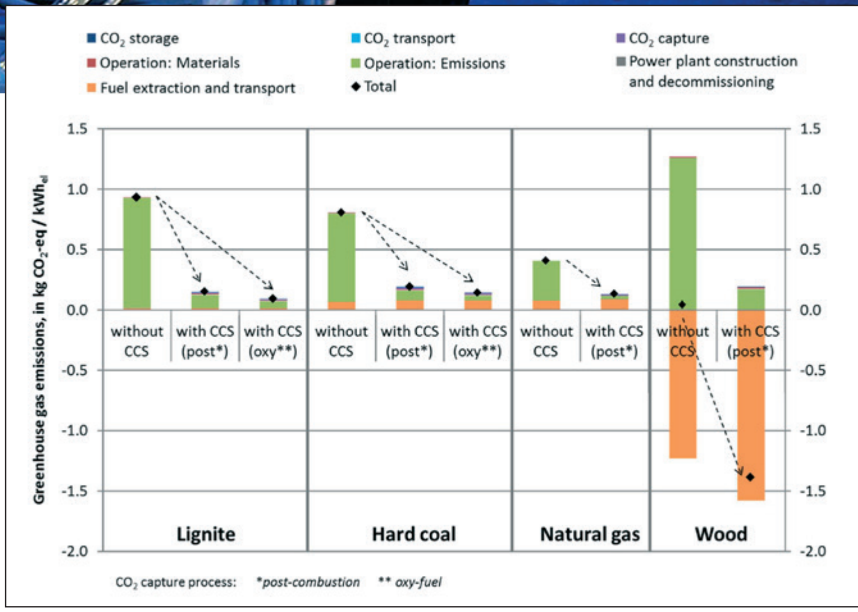

Figure 4: Greenhouse gas emissions per kilowatt-hour of electricity from power plants with and without CCS. The CO_2 emissions from burning the coal, gas and wood dominate the balance. With wood-fired power plants the CO_2 taken up by the growing trees is shown as negative emissions. *Source: PSI, 2013*

Costs

Between 40% and 90% more – that's how much the electricity from coal and gas-fired power plants costs in comparison with plants without CCS (Figure 5). This is because power plants with CO_2 separation are more expensive and require more coal or gas to operate. The increased costs appear high at first, but only because today it is essentially free to release CO_2 into the air. If a CO_2 tax would be imposed that reflected the possible consequences of climate change, CCS would be economic. CCS would pay for itself in coal plants at a CO_2 price of about 50 EUR/t, and in gas plants at a price of about 100 EUR/t where the CO_2 reduction is less. This far from the current CO_2 price, which in the EU is less than 10 EUR/t. Compared to electricity from the less expensive renewable energy sources, low CO_2 electricity from power plants with CCS is similarly expensive.

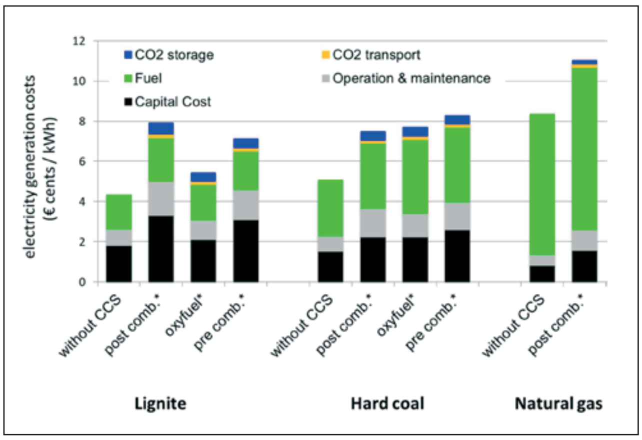

Figure 5: Costs of electricity from coal and gas power plants with and without CCS. *process for CO_2 separation.

Source: PSI, 2012

Risks and public perception

Above all it is the underground storage of CO_2 that causes fear. Some pilot projects in Europe have therefore encountered massive opposition. The total risks of CCS are comparable with those of the gas industry. As the successful research project on CO_2 storage has shown in Ketzin near Berlin, it is decisive to carefully choose and monitor the geology for the CO_2 repository. Continuous measurements over the long term must ensure that possible CO_2 leaks and contamination of drinking water reservoirs are recognized and can be stopped. Local environmental and health risks can thus be minimized.

CCS in the future energy mix

A climate-friendly energy supply in the future needs more low CO_2 technologies. Does it make sense to rely on CCS? Or will renewable energy and efficiency measures be sufficient?

