The role of industrial carbon capture and storage (CCS) in emission mitigation

Jessica Farrell[a], Jennifer Morris[a], Haroon Kheshgi[b], Hans Thomann[b], Sergey Paltsev[a*], Howard Herzog[a]

[a]Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge MA 02139, USA
[b]ExxonMobil Research and Engineering Company, 1545 Route 22 East, Annandale NJ 08801, USA

Abstract

Carbon capture and storage (CCS) technology is an important option in the portfolio of emission mitigation technologies in scenarios that lead to deep reductions in greenhouse gas (GHG) emissions consistent with limiting increases in global average surface air temperature to 2 degrees Celsius (2C) above pre-industrial levels. Industrial CCS applications are more challenging to analyze than CCS in the power sector -- mainly due to the vast heterogeneity in industrial and fuel processes. Our study focuses on the cement industry and provides the estimated costs associated with several CCS options: coal-fired post-combustion capture (PCC), natural gas-fired PCC, and Cryogenic Carbon Capture (CCC). We explore regional cost estimates with variations in costs of capital and fuels to provide a basis for regional and global projections of industrial CCS deployment. We offer a methodology for incorporating the CCS cost information into energy-economic and integrated assessment models. Our methodology can be applied to other applications of CCS in the industrial sector. We illustrate our method by introducing the industrial CCS options into the MIT Economic Projection and Policy Analysis (EPPA) model, a global energy-economic model that provides a basis for the analysis of long-term energy deployment, and we discuss different scenarios for industrial CCS deployment in different parts of the world. We tested in the EPPA model the potential for industrial CCS under the assumptions that CCS is the only mitigation option for deep GHG emission reduction in industry and that negative emission options are not available for other sectors of the economy. When industrial CCS is not available, global costs of reaching the 2C target are higher by 12% in 2075 and 71% in 2100 relative to the cost of achieving the policy with CCS. Overall, industrial CCS enables the continued use of energy-intensive goods with large reductions in global and sectoral emissions. We find that in scenarios with stringent climate policy, CCS in the industry sector is a key mitigation option, and our approach provides a path to projecting the deployment of industrial CCS across industries and regions.

Corresponding author: Sergey Paltsev (paltsev@mit.edu)

1. Introduction

As greenhouse gas (GHG) emissions continue to rise around the globe [1,2], deep reductions in GHG emissions are necessary if the aim of the Paris Agreement [3] -- to keep the global average surface temperature rise well below 2 degree Celsius -- is to be achieved. While GHG emission reduction in power generation is considered to be the key area for initial mitigation [4], a large fraction of emissions are generated from energy intensive industrial sources, such as cement plants and iron and steel mills. For some industrial processes, CO_2 is generated from both fuel combustion and non-combustion related industrial processes. In 2014, these industrial (combustion and non-combustion) emissions totaled globally approximately 11,000 million tonnes of CO_2 ($MtCO_2$), making up approximately 31% of all CO_2 emissions globally, with the proportion of emissions from industrial sources varying widely by region [5]. For example, in China, industrial emissions make up approximately 45% of total fossil CO_2 emissions, while in the United States industrial emissions make up 14% of total fossil CO_2 emissions. The demand for industrial products is expected to continue to grow putting upward pressure on GHG emissions from the industrial sector [5].

Industrial processes have few alternatives for emission reductions. Efficiency improvements have potential to reduce emissions, but to a limited extent [6]. Another option is industrial carbon capture and storage (CCS), which allows for the removal of 90-99% of CO_2 emissions from an industrial plant. Though CCS technology is relatively new and its deployment has been limited, it provides a valuable future option for countries to make deep reductions in their GHG emissions. The goal of this paper is to assess the role of industrial CCS when GHG emission mitigation is applied to limit temperature rise to 2°C above the pre-industrial level. To accomplish this task, we provide an analysis and comparison of various CCS technologies that can be used in the industrial sector with a focus on the cement industry.

We then use this information to enhance the MIT Economic Projection and Policy Analysis (EPPA) model [7], a global general equilibrium model that spans 18 different regions of the world and evaluate the potential role of industrial CCS under a variety of policy scenarios. [1] For this assessment, we approximate the CCS costs for all energy-intensive industrial CCS applications with the estimated cost of CCS applied to cement plants. We do not consider other approaches that may offer the potential for deep GHG reduction in industry, such as hydrogen and material substitution because cost estimates for these options are almost non-existent in scientific literature.

2. Industrial GHG Emissions

Despite the current attempts to reduce GHG emissions, total amounts of CO_2 emissions from industrial sources continue to rise [1]. In 2015, total global emissions from all sources of fuel combustion (including electricity) and industry accounted for approximately 35.6 gigatonnes of CO_2 ($GtCO_2$), with China, EU, India, and USA collectively contributing approximately 21.4 $GtCO_2$. Global emissions from the industrial sector rose from 6.91 $GtCO_2$ in 1990 to 11.1 $GtCO_2$ in 2014, with the increases in emissions in China making up approximately 84% of the global increase in industrial CO_2 emissions [9].[2] Figure 1 shows the industrial emissions in major regions from 1990 to 2015, obtained from the EDGAR database [9]. China's emissions grew dramatically from 2002 to 2010, but the growth has slowed down after 2010. India's emissions are still growing and emissions in the USA and EU are gradually decreasing.

[1] Here we report the results for a limited set of scenarios. For additional sensitivity analysis, see [8].

[2] These emissions do not include the indirect CO_2 emissions from the production of electricity and heat obtained from the industry. When included, the global emissions in the industrial sector rose from 10.37 $GtCO_2e$ in 1990 to 15.44 $GtCO_2e$ in 2010 [6].

