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CO_2 CAPTURE AND STORAGE: inevitable for a climate friendly Belgium

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CO2 Capture and Storage : Inevitable for a climate friendly Belgium

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1 Summary

The use of fossil fuels is deeply embedded in our Western way of life, and it is a fundamental pillar of our economy. Developing nations are choosing the same path, resulting worldwide in increasing emissions of CO_2. At the same time, the International Panel on Climate Change (IPCC) warns that the emissions of greenhouse gasses should be reduced drastically to avoid important adverse effects of climate change.

First-line measures include extensive use of renewable energy resources, increased energy efficiency, and an energy lean consumption pattern. Such instruments are essential, but are likely to be insufficient by themselves. This is where CO_2 capture and storage (CCS) is considered as an additional and necessary technology.

Particularly in industrial installations, but also for power production, **it will be difficult or impossible to avoid the use of fossil fuels in the short to medium future**. It is exactly for these applications that CCS can be applied to drastically reduce the emission of CO_2.

The industry in Belgium is CO_2 intensive and CO_2 capture appears therefore as an inevitable option to meet environmental goals without jeopardising general well-fare. All capture activities are to be balanced by geological storage, and the potential for that is uncertain in Belgium. Transport of CO_2, by pipeline or ship, is however relatively cheap and efficient, even over distances of several hundreds of kilometres. It is therefore reassuring that the European storage potential is sufficiently large for large scale CCS activities throughout the EU. Nevertheless, **it is highly recommendable to start exploration for domestic storage reservoirs**.

CO_2 capture and storage is a climate friendly measure that does not need sustained financial support to be viable. After a relatively short commercialisation phase the Emission Trading System (ETS) price of CO_2 will by itself be a sufficient economic stimulus. Nevertheless, **early support is crucial for fast and large-scale application of CCS**. Therefore, this report includes recommendations that should lead to a clear energy policy that includes CCS and public funding for a correctly balanced public-private investment scheme for essential developments that will contribute to the common good.

CCS is not a perfect solution. **The option of CCS would not be on the table, were it not essential and inevitable**. This is true for the world as a whole, but also for Belgium and its regions Flanders, Wallonia and Brussels-Capital.

2 Technical fix to bridge the gap

More than 100 years have passed since Svante Arrhenius stated in 1896[1] that the emissions of carbon dioxide from human activities would change climate on Earth. The Intergovernmental Panel on Climate Change (IPCC)[18] confirmed that the impact of anthropogenic emissions is severe and rapidly affects shifts in climate worldwide. Today, we are closer than ever to a nearly worldwide agreement to reduce the emission of greenhouse gasses into the atmosphere. Although this is a great achievement by itself, the journey is far from completed with many stakeholders still looking at each other instead of considering how to maximize their own efforts.

Decarbonising the world economy without negatively affecting growth in both developing and developed countries is also a technical challenge of unprecedented size. CO_2 reduction is needed in spite of any current or future recession, at all scales and in all sectors, from daily activities of individuals to large industrial installations, and including agriculture, transport, the building sector, and many more. Deep reductions in CO_2 emissions are required by 2050, the level of 80% for developed regions being increasingly cited in order to reach an overall reduction of around 50%[13], and at the same time it is stressed that urgent action is needed. The urgency and scale can be compared to the actions taken in Belgium since 1990, which have resulted in a reduction of all greenhouse gasses of 8.3% by 2007. Note that the reduction of CO_2, the main greenhouse gas (87% of greenhouse gasses), was only 3.4%[35].

Among the mitigation measures improving energy efficiency has the highest priority. This includes technical aspects, such as more efficient lighting, cars, and industrial production processes, but especially behavioural changes, such as the way we travel, transport and consume goods, and in general organize our lives. One way to measure this overall efficiency is by expressing the national CO_2 emissions per unit of GDP (Gross Domestic Product), which was about 30% lower in 2007 than in 1990.

Also in a highly efficient society, significant amounts of energy will still be consumed. Ideally this will exclusively come from renewable energy that is extracted from sun, wind, water, biomass or geothermal heat. Although a fast and complete switch to renewables is proposed by some[14], most techno-economic forecasts[18,15] indicate a transition period of several decades during which renewable energy production will steadily grow, but is unable to dominate the European and worldwide energy portfolio. The main other CO_2 free energy source operational to date is nuclear power. But also nuclear energy has its limita-

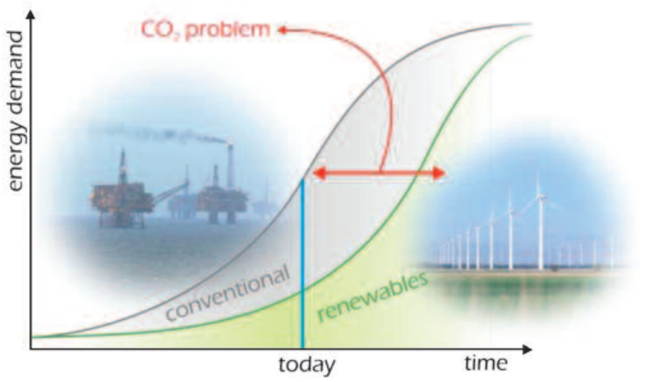

Figure 1. — Renewable energy is not able to replace conventional power production fast enough. Additionally, the demand for energy in developing countries continues to rise. This leads to a situation where conventional energy continues to dominate the overall supply for the next decades. CCS is a solution that can bridge this CO_2 problem.

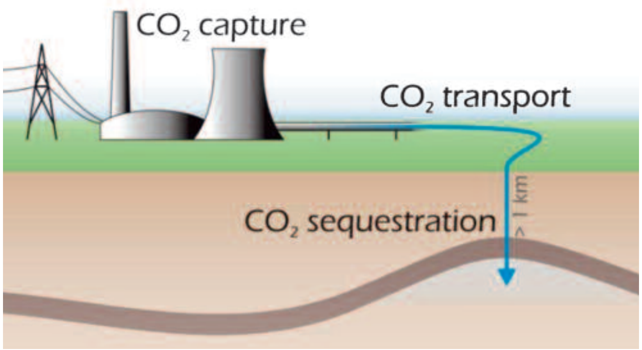

Figure 2. — The CCS chain consists of three parts. CO_2 is first captured at an industrial CO_2 source. It is then compressed and transported through pipelines or with ships. In a last stage, the CO_2 is injected into a suited geological reservoir from where it can not escape to the surface.

tions and can therefore, if found acceptable, only contribute partly to mitigate the climate change problem.

Power generation is only one source of CO_2 emissions, as CO_2 production is actually intrinsic to several industrial processes. This is well illustrated by the lime and cement sectors where calcium carbonate ($CaCO_3$) is converted into calcium oxide (CaO). The CO_2 that is set free thus comes for 60 to 70% from the carbonate rock, and not just from the fossil fuel. In still other sectors, production processes use fossil fuels as feedstock. This is done in the production of ammonia, ethylene and hydrogen in which CO_2 is again an inevitable by-product and partly used to sparkle soda pops.

Fighting climate change thus puts us in a tight position. On one side, there is the ambition to lower CO_2 emissions fast and drastically. On the other side, there is the plain truth that fossil fuels can not simply be banned from society in the nearby future. We are therefore in danger of being crushed between reality and ambition (fig. 1).

Fortunately, there is one technical solution allowing clean use of fossil fuels : CO_2 Capture and geological Storage (CCS). This technology allows for drastic reduction of CO_2 emissions from large point sources such as power plants and other industrial facilities. This is done by separating CO_2 from the flue gas or fossil fuel, and transporting it to a geological location for safe and permanent underground storage (fig. 2).

As such, CCS is proposed as a technology that makes it possible to turn our ambitions into striving, but realistic targets. CCS should be seen as an important, albeit additional mitigation measure (fig. 3), and as an intermediate solution, important for the decades

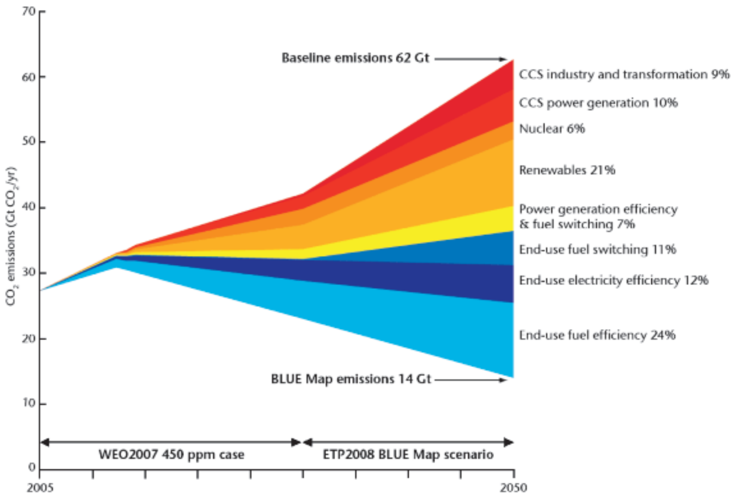

Figure 3. — Greenhouse gas reduction wedges that show, according to the IEA[16], the impact of different measures. CCS will in this scenario cover 19% of the total mitigation effort. According to these projections the same emission targets can be reached without CCS, but this would increase the cost for the world economy by 70%[16].

to come. It has to be complemented by the implementation of renewable energy and alternative production processes. It is in this context that CCS will be explained and discussed in the following chapters, focussing especially on the implications for Belgium.