If Switzerland wants to achieve its contribution to the international "2 degree target," it must reduce its domestic CO_2 emissions at least 60 % by 2050. This can be achieved in different ways. The best would be a combination of higher energy efficiency and renewable energy sources. But the potential of hydro power, sun and wind energies is limited. If additional low CO_2 electricity from gas plants with CCS is available, the CO_2 emissions from households and traffic can be reduced more efficiently, for example by using heat pumps instead of oil-fired heating and with electric vehicles. This is shown by PSI's current energy scenarios (Figure 6).

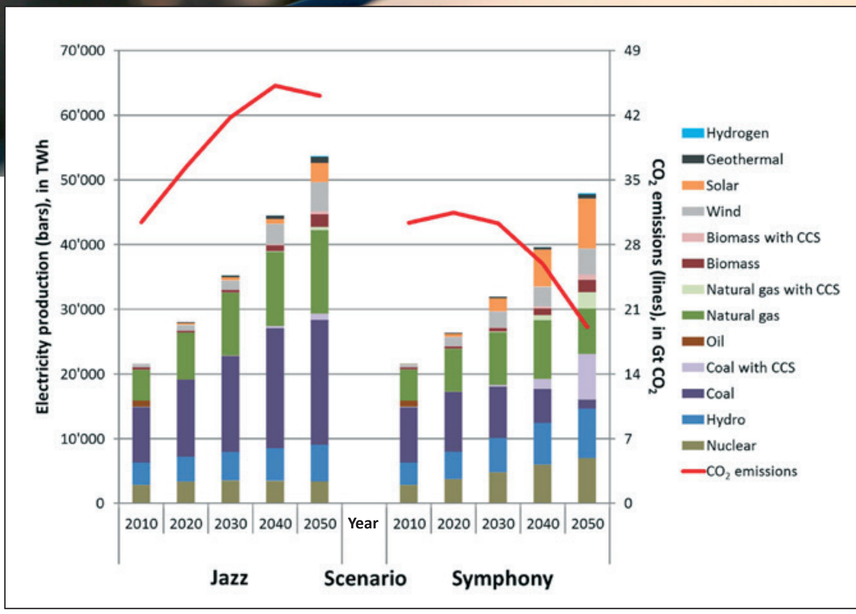

Figure 8: Electricity supply and CO_2 emissions from the global energy supply in the „Jazz" (market oriented) and „Symphony" (regulation oriented) scenarios from Energie-Spiegel No. 22. *Source: PSI, 2013.*

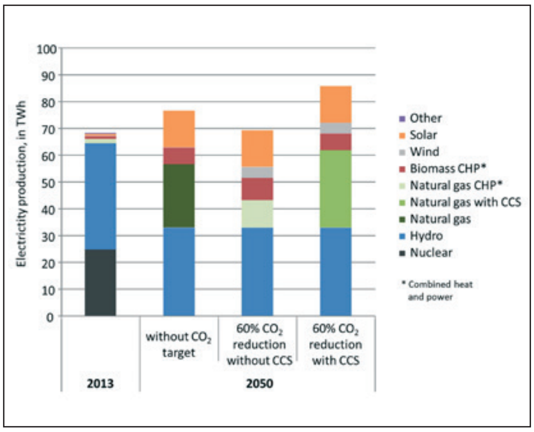

Figure 6: Swiss electricity production in 2013 and 2050 for different scenarios with and without targets for CO_2 reduction. Gas power plants with CCS (green in the right hand column) could provide a substantial contribution to a climate-friendly electricity supply. *Quelle: BFE; PSI, 2013*

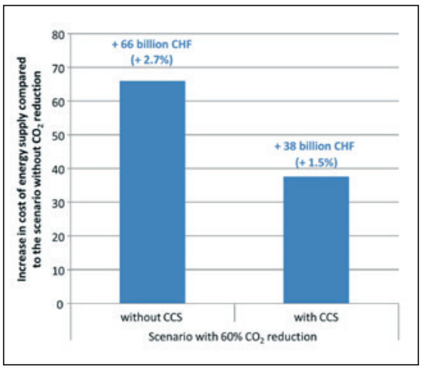

Figure 7: Increases in the cost of the Swiss energy supply with a CO_2 reduction of 60% by 2050. *Source: PSI, 2013.*

Costs in Switzerland

A substantial reduction of CO_2 in Switzerland will result in any case in climbing costs for the energy supply (Figure 7). But if gas power plants with CCS are available it will be less expensive. Without CCS the cost of a 60 percent CO_2 reduction for the entire energy supply by 2050 will be about half again as expensive than with the use of gas power plants with CCS (+30 versus +19 billion CHF). Because of the additional, low CO_2 electricity from CCS power plants, the most expensive energy efficiency measures and more expensive electricity from renewable energy are not needed. A far stronger reduction in the CO_2 emissions would be much more expensive.