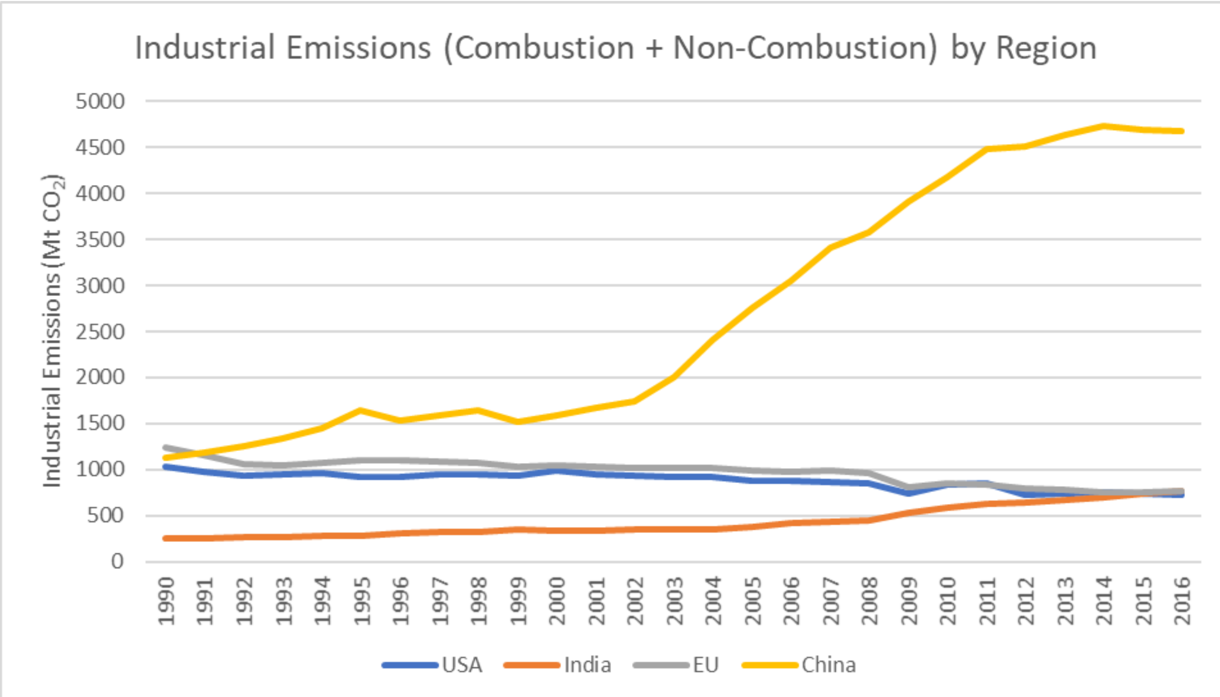

Figure 1. Industrial Emissions in major regions from 1990 to 2015. Data source: [9].

Data on the further disaggregation of the industrial emissions (i.e., cement, chemicals, iron and steel, etc.) is limited and mostly available for developed countries. The Netherlands Environmental Assessment Agency [10] provides one of the few resources that assess global emissions from the cement industry. According to PBL, China makes up about 51% of global non-combustion (i.e. process-related) emissions from the cement industry, with India, the European Union, and the United States making up 6.9%, 4.8%, and 2.7% of global emissions, respectively. Non-combustion emissions in China have risen from 0.59 $GtCO_2$ in 2010 to 0.73 $GtCO_2$ in 2015, rising approximately 4.5% annually. Globally, non-combustion emissions have also risen from 0.51 $GtCO_2$ in 1990 to 1.2 $GtCO_2$ in 2010 to 1.4 $GtCO_2$ in 2015, with cement non-combustion emissions alone making up approximately 4% of global emissions and 13% of all industrial emissions [10]. In total, including both process and combustion emissions, cement-related emissions made up approximately 6.7% of global emissions and 22% of all industrial emissions, with over 2.4 $GtCO_2$ emitted in 2016.[3]

Table 1 shows the breakdown in CO_2 emissions by the cement, iron and steel, and chemicals sectors. When compared to other industries, cement is one of the larger sources of industrial emissions. In USA, non-combustion cement emissions make up approximately 24% of all industrial non-combustion emissions, second only to emissions from the iron and steel industry. In Europe, it makes up 32% of all industrial non-combustion emissions, or about 9% of all industrial emissions. While detailed data for industrial sectors is not available for China or India, cement emissions make up a large portion of the non-combustion industrial emissions. Cement produces about 48% of each country's non-combustion emissions.

[3] In the PBL dataset, only process-related CO_2 emissions were included – to estimate the total emissions, it was assumed that process-related emissions made up 60% of the total cement plant emissions [12].

Table 1. Non-combustion emissions by the cement, iron and steel, and chemicals sectors. Data source: [12]

	China	EU	India	United States
Ratio of Non-Combustion Cement Emissions to All Industrial Non-Combustion Emissions	0.481	0.316	0.479	0.243
Ratio of Non-Combustion Cement Emissions to All Industrial Emissions	0.156	0.089	0.135	0.053
Ratio of Non-Combustion Iron and Steel Emissions to All Industrial Non-Combustion Emissions		0.302		0.305
Ratio of Non-Combustion Iron and Steel Emissions to All Industrial Emissions		0.086		0.066
Ratio of Non-Combustion Petrochemical and Ammonia Emissions to All Industrial Non-Combustion Emissions		0.184		0.242
Ratio of Non-Combustion Petrochemical and Ammonia Emissions to All Industrial Emissions		0.052		0.053

3. Cement and CCS

Cement production is a good candidate for initial consideration of CCS. While there are differences between some cement plant configurations, in comparison to other industrial plants, cement plants are quite homogenous, with non-combustion and combustion emissions combined in the flue stream. Furthermore, the percent of CO_2 in the flue stream of a cement plant is greater than the CO_2 concentration of the flue gas of a coal-fired power plant, where CCS has already been deployed at a million ton per year scale [13].

The total emissions from the cement production process depend on two main components: the process-related (non-combustion) emissions resulting from the calcination of the limestone and the fuel combustion-related emissions generated in the pre-calciner and the kiln. The clinker-cement ratio is one way of measuring the total amount of clinker needed to produce the cement. A low ratio indicates that the cement was formed using less clinker, which inherently emits less CO_2 (per unit mass of cement) from the calcination process which is used to form clinker. Various substitutes could be used in place of clinker to produce cement, including fly ash, slag, and limestone, but their applications are limited by their availability [11]. Other potential methods of reducing CO_2 emissions from the cement industry include the applications of alternative raw materials, the utilization of alternative fuels, and increased energy efficiency using pre-calciners.