3 International drive for a prosperous future

The concept of CO_2 capture and storage was proposed by Norwegian researchers between 1986 and 1988 to reduce emissions from a natural gas fired power plant[32]. In their concept the produced CO_2 would be injected in a nearby porous reservoir in the subsurface. Production of CO_2 from natural CO_2 reservoirs and injection to enhance oil production was by then already common practice in the US, although with the intention of maximising oil production, not reducing CO_2 emissions.

EU support for CCS research started in 1992, initially focussing on capturing emissions from the power sector. These cover only a part of the industrial sources of CO_2 to which CCS is applicable (fig. 4), and in recent years, also the iron and steel, and cement sector have received attention and dedicated research projects.

In 1996 the Norwegian off-shore gas platform Sleipner became operational, which was the first industrial CCS project. At this site in the North Sea, natural gas is produced that contains too much natural CO_2. It is common practice in such cases, to separate the CO_2 from methane and release it into the atmosphere. The Norwegian government had, even before the Kyoto protocol of 1997, imposed a climate tax of 340 Norwegian kroner (~40 euro) per metric ton of CO_2 vented from gas and oil activities. This was a sufficient stimulus at Sleipner to reinject the CO_2 into an underlying reservoir, the Utsira sandstone aquifer. Approximately one million ton of CO_2 is separated and injected each year.

In 2007 Europe announced the need for 10 to 12 operational CCS demonstration projects by 2015. These demonstration plants are needed to bridge the gap between the pilot scale of the research projects and commercial application at industrial level. This objective is also repeated in the EU directive on CCS[11], which was finalised in December 2008. The directive itself regulates mainly the storage aspects of CCS as well as the cross-border issues for transport and storage, and needs to be implemented by the member states by 2011.

Due to early action two decades ago, and fast developments during the last years, Europe has been in the lead in developing and deploying CCS technology. However, other regions are catching up (fig. 5). Australia for example, was in 2008 the first country to establish a regulatory framework for CCS, and also Japan, USA and Canada are progressing quickly with setting up demonstration projects.

To date four major commercial CCS projects are operational world-wide (Sleipner and Snøhvit in Norway, In Salah in Algeria, and Weyburn-Midale in

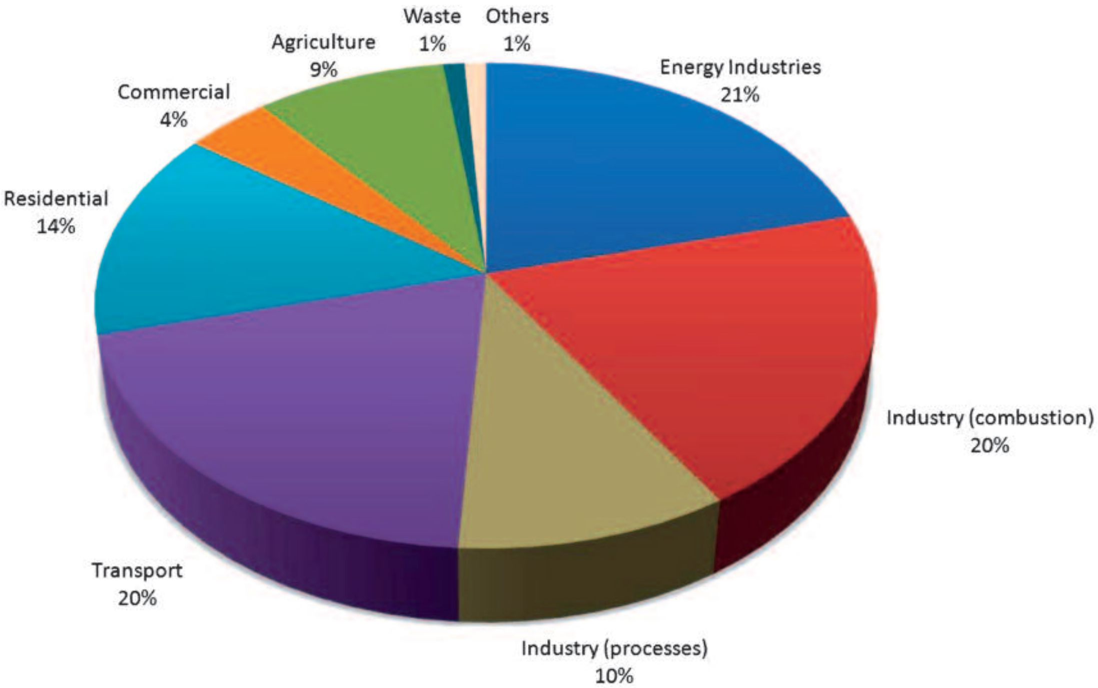

Figure 4. — Overview of the contribution of the main sectors to Belgium greenhouse gas emissions. Energy industries, manufacturing industry, transport, space heating and industrial processes are the most important sectors in the total GHG emissions of Belgium in 2007.[35] Capture of CO_2 is only feasible at large, industrial sources that are found in the energy and industry sectors (right hand side of the pie chart). The total emission of greenhouse gasses in Belgium was 131 Mt of CO_2 equivalents in 2007.

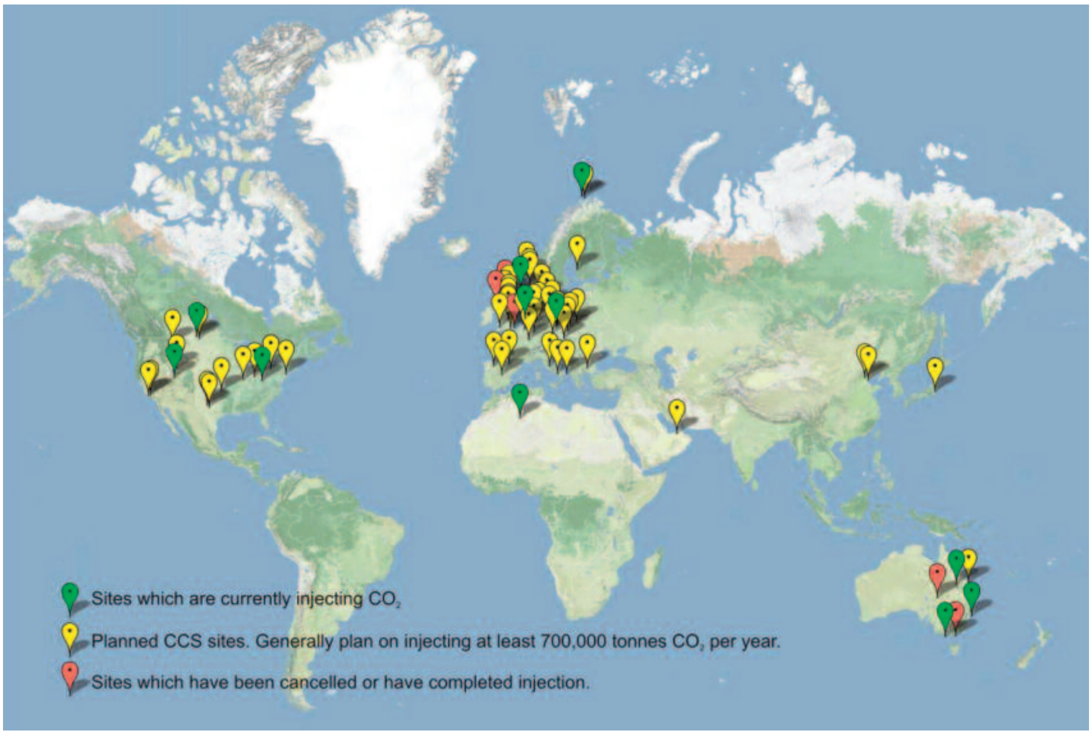

Figure 5. — CO_2 storage projects throughout the world with a minimum injection rate of 700 000 t/y (demonstration projects). Europe, North America, Canada and Australia are clearly on the forefront (from the Scottish Centre for Carbon Storage[29]).

