

*Full Length Research Paper*

# A life cycle assessment of a coal fired power plant with carbon capture and storage in Mexico

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**A life cycle assessment (LCA) was conducted for three cases with the goal of assessing the environmental viability of carbon capture and storage (CCS) as a method of reducing greenhouse gas emissions from the electricity infrastructure in Mexico. Case 1 is standard coal fired power plant, 350 MW and 35.7% efficiency. Case 2 is the same power plant with facilities for carbon dioxide capture using absorption by the solvent monoethanolamine (MEA), compression of the collected gas, transport by pipeline, and injection for geologic storage into a deep saline aquifer. Case 3 is the same power plant and capture and transport system as Case 2, but instead with injection for use in enhanced oil recovery (EOR) in an oilfield. CCS was able to reduce the global warming potential (GWP) of the power plant by 75%, while also reducing impacts of acidification and photochemical oxidation. However, impacts in all other categories explored were raised significantly. Sensitivity analysis indicates that increasing plant efficiency reduces impacts for all categories, and it is suggested that CCS in Mexico be investigated in conjunction with increasing plant efficiency.**

**Key words:** Mexico, carbon capture and storage, life cycle assessment, electricity generation, environmental impact.

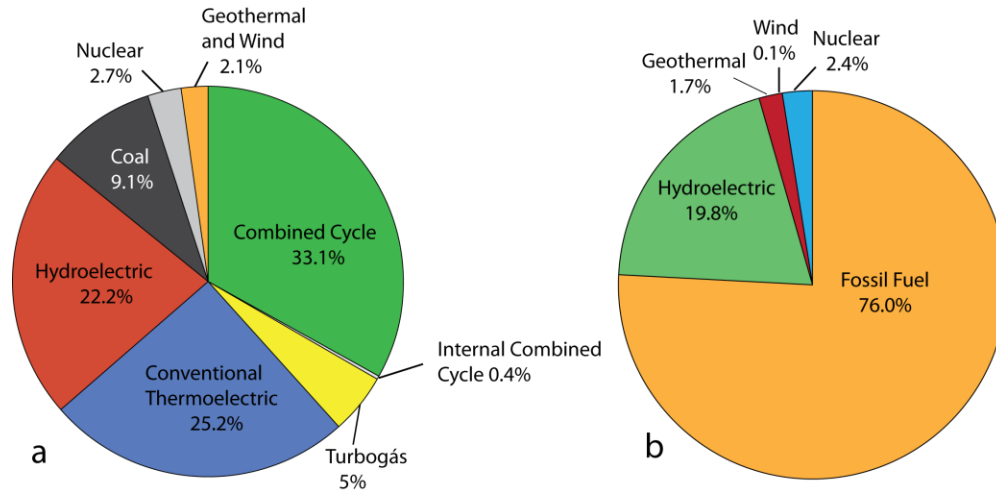
## INTRODUCTION

Rising concerns over the emission of greenhouse gases (GHG), such as CO<sub>2</sub>, to the atmosphere and their contribution to global warming have led to increased research in methods of reducing such emissions. The Intergovernmental Panel on Climate Change (IPCC) lists carbon capture and sequestration (CCS) as one of the technologies that could help reduce the emissions of CO<sub>2</sub> from large point sources such as power plants, and it is the subject of its Special Report on Carbon Dioxide Capture and Storage (IPCC, 2006). CCS allows CO<sub>2</sub> to be captured at a point source and then be stored in a location where it will remain secluded from the atmosphere, such as a geological trap or the ocean. The IPCC estimates that CCS could constitute 10 to 55% of the carbon dioxide reduction to the year 2100 (IPCC, 2006). This is an appealing solution, because it allows

the generation of power using current technology and fossil fuels which are both proven and available. Several CCS projects are under way or in pilot and planning stages in developed economies throughout the world (DOE, 2008; Gale et al., 2001).

Climate change is inherently a global problem, and thus the solution will have to incorporate power generation worldwide. This paper attempts to assess the environmental viability of installing CCS facilities in Mexico. Mexico is the world's twelfth largest emitter of CO<sub>2</sub>, emitting 1.4% of the world emissions in 2006 (Boden et al., 2009). The Federal Electricity Commission (CFE) provides majority of the electricity for the country, and therefore is one of the largest emitters of GHGs. The overarching goal for CFE is to provide cheap, reliable electricity for a growing economy and population. However, due to a corporate commitment to the environment as well as environmental policies, agreements, and regulations, CFE has begun to explore the possibilities of reducing its GHG emissions through

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**Figure 1.** Mexican electricity by (a) production method and (b) fuel type.

CCS. This study is the first attempt to look at all the environmental impacts of CCS in Mexico, including those not related to climate change. We use a tool called Life Cycle Assessment (LCA) to evaluate the overall environmental impact of CCS in Mexico. LCA was chosen because it allows a complete assessment of the environmental impacts from cradle to grave including both upstream fabrication processes and eventual disposal. This study is intended to guide Mexico, and potentially other developing economies, in its approach to reduce GHG emissions.

### Power generation in Mexico

Since 1879, the Mexican electrical sector has been generating electricity using a combination of available technologies, ranging from standard to state of the art (Resendiz, 1994). In December 2008, the total installed electrical capacity in Mexico was 52,742 MW, including both CFE and external private suppliers (Productores Externos de Energía, PEE) (Comisión Federal de Electricidad, 2010). This is produced in 177 plants that generate electricity with a mixture of technologies (Figure 1a) and various energy sources (Figure 1b).

Mexican public electricity (81%) is produced by fossil fuels, and as a result 100 million tons of CO<sub>2</sub> are released each year (Arevalo, 2012). Efforts are being made to use current technologies to reduce these emissions, but the need to provide electricity to consumers will require the continued use of fossil fuels for at least the next two decades. Projections for the future include the construction of new natural gas powered plants, and a conversion of plants that currently burn fuel oil to burn coal.

There are three coal-fired plants currently in use: the Carbon I and Carbon II plants in the state of Coahuila, and the Lazaro Cardenas plant in the state of Michoacan.

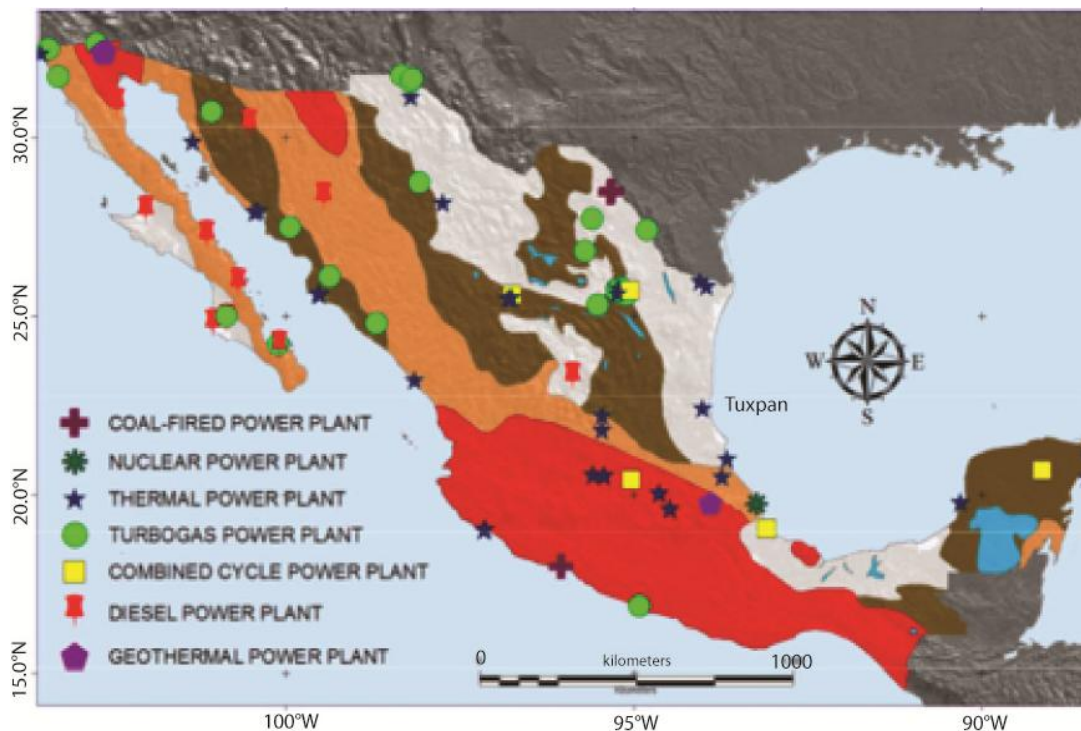
These plants currently use about 15 million tons of coal per year. Plans for future coal-fired plants project to increase this consumption to 33 million tons per year from 2018 to 2030. This rise in emissions from coal-fired power generation is a problem that should be faced by the Mexican power sector, and one possible method of mitigation is CCS with geologic storage.

Research for geologic storage of emissions from the Mexican public electricity sector has begun, and a country and basin scale assessment of possible locations for storage has been completed as part of a project to create the North American atlas for geologic storage (North American Carbon Storage Atlas, 2012). The atlas splits the country into zones of inclusion, where carbon storage is possible, and zones of exclusion where it is not recommended, and estimates about 100 gigatons of storage potential in Mexico (North American Carbon Storage Atlas, 2012). Figure 2 shows the distribution of these zones in relation to the locations of thermal power plants in Mexico. This LCA focuses on the Northeast of Mexico, because of its larger potential for CO<sub>2</sub> storage.