In 2014, the United States made up approximately 2% of global cement production; China made up approximately 60% of total production. Total global cement production has grown significantly in the past 20 years, from 1.53 billion metric tons in 1998 to 4.17 billion metric tons in 2014. The primary driver of this growth has been Chinese production – in 1998, China produced 536 million metric tons of cement (or 35% of the world's total production in 1998) and in 2014 China produced 2.49 billion metric tons of cement (or 60% of the world's total production in 2014). These production levels have primarily been used to fuel the country's building boom and national investments in infrastructure. Figure 2 shows cement production in China, the European Union, India, and USA from 1998 to 2014.

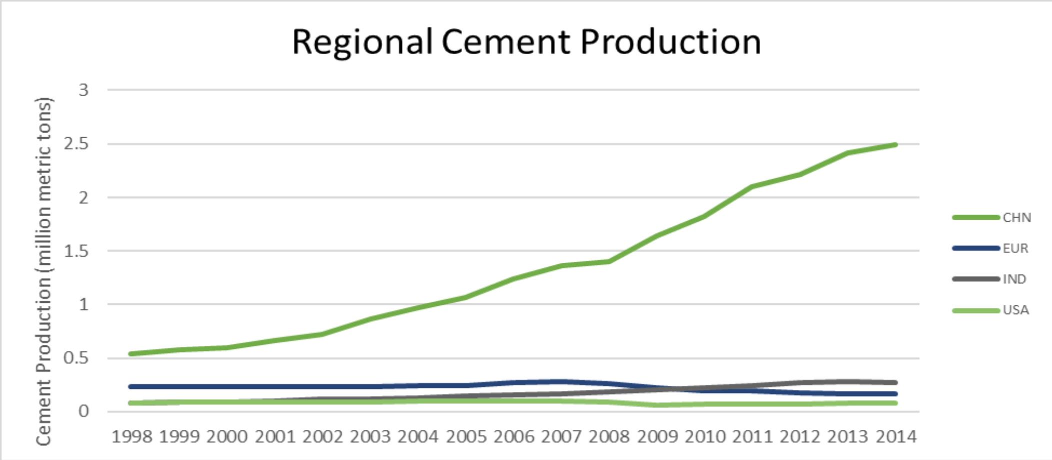

Figure 2. Cement production in China, the European Union, India, and USA. Data source: [14].

Cement demand is expected to continue to increase in many countries. According to the World Cement Association, demand for cement is expected to increase 1.5% globally, with markets in France, Germany, Spain, and USA expecting demand growth of 4%, 5%, 10%, and 6%, respectively [15]. According to the IEA [16], cement demand per capita is expected to stabilize, but with increases in population, the total global demand for cement is expected to increase into 2050.

While the power sector has alternatives to CCS that can also significantly reduce GHG emissions from fossil-based generation (e.g., by using wind, solar, nuclear, hydro), there are no viable alternatives for CCS for many industrial processes, including cement. Below we briefly describe the main capture technology options for cement.

3.1. Post-combustion capture

Post-combustion capture (PCC) is a technology that captures CO_2 from the flue gas of a cement plant. It does so by applying liquid solvents to low-pressure, low-concentration flue gases [17]. The acidic CO_2 in the flue gas stream chemically bonds with an alkaline solvent (such as Monoethanolamine, or MEA) [18]. Once the CO_2 is removed from the flue stream, the liquid solution is then heated to release the bonded CO_2. The CO_2 is then cooled and compressed and transported for long-term storage. The heat applied to the solution is also used to regenerate the solvent for future capture. Because post-combustion technology is an "end-of-the-pipe" technology, it is can be retrofitted onto existing plants and does not affect the cement production process itself.

According to IEAGHG, post-combustion capture can produce a stream of CO_2 with 99.9% quality [18]. The percent of CO_2 captured from the flue stream is estimated to be between 85% and 90%, but the IEA states that 95% capture can be achieved without significantly affecting the cost of capture. However, post-combustion capture has several requirements that can be costly to a traditional cement plant. The solvent is sensitive to impurities typically found in cement flue gas, so extra equipment is needed to remove SO_X, NO_X, and dust from the flue gas. The regeneration of the solvent requires large amounts of low-to-intermediate pressure steam [11]. The waste-heat from a cement plant can only supply 15% of the total heat needed – because of this, either a low-pressure boiler or a combined heat and power (CHP) unit is needed. The boiler or CHP unit can be fired using either coal or natural gas (referred to as coal-fired PCC or gas-fired PCC in this paper).

3.2. Oxy-combustion

In the oxy-combustion process, the fuel is burnt in oxygen rather than in air. The combustion exhaust gases are mainly water, CO_2, SO_2 and particulates and above all do not contain nitrogen (the major component in air that dilutes the flue gas and results in high costs for the separation step in the post-combustion case). After separation from SO_2 and particulates, the high concentrated CO_2 stream can be processed for storage. While the oxygen (O_2)

production is energy-intensive and may add to the overall cost of the process, oxy-combustion has the potential to be cost-competitive with other capture technologies.

A partial oxy-fuel process uses oxygen only to fire the pre-calciner, while a full oxy-fuel process uses oxygen to fire both the pre-calciner and the rotary kiln. A full oxyfuel process can capture approximately 85-90% of all CO_2, while a partial oxyfuel process (located only on the pre-calciner) can only capture approximately 60% of the CO_2. There is very little experience with this technology to date, but the elements of the oxy-combustion technology all exist and are used, for example, in the metal and glass melting industries.

3.3. Cryogenic carbon capture

Cryogenic Carbon Capture (CCC) is a technology developed by Sustainable Energy Solutions (SES) company [19]. It is a post-combustion technology, and SES claims that up to 99% of CO_2 can be removed from the flue-stream of a plant by cooling the CO_2 to minus 140 degrees Celsius so that it changes phase from a gas to a solid. The solid CO_2 is then mixed with a variety of liquid hydrocarbons, pressurized, separated from the liquid solvent, melted into liquid CO_2, and delivered at pipeline pressure. An off-stream of N_2 is also produced. The pollutant streams of SO_X and NO_X are also separated using this method, so the costs of removing these pollutants are included in the capital and operational costs. Figure 3 presents the flow diagram of SES's Cryogenic CO_2 Capture (CCC) process.