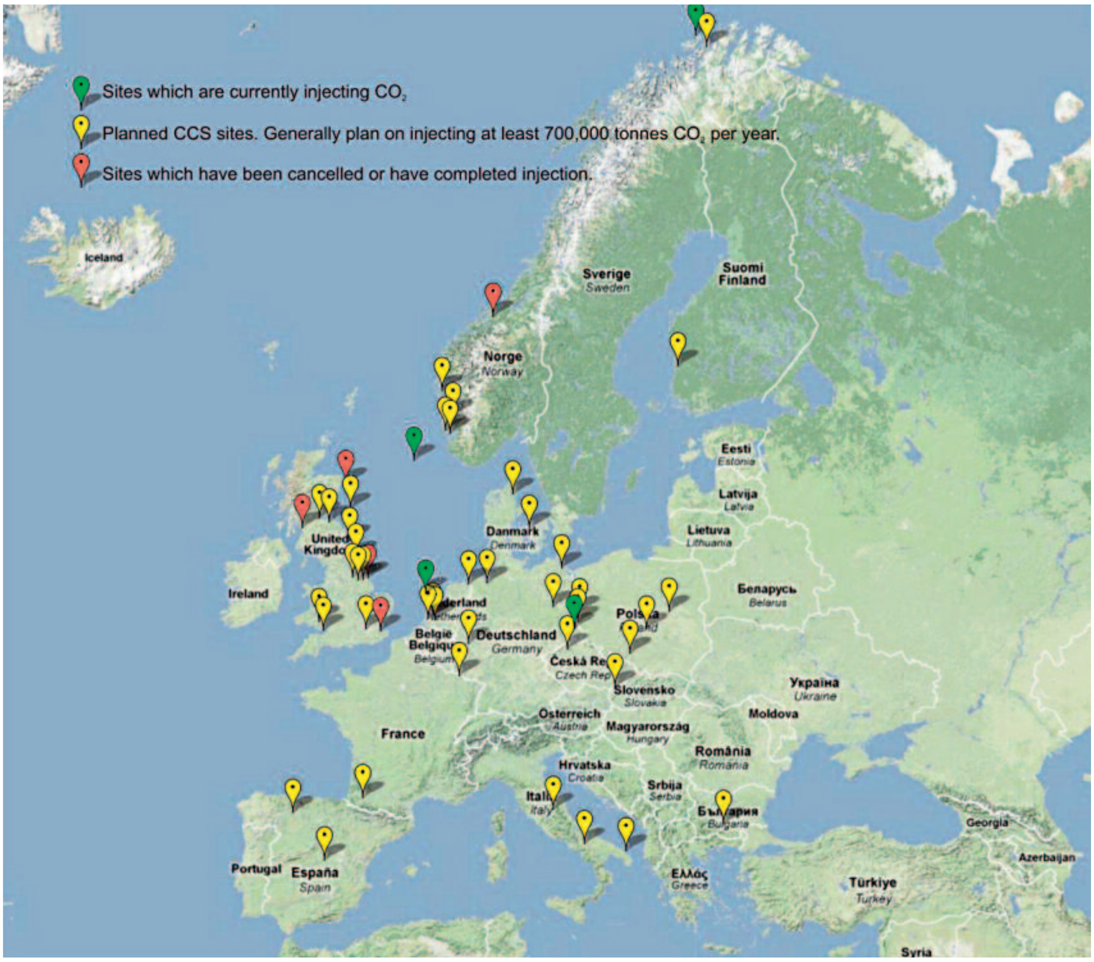

Figure 6. — CO_2 storage projects in Europe. Several CCS projects are planned or active in Western-Europe, but none in Belgium (modified after the Scottish Centre for Carbon Storage[29]).

Canada-USA[a]), all related to oil or gas production. In fact abandoned and empty oil and gas fields act as first potential reservoirs for future CCS. The challenge now is to apply it also to power production and other industrial processes. In Europe alone, around 40 such projects in 12 countries have been announced, including 2 in France, 5 in Germany, 6 in the Netherlands, and 9 in the UK. These projects can benefit from funding under the economic recovery plan (€1 billion for projects in Germany, Italy, Netherlands, Poland, Spain and the UK) and ETS[b] financing for CCS and innovative renewables[c].

Several countries have set up national funding schemes for pilot and demonstration projects. In view of the rapid evolution, an actual overview can only be given by on-line applications. The demonstration projects for storage only (fig. 6) are well summarized by the Scottish Centre for Carbon Storage[29]. A project that deserves attention is located in the Netherlands, where GTI (Suez group) together with the Flemish research institute VITO were selected following an international government tender to develop the Dutch Geleen-Sittard demonstration project. The objective is to store a total of 2 Mt of CO_2 coming from the nearby DSM agro ammonium production plant.

In Belgium there are no concrete plans for CCS demonstration projects yet. Nevertheless, applications are running for constructing capture-ready coal fired power plants, making the option very real for Belgium. This is not surprising as the impact assessment of the Commission of the European Communities[5] has shown that the CO_2 intensity of the industry in Belgium is high, resulting in a very high impact of mandatory CCS (4th after Germany, Poland and the UK), but also making Belgium a natural candidate for CCS. This does not mean that the mainly export-oriented heavy industry in Belgium is particularly polluting. It is on the contrary highly efficient compared to international standards, which makes it difficult to reduce the CO_2 emissions by improving the production processes.

The interest from industry, the international involvement of our research institutes, and the fast developments in Europe and especially in our neighbouring countries, have now put CCS on the agenda in Belgium.

This does not necessarily mean that CCS is considered a key technology for the future energy and industrial policy of Belgium and its regions. Belgium is in favour of international research and demonstration projects in order to obtain more data and information on CCS, but it is for the moment unlikely that Belgium will be a pioneering country. It, however, does wish to keep the option of CCS open for both power production and for other industries. The uncertain geological storage potential is acknowledged resulting in attention for the option of exporting CO_2 to neighbouring countries from capture projects in Belgium. This naturally leads to stressing the importance of international transport networks for CO_2 and that of EU level playing rules.

4 Capturing emissions : aiming at industry

Capturing CO_2 means separating the CO_2 molecules from other components in a mixture of several gasses. Compare this to milk and sugar in coffee. These are easy to mix into a homogeneous mixture, but it is much more difficult to recover the milk and the sugar from the coffee after their mixing. This is due to the fact that mixing two or more substances in gaseous or liquid states is an irreversible process with an entropy production. Consequently, extracting one component from a mixture requires energy.

For a CO_2 capture process, this energy mainly depends on the concentration of CO_2 in the mixture and on the separation process that is used (absorption of CO_2 with solvents, selective adsorption on a solid, diffusion through a membrane or cryogenic distillation). Industrial installations such as steel, cement, petro-chemistry, refineries, glass, are the biggest and most concentrated CO_2 emitters, and compared to power generation quite important in Belgium (fig. 8).

Three main capture technologies are currently under development, namely : 1) the removal of CO_2 from the flue gas both in coal and natural gas fired power plants, boilers and furnaces, also known as post-combustion capture or decarbonisation of the flue gas (fig. 7b) ; 2) the removal of carbon from the fuel after reforming of natural gas or gasification of coal into H_2 and CO_2, also known as pre-combustion capture or decarbonisation of the fuel (fig. 7a), and 3) oxy-fuel combustion, both in boilers and in gas turbine cycles (fig. 7c). Oxy-fuel combustion is commonly referred to as a capture technology, but is actually a combustion technology with pure oxygen, limiting the capture process to water elimination and minor purification of the CO_2.

These capture techniques seriously affect the performance and impose additional cost of the energy generated. But it also drastically reduces the emission of CO_2 by 85 to 90% of the amount formed in the conversion process. This goes also for the emissions

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[a] Information on these projects is summarized on the website of the Zero Emissions Platform (ZEP). Look under commercial projects on www.zeroemissionsplatform.eu/projects.html/fossil-fuel-power-plants-announced-pilot-demonstration-programmes#.

[b] ETS or Emission Trading Scheme is a financial system on European scale where emission units can be traded. The price of these allowances is therefore not fixed. The price is currently around 15 €/tonCO_2, and is expected to increase on mid to long term.

[c] Instead of a fixed sum, the amount of financing is expressed in ETS and will thus depend on the price at which CO_2 will be traded. The ETS allowances are agreed to come from the new entrant reserve (NER, reserve aside by member states originally for new or additional capacity subject to ETS). In total 240 million ETS allowances by 2011 and an additional 60 million allowances by 2014 will be made available.