The global view

CCS is much more important outside rather than inside of Switzerland. Countries like China or India will not be able to meet their rapidly growing electricity demand in the foreseeable future without new coal and gas power plants. Independence from energy imports is also an important advantage of domestically produced coal. The global demand for steel and cement will also increase further. The comparison of the "Jazz" and "Symphony" scenarios from PSI and the World Energy Council WEC (see Energie-Spiegel No. 22) shows: In the climate protection oriented scenario "Symphony" coal and gas power plants together with renewable energy carriers could contribute to a massive reduction in CO_2 emissions in the next decades (Figure 8). And the reverse is also true: without CCS it will be significantly more difficult and expensive to reduce global CO_2 emissions and limit climate warming to a bearable amount.

PSI research is currently not dealing with the storage, but rather with the **Uses of CO_2.**

Electricity from photovoltaics and wind turbines is available irregularly, but is needed to replace fossil energy carriers for climate protection. When more electricity is produced than the immediate demand, the excess must be directly stored or transformed into other energy carriers. This can be done by the so-called "power to gas" process: hydrogen is produced by electrolysis. This can be combined with the CO_2 that is separated from power plants or cement production. The resulting methane can be stored, distributed and converted again at any time into electricity, or used in combustion motors for transportation. This reduces the overall use of fossil fuels for heat and transport, and also the CO_2 emissions.

„CCS and renewables must each make their own contribution“

How can a layman best imagine the concept of CO_2 capture and storage (CCS)?
Mazzotti: Fossil energy carriers are burned in a power plant to generate heat and electricity. This creates large amounts of the greenhouse gas CO_2, which today are released to the atmosphere, in spite of being damaging to the climate. Instead of this, the technologies are available to separate the CO_2 from the exhaust, compress it and store it in deep underground formations. Porous geological layers are suitable for this storage, which are filled with salt water and capped by an impermeable layer of stone. Such formations exist globally, and they similarly function for the storage of oil and gas.

Marco Mazzotti is professor at the Institute for process technology at the ETH Zurich and heads the ETH Energy Science Center. Prof. Mazzotti has researched CO_2 separation and storage for many years, led the CARMA project and and was author of the 2005 IPCC report on CCS.

Mischa Repmann is a researcher in the Institute for Process Technology at the ETH Zurich. Dr. Repmann completed his dissertation in 2014 on mineralization processes for carbon sequestration and storage.

The idea that CO_2 can simply disappear deep in the ground, appears strange or risky to many. Are these concerns unfounded?
Repmann: The reality is that we find underground deposits of fossil energy carriers today. This shows us that the geological storage structures are available where light liquids like oil, natural gas or compressed CO_2 can be stored in the porous rocks for millions of years. For CO_2, there are also natural physical and chemical processes that increase the permanence of the storage the longer that the CO_2 is in place. For example: CO_2 dissolves over time in the salt brine, which increases its density. The brine containing the CO_2 therefore sinks deeper, no longer needing the impermeable capstone layer. Another example: CO_2 dissolves in the saltwater to form carbonic acid (as we know from soda water). The carbonic acid reacts with the surrounding rock and can result in the formation of carbonate rocks. The stored CO_2 is thus captured and permanently bound as a solid mineral.

> „No one feels directly affected by climate change today”

What is the status of transforming theory into practice? Are there already successful projects?
Mazzotti: Different technologies for carbon capture are available, some of which have been used commercially in industry for decades. Geological storage of CO_2 is less advanced, but there are successful pilot projects, for example in neighboring Germany and France, as well as some commercial projects where it has made economic sense to store CO_2 underground instead of releasing it into the air. One such example is the case of the Sleipner offshore gas platform in Norway, where CO_2 in the gas must be separated before sale. To avoid the CO_2 tax over a million tons of CO_2 have been separated and stored every year since 1996. Another example is the Boundary Dam project in southern Canada, which started in 2014. There the entire value-added chain of CCS has been demonstrated for the first time, from the CO_2 separation in a 110 MW coal-fired power plant, through CO_2 transport by pipeline, to CO_2 storage in an exhausted oilfield.