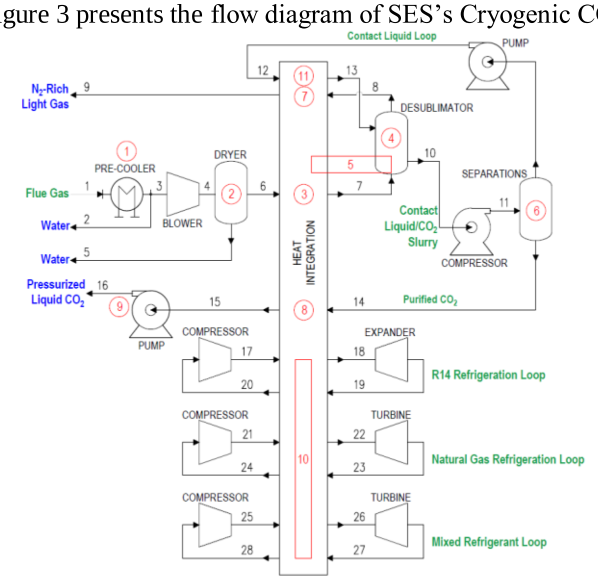

Figure 3. Cryogenic CO2 Capture (CCC) Process [19]

This process uses the solidified CO_2 to cool the warm flue gas from the cement plant and the flue gas to melt the CO_2, which improves the energy efficiency of the process. Unlike other PCC technologies, CCC requires electricity to power the capture process and not steam. CCC does not require a separate compression unit because the CO_2 is condensed at elevated pressure and boosted to pipeline pressures by an electrical pump.

3.4. Cost of CCS

Table 2 provides a summary of the relative cost of cement production with and without CCS. We calculate the costs of production based on selected input data from several studies: Barker et al. (2009) [20], IEAGHG (2013)[4] [11], NETL (2014) [21], and Hegerland et al. (2006) [22]. We also used the data provided by Sustainable Energy Solutions (SES) company [19]. The details of our calculations are provided in the Appendix. For CCS technologies based on Barker et al. (2009), we compare them to the reference (i.e. without CCS) plant analyzed in that study (this comparison is denoted by green section of Table 2). Other studies do not provide data for their reference plants;

[4] We later refer to IEAGHG (2013) estimates as IEA.

therefore, we have related their costs to the IEA reference plant (this comparison is denoted by brown section of Table 2).

Table 2 also provides the data for overnight capital cost, plant capacity in terms of cement production per year, and CO_2 capture rates. The markup is calculated as the relative cost of production of one tonne of cement with different technology options (the markup for a reference plant is 1). The highest markups (>2) are for the coal-fueled PCC (based on Barker and IEA data) and natural gas-fueled PCC (based on NETL data). The lowest markups (<1.4) are for partial oxy-CCS and CCC. In terms of maturity of CCS technologies, post-combustion options have been tested on industrial-scale projects and CCC has been piloted at 1 ton per day. Because oxy-CCS and CCC are still in earlier stages of development, their costs are more uncertain and their smaller markup should be treated as a longer-term potential.

Table 2. Relative costs of different cement technologies.

	"Overnight capital cost", $/t cement	Plant capacity, Mt cement/year	CO2 capture rate, %	Markup over the corresponding regular (no CCS) plant
no CCS plant, Barker	340	1.11	0	1
coal PCC, Barker	722	1.11	85	2.02
oxy CCS partial, Barker	423	1.11	62	1.31
no CCS plant, IEA	177	1.36	0	1
coal PCC, IEA	493	1.36	90	2.19
gas PCC, IEA	400	1.36	90	1.43
oxy CCS, IEA	262	1.36	90	1.47
oxy CCS partial, IEA	248	1.36	65	1.38
gas PCC, NETL	436	0.992	85	2.34
gas PCC, Hegerland	436	1.4	85	1.85
coal PCC, Hegerland	488	1.4	85	1.94
CCC	256	1.66	90	1.24

4. Representing Industrial CCS in Energy-Economic Models

We use our cost methodology to represent the industrial CCS technologies in an energy-economic model in order to conduct an analysis on their potential role in emission mitigation. We use the MIT Economic Projection and Policy Analysis (EPPA) model [7], which is a general equilibrium economic model that is used for long-term (up to 2100) projection of energy, economy, and emissions. The model explicitly represents international trade, inter-industry linkages, distortions (including taxes and subsidies), and determines GDP and welfare effects. The model tracks the carbon emissions of each industry and technology (including industrial CCS, CCS in the power sector, renewables, and nuclear power, among others). The EPPA model offers an analytic tool that includes a technology-rich representation of power generation sector and also captures interactions between all sectors of the economy, accounting for changes in international trade.

Figure 4 shows the 18 different regions in EPPA, and Figure 5 shows the economic sectors. Data on production, consumption, intermediate inputs, international trade, energy and taxes for the base year of 2007 are from the Global Trade Analysis Project (GTAP) dataset [23]. The model includes representation of CO_2 and non-CO_2 (methane, CH_4; nitrous oxide, N_2O; hydrofluorocarbons, HFCs; perfluorocarbons, PFCs; and sulphur hexafluoride, SF_6) greenhouse gas (GHG) emissions abatement, and calculates reductions from gas-specific control measures as well as those occurring as a byproduct of actions directed at CO_2. The model also tracks major air pollutants (sulfates, SO_x; nitrogen oxides, NO_x; black carbon, BC; organic carbon, OC; carbon monoxide, CO; ammonia, NH_3; and non-methane volatile organic compounds, VOCs). The data on GHG and air pollutants are documented in Waugh et al., (2011).

Table 3. Sectors in the EPPA model.