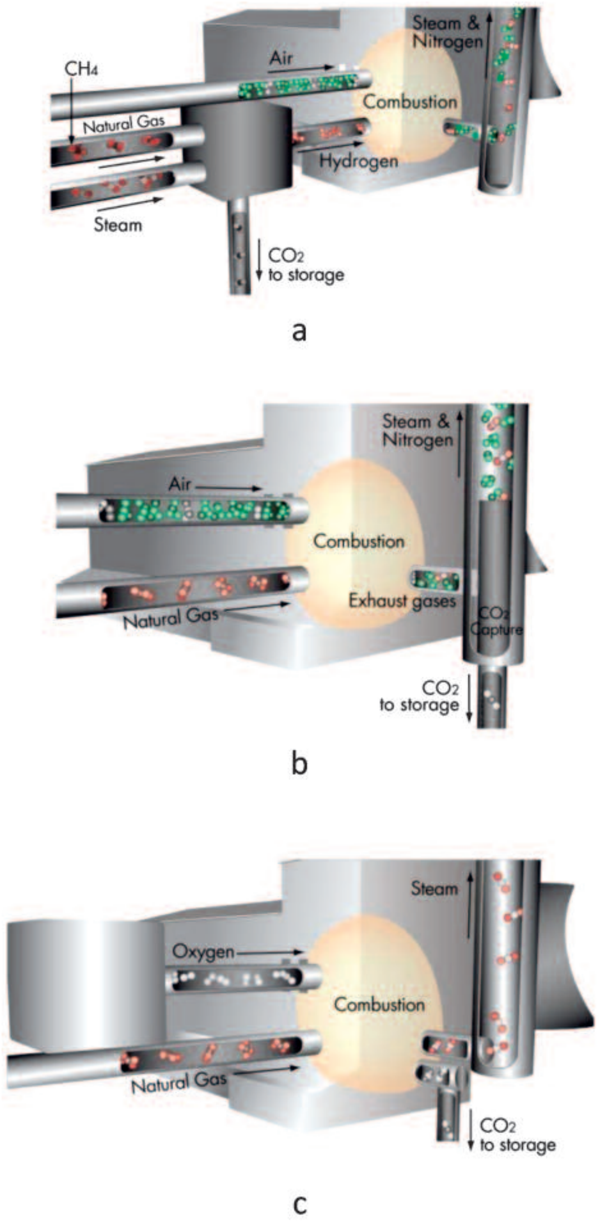

Figure 7. — (a) In a pre-combustion installation, natural gas is reformed or coal is gasified to produce a syngas (CO and H_2). Reacting with water, the CO is shifted into a mixture of hydrogen and CO_2. The CO_2 is then separated (captured), while H_2 is burned to produce energy.[3]

(b) Post-combustion capture is the most classic option in which a solution with a high CO_2-affinity (amine) to take out (capture of about 90% of the CO_2 formed in the combustion) the CO_2 is sprayed in the flue gas in a reactor called the absorber. The CO_2-depleted flue gas containing still about 10% CO_2 is released to the atmosphere through the stack, while the solution is treated in a separate reactor called the stripper or desorber to release the CO_2 [3] from the solution and recover and recycle the amine.

(c) In oxyfuel capture, pure oxygen instead of air is used to burn the fuel. The flue gas then mainly consists of H_2O (steam) and CO_2, which are relatively easy separable by water condensation. [3]

of the pollutants formed during the combustion process such as the acid oxides of sulphur and nitrogen. It is likely that CO_2 will need further purification before it can be transported and stored in order to avoid corrosion or increased compression costs in pipelines or injection installations.

Post-combustion capture or flue gas decarbonisation appears today as the closest to a commercial deployment (fig. 9). The capture process relies on solvents. Chemical absorption is currently most suited for the removal of CO_2 from the flue gas. The consumption of heat for the CO_2 extraction from the solvent solution (the solvent regeneration) is very penalizing on the system performance, and R&D has the objective of developing solvents with lower regeneration energy, longer life times and lower corrosivity.

Post-combustion capture is closely followed by oxy-combustion in existing (retrofit) or newly designed boilers (fig. 10). The oxyfuel combustion is at present applied to boilers at atmospheric pressure, fuelled with coal or gas or any burnable stuff (biomass, wastes…). Another option is the application of oxy-combustion to gas turbine cycles using natural gas as the fuel. These cycles are nowadays at the R&D level and one of them (the so-called MATIANT cycle) has been designed and developed at the department of power generation at the University of Liège[21,21,23]. Pilot power plants have recently been commissioned in Europe on both options and commercialisation is expected at the 2020 horizon. However, R&D on pilot plants is still needed to overcome the bottlenecks, fill the gaps in knowledge and validate the models in order to scale up the pilots to commercial plants.

The option of fuel decarbonisation is based on integrated gasification technologies (IGCC), using solid fuels such as coal or biomass. The pre-combustion capture is currently less advanced than the two other options since the gasification IGCC technology itself is not widely commercialized yet in power generation. Decarbonation of the fuel is currently best done using physical adsorption because of the high CO_2 concentrations.

All capture technologies reduce the power plant efficiency by 7 to 14% points[a] and in average by some 10% points in highly efficient (supercritical) coal fired plant. According to the efficiency drop, the additional cost of electricity when capture is implemented is in the range 50 to 100% for coal and 30 to 60% for natural gas[17]. In the case of a supercritical plant, this extra cost amounts to some 40%[27]. When 90% of the CO_2 formed in the combustion is removed, the capture cost is 40 to 60 €/t CO_2 [17,24].

This includes the compression necessary for transporting CO_2. Compression normally goes through several stages with intercooling up to about critical

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[a] A typical power plant has an efficiency of 45%, a drop of for example 10% points reduces the plant's efficiency to 35%.

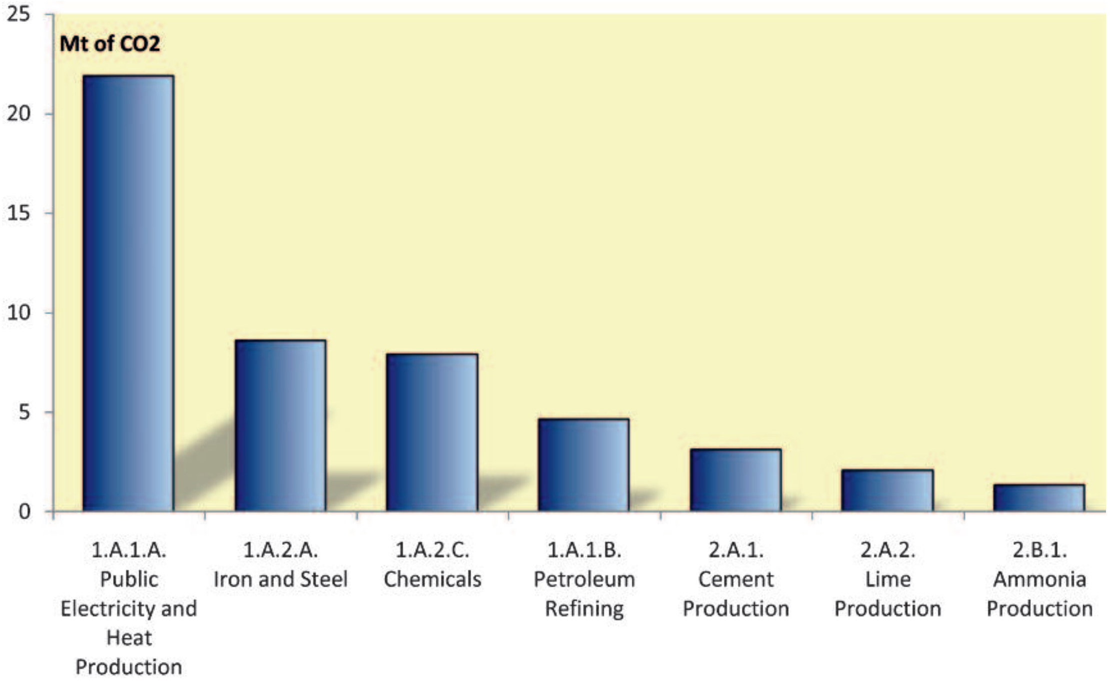

Figure 8. — The industrial emissions of some industrial sectors in Belgium that can be considered as sources for CCS projects. Numbers, expressed in Mt of CO_2, are for 2007. Sector numbers according to IPCC guidelines. Source Environmental Energy Agency (http://dataservice.eea.europa.eu/pivotapp, see also reference 35).