### METHODS

LCA is a tool developed to assess the full environmental impact of a product or process from production through use and disposal. The International Organization for Standardization (ISO) has created a set of standards and guidelines for LCA use, and this study is intended to conform to the ISO standards (ISO 14040 series). An LCA consists of four steps:

- 1) The definition of the goal and scope of the study.
- 2) The life cycle inventory (LCI) in which data is gathered for the system. Ideally all of the inputs, outputs and processes are accounted for. For complex processes, this requires quite a lot of data, and databases are often used to expedite the process and make it more complete.
- 3) The life cycle impact assessment (LCIA) in which the environmental impacts are categorized for comparison. At this stage they can also be normalized and weighted. There are quite



**Figure 2.** Areas indicating regional geologic carbon storage potential in Mexico. Red and orange areas represent areas where geologic storage is not possible or not recommended. Brown, white and blue areas represent regions with potential for geologic carbon storage. The existing power plants in Mexico are shown, and Tuxpan, the power plant chosen for this LCA is marked. Modified after Dávila et al. (2010).

few different methods for LCIA with different environmental impact categories and weighting regimes.

4) Interpretation of results. Results are compiled and analyzed to make recommendations. Often a sensitivity analysis is undertaken as part of the interpretation stage.

The method of evaluation chosen for this study is the CML 2001 baseline impact categories (Guinée, 2002), evaluated in the World 1995 reference frame (Huijbregts et al., 2003). These categories are abiotic depletion, acidification, eutrophication, global warming potential (GWP), ozone depletion, human toxicity, fresh water ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity and photochemical oxidation potential. CML 2001 is a weighting assessment scheme that was chosen because it is widely used and applicable globally. This means it is relevant for Mexico, whereas some of the other evaluation methods are focused more on Europe or other developed countries. The World 1995 reference frame was also chosen, because it is the only one which takes into account the developing world. The World 1995 reference frame provides total emissions for the reference year in all categories, so that the relative contributions in the system of study in the LCA can be assessed.

The LCI stage requires the gathering of immense amounts of data, and in this case much of the data was taken from the Ecoinvent v2.0 database set (commercially available). When possible, the Global or Latin American datasets were used. Some data were gathered specifically for Mexico, therefore some of the Ecoinvent processes were modified to better reflect Mexico, and some additional data was gathered for the model. Database processes specific for the Mexican cement, electricity, and polyethylene industries were included. Subsequently, the overall processes in the model are described, specifically the modifications

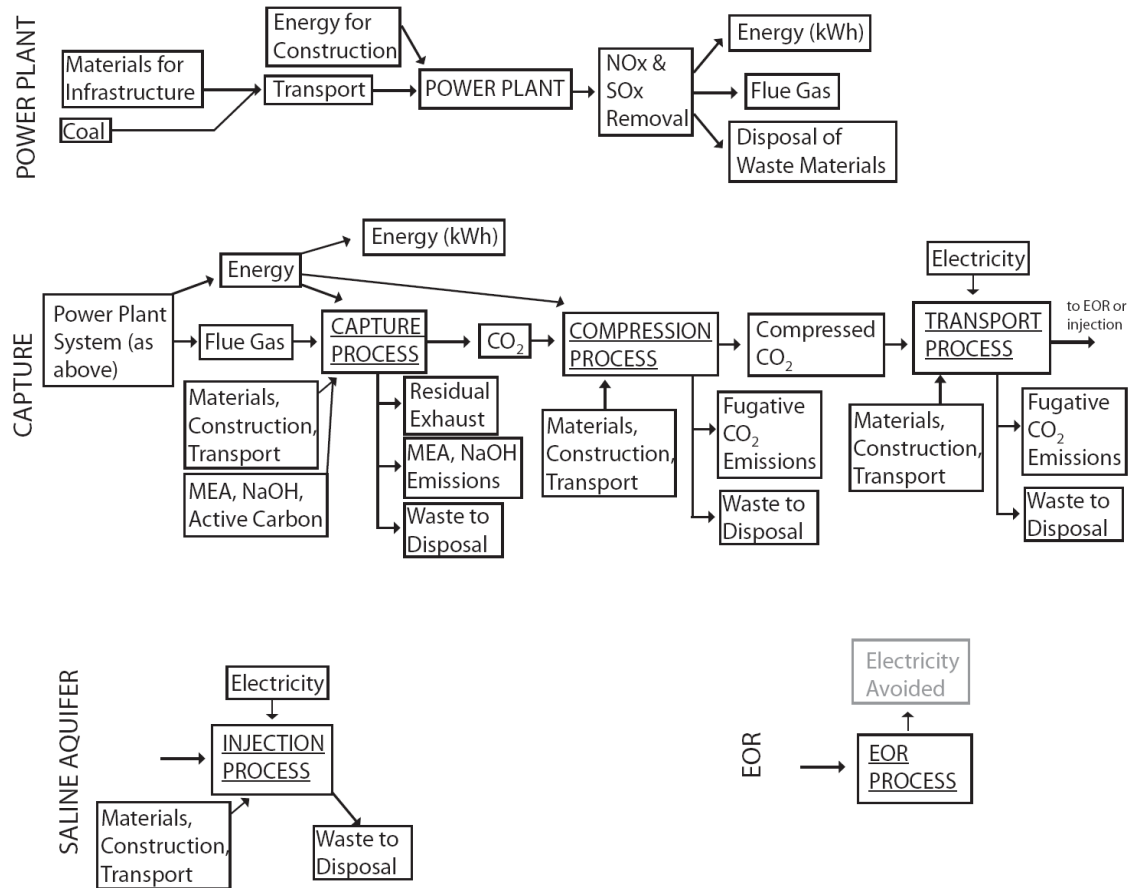
and additions that have been made to the data found in the Ecoinvent database. The LCI was compiled and assessed using the SimaPro software from PRé Consultants.

### Goal and scope

The goal of this LCA is to assess the environmental viability of a geologic carbon storage facility in Mexico to help decide whether such technology should be implemented to reduce GHG emissions from the electricity infrastructure. Three systems were studied. The first is a model for a coal-fired power plant, being built in Mexico now or in the next few years. The second is the same coal fired power plant, but with a post combustion carbon capture system, CO<sub>2</sub> compression, pipeline transport, and injection of CO<sub>2</sub> into a deep saline aquifer. The third is the same power plant, carbon capture and transport system, but rather than injection into a saline aquifer, the CO<sub>2</sub> is used for EOR and stored in spent oil wells as part of the process. The system boundaries and simplified systems are as shown in Figure 3.

Similar LCA studies have already been undertaken for power plants with CCS technology (Khoo and Tan, 2006b, Koornneef et al., 2008; Korre et al., 2010; Odeh and Cockerill, 2008; Pehnt and Henkel, 2009), with some variety in their depth and models, but none have been undertaken for Mexico or other developing economies. This study focuses on Mexico, and attempts to focus on the differences between Mexico and the localities where other studies have been done, particularly since much of the technology will have to be imported from outside Mexico. Much of it is modification of models available in the literature to be applicable to Mexico.

The choice of a functional unit, or the unit of comparison, is an



**Figure 3.** Flowchart showing the LCA system boundaries. The first case studied includes only the power plant part of the flow chart. The second portion of the cases include both the power plant and capture sections, as well as either the saline aquifer portion or the EOR portion.

important step in an LCA. In this case, when looking at the whole system, the goal of a power plant is to produce electricity, therefore 1 kWh of electricity produced was chosen as the functional unit.

### Life cycle inventory

It is hoped that this LCA will be applicable for power plants anywhere in Mexico, however, some of the specific data about the power plant was taken from data on the Tuxpan Plant, Veracruz State, a fuel oil powered plant which is planned for conversion to a coal-fired plant, and a good candidate for carbon capture in Mexico. One aspect that was modified for all processes was the transport distances of materials to reflect distances for Mexico origins and approximate distances are shown in Table 1. Much of the data for the infrastructure and energy requirements of the CCS system were taken from previously published models in the literature (Koornneef et al., 2008).

Power plants in Mexico are decommissioned and dismantled by selling the parts either for reuse or as scrap metal, which is usually transported back to the metallurgy centers to be melted down and recycled. Recycling is a process that is somewhat challenging to include in an LCA, as it is often unclear whether or not it falls inside the system boundaries, and its handling is left up to the LCA practitioner. The recycling processes in the Ecoinvent database are all empty processes and considered to fall outside the system boundaries. In this case, recycling was modeled by using metals

produced from recycled metals as an input, rather than virgin metal, and having the recycling process include transport back to the metal processing plant. The concrete in decommissioned plants is broken down and used for fill in low-lying areas that are subject to inundation. This was modeled by the Ecoinvent process for an inert landfill.

### Power plant

Majority of the data for the power plant was taken from the Ecoinvent database for coal fired power plants. The converted plant will have six 350 MW generators, operating at 35.7% efficiency on coal from the Sabinas Basin in the State of Coahuila, Mexico. This study focuses on only one of the 350 MW generators. The amount of coal burned in the plant was modified to reflect the efficiency. Additionally, the Ecoinvent process was modified to reflect the calorific heating value of Sabinas coal (5300 to 5400 cal/g), transport of coal from the Sabinas basin, and transport distances of construction materials for Mexico. Table 2 shows the important parameters for the power plant modeled.