Sectors	Abbreviation
Energy-Intensive Industries	EINT
Energy-Intensive Industries with CCS	EINT-CCS
Other Industries	OTHR
Services	SERV
Crops	CROP
Livestock	LIVE
Forestry	FORS
Food Processing	FOOD
Coal Production	COAL
Oil Production	OIL
Refining	ROIL
Natural Gas Production	GAS
Coal Electricity	ELEC: coal
Natural Gas Electricity	ELEC: gas
Petroleum Electricity	ELEC: oil
Nuclear electricity	ELEC: nucl
Hydro Electricity	ELEC: hydro
Wind Electricity	ELEC: wind
Solar Electricity	ELEC: solar
Biomass Electricity	ELEC: bele
Wind combined with gas backup	ELEC: windgas
Wind combined with biofuel backup	ELEC: windbio
Coal with CCS	ELEC: igcap
Natural Gas with CCS	ELEC: ngcap
Advanced Nuclear Electricity	ELEC: anuc
Advanced Natural Gas	ELEC: ngcc
Private Transportation: Gasoline & Diesel Vehicles	HTRN: ice
Private Transportation: Plug-in Hybrid Vehicles	HTRN: phev
Private Transportation: Battery Electric Vehicles	HTRN: bev
Commercial Transportation	TRAN
First-Generation Biofuels	BIOF
Advanced Biofuels	ABIO
Oil Shale	SOIL
Synthetic Gas from Coal	SGAS

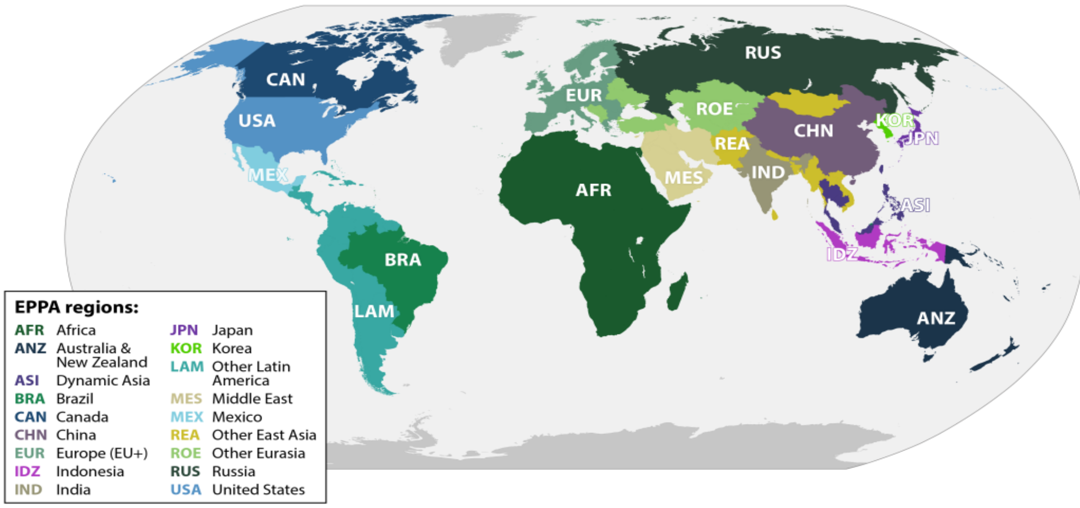

Figure 4. Regional representation in the EPPA model.

Energy-intensive industries (EINT) are aggregated in the EPPA model into a single sector, which includes paper product manufacturing, chemical and plastic manufacturing, mineral product manufacturing, iron and steel production, and cement production.[5] While our CCS cost estimates are focused on CCS for cement production, we apply the costs and input shares of CCS in the cement sector to other energy-intensive industries. Therefore, in the scenarios considered in this paper, CCS is included as a general option for the entire EINT sector.

From 2015 the model solves at 5-year intervals, with economic growth and energy use for 2010-2015 calibrated to data and short-term projections from the International Monetary Fund [24] and the International Energy Agency [1]. Each interval is solved using economic principles of supply and demand and utility maximization. For the benchmark year, the model requires inputs on each technology's costs in the base-year of the model in different regions. The two inputs required are markups and cost shares. We use information from Table A2 and Table A3 (see Appendix) to calculate them.

The markup is calculated as the increased cost of a new technology relative to a base technology. While the markup describes the increase in costs for a cement with CCS plant, the cost shares determine the value each input needed to produce a unit of cement. By design, the cost shares sum up to 1.0. Based on GTAP data, the input costs of are divided into 18 separate categories, 12 of which are shown separately in Table 4. The remaining categories are grouped into the "Other" category. For example, in the energy-intensive sector in the United States, the costs of labor make up approximately 24.75% of the cost inputs to creating a unit of cement.

[5] Based on GTAP sectoral reprsentation, petrochemical production is not included in the EINT sector; it is instead included in the Refined Oil (ROIL) sector.

Table 4. Cost shares of the energy-intensive sector.

Sector	**Sector Description**	**Cost Share**
EINT	Energy-Intensive Industries	0.3052
SERV	Services	0.1413
TRAN	Transport	0.043
COAL	Coal	0.0006
ROIL	Refined Oil	0.0227
GAS	Gas	0.009
ELEC	Electricity	0.0467
Labor	Labor	0.2475
Capital	Capital	0.1197
LSEQ	Labor for Sequestration	0
KSEQ	Capital for Sequestration	0
Other	Other Industries	0.0642
Total		**1**

The cost shares for the cement with CCS technologies are calculated using the information from Table A3. Table 5 shows the resulting cost shares of the CCC, coal-fired PCC, and natural gas-fired PCC. To reflect additional input requirements for CCS, the shares sum up to a value, which is equal to a corresponding markup (rather than to 1 as in the case of industry without CCS).

Table 5. Cost input shares for CCC, coal-fired PCC, and natural gas-fired PCC.

	EINT (Reference Plant)	**CCC**	**Hegerland Coal-fired PCC**	**Hegerland Natural Gas-fired PCC**
EINT	0.3052	0.3052	0.3052	0.3052
SERV	0.1413	0.1413	0.1413	0.1413
TRAN	0.043	0.043	0.043	0.043
COAL	0.0006	0.0004	0.0908	0.0006
ROIL	0.0227	0.0227	0.0227	0.0227
GAS	0.009	0.009	0.009	0.1462
ELEC	0.0467	0.1279	0.0598	0.0598
Labor	0.2475	0.2475	0.2475	0.2475
Capital	0.1197	0.1197	0.1197	0.1197
LSEQ	0	0.0016	0.1166	0.1156
KSEQ	0	0.1605	0.7166	0.5882
Other	0.0642	0.0642	0.0642	0.0642
Total	**1.00**	**1.24**	**1.936**	**1.854**

The production of EINT depends on the relative costs of inputs and the value of EINT goods in the marketplace. Because a cement plant with CCS produces the exact same good as a regular cement plant, in the model, cement with CCS is modeled as an alternative technology to a regular cement plant, producing the same unit of cement with a larger share of input costs and with fewer emissions. The increased amount of fuel use for a cement with CCS plant is included in the additional costs, in addition to capital and labor required for the CCS equipment and transportation and storage of the CO_2.