Figure 9. — The Charleston DOW – ALSTOM pilot CO_2 capture plant in West-Virginia, USA (post-combustion capture, http://dow-alstom.charlesryan.com)

1. Flue gas inlet duct
2. Air quality control system (Removes pollutants from the flue gas)
3. CO_2 absorber (The flue gas flows upward in contact with a amine solution which flows downward and absorbs the CO_2. The remaining flue gas exits at the top.
4. Amine regenerator (Energy is added to the CO_2-rich amine solution and the absorption process is reversed. The amine solution is pumped back in the CO_2 absorber, and the CO_2 is compressed and purified for transportation or storage.)

Figure 10. — Schwarze Pumpe in Germany. This power plant by Vattenfall has a 30MW th pilot oxyfuel capture plant (www.vattenfall.com/www/co2_en/co2_en/index.jsp).

pressure. The CO_2 will condense into a supercritical state at ambient temperature. CO_2 in supercritical state can be pumped up to higher pressure consuming much less energy than by compressing gas.

Furthermore, on top of the power generation sector, industrial installations emitting large volumes of CO_2 (larger than 250000 t/y) such as steel, concrete, chemical and petrochemical factories are good candidates for the early application of capture technologies. In some cases the CO_2 concentration in the gas streams is higher than in power generation, and therefore the cost of capture can be lower[27]. Due to different characteristics of the gas streams in industrial installations, different capture techniques may be applied : absorption in a solvent, cryogenic distillation, the selective adsorption (pressure swing) and membranes, these two latter being used when the CO_2 concentration is higher than in the flue gas of power plants. This concentration is in the range 3 to 15% by volume for gas and coal respectively whereas it is about 15% for iron and steel factories, 15 to 30% for cement factories, 3 to 13% in refineries and nearly 100% in ammonia and hydrogen production.

Some future improvements of already existing capture techniques, such as the development of new solvents (for example the chilled ammonia), as well as new concepts, such as anti-sublimation (separation of CO_2 from the flue gas by solidification) are currently tested in pilot installations. Together with a better integration, they should decrease the energy consumption in the capture process and reduce the cost of capture for the same capture efficiency.

5 Store to avoid climate mitigation : geological storage

Geological storage of CO_2, also referred to as sequestration, consists of injecting CO_2 in deep, porous rocks, called reservoirs or sinks (fig. 11). At depths below 800 m, CO_2 will stay compressed as a supercritical fluid. This physical state combines a high density with a low viscosity, which results in an efficient use of the storage space and at the same time facilitates the injection of the CO_2 in the porous reservoir rock.

Conventional reservoirs consist of sandstones or carbonate rocks (limestones and dolostones). Suitable reservoirs must allow CO_2 to flow from the injection wells into the rock under a limited pressure difference. In any case injection should be possible without damaging the overlying seal, otherwise CO_2 may escape to the surface due to its buoyancy. That such reservoirs exist, is proven by the existence of producing oil and gas fields. However, in places where production data from old oil or gas fields is lacking, the flow properties of the reservoir rock and the quality of the seal have to be assessed through well tests.

Safe trapping of the CO_2 is in the first place ensured by a seal covering the reservoir, i.e. a caprock of low-permeability rocks such as claystones or stone salt. Caprocks are usually defined as physical barriers against fluid migration (e.g. CO_2) but evidence is growing that chemically active layers such as carbonaceous shale and marl may also serve as efficient seals or can act as a secondary barrier against CO_2 leakage. Residual trapping, dissolution, density flows and mineralisation will add to the long-term stability of the stored CO_2.

The situation is different for an unconventional reservoir such as coal reservoirs. Here, CO_2 may be effectively trapped by adsorption under hydrostatic pressure, theoretically eliminating the need for a seal (fig. 11). Vast coal deposits occur in the subsurface of Belgium at suitable depths. They could serve as stable, chemical sinks for several hundreds of million tons of CO_2 in both the Flemish and Walloon basins. However, under real conditions, free, over-pressurized CO_2 would likely occur in the coal for some time due to slow sorption kinetics. Therefore, physical and chemical integrity of the caprock, typically thick clay- and siltstones interbedded with the coal beds, should guarantee containment during the soaking period when part of the CO_2 is still present as a free phase. One economic advantage of storing CO_2 in the coal is the possibility of producing the methane released by desorption (ECBM : Enhanced Coal Bed Methane).

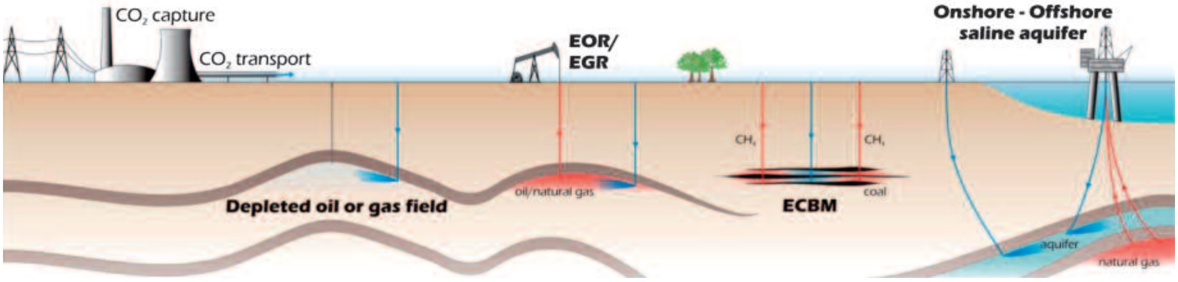

Figure 11. — An overview of geological CO_2 storage possibilities26. CO_2 can be stored in depleted oil and gas fields or in an EOR/EGR system for enhanced recovery (ER) of remaining oil and natural gas. Such reservoirs are not available in Belgium, but storage opportunities exist in saline aquifers and coal. The latter offers the opportunity to recover methane using Enhanced CoalBed Methane (ECBM).

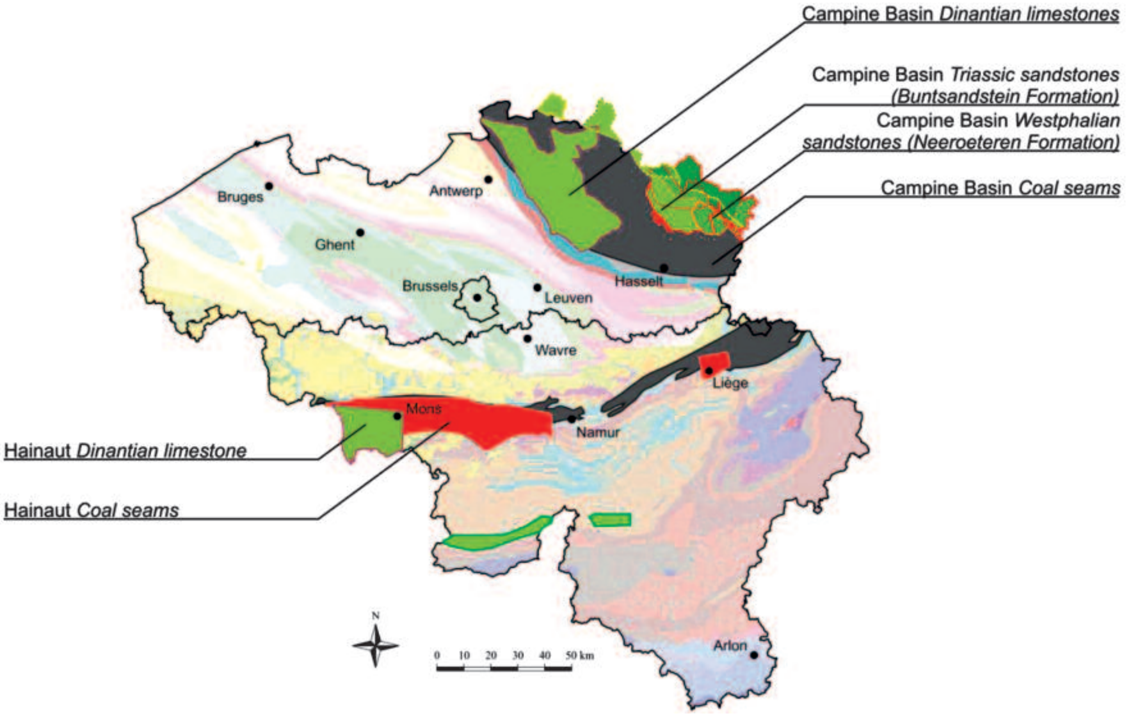

Figure 12. — Geological map of Belgium26, with indication of possible CO_2 storage locations discussed. Green = aquifer, red = coal, grey = all coal depositions.