### Carbon capture process

This model uses a post combustion capture system, where the flue gas, after desulphurization, is filtered through a capture facility

**Table 1.** Transport distances for construction materials in Mexico to Tuxpan, Veracruz. In general it is cheaper and more environmentally friendly to ship by rail, so this method was chosen where the option exists.

Material	Origin	Rail (km)	Road (km)
Steel	Monclova, Coahuila	855	155
Steel	México, Distrito Federal	325	155
Copper	San Luis Potosí, San Luis Potosí	325	155
Cement	Poza Rica, Veracruz	-	50
Polyethylene	Coatzacoalcos, Veracruz	-	445
Capture infrastructure	Houston, Texas	1500	155
Coal	Sabinas, Coahuila	960	155

**Table 2.** Parameters used to model the power plant for cases both with and without CCS.

Parameter	Unit	Power plant	Power plant with CCS
Thermal capacity	MW	350	350
Electrical output	MW	350	229
Lifetime	Years	30	30
Operational hours	h/year	7800	7800
Efficiency	%	35.7	23.4
Coal burn heat	kg/MJ	0.0448	0.0448

which contains an amine solvent which absorbs the CO<sub>2</sub> and some other components of the flue gas. In this case, the solvent monoethanolamine (MEA) was used, as it is well documented in the literature and likely to be one of the closest to commercial use (Abu-Zahra et al., 2007; IEA GHG, 2000; Rao and Rubin, 2002), and it absorbs 85 to 95% of the CO<sub>2</sub> present in the flue gas (IPCC, 2005). The residual flue gas is released, and the CO<sub>2</sub>-rich solvent is then re-heated to release the CO<sub>2</sub> which is collected. Some of the MEA is reclaimed and reused, while some is lost to emissions or the formation of heat stable salts (HSS) (IPCC, 2005). The environmental impacts of the emission of MEA are not included in the weighting process of the CML 2001 impact method, therefore, it was added using the weighting factors estimated by Huijbregts (2005). HSS form when impurities in the flue gas react with the MEA, and they become a solid waste product that must be disposed of properly. The LCA model by Koornneef et al. (2008) included the disposal of these reclaimer bottoms by estimating the emissions from a hazardous waste incinerator from the estimated elemental composition of the reclaimer bottoms. In Mexico, these reclaimer bottoms would likely be incinerated in a cement plant, and a municipal waste incinerator was used as a proxy. The emissions were estimated using the tool by Doka (2002). Table 3 shows the parameters for the capture process, and infrastructure requirements and composition of reclaimer bottoms are listed in Appendices A and E. Much of the infrastructure and parameters for the capture process are based on contact by Koornneef et al. (2008) with the Fluor Company in Netherlands, one of the manufacturers of such facilities.

The energy used to reheat the CO<sub>2</sub>-rich MEA and release the CO<sub>2</sub> comes directly from the steam produced by the power plant, and therefore results in a reduced output for the plant. The steam as well as the electricity used for the capture process and compression was assumed to be taken from the power plant, and this lowers the electrical output of the plant from 350 to 229 MW, essentially an efficiency reduction from 35.7 to 23.4%, a significant 34.5% overall drop in efficiency.

### Compression and transport

The purified CO<sub>2</sub> is then compressed to 11 MPa for transport by pipeline. The infrastructure for the compressor was taken from literature data, and can be found in Appendix B. The infrastructure for the pipeline was modeled using the Ecoinvent process for a high capacity natural gas pipeline. The energy requirement for compression and transport is also taken directly from the power plant, contributing to the reduction in efficiency.

The pipeline length was somewhat arbitrarily chosen at 250 km. Tuxpan Power Plant, in Northern Veracruz is well within an area of inclusion for geologic carbon sequestration (Dávila et al., 2010) (Figure 2), as well as close to operational oil basins, in the case of PEMEX's Proyecto Chicontepec ([www.pemex.com](http://www.pemex.com)). So for this location, it is unlikely that the CO<sub>2</sub> would have to be transported very long distances; however, from other locations in Mexico it is possible that the pipeline would have to be significantly longer, thus the pipeline length is subject to a sensitivity analysis later in the paper.

### Injection

There are two different scenarios for injection: injection into a deep saline aquifer, and use for EOR. There is a fundamental assumption for both scenarios that once the CO<sub>2</sub> is injected, it does not escape back into the atmosphere, essentially a no leak assumption. Natural geologic CO<sub>2</sub> deposits exist, that have been estimated to be 10<sup>5</sup> to 10<sup>7</sup> years old (Holloway, 2005), so there is evidence that CO<sub>2</sub> can be retained in the earth on a geologic timescale, however, the no leak assumption is certainly subject to debate, and some of the other LCA models investigate this. Both models also include monitoring for leakage using the USA Input-Output Database process for geophysical exploration for petroleum and mining as a proxy. The input-output database allows a dollar amount to be used as an input into the database to estimate the

**Table 3.** Parameters for the capture and transport processes with associated references.

Parameter	Unit	Process	Notes and references
CO <sub>2</sub> removal	%	90	IPCC (2005): 85 to 95%
SO <sub>2</sub> removal	%	90	Rao and Rubin (2002) and Koornneef et al. (2008)
NO <sub>x</sub> removal	%	1.25	Rao and Rubin (2002)
HCl removal	%	95	Rao and Rubin (2002)
HF removal	%	90	Koornneef et al. (2008) based on Strazisar et al. (2003)
PM removal	%	50	Iijima et al. (2007) and Rao and Rubin (2002)
NaOH use	Kg/tCO <sub>2</sub>	0.13	Rao and Rubin (2002)
Activated carbon use	Kg/tCO <sub>2</sub>	0.075	Chapel et al. (1999)
MEA use	Kg/tCO <sub>2</sub>	2.34	Koornneef et al. (2008) based on Knudsen et al. (2006), Chapel et al. (1999), IEA GHG (2006) and Rao et al. (2004).
MEA reclaimed	Kg/tCO <sub>2</sub>	0.20	Koornneef et al. (2008)
MEA emission	Kg/tCO <sub>2</sub>	0.014	IEA GHG (2006) and Thitakamol et al. (2007)
Reclaimer bottoms	Kg/tCO <sub>2</sub>	2.4	IEA GHG (2006) and Thitakamol et al. (2007)
Capture energy	kWh/tCO <sub>2</sub>	245	This capture energy assumes that 4 GJ steam is needed to reclaim 1 ton CO <sub>2</sub> (Alie et al., 2005; Rao et al., 2006) and the power ratio of 0.2 GJ <sup>electricity</sup> /GJ <sup>steam</sup> (Peeters et al., 2007)
Compression energy	kWh/tCO <sub>2</sub>	111	Koornneef et al. (2008) assumes compression to 11 MPa
Fugitive CO <sub>2</sub> emission-compressor	tCO <sub>2</sub> /MW/year	23.2	IPCC (2006)
Fugitive CO <sub>2</sub> emission-pipeline	tCO <sub>2</sub> /km/year	2.32	IPCC (2006)
Pipeline length	km	250	-

environmental impacts for a process. The dollar amount used (\$54 million USD) was estimated using the IEA GHG tool for monitoring of geologic CCS (IEA GHG).

For injection into a saline aquifer, the infrastructure for an injection site must be built and wells drilled for injection. Infrastructure data was taken from the literature and can be found in Appendix C. The Ecoinvent process for drilling of onshore petroleum wells was used as a proxy for the drilling of wells for CO<sub>2</sub> injection. The gas is first recompressed to about 15 MPa before being injected. The energy for this is assumed to come from the electricity grid rather than the power plant.

For the scenario when the CO<sub>2</sub> was used for EOR, the assumption was made that the infrastructure and wells already exist for previous oil production, and therefore would not need to be built especially for CO<sub>2</sub> storage. The injection of CO<sub>2</sub> assists in the oil recovery process, and makes the recovery less energy intensive, 94 kWh/ton oil rather than 138 kWh/ton oil (Khoo and Tan, 2006a). Thus, the EOR process includes a certain amount of energy saved (Appendix D), under the assumption that the oil would have otherwise been recovered by conventional methods. This is perhaps a simplistic assumption and may underestimate the environmental impacts of EOR, but it is consistent with the choice of system boundaries.