In order to account for regional variations in the costs of capital, a capital scalar was used based on the IEA data on the capital costs of electricity-generating technologies [25] and capital costs in the GTAP database [23]. The results are provided in Table 6**.** For example, USA has a capital scaling factor of 1.10. This indicates that the cost of capital in the United States is 10% greater than the global median cost of capital provided by the IEA. Mexico, on the other hand, has a capital scaling factor of 0.44, which indicates the costs of capital in Mexico are 56% lower than the global median costs of capital. The capital scaling factors in the Middle East, Indonesia, and Russia were much lower than 1.0, however, so they were adjusted to match the capital scaling factors in China, while the capital scaling factor in Brazil was significantly higher than 1.0 and was adjusted to match the capital scaling factor in Central and South America. In order to account for variations in fuel prices, GTAP data on fuel costs by region were used, as reported in Table 6.

Table 6. Regional variations in prices of electricity, coal, and natural gas, and regional variations in capital.

Region	**Electricity $/MWh**	**Coal $/tonne**	**Gas $/Sm^3**	**Capital Scalar**
Africa (AFR)	64.24	41.08	0.14	0.58
Australia-New Zealand (ANZ)	100.98	77.41	0.18	1.21
Asia Pacific (ASI)	77.57	76.33	0.21	0.42
Brazil (BRA)	105.96	92.81	0.13	1.09
Canada (CAN)	72.54	64.43	0.17	1.44
China (CHN)	50.54	49.11	0.23	0.33
Europe (EUR)	139.09	84.94	0.24	1.42
Indonesia (IDZ)	72.67	55.55	0.15	0.33
India (IND)	89.14	43.27	0.20	0.79
Japan (JPN)	146.47	85.99	0.23	1.23
Korea (KOR)	80.23	78.46	0.27	0.62
Latin America (LAM)	89.88	79.37	0.06	1.09
Middle East (MES)	88.77	79.03	0.11	0.33
Mexico (MEX)	95.70	73.34	0.19	0.44
Rest of Asia (REA)	105.95	70.12	0.17	0.87
Eastern Europe and Central Asia (ROE)	91.74	80.24	0.20	0.67
Russia (RUS)	31.89	51.68	0.14	0.33
United States (USA)	89.70	65.69	0.13	1.10

The regional variations in capital and fuel prices affect the levelized cost of production for the various cement plants. For example, depending on the capital scalar factor and the fuel prices, the estimated levelized cost of production for a reference cement plant using the IEA values varies between $43 and $84 per tonne of cement produced. In addition to the different costs of production, the distribution of costs between capital, O&M, and fuel also vary significantly by region. For example, in the European region, capital costs make up 41% of the total costs, while capital costs make up 15% of costs in the Middle East region.

5. Scenarios and Results

We consider the following scenarios to assess a potential development of industrial CCS in the 21st century. First, we develop a Reference case without any climate-related targets. Next, we consider GHG emission constraints in the 2C policy scenario, which is consistent with limiting average global surface temperature below 2°C [26]. The

2C scenario is evaluated in four different configurations regarding CCS availability for the EINT sector of the EPPA model: 1) without industrial CCS; 2) with CCC; 3) with coal-fired PCC; and 4) with natural gas-fired PCC.

Figure 5 shows the index (i.e., relative change to the level in 2010; 2010 = 1) for global production of energy-intensive industries in these five settings. In the Reference scenario the output (in value terms measured in 2010 US dollars) grows about 8 times between 2010 and 2100. All settings of the 2C scenario result in a reduced global output driven by higher input prices and reduced overall economic activity. In the setting when industrial CCS is not available, there is no viable options for emissions reduction other than energy efficiency improvement, fuel switching, electrification, and reduction in production. In this setting global EINT output peaks in 2075 at approximately 3.5 times the 2010 production and then declines to about 1.6 level.

One can look at PCC as current CCS technology and CCC as advanced CCS technology. When CCC is available, in a 2C scenario global production in 2100 is about 6.5 times the 2010 production, which is lower than in the reference case, but significantly higher than in the policy case without a CCS option. Both coal-fired PCC and natural gas-fired PCC end up with about 4 times increase in the global 2100 output relative to 2010. The timing when CCS deployed also differs: CCC option expands after 2040, while both PCC options expand after 2060.