However, as shown by recent pilot projects (e.g. RECOPOL[34] and MovEcbm[33] project), the low permeability of most coals, especially in Europe, is a major limitation to the current up-scaling of ECBM techniques.

Potential geological reservoirs in Belgium were identified in deep aquifers and coal seams from both the North and the South of the country[27] (fig. 12). Capacity estimates based on available data show a limited but significant potential in the order of 1000 Mt CO_2 with a balanced share between Flanders and Wallonia. Adequate exploration and field tests however are needed to verify what percentage of this capacity can be effectively developed.

The most prospective reservoirs appear to lie in the Campine (NE Belgium) and the Hainaut-Centre basins. In the Hainaut area, unmined coal seams interbedded with sandstones and shales are overlying the Dinantian limestone aquifer that may also store huge amounts of CO_2. The storage capacity in the Hainaut deep geothermal aquifer alone is likely to be huge, i.e. about 500 Mt CO_2, on a basis of a reservoir extending from near the French border to the Centre region. However, there is a potential conflict of use with geothermal energy production and it should be investigated whether both applications are compatible[28]. In the Campine area, storage sites are present in the Dinantian limestone, but the number of structural traps and the capacity of each of them is limited[9,20]. Additional storage opportunities may be located in Latest Westphalian and Triassic sandstones of the Campine basin[19].

More detailed and technical figures for CO_2 storage in Belgium exist but most are highly prospective due to the lack of necessary geological data, especially for deep aquifers. Reducing geological uncertainties below acceptable levels for accurate assessing of CO_2 storage in Belgium is not conceivable without new research involving seismic exploration, drilling programs and pilot projects.

6 An EU network for CO_2 transport

CO_2 will be captured at e.g. a power plant or a steel factory, which will rarely be at the same location as where it can be stored. Therefore it usually will have to be transported over some distance. Transporting large quantities of CO_2 can be done by ship, or, most relevant for Belgium, along pipelines.

Pipelines for CO_2 are basically similar to the main pipelines for natural gas. They will be constructed out of high-grade steel with dimensions up to 1 meter in diameter. The pressure during transport will be between 80 and 160 bars in order to keep the CO_2 liquid and avoid two-phase flow. Such pipelines have been used in the USA and Canada for several decades for transporting CO_2 to enhanced oil recovery projects, into which CO_2 is injected to increase the hydrocarbon production. Since 2008 an offshore CO_2 pipeline is active in Europe as well, transporting CO_2 for the Snowith project over a distance of 153 km.

The construction of a pipeline is expensive, but once build it can transport CO_2 efficiently over large distances. During a first stage, pipelines will connect a single capture facility with a single reservoir. With time and growing CCS activities, a whole pipeline network will develop that receives CO_2 from industry and delivers it to several geological reservoirs. Pipelines are infrastructures that require extensive up-front investments but because of the large volumes that will be transported, it will probably be the cheapest part in the CCS chain when the scale of transport is sufficiently large, costing on the order of 1 to 3 €/tonCO_2 for transporting 10 Mt/y over a distance of 100 km.

Comparable to e.g. the natural gas distribution network, transport of CO_2 will develop in a European context. Pipelines will cross national borders, and CO_2 produced in one country may well end up being stored in another. Such an outlook is extremely important for a country such as Belgium, where still significant uncertainty exists on its domestic geological storage potential.

In one likely scenario, part of the CO_2 captured in Belgium, especially around Antwerp, would be transported to neighbouring countries. From there, it would then be shipped onwards to reservoirs on- or offshore, such as storage locations in the North Sea.

It is this international outlook that allows Belgium to ascertain a future for CCS, as it guarantees that all CO_2 captured in Belgium can also be stored, which is a reassuring fact.

On the other hand, identifying new CO_2 reservoirs in Belgium is likely to be awarded. Exporting CO_2 will lead to longer transport distances and possibly export fees, both of which are avoided when CO_2 can be stored in Belgium. More importantly, export oriented CCS activities will make Belgium more dependent on the international willingness and ability to store our CO_2, and developing domestic storage capacity will therefore improve the autonomy of the Belgian industrial poles. CO_2 storage also offers opportunities. Economic activity and expertise associated with storage projects should not be underestimated, and there may be an economic bonus in developing coal reservoirs as enhanced coal bed methane projects (ECBM, see chapter 5).

7 How dangerous is handling CO_2 ?

CO_2 is an essential chain in the carbon cycle, steering plant and animal metabolism, and a normal, non-toxic constituent of our atmosphere. CO_2 is colourless, odourless, tasteless, non-flammable, non-poisonous, and soluble in water. CO_2 is not dangerous ; however, the increase of its concentration creates environmental change. Growing atmospheric CO_2 levels from 0,03 to 0,05% do not create health problems but induce a greenhouse effect. Combined with water CO_2 forms carbonic acid that may contribute to acidification of aquatic ecosystems and the oceans. Removal of excess CO_2 is thus beneficial for the biosphere, but as each industrial process subject to environmental regulation and risk management. Moreover, clean power generation leads to a general reduction of pollutants and not only of CO_2. For example, the particulates, the NOx and SO^2 levels are lower than in a power plant without capture.

Handling CO_2 is not new. Concentrated CO_2 streams from chemical plants have ever supplied the bubbles in non-alcoholic beverages and the dry ice for hospitals, fishmongers or rock concert stages. Enhanced Oil Recovery (EOR) based on CO_2 mining and pipeline transport is practiced on industrial scale since the sixties of last century, mainly in North America. As measured by the lack of fatalities and injuries and significantly lower property damage, impacts from CO_2 transport by pipeline incidents are lower than those from natural gas and hazardous liquid pipelines. However, a continuous exposure at just over a 2% concentration can cause depression of the central nervous system in humans. At concentrations above 10%, it can cause severe injury or death due to asphyxiation[36]. CO_2 is denser than air and can therefore accumulate to potentially dangerous concentrations in low-lying or confined areas, which has led to stringent health regulations. CCS will not pose imminent health problems for the public. At aerated spaces, potentially dangerous CO_2 levels will not be reached beyond a few meters distance of eventual leakage points.

The risks caused by CCS rather relate to materials failure and long-term effectiveness, hence usefulness, of underground storage. Carbonated water has the potential to corrode pipelines and cement. Moreover, the captured CO_2 can contain traces of H_2S and other combustion gases, making it even more aggressive. The main cause for technical problems related to EOR, and therefore CCS, appears to be material failure following corrosion and outside forcing of the gases[12].

Based on experience from underground gas storage, leakage of CO_2 out of the reservoir appears to be the major pitfall associated with the geological sequestration of CO_2 (fig. 13). Migration of brines and CO_2, possibly affecting groundwater and drinking water seems to be a minor risk. Triggering of ground movement, subsidence or uplift due to pressure and stress changes, constitute only low risks. However, fluid-induced seismicity might occur as reported from gas fields in the Aquitaine Basin in France[31,30,2]. Although underground reservoirs are generally considered to be safe sinks for CO_2 sequestration, they represent natural environments, which means that properties and morphology can be quite variable and distinctive. Consequently, no sites are identical and absolutely tight. CO_2 might migrate out the reservoir through spillpoints, guided by faults, across the caprock. Processes reducing caprock integrity include capillary leakage, CO_2 diffusion and hydraulic fracturing due to over-pressurizing the reservoir[4]. CO_2-leakage along man-made access wells can be caused by tubing and cementation defects or corrosion by CO_2 or brine.