## RESULTS

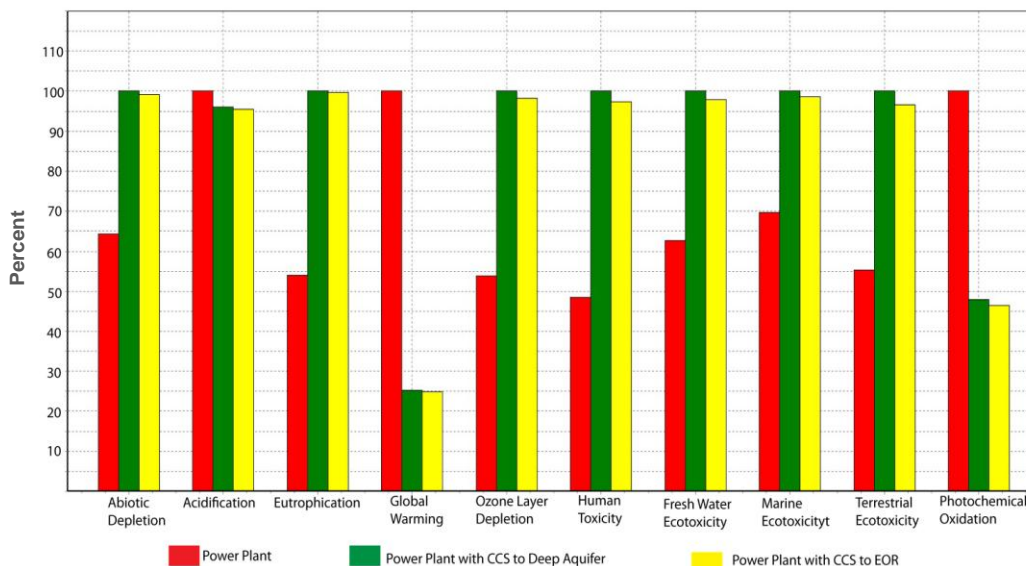
In general, the CCS scenarios significantly reduce the environmental impact in the GWP category, for which they are designed. They also exhibit co-benefits in

the reduction of impact in the acidification and the photochemical oxidation categories. However, in all of the other impact categories, they show a significant increase. Overall comparison results are as shown in Figure 4 and Table 4. In general, this increased impact in most categories is caused by large increase in resources, specifically coal, that are used to produce an equal amount of electricity. The increase in coal consumption stems mostly from the large energy requirements of the capture process. Thus, reductions in the energy requirements for the capture process would allow the environmental impacts for CCS in to be lowered.

For all of the categories, the EOR scenario has a somewhat lower impact than the Deep Aquifer scenario. That results from two factors, the first being that the infrastructure for EOR injection is already assumed to exist in this model, so the impacts of building that infrastructure are not seen for EOR. Secondly, the use of CO<sub>2</sub> as technique to recover more oil is already in use in the oil industry, and it results in the recovery of more oil for the amount of energy used as net energy savings.

### Abiotic depletion

The abiotic depletion category measures the depletion of material resources to the earth, essentially fossil fuels,



**Figure 4.** Overall comparison for the three cases in all categories. All are shown as a percentage of the largest impact for each category. All are evaluated with the CML 2001 method, with the impacts of MEA emission added on the world 1995 scale.

**Table 4.** Overall results for each category for all three cases.

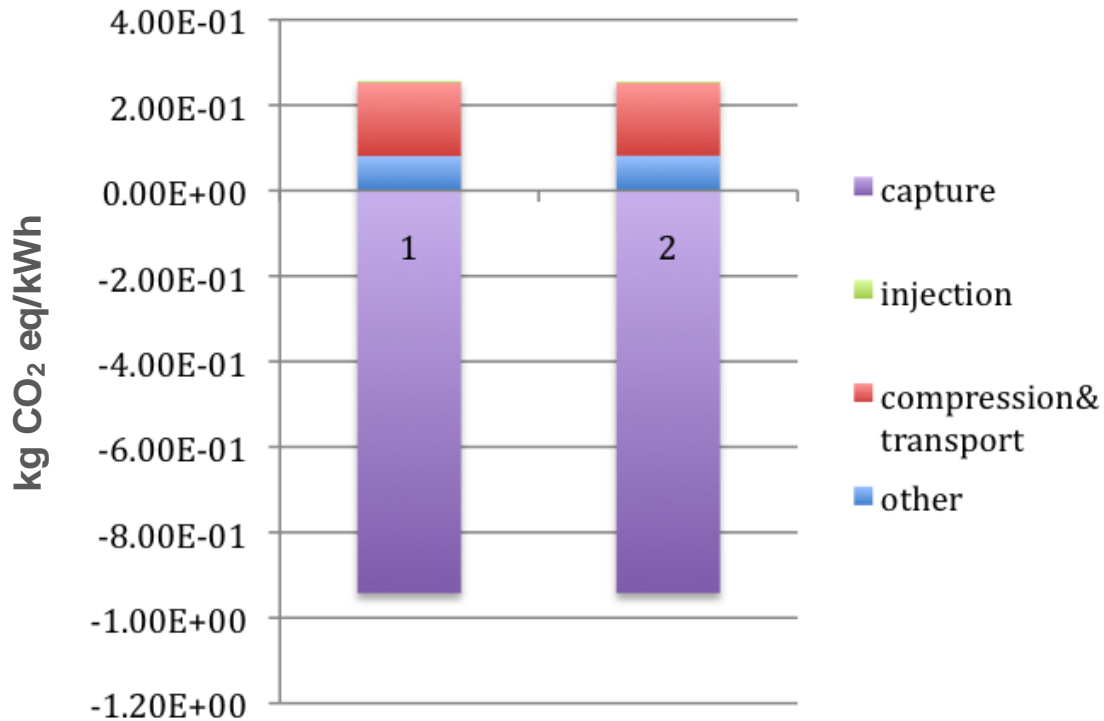
Category	Unit	Power plant	Power plant deep aquifer	Power plant_EOR
Abiotic depletion	kg Sb eq	0.00786	0.0122	0.0121
Acidification	kg SO <sub>2</sub> eq	0.0033	0.00317	0.00315
Eutrophication	kg PO <sub>4</sub> <sup>3-</sup> eq	0.000397	0.000736	0.000734
Global warming	kg CO <sub>2</sub> eq	1.02	0.257	0.255
Ozone layer depl.	kg CFC-11 eq	7.05E-09	1.31E-08	1.29E-08
Human toxicity	kg 1,4-DB eq	0.275	0.567	0.551
Fresh water ecotox	kg 1,4-DB eq	0.0692	0.111	0.108
Marine ecotox	kg 1,4-DB eq	152	219	216
Terrestrial ecotox	kg 1,4-DB eq	0.000811	0.00147	0.00142
Photochemical oxid.	kg C <sub>2</sub> H <sub>4</sub>	8.68E-05	4.16E-05	4.03E-05

Eq: Equivalent.

metals, and minerals, and is measured in kg Antimony (Sb) equivalents. The impact is calculated based on ultimate reserves and extinction rates (Guinée, 2002). The two scenarios with CCS have a significantly higher impact in this category, a 56% increase for deep aquifer injection and 54% increase for EOR. The original power plant had an impact of .00786 kg Sb equivalent when compared with 0.0122 and 0.0121 for the deep aquifer and EOR. This is large, because of the extra coal necessary to produce 01 kWh of electricity, thus the increased depletion of coal resources which accounts for 96% of the contribution in this category for CCS solutions. The use of materials for construction of infrastructure of the CSS process also contributes to this impact category, but it overall has a small effect, the extra use of fossil fuels accounts for considerably more.

### Acidification

The acidification category is a measure of the potential for acidification of air or water, measured in kg SO<sub>2</sub> equivalents. In this category, there is a slight reduction in the impact with the use of the CCS systems, a 4.5 and 3.9% reduction for EOR and saline aquifer injection, respectively, a co-benefit of the CO<sub>2</sub> capture system. The chemicals that contribute most to the acidification category are NO<sub>x</sub>, ammonia, SO<sub>2</sub>, and N<sub>2</sub>O. The capture process also reduces the SO<sub>2</sub> and NO<sub>x</sub> in the flue gas, though in the case of NO<sub>x</sub> the reduction is more than balanced by emission in other parts of the process. Thus, the reduction of SO<sub>2</sub> by the capture process that causes the reduction for the CCS cases. For the overall process, EOR reduces airborne SO<sub>2</sub> emissions by 74.8% and



**Figure 5.** Contributions to the Global Warming Potential category from the CCS chain. Column 1 is for CCS with storage in a deep saline aquifer, and column 2 is for CCS with EOR. The energy for the compression and transport process contributes much more significantly than the injection. eq: equivalent.

saline aquifer injection by 74.3%. However, the emissions of other acidifying gases in different parts of the process chain counteract the effect of this reduction.