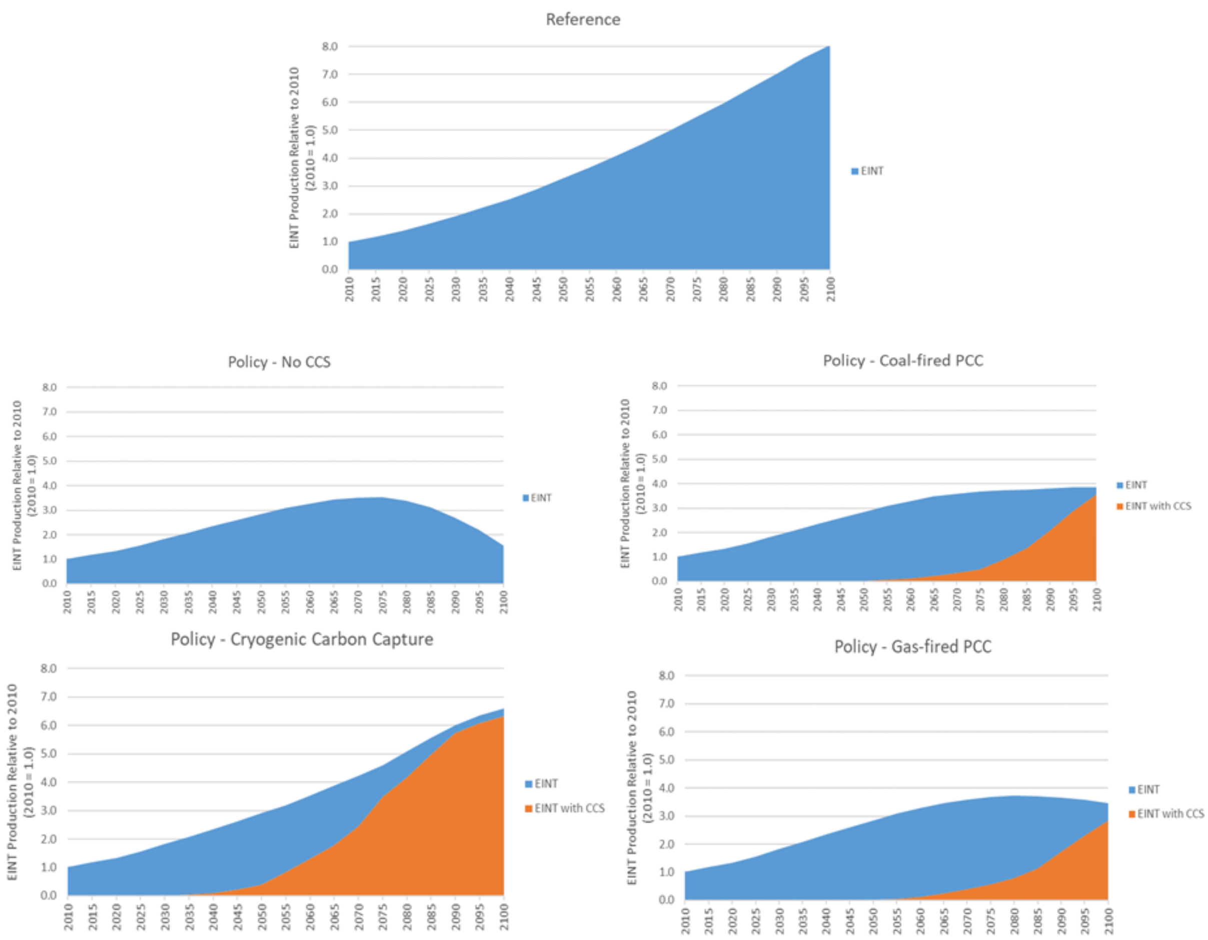

Figure 5. Index of global production of energy-intensive industries in different scenarios.

Global GDP costs of reaching the 2°C target differ dramatically with availability of industrial CCS. Figure 6 presents the results for a change in global GDP relative to the least cost CCS option: CCC. No availability of industrial CCS increases the cost of achieving the 2°C target by about 70%, while more expensive CCS options (coal-fired PCC and gas-fired PCC) result in 25-30% increases relative to CCC.

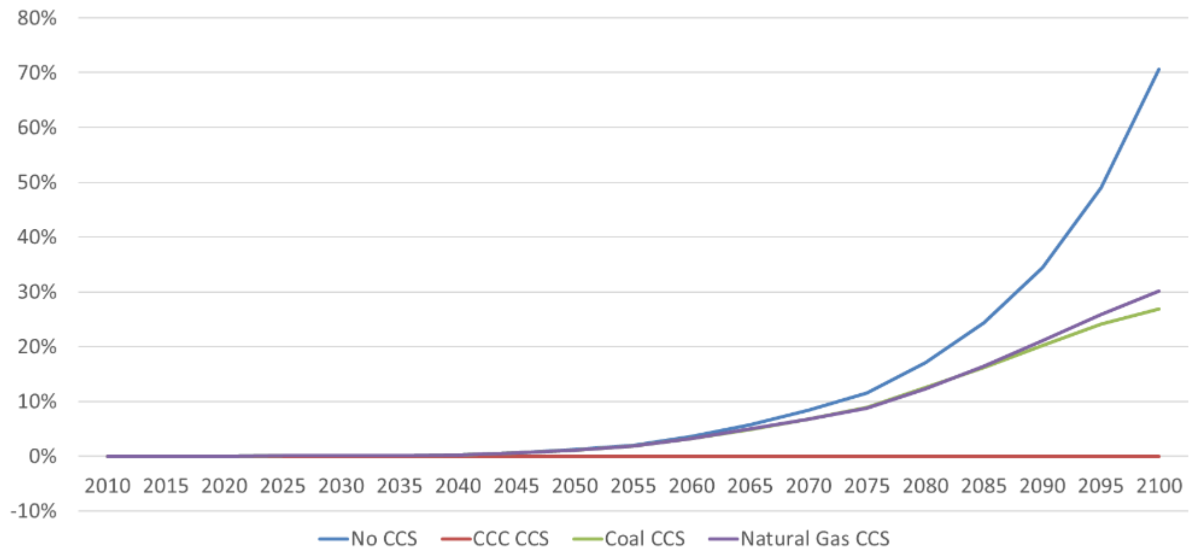

Figure 6. Percent increase in cost of meeting the 2°C target relative to the CCC option.

The GDP costs of meeting the 2°C target are driven by the need for a substantial reduction in emissions. Figure 7 provides the global CO_2 emission profiles by sector (see Table 3 for sectoral description) for three cases: (1) reference case, (2) the 2C scenario without industrial CCS, and (3) the 2C scenario with CCC. Without industrial CCS, energy-intensive industries remain the largest source of the remaining global CO_2 in the 2C scenario. Emissions from other economic sectors are almost eliminated, but limits to electrification of the industrial processes with specific heat and feedstock requirements result in substantial CO_2 emissions from the industrial sector. By the end of the century, CO_2 emissions from the industrial sector are about 95% of all remaining emissions in the world economy. When CCC is available, by 2100 emissions from the industrial sector are reduced by 87% relative to 2010 levels and they account for about 40% of all emissions in the world economy in 2100.