CCS could make an essential contribution to reaching climate protection targets – as most experts agree. So why has it not moved forwards more quickly?
Repmann: If one asks industry, the main problem lies in the lack of financing. To retrofit a power plant with CCS, or to build and operate a new power plant with CCS leads to considerable investment and higher operating costs, compared to a power plant without CCS. This could be changed by political incentives, for example through air quality laws or a CO_2 tax that is high enough. The fundamental problem is the lack of a public acceptance of CO_2 storage. CCS is a new and therefore unknown technology without easily grasped benefits. No one feels directly affected by climate change today. So why should you advocate for CO_2 storage under your own property without the prospect of any personal advantage?

What could research and policy do to help CCS achieve a breakthrough?
Mazzotti: We researchers can contribute first and foremost to better understanding the single technology steps and how they can be further improved. It is also our task to communicate the knowledge gained to the population and to politicians, and to do so in language that non-experts can understand.

Policy can only set sustainable incentives if the populace supports the technology and understands its uses, strengths and weaknesses.

Wouldn't it make more sense to invest more resources in the development of renewable energy rather than supporting CCS?

Repmann: In the year 2013 the increase in worldwide CO_2 emissions was stronger than in any year of the previous decades; China overtook Switzerland in per capita CO_2 emissions; the hurdles to a follow-on Kyoto Treaty appeared insurmountable… We are convinced that all possible means will be necessary to throttle greenhouse gas emissions to finally get a grasp on the CO_2 problem. CCS and renewables must each make their own contribution. All the energy system models say this without exception. Fossil power plants built today, for example in transitional and developing countries, but unfortunately also in the West, have an operating life of 30 to 40 years and will not be voluntarily shut down before they are amortized. The same is true for steel and cement plants that cannot avoid generating large amounts of CO_2. Only retrofitting with CCS will allow us to reduce the emissions from this existing infrastructure. This is exactly why CCS is so important for the world's climate.

In Switzerland there are hardly any large sources of CO_2. Why should anyone here occupy themselves with this topic?

Mazzotti: The five largest CO_2 point sources in Switzerland are exactly those cement plants that were previously mentioned. But much more important are developments with regard to the Energiestrategie 2050. If we really build gas power plants to compensate for the exit from nuclear power with domestic generation, then the CO_2 emissions of these plants must be fully compensated for – that is correspondingly reduced elsewhere. Already today domestic compensation measures are rare and expensive. If we can show with a pilot experiment that the geology of the Swiss midlands, which until now have only been theoretically examined, are suitable for CO_2 storage, then we can begin to regard CCS as a method for avoiding these emissions. The costs would be calculable from the beginning.

How do the future prospects of CCS appear, worldwide and in Switzerland?

Repmann: As is true for every young technology, it is desirable to complete as many projects as quickly as possible, so that developers, operators, regulators and the populace can gain experience and so reduce the costs. Last fall the largest conference yet on the topic of CCS took place in Austin, Texas. We were there and could feel the general mood that the researchers are ready for the transition of their work from the laboratory on to a demonstration project at a large plant. The CCS pessimism that is holding on in Europe stands in contrast to detectable optimism in North America and China. These regions will determine whether the implementation on the market succeeds, or whether the general hesitation coming out of the economic crisis of 2008/09 will continue. For Switzerland the main thing is that we start pilot experiments and determine the storage potential more exactly, so that the population can seriously decide whether or not it wants gas power plants with CCS.

Impressum

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Energy systems analysis at PSI: The goal of energy systems analysis at the Paul Scherrer Institute in Villigen is to analyze present and future energy systems in a comprehensive and detailed way, considering in particular health, environmental and economic criteria. On the basis of Life Cycle Assessment (LCA), energy-economic models, risk analysis, pollution transport models and finally multi-criteria decision analysis, it is possible to compare different energy scenarios to create a basis for political decision-making.

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PSI-Publications on the topic of CCS:
Giannoulakis S., Volkart K., Bauer C. (2014) Life cycle and cost assessment of mineral carbonation for carbon capture and storage in European power generation. *Int J of Greenhouse Gas Control*, 21, 140-157.
Volkart K., Bauer C., Boulet C. (2013) Life cycle assessment of carbon capture and storage in power generation and industry in Europe. *Int J of Greenhouse Gas Control*, 16, 91-106.
Weidmann N. (2013) Transformation strategies towards a sustainable Swiss energy system – An energy-economic scenario analysis. Diss. No. 21137, ETH Zurich