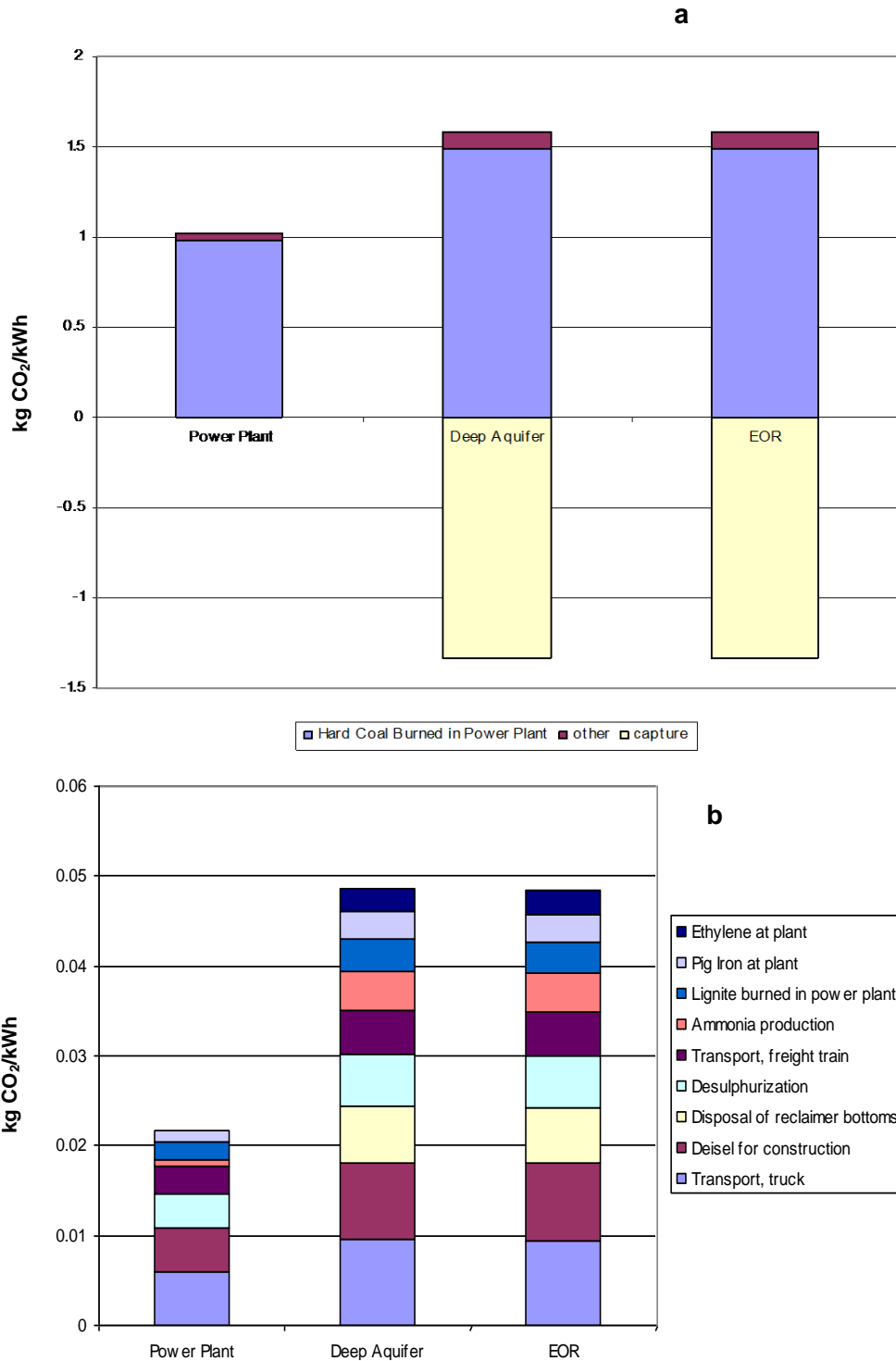
### Eutrophication

Eutrophication is the impact of the measure of the impact of additional macronutrients to ecosystems, which can disturb the balance of the ecosystem, and is measured in kg PO<sub>4</sub><sup>2-</sup> equivalents. The power plants equipped with CCS systems have a larger impact in this category largely because of the increase in coal burned. There is an 84.5% increase for EOR and an 85.2% increase for saline aquifer injection. Also contributing to this category, apart from the increase in coal used, are blasting from construction and geophysical exploration, as well as the emissions from the capture process, specifically the emission of ammonia. The chemicals with the largest impact in this category are the emissions of NO<sub>x</sub> and ammonia to air, and the emissions of phosphate and nitrate to water. In this case, the removal of some NO<sub>x</sub> by the capture process is not enough to balance the additional emissions represented by the reduced plant efficiency and the extra materials and transport needed for CCS. In fact, additional NO<sub>x</sub> emissions by the other parts of the CCS process account for a significant part of the increased impact in this category.

### Global warming

This category measures the GWP in terms of radiative heat forcing of the atmosphere on the 100-year timescale as defined by the IPCC, measured in kg CO<sub>2</sub> equivalents. Reduction in this category is the goal of installing a CCS system, and the power plants with CCS show a significant impact reduction in this category, as intended. The CCS systems reduce the GWP by 74.8% for deep aquifer and 75.1% for EOR, from 1.022 kg CO<sub>2</sub> equivalent/kWh for the original power plant to 0.257 for the deep aquifer case and 0.254 for EOR. Since ideally a 100% reduction is desirable, it is useful to understand the source of this 25% of kg CO<sub>2</sub> equivalent which is not recovered. The capture efficiency of CO<sub>2</sub> by MEA is assumed to be 90% in this model, so the inability to capture all of the CO<sub>2</sub> contributes heavily.

Additionally, some CO<sub>2</sub> are leaked during the compression and transport processes. The other portions of the CCS process also contribute, and Figure 5 shows the impacts of these other parts of the CCS process. For the CCS processes, only 92% of the GWP is due to CO<sub>2</sub>, whereas for the normal power plant, 99% is due to CO<sub>2</sub>. Other contributors are NO<sub>2</sub>, methane, carbon monoxide, and ethane. These are emitted in other parts of the process, and not absorbed by the capture process. For the CSS processes, the gases N<sub>2</sub>O and fossil methane



**Figure 6.** Process contributions to the Global Warming Potential category. (a) Overall contributors, the largest by far being the burning of coal. (b) Breakdown of the other top ten contributors, excluding coal.

have a larger impact. The process which contributes most to this category is the burning of coal in the power plant, but in addition, transportation, construction, disposal of reclaimer bottoms, and ammonia and iron

production also fall in the top ten contributing processes (Figure 6). Thus, all of these represent areas in which improvements could be made to lower the impacts in the GWP category.

### Ozone layer depletion

This category is a measure of the potential to destroy stratospheric ozone, based on the model developed by the World Meteorological Organization (WMO) and is measured in kg CFC-11 equivalents. The processes with CCS have a higher impact in this category, and the largest contributors to this are the increased coal necessary to produce 1 kWh, as well as some parts of the crude oil production process, as more crude oil is needed for the extra transport, infrastructure, and building requirements for the CCS process. The chemicals that contribute most significantly to this category are bromotrifluoro methane (Halon 1301), monochloro methane (R-4), bromochlorodifluoro methane (Halon 1211), tetrachloro methane (CFC-10), and 1,1,1-trichloro ethane (HCFC-140). This category increases by 86.1% for the deep aquifer case and 82.9% for the EOR case.

### Human toxicity

The human toxicity category measures the impact to human health by toxic substances on the infinite horizon, and is measured in kilogram 1,4-dichlorobenzene (DB) equivalents. The CCS systems have a larger impact in this category also, derived mostly from the increased coal and the disposal of the coal ash waste. In this category, the fabrication of the MEA solvent is the process with the second largest impact, contributing 22% of the impact in the CCS processes. CCS with storage in a deep aquifer increases this category by 106%, while CCS with EOR increases by 100%. The top chemical contributors in this category are polyaromatic hydrocarbons, chromium VI, ethylene oxide, arsenic, vanadium, and selenium.

### Fresh water ecotoxicity

Fresh water ecotoxicity category assesses the toxic impact of processes on the fresh water aquatic ecosystem, and is also measured in kg 1,4-DB equivalents. The CCS systems also have a larger impact in this category, increasing by 59.8% for the deep aquifer case and 56.3% for EOR. In this case, it is not the direct burning of the coal that causes the increased impact, but the disposal of the hard coal ash, the volume of which is also increased by the reduced efficiency of the CCS system. The emissions of vanadium, beryllium, nickel, cobalt, copper, selenium, and molybdenum are the main contributors to this category, mostly derived from leaching of landfill waste from the coal combustion process.

### Marine ecotoxicity

The marine ecotoxicity category measures the toxic

damage to oceanic ecosystems, and is also measured in kg 1,4-DB equivalents. The CCS systems have a larger impact in this category, an increase of 43.5% for storage in a deep aquifer and an increase of 41.6% for EOR. Similarly, to the freshwater ecotoxicity category, this is dominated by emissions from the landfill waste of the hard coal ash. The chemicals that contribute most heavily are emissions of beryllium, vanadium, selenium, nickel, cobalt, and molybdenum to water, and selenium, beryllium, hydrogen fluoride and barite to air. The capture process reduces the emissions of hydrogen fluoride to air, from 16 to 2.79 kg 1,4-DB equivalent/kWh, but this does not have enough of an impact on the overall score to make CCS beneficial in this category on the whole.