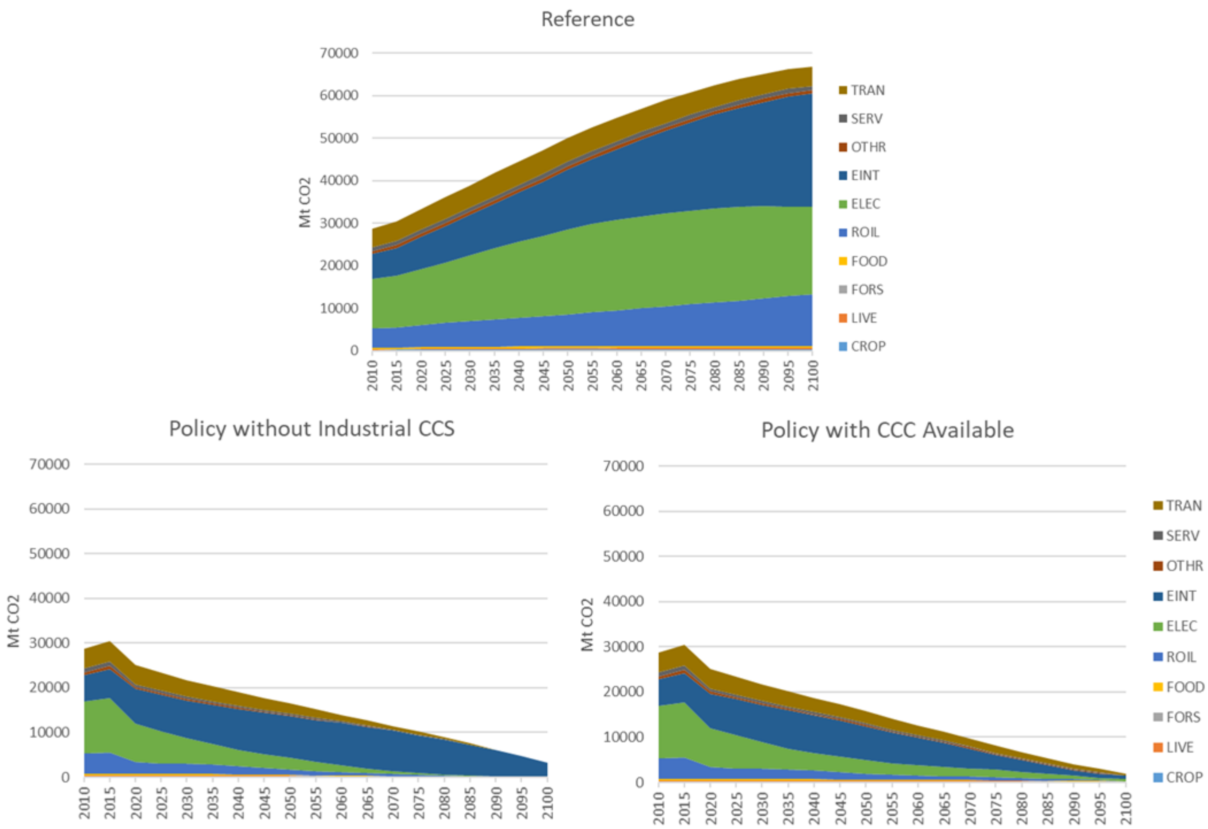

Figure 7. Global CO_2 emissions in the reference and the 2C scenarios when industrial CCS is not available and when CCC is available.

We also explored industrial CCS deployment by region and with different assumptions about CCS costs, global trading in CO_2 emission allowances, and alternative emission reduction targets [8]. Our overall findings are robust in these alternative specifications: industrial CCS plays a major role in reducing the costs of reaching the 2°C targets. In terms of regional results, industrial CCS enters in all regions of the EPPA model in the second half of the century with the largest deployment in China, EU and USA. Coal-fired PCC has especially large deployment in China, while EU and USA see a large use of gas-based PCC. Availability of CCC provides a larger expansion of industrial CCS in all regions.

6. Conclusion

While there are numerous cost assessments for CCS in power generation and substantial experience in implementing power CCS in integrated assessment models (IPCC, 2014), both cost information on industrial CCS and implementation of industrial CCS options in economy-wide modeling are extremely limited. In our paper, we approximate the CCS costs for the cement industry to all industrial CCS applications. In order to compare the costs of cement with CCS technologies, we develop a methodology by standardizing the costs and inputs of CCS units and adding them to the costs and inputs of cement plants. While in this study we apply the cost information to the MIT EPPA model, our methodology can be used in other energy-economic and integrated assessment models. Our analysis of the impact of industrial CCS on total industrial production, global, sectoral and regional emissions, and global welfare shows that the availability of industrial CCS in the 2C policy allowed for a significant increase in the production of energy intensive goods relative to the 2C policy without the availability of industrial CCS. Without CCS, 2100 industrial production became constrained to 1.6 times 2010 levels, while with coal-fired post-combustion capture (PCC), natural gas-fired PCC, and Cryogenic Carbon Capture (CCC) 2100 production was 3.7, 3.5, and 7 times 2010 levels, respectively.

Our illustrative analysis shows the magnitude of the challenge. While our study uses a very dramatic assumption that CCS is the only option available for deep reductions of GHG emissions in industry (efficiency improvements have limited impacts and we do not consider hydrogen options or material substitution), the main message remains strong – industrial CCS has the potential for deep reductions in industrial emissions and it is important to advance the development of the technology.

The availability of industrial CCS significantly decreased the emissions in the industrial sector relative to the policy scenario without industrial CCS, with reductions in 2100 of 14%, 17%, and 45% using coal-fired PCC, natural gas-fired PCC, and CCC, respectively, relative to a 2C policy without industrial CCS. Without industrial CCS, the costs of reaching the 2C emissions target increase by 12% in 2075 and 71% in 2100 relative to the cost of achieving the policy with CCC. Overall, industrial CCS allows for the continued consumption of energy-intensive goods with large reductions in global and sectoral emissions.

This research also analyzed the competitiveness of several types of CCS technologies in a global economic model. Coal-fired PCC, natural gas-fired PCC, and CCC were each separately evaluated in EPPA with their specific costs and inputs. CCC was the most competitive CCS technology, as its costs were only 24% greater than the costs of a reference cement plant in the United States. The lower costs of the CCC process are primarily due to the process not requiring steam from an on-site boiler. Coal-fired PCC also showed promise in several regions, despite being 94% more expensive than a traditional cement plant in USA. Natural gas-fired PCC, while being less expensive than coal-fired PCC, was not as competitive under the 2C scenario, primarily because of its failure to replace traditional plants in China. Should the costs decrease, CCS technology will become increasingly competitive. Overall, industrial CCS allows for the continued consumption of energy-intensive goods with large reductions in global and sectoral emissions. We find that in scenarios with stringent climate policy, CCS in the industry sector is a key mitigation option, and our approach provides a path to projecting the deployment of industrial CCS across industries and regions.

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