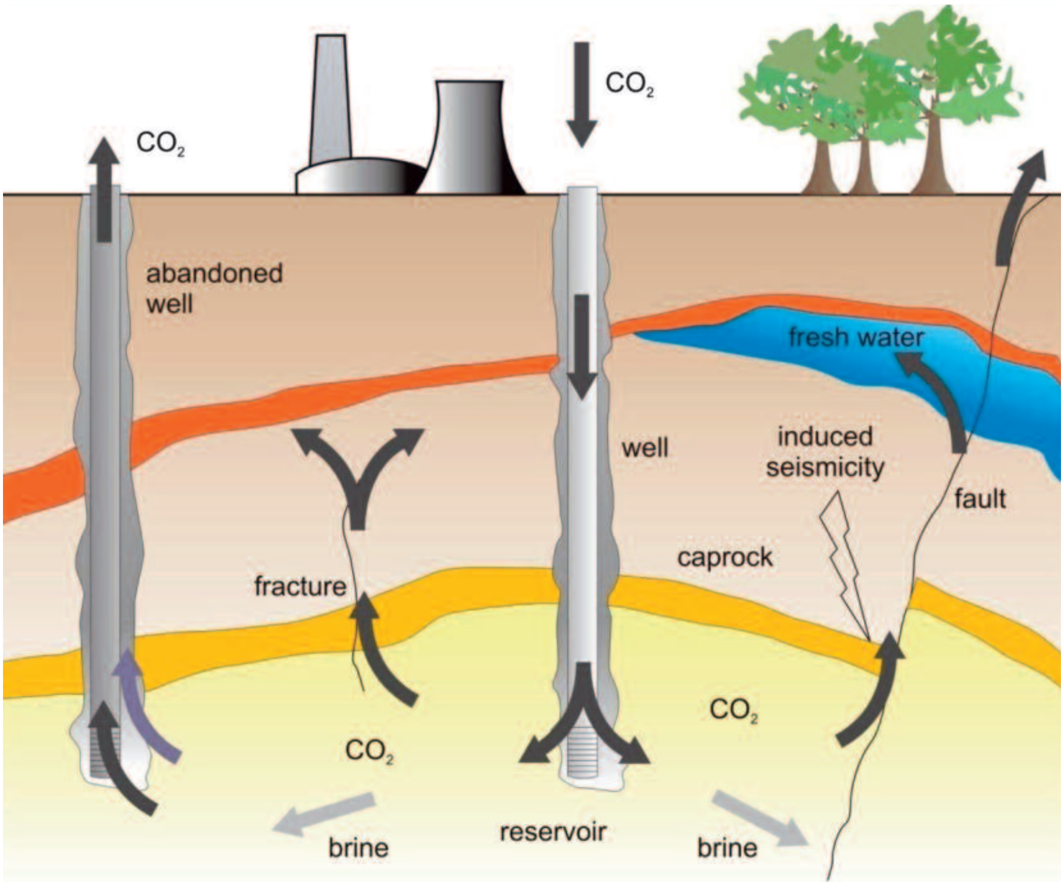

Figure 13. — Risks of underground CO_2-sequestration. Arrows represent CO_2 flows (along abandoned wells, fractures and faults) and brine displacement (after reference 7).

Knowledge about the latter however exists from oil and gas producing facilities. Fortunately, the number of deep wells drilled inadvertently in deep saline aquifers or coal beds, and consequently the potential for leakage along old wells is relatively low. Leakage through a failed cap rock poses the highest risk, and thus needs future attention. Leakage from coal beds will probably be intercepted by the numerous overlying shale sequences or even trapped by interbedded porous sandstone beds (e.g. Campine Basin, Belgium and adjacent coal fields).

8 With or without CCS

Based on the earlier chapters, an assessment can now be made of the importance of CCS for the mitigation of CO_2 emissions in the coming decades in Belgium.

How sustainable is CCS?

It is important to start from the notion that CCS is not a-priori a fully sustainable solution when compared to for example wind energy. This is because CCS is normally associated with the combustion of non-renewable fossil fuels, although biofuels may of course also be used. However, it clearly is a climate friendly solution, capable of very strongly reducing CO_2 emissions from large industrial sources (exceeding up to 90% for individual installations). In general CCS has a relative low environmental impact, also when used in combination with coal fired power production (clean coal technologies).

Benefits for Belgium

Stringent mid and long term climate targets are currently discussed, such as a reduction of as much as 80% by 205013. An energy portfolio with such target will always include CCS for the power sector as an economic option, meaning that CCS is successful in mitigating the impact as well as the costs of climate measures. Also from a technical viewpoint, deep reductions become more feasible and less risky when CCS is included as a sequestration option in relation to energy production.
Belgium currently has a CO_2 intense industry. For iron and steel, cement, lime, petrochemistry, and other sectors, CCS is the only medium term solution capable of drastically reducing CO_2 emissions. CCS could therefore be a prerequisite for safeguarding these industrial sectors with respect to the mid and long-term climate objectives of Belgium.

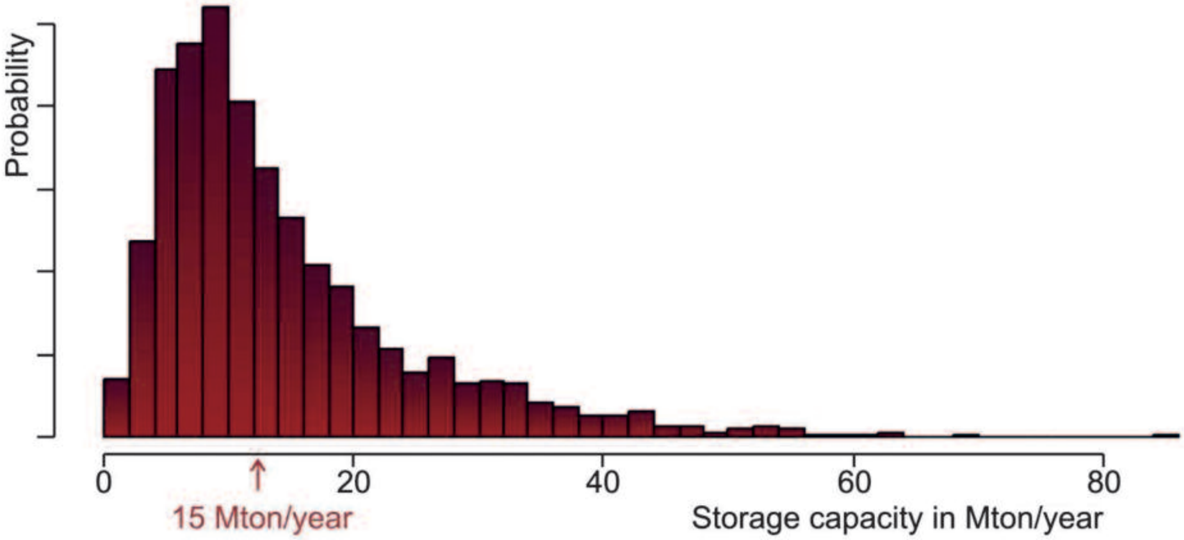

Figure 14. — Storage potential in Belgium per year. The storage capacity per year depends on the CO_2 storage price and an uncertainty factor. This histogram represents the storage capacity for a CO_2 storage price of €15/t. The average annual storage capacity will then be 15 Mt.

Bottlenecks for Belgium

The most apparent pitfall for CCS in Belgium is the uncertain storage potential. This potential is roughly estimated in the order of 1 Gton, possibly allowing to store 10 to 15 Mt per year once the full potential is explored (fig. 14). This is significant, but clearly insufficient for full deployment of CCS activities, which aims at the capturing of over 40 Mt of CO_2 each year[27] of industrial sources (see fig. 4).

Domestic storage capacity however will not be a limiting factor for the development of CCS. Rather, it is an issue that emphasizes the relevance of the international context in which CCS will develop for Belgium. Techno-economic simulations show that a significant part of the CO_2 captured in Belgium will need to be exported to neighbouring regions, either because of geological restrictions in Belgium or because international storage options may be more economic and safe. Noteworthy here is that several countries, in particular the Netherlands, are preparing for a future in which they will act as an international distribution hub for CO_2.

The assumption that Belgium could rely on the export of captured CO_2 does not imply that storage options in Belgium should not be explored. On the contrary, these should be seen as economic and strategic opportunities. However, the uncertainty on the outcome of exploration is currently too high to rely only on private investments for identifying potential reservoirs.

The pipeline transport network for CO_2 could grow in Belgium to comprise over 1000 km of high-pressure pipelines[8,27] which approaches the scale of the current day transmission pipeline network for natural gas[25]. Some areas dedicated to underground workings such as pipelines are already approaching saturation. It is therefore important that infrastructural decisions relevant to pipeline construction are taken soon in function of the expected further expansion of the network.

With very few pilot tests and without any demonstration projects, Belgium is currently depending on the development of capture and storage technologies in other countries. If this passive approach is sustained, technology and expertise will have to be imported at the time that these technologies are fully commercialised, which will likely be around 2020.

A problem which is not specific for Belgium is that CCS will increase the energy production cost. This would evidently lead to unfair competition in case the CO_2 reduction targets would be different for developed and developing regions. Such concerns are highly relevant to sectors that face international competition, such as cement production, but of less importance to products focussing on local markets, such as the power sector. This discussion exceeds the context of CCS, and has proven to be a highly sensitive topic during the UN Climate Change Conference in Copenhagen in December 2009.

Some lessons can be drawn from recent demonstration projects in other European countries on the social acceptability of CCS. A subjective feeling of risk associated with storage of CO_2 formed the basis for strong local opposition, e.g. recently at Barendrecht, The Netherlands. This emphasizes the need for early research on integrating communication and information actions in decision strategies in order to get local support.