### Terrestrial ecotoxicity

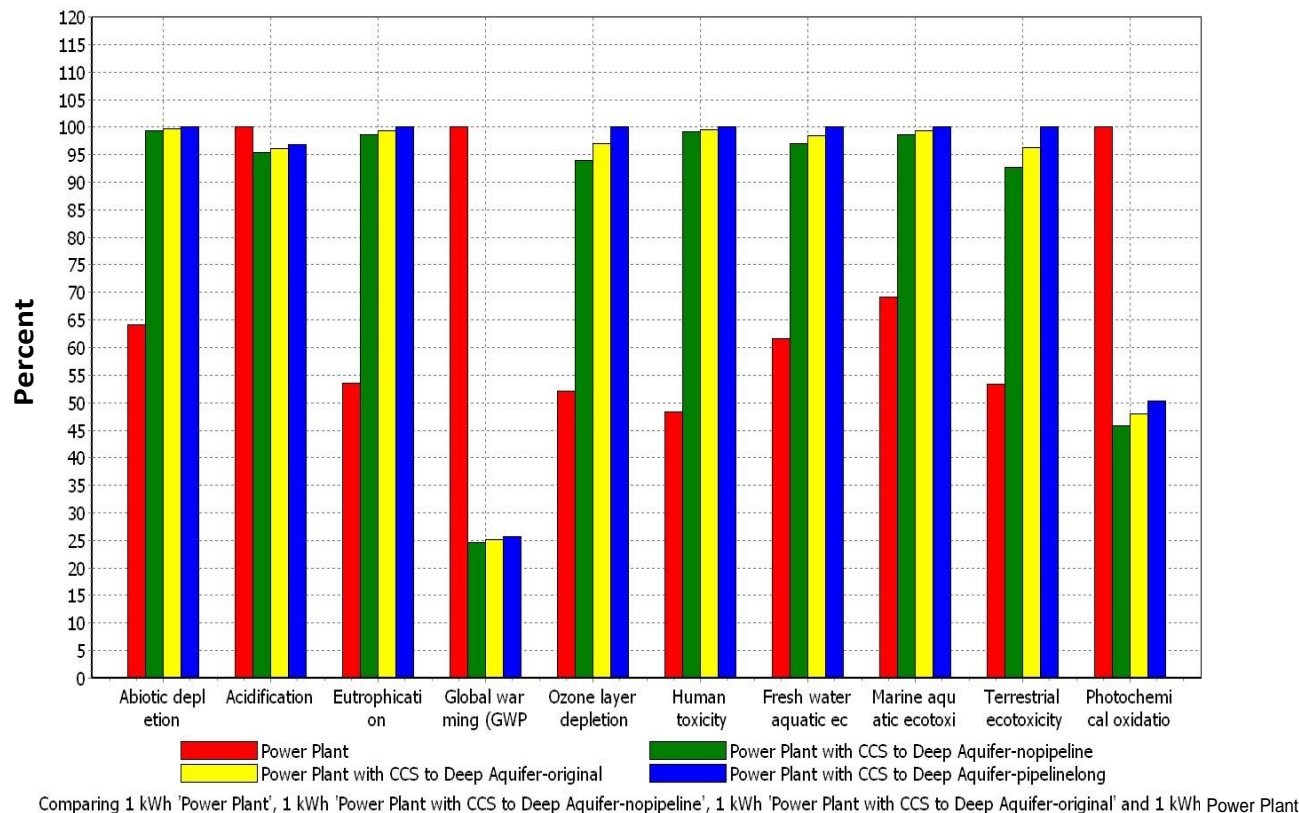
Terrestrial ecotoxicity measures the impact of toxic substances to terrestrial ecosystems, also measured in kg 1,4-DB equivalents. In this category, the CCS systems have a much larger impact, an increase of 74.4% for EOR and 80.6% for deep aquifer injection as compared to the standard power plant. The top process contributor is the burning of coal; however, the second is the production of steel. More steel is needed for the infrastructure for CCS activities, and it significantly affects the impact in this category. Largest contributors by specific emissions are the emissions of mercury, arsenic, vanadium and chromium VI to the air.

### Photochemical oxidation

Photochemical oxidation measures the formation of chemical compounds, such as ozone and carbon monoxide, which react with sunlight to produce compounds that constitute summer smog (Guinée, 2002). It is measured in kg ethylene equivalents. In this case the CCS systems lower the impact for photochemical oxidation by 53.5 and 52% for EOR and deep aquifer injection, respectively. This reduction is due to the reduction of SO<sub>2</sub> emissions by the capture process. The largest impact contributors are SO<sub>2</sub>, carbon monoxide, methane, ethane, pentane, butane, ethane, and toluene.

### Sensitivity analysis

Sensitivity analysis is a step in which specific parameters are varied to understand their effect on the overall results. This is particularly important for parameters that are uncertain and might have large impacts on the results. Since this study is based on a product that is still in the theory and planning stages for Mexico, it is particularly important to do a sensitivity analysis.



**Figure 7.** Changes in impact with pipeline length. Red shows a normal power plant without CCS, and the others area plant with CCS injection into a deep aquifer. Green has onsite injection, yellow is the case studied with a 250 km pipeline, and the blue is a longer case with a 500 km pipeline.

The first parameter tested was the length of the transport pipeline for the compressed carbon dioxide. The default length used in this study was 250 km, but it was compared with lengths of 0 km, as for on site injection, and 500 km. Figure 7 shows the comparison of the power plants with CCS and injection in a deep aquifer with pipeline transports of each of these three lengths, as well as the normal power plant. It is apparent from this figure that the pipeline length affects each category roughly linearly, with an increase in length correlating to an increased impact, though the amount of this increase varies between categories. Thus, choosing an injection site close to the power plant source is beneficial for all impact categories.

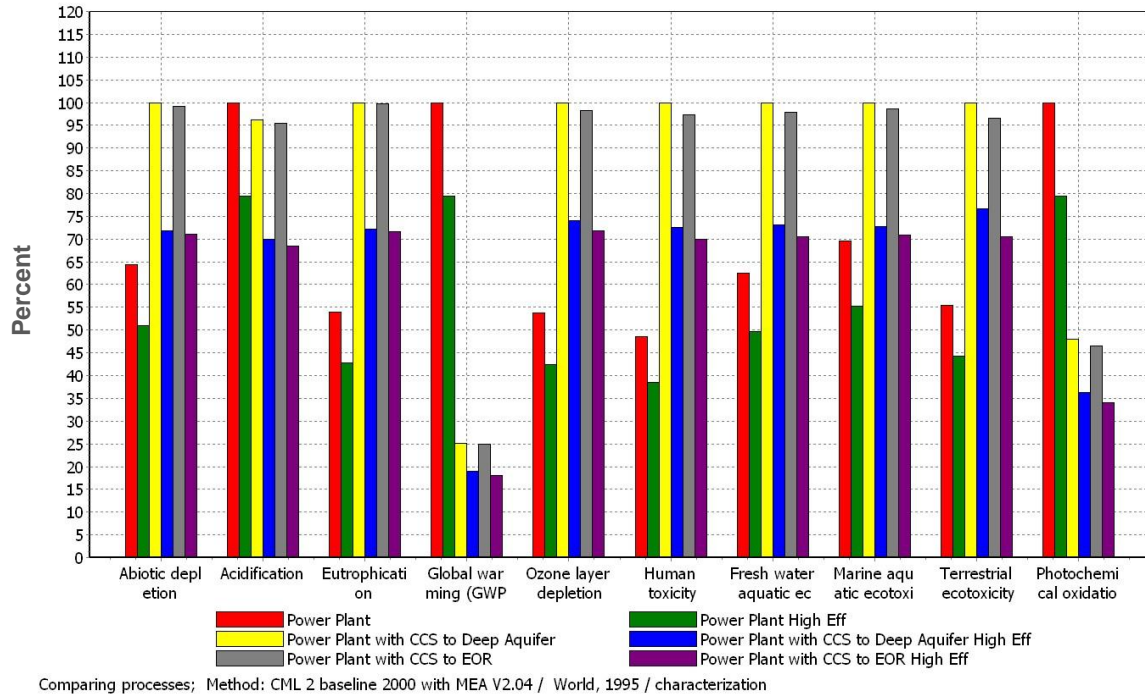
Since the use of coal contributes heavily to all categories, the effect of increasing power plant efficiency was explored, because it is likely to lower the impacts in most categories. In fact, most LCA studies of CCS are for state of the art super critical boilers, which generally lower all impact categories. For this study, plant infrastructure remained the same, but the efficiency of the plant was increased to 45%. It should be noted that in reality, a high efficiency plant has additional infrastructure differences. Figure 8 shows the standard power plant for all the three cases as compared to the increased

efficiency power plant for the same three cases.

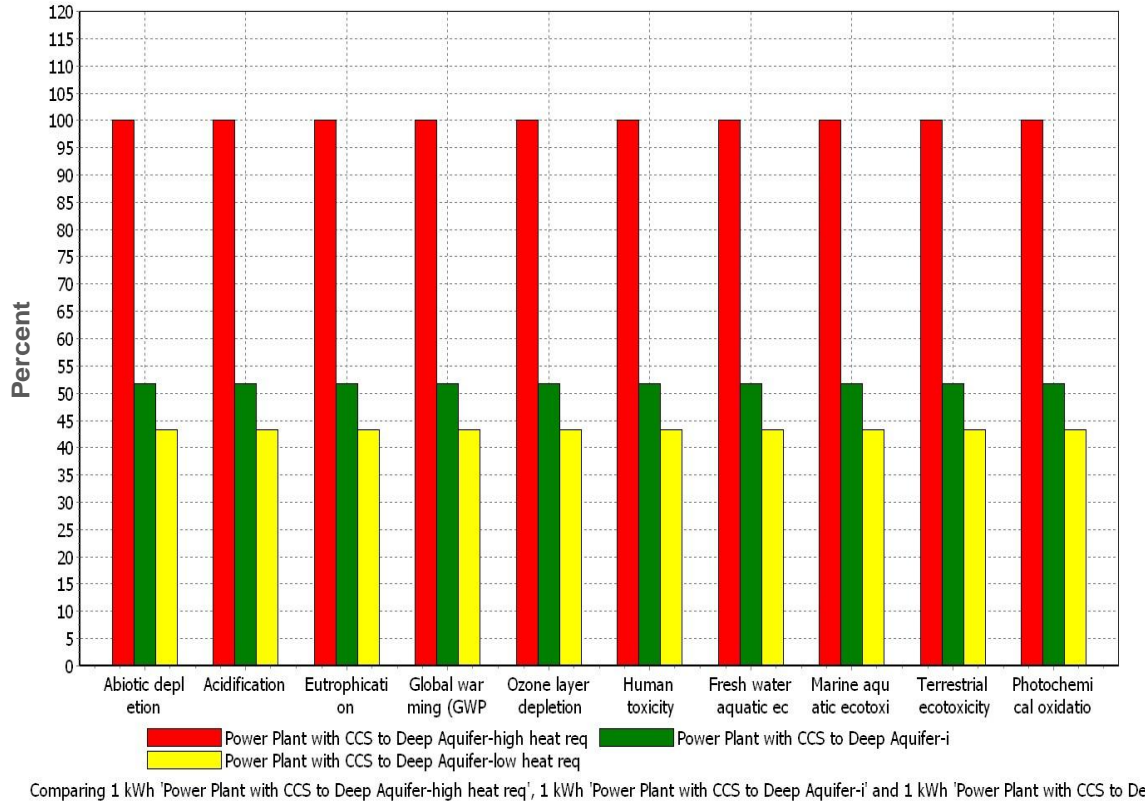
Increasing the efficiency reduces impacts across the board, with a significant reduction in all categories even just for the power plant without CCS. This indicates that increasing efficiency could be a viable way to reduce environmental impacts, and that perhaps increasing efficiency should be explored concurrently with CCS, as it makes CCS more environmentally favorable.

