Carbon Capture and Storage (CCS) in 2100:

Price Estimate for 'Technological Learning'

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Term Paper

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