Conclusion on CCS in Belgium

CO_2 capture and storage in the Belgian subsurface shows clear techno-economic benefits for Belgium, especially in a context of deep greenhouse gas reduction targets[6,10]. Domestic geological constraints and uncertainties should be addressed, but will not hinder deployment of CCS because of the availability of international storage options and initiatives.

Also other concerns should be taken into account. CCS is largely an environmental friendly technology, especially when compared to the current best industrial technologies, but it is not fully sustainable since it e.g. relies on non-renewable energy. As such it is usually proposed as a bridging technology for the next decades, during which fully sustainable alternatives are to be developed and implemented.

Some risks during processing, transporting and injection of CO_2 are inherent to CCS, but they are well known and predictable, and both the frequency and impact of the risk level is very low. This scientific and objective evaluation does not exclude the subjective feeling of risk of a local community, which may lead to strong opposition against especially storage projects. This emphasizes the importance of social aspects, next to all technical factors.

The final balance tips clearly towards the benefits of CCS. This is why CO_2 capture and storage is proposed here as a viable and valuable technology for Belgium in the next decades, during which it will help to bring power and CO_2 intense industry in line with the objectives of a strict climate policy.

9 Expert Recommendations : establish correct framework for industrial driven development

This report acknowledges a priori the importance of energy efficiency and renewable energy as priority measures to curb the national and worldwide emissions of carbon dioxide. Nevertheless, it also stresses the need for additional measures, and highlights CO_2 capture and geological storage as an essential and important complementary option for Belgium. In this chapter, recommendations are made to environmental and energy agencies at national and regional levels.

The perspective of these recommendations is important : CCS will bring a technological revolution in which the drive (investments) will come from industry, but where the government is responsible for paving the road (enabling framework) and starting the engine (incentives).

9.1 Enabling framework

1. The transposition of the EU directive on CCS, which focuses on the storage aspects, is well underway in Flanders, but needs to be speed up in the other regions. It is commendable to verify existing and new legislation and administrative procedures on timing and juridical bottlenecks for integral CCS projects (capture, transport and storage), including interregional and international aspects.
2. In order to avoid technology lock-in after 2020, the concept of capture readiness should be well-defined and embedded in the application procedures for building new power plants and other CO_2 intensive industrial installations.
3. The EU directive refers to a ‘competent authority’ to evaluate and follow-up on proposed storage projects. The regional institutes need to be reformed in order to guarantee their objective judgment.
4. Carbon Capture and Storage is multi facetted and cross cuts through federal and regional competences. With due respect for regional autonomy, extensive coordination and cooperation at federal level seems strongly advisable, also on the international aspects.
5. Potential public opposition against CCS, and especially CO_2 storage projects, are already acknowledged as a major item of concern. Communication strategies should be prepared early and be coordinated. Federal or regional authorities should be pedagogic with the public and assume their responsibility. Additional support will come from scientific institutes and certain NGO’s, but by itself not in an organised way.
6. The pipeline infrastructure for CO_2 may become extensive, second in size only to the transmission network for natural gas. Such an outlook calls for long-term planning, especially on reserved zones for underground utilities (pipeline corridors), over-dimensioning of pipeline tunnels, and interconnections with neighbouring countries.

9.2 Incentives for industry

1. Carbon capture and storage is not an explicit option for the future (post 2020) energy portfolio in Belgium. A clear choice should be made in favour of CCS in order to provide industry with clear choices.
2. In other sectors, the number of possible technologies is much more restrained than for power production. Only a few of these sectors (iron & steel and cement) are relatively well organised on the topic of CCS. A dedicated national or regional platform should tackle concerns for specific sectors and facilities, and assist in consolidating technology and emission targets.
3. The anticipated progress of industry will result in a roadmap. It is important to define indicators that allow the monitoring of the actual progress towards the targets defined.

9.3 Public funding to take away uncertainties

1. Uncertainties on investment costs, efficiencies or life-time result in an overall economic uncertainty that forms a major hurdle for the commercialisation

of all capture technologies. This is why demonstration projects with public-private participation are urgently required. Such projects are well underway throughout Europe and the world. It is unlikely that Belgium can at this point still get involved in demonstration projects on capture. A close technology watch of ongoing initiatives and results seems currently the best option to prepare for the technological revolution that CCS will bring. Such a technology watch may include the participation in dedicated implementing agreements.

2. There are no demonstration projects in Belgium for storing CO_2. One project with relevance to Belgium is the demonstration project in Geleen, Southern Limburg (The Netherlands) where Belgian expertise is being deployed. However, successful geological storage strongly depends on site specific conditions. Therefore, and in contrast to the capture side of the story, expertise building in true Belgian demonstration projects is required in addition to involvement in international storage projects, such as the Geleen project.
3. Most leading countries on CCS are industrialised and have a significant storage potential. The cross border issues related to the international transport of CO_2, with carbon captured and stored in different countries, remains out of scope of the currently proposed demonstration projects. In view of the interests of Belgium and its Regions, it is advisable to take a leading position on this specific issue, starting with the screening of potential initiatives and partners.
4. The aquifer storage potential in Belgium is poorly known because of insufficient direct data. Only exploration drilling and seismic surveying with integrated follow-up research can render these data, and will also serve other purposes, such as e.g. the evaluation of the geothermal potential and storage of natural gas. Early exploration is a high-risk investment with long-term return, and public funding may help to trigger private investments.
5. Storage in coal deposits is promising for Belgium because of its relatively large potential, several hundreds of million tons in a chemical sink with the option of recovering methane (see chapter 5), but also raises an important geotechnical challenge. The potential therefore remains to be proven. An estimated 8 years of R&D and pilot tests are needed to reach sufficient maturity for industrial application. Coal is only a secondary storage option in other leading EU countries, where (depleted) oil and gas fields or well-known aquifers are easier targets. The potential importance of coal reservoirs for the Belgian Regions justifies investing in research to develop this new technology, and as such taking an international lead. If commercialisation of this technology is successful, then CO_2 injection and enhanced coalbed methane production may find global application, in particular in rising world economies such as China and India.
6. Conflicts of interest of geological reservoirs should be addressed. These are critical issues for future renewable (geothermal energy) and non-renewable (coal reserves) energy prospects in Belgium. Unmined coal deposits are strategic reserves that could be mined either by conventional or advanced techniques (CBM, ECBM, underground gasification) and could make sense under critical economical situations. Belgian deep aquifers are already used for underground gas storage and geothermics (Heibaart and Saint-Ghislain plants respectively). Domal structures should be reserved for gas storage, which is not a true competition because such gas storage sites are usually too small for CO_2 storage. The eventual competition between CO2 storage and geothermics, as well as CO2 storage and valorisation of coal deposits, are more complicated and poorly studied. These issues are highly relevant for Belgium and dedicated research on this topic needs to be prioritized.

10 Further information

A vast amount of information on CCS can easily be accessed through the internet, but is sometimes overwhelming. This chapter websites that can be used as reliable starting points. The link pages of these websites provide further guidance.

- www.PSS-CCS.be
  The project PSS-CCS (Policy Support System for Carbon Capture and Storage) is the reference project for CCS in Belgium. Information on the project can be found on the project website, but especially the report of the first phase of the project may be of interest, of which an online version can be found on the website of Belspo :
  www.belspo.be/belspo/ssd/science/FinalReports/Reports/PSS-CCS_FinRep_2008.DEF.pdf.
- www.zeroemissionsplatform.eu
  A good and extensive introduction to CCS that is aimed at a general, but interested public, can be found on the website of the Zero Emissions Platform (ZEP). ZEP is an official European platform that is industry based.
- www.co2geonet.com
  CO2GeoNet is an FP6 funded network that is based on research institutes with focus on the geological storage aspects. They also work on training and public communication.
- www.ieaghg.org
  The IEA Greenhouse Gas R&D Programme (IEAGHG) is an international collaborative research programme as an Implementing Agreement under the International Energy Agency (IEA). A very large part of its activities are focussed on CCS, and the

website includes several interesting information pages and fact sheets.

- www1.ipcc.ch/ipccreports/srccs.htm
  The International Panel on Climate Change (IPCC) published in 2005 a special report on CCS, which is still considered as an important reference work. It can be downloaded or consulted online.
- www.geos.ed.ac.uk/ccsmap
  The Scottish Centre for Carbon Storage maintains an up-to-date map of important CCS projects around the globe. Only true CCS projects, with capture and storage at a meaningful scale, are included.

Scientific publications can be found in many international journals. One that is largely dedicated to CCS, and covers all parts of the CCS chain, is the International Journal of Greenhouse Gas Control :
www.elsevier.com/wps/find/journaldescription.cws_home/709061/description#description

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