One of the factors which significantly contribute to the reduction of power plant efficiency from the CCS chain is the energy requirement for the capture process. A significant contributor to this is the heat requirements for regeneration of the MEA solvent, and large ranges for this value exist in the literature. Additionally, reductions of the heat necessary can be expected as the technology continues to develop. Upper and lower bounds for the energy required were taken from the literature, and compared with the value used in this study (Figure 9).

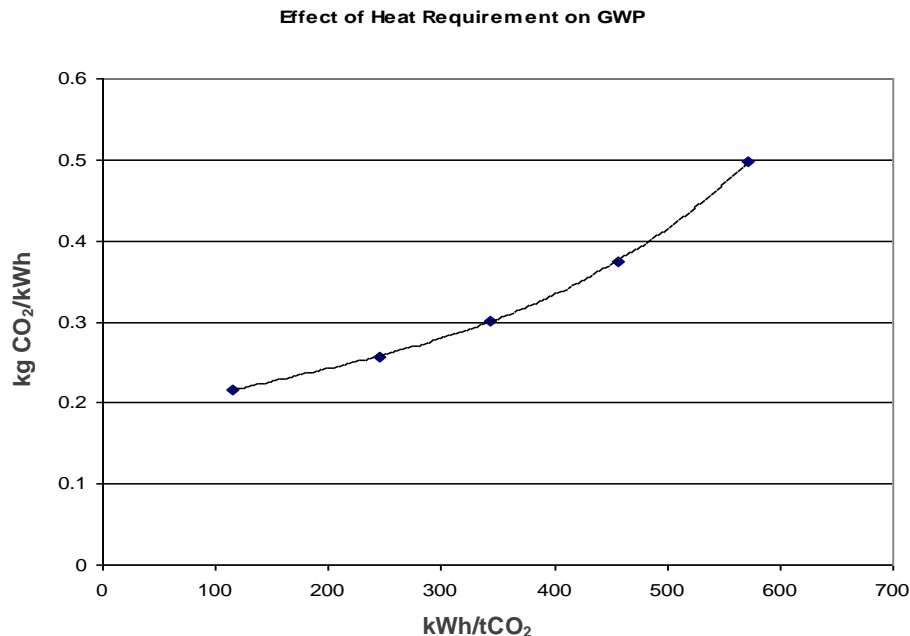
The overall energy required is a combination of the heat estimate needed directly from the steam, and the power equivalency factor for conversion of steam into electricity, both of which have ranges. Literature ranges for the steam requirement are 3.5 to 6  $\text{GJ}_{\text{steam}}/\text{tCO}_2$  (Rao et al., 2006), and the power equivalency factor ranges from 0.094 (Mimura et al., 1997) to 0.329  $\text{GJ}_e/\text{GJ}_{\text{steam}}$



**Figure 8.** Sensitivity analysis of plant efficiency. Shows all cases for the original power plant with 35.7% efficiency and a high efficiency power plant with 45% efficiency.



**Figure 9.** Sensitivity analysis for varying heat requirements for the amines in the capture process. Red is the upper bound heat requirement of 572 kWh/tCO<sub>2</sub>, green is the case used in this study of 245 kWh/tCO<sub>2</sub>, and yellow is the lower bound heat requirement of 115 kWh/tCO<sub>2</sub>. All cases with CCS and aquifer injection.



**Figure 10.** Relationship between the energy requirement for capture and GWP impact. It shows a nonlinear, positive. All impact categories react similarly (as can be seen in Figure 8), so this graph would be similar for all impact categories.

(Buchanan, 2000) (Peeters et al., 2007). Using these numbers, the upper bound for the heat requirement was 572 kWh/tCO<sub>2</sub> and the lower was 115 kWh/tCO<sub>2</sub>. Figure 7 compares these bounding values with the 245 kWh/tCO<sub>2</sub> used in the study. Reduction in power requirements reduce all categories by an equal percentage, though it does not appear to be a linear relationship, with decreasing returns as the value gets lower (Figure 10). Thus, reductions in the heat requirement in the future will decrease all categories.

### Normalization

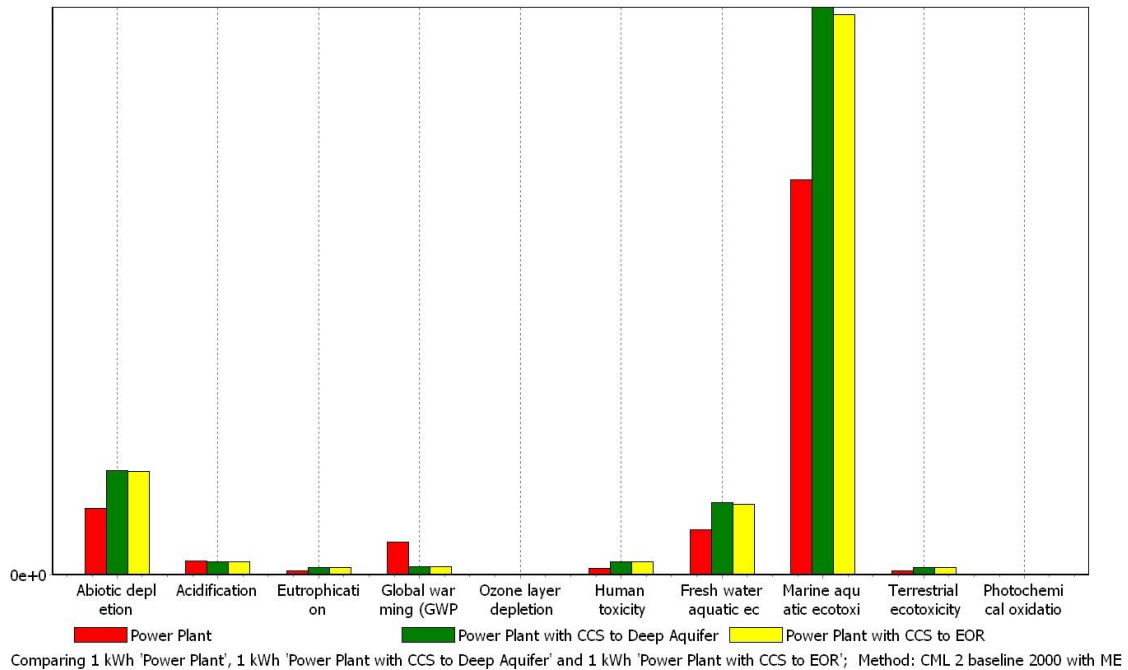
Normalization is the comparison of results with reference information for a given community, in this case, world averages from 1995 (Huijbregts et al., 2003), and it is strongly recommended for any LCA (Guinée, 2002). Comparison with overall emissions from a given population allows the practitioner to evaluate the severity of the impact from the studied system in a wider reference frame. Figure 11 shows the normalizations for this study. It is immediately obvious that the marine ecotoxicity is much higher than the other categories, which is surprising considering there is no direct contact with the marine ecosystem, raising the question of bias. Heijungs et al. (2007) show an example of bias where hydrogen fluoride causes a similarly large normalized impact in marine ecotoxicity, because it is emitted by the process studied, but there is no information on the emission of hydrogen fluoride by the weighting set, thus

it is assumed to be zero. The marine ecotoxicity category in this case is dominated by the emissions of beryllium and vanadium to water, thus the hydrogen fluoride is unlikely to make such a large impact on the category. However, inspection of the normalization factors for the CML 2001 impact categories indicates that neither beryllium nor vanadium emissions to water are included for the World 1995 reference emissions, which leads to a much higher than accurate normalization in this category. Inspection of the other categories reveals that while the marine ecotoxicity is the most extreme, many of the other categories also have substances missing from the normalization set that could cause the normalization to be biased, particularly fresh water ecotoxicity and ozone layer depletion.

In this case, normalization is not very useful as a decision making tool, mostly because of lack of information on worldwide emissions of certain substances. This highlights the importance of studying each category and the changes in emissions to evaluate the process as a whole.

### DISCUSSION AND IMPLICATIONS FOR MEXICO

Overall, the use of CCS technology lowers the impact in the GWP category significantly, as intended, with some co-benefits in the lowering of the impacts in the acidification and photochemical oxidation categories. However, all other categories show significant increases with the use of CCS systems as compared to a regular



**Figure 11.** Normalization of results on the world 1995 scale. While this is a recommended step for LCA analysis, it is evident that there are errors in the weighting scheme in this case due to emitted chemicals absent in the weighting scheme.

power plant. LCA steps like normalization and weighting are designed to help evaluate the overall impact, but in this case the subjective choice of how to weight different categories affects the outcome significantly.

The results from this LCA analysis are overall similar to other LCA studies that have been completed for fossil fuel fired power plants. These previous studies are all for developed countries, mostly in Europe, and most consider high efficiency power plants rather than the standard one considered in this study. This study lowered GWP by 75%, and other published studies lower GWP by a comparable range of 70 to 80% (Khoo and Tan, 2006b; Koornneef et al., 2008; Korre et al., 2010; Nie et al., 2011; Odeh and Cockerill, 2008; Pehnt and Henkel, 2009; Singh et al., 2011; Zapp et al., 2012). The published studies reviewed by Zapp et al. (2012) showed a range of energy penalties, or the overall reduction in plant efficiency from 22 to 33%. This study indicates an energy penalty of 34% for standard plants in Mexico, higher than the other published studies. In the other impact categories for which CCS increased the overall impact, this study had impacts which were on the high end of other published studies (Zapp et al., 2012). These higher energy penalties and increased impact are related to the fact that this study focused on a standard plant in the developing world.

Mexico, like other developing economies, faces different challenges than the developed countries that lead the way in research and implementation for technologies such as CCS. Shackley and Verma (2008)

point out that for India, the overall goal is to continue a high rate of economic growth, which means providing reliable low cost electricity. Therefore, they are unlikely to adopt an expensive CCS system that uses more coal resources without increasing electricity output. Mexico is by no means the same as India, but it faces similar challenges in terms of the need to provide cheap, reliable electricity, and often not having the resources to be at the forefront of research on CCS technology. There are several other studies assessing the state of CCS policy and development of developing countries including India, Mexico, Brazil, China, and South Africa (Condor et al., 2011; Modahl et al., 2012; Román, 2011), but they look only at the progression of the technology without considering the additional environmental impacts.

One of the reasons that the results from this LCA for CCS in Mexico make CCS seem less promising than many of the LCAs for CCS that are in the published literature is that a standard power plant, like the ones in operation now in Mexico, is studied rather than a high efficiency plant. An LCA by Koornneef et al. (2008) indicates that a state of the art high-efficiency supercritical coal power plant lowers GWP by more than 20% per kWh as compared to a standard coal plant, and lowers all other impact categories significantly, which is also shown in this study's sensitivity analysis (Figure 6). Adding CCS to this supercritical plant lowers GWP by another 75%, and raises most other categories, but only about half reach the same levels as the standard power plant in Koornneef et al. (2008) study. They also note in

their sensitivity analysis that the thermal generating efficiency has a non-linear equal effect on all categories, where lowering the efficiency causes increases in all categories. Mexico does not have any supercritical power plants, which is why this study used a conventional power plant. However in light of the higher impacts in most categories shown by this study, it is perhaps prudent to consider whether installing several state of the art power plants would be economically as well as environmentally better option for reducing CO<sub>2</sub> emissions and other environmental impacts. It is apparent from Figure 6 that replacing 4 standard plants with high efficiency plants would be roughly equivalent in terms of reduction of GWP as installing a CCS facility on a standard plant, and the high efficiency plants would significantly reduce impacts in all other categories. This study does not deal with economics, and it is beyond the scope of this project, but it is an important question for further research. The IPCC report on carbon dioxide and capture and sequestration indicates that most CCS facilities built will be on supercritical plants, because the cost is lower (IPCC, 2005). Even for retrofitting older plants, Gibbins et al. (2005) indicate that it could be economically beneficial in the long term to upgrade the boiler to super critical when retrofitting an existing power plant for CCS, because of the improved efficiency and therefore reduced fuel use.

Despite the costs, there are arguments that investing in CCS technology could benefit Mexico over time, especially when CSS is combined with EOR (Lacy, 2005). With the system boundaries as they are for this model, EOR also shows a lower environmental impact in all categories as compared to injection in a deep saline aquifer. Additionally, EOR would increase resource production and in a way partially balance the extra resources needed for electricity production with CSS, though that is not included in this LCA model.

Additional improvements in the solvent technologies are likely to lower the energy requirements for regeneration of the solvent, as well as perhaps the solvent lost during the process. A reduction in energy required for solvent regeneration would increase the overall efficiency and decrease the impacts in all categories, as shown in the sensitivity analysis (Figures 7 and 8). There is ongoing research on this subject, for instance pilot plant studies by Idem et al. (2006) indicate that a mixture of MEA and methyldiethanolamine (MDEA) could achieve a large reduction in the regeneration energy of the solvent. Such advances could improve the overall impacts of CCS considerably and make CCS much more attractive in all locations including Mexico.

## Conclusion

Implementing carbon capture by chemical absorption by MEA and geologic sequestration of carbon on coal fired power plants in Mexico could reduce the global warming impact of generating power by 75%, a significant

reduction. However, this would have a large negative impact on the efficiency of the plant, as well as nearly all other environmental impact categories studied, including abiotic depletion, eutrophication, human, marine, freshwater, terrestrial ecotoxicity, and ozone layer depletion. There are some co-benefits in lower impacts in the photochemical oxidation potential and acidification categories. In this case, normalization was not particularly helpful in the interpretation stage for whether installing CCS would be worthwhile. The intended carbon dioxide reduction exists, but the environmental and efficiency trade offs are significant, so it becomes a valid judgment. With technological advances in the energy requirement of the solvent and a more highly efficient super critical plant, the environmental and efficiency trade offs can be reduced significantly, thus CCS, especially in conjunction with highly efficient plants, is worth exploring. Because a highly efficient plant lowers all impact categories across the board, future studies should compare at the costs installing CCS on a standard plant with the costs of retrofitting plants to be high efficiency before installing CCS, or even just retrofitting multiple plants to be high efficiency. Both options have lower environmental impacts than installing CCS on a standard plant, and may also have a lower or equivalent economic cost.

Based on the results of this study, it is recommended that Mexico will continue to explore CCS, but only in conjunction with high efficiency power plants. Future studies which include economic analysis are needed, and additional environmental studies will be needed as technology improves and when specific power plants and storage locations are chosen for CCS.

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**Appendix A.** LCI data for capture infrastructure according to Koornneef et al. (2008) based on their contact with the manufacturer Fluor in the Netherlands.

<b>Process</b>	<b>Amount</b>	<b>Unit</b>
Steel, high alloy, secondary	317	Ton
Concrete	1	m <sup>3</sup>
Transport, truck	49290	Tkm
Transport, rail	480000	Tkm
Lifetime	30	years
Steel to recycling plant	317	ton
Concrete to inert material landfill	2.4	ton

**Appendix B.** LCI for compression infrastructure according to Koornneef et al. (2008) based on Faist Emmenegger et al. (2003).

<b>Process</b>	<b>Amount</b>	<b>Unit</b>
Concrete	65	m <sup>3</sup>
Diesel and fuel oil for construction	1978	GJ
Electricity	61	MWh
Steel, high alloy, secondary	3.25	ton
Steel, low alloy, secondary	61.8	ton
Copper	7	ton
Polyethylene, HDPE	20	ton
Compressor capacity	40	MW
Lifetime	20	Year
Transport, truck	20916	tkm
Transport, rail	38317	tkm
Copper to recycling plant	7	ton
Steel to recycling plant	55	ton
Concrete to inert material landfill	156	ton

**Appendix C.** LCI for injection into a saline aquifer. Most from Koornneef et al. (2008), while the monetary value for exploration is from the IEA GHG monitoring tool (IEA GHG).

<b>Process</b>	<b>Amount</b>	<b>Unit</b>
Well for exploration and production, onshore	18	km
Sand	712000	ton
Steel, un-alloyed, secondary	3800	ton
Steel, high alloyed, secondary	8100	ton
Concrete	10463	m <sup>3</sup>
Copper	425	ton
Transport, truck	74406310	tkm
Transport, rail	7153175	tkm
Lifetime	30	Years
Steel to recycling plant	11900	ton
Copper to recycling	425	ton
Concrete to inert material landfill	25111	ton
Petroleum, natural gas and solid mineral exploration	54000000	USD

**Appendix D.** LCI for EOR process. Most parts of the process are considered to be outside the system boundaries. Monetary value using IEA GHG monitoring tool (IEA GHG).

Process	Amount	Unit
Petroleum, natural gas and solid mineral exploration	54000000	USD

**Appendix E.** Estimated elemental composition of reclaimer bottoms from the capture unit. From Koornneef et al. (2008) after Strazisar et al. (2003).

Element	Mass (kg/kg)
LHV	0
O	$2.53 \times 10^{-1}$
H	$8.83 \times 10^{-2}$
C	$4.28 \times 10^{-1}$
S	$8.33 \times 10^{-5}$
N	$1.79 \times 10^{-1}$
P	$7.51 \times 10^{-5}$
Cl	$4.90 \times 10^{-2}$
Br	$8.00 \times 10^{-5}$
F	$1.50 \times 10^{-3}$
As	$1.70 \times 10^{-6}$
Cu	$1.00 \times 10^{-7}$
Hg	$1 \times 10^{-9}$
Se	$1.74 \times 10^{-5}$
Zn	$2.00 \times 10^{-7}$
Fe	$1.10 \times 10^{-6}$
Ca	$1.30 \times 10^{-6}$
Al	$4.00 \times 10^{-7}$
K	$1.80 \times 10^{-5}$
Na	$8.21 \times 10^{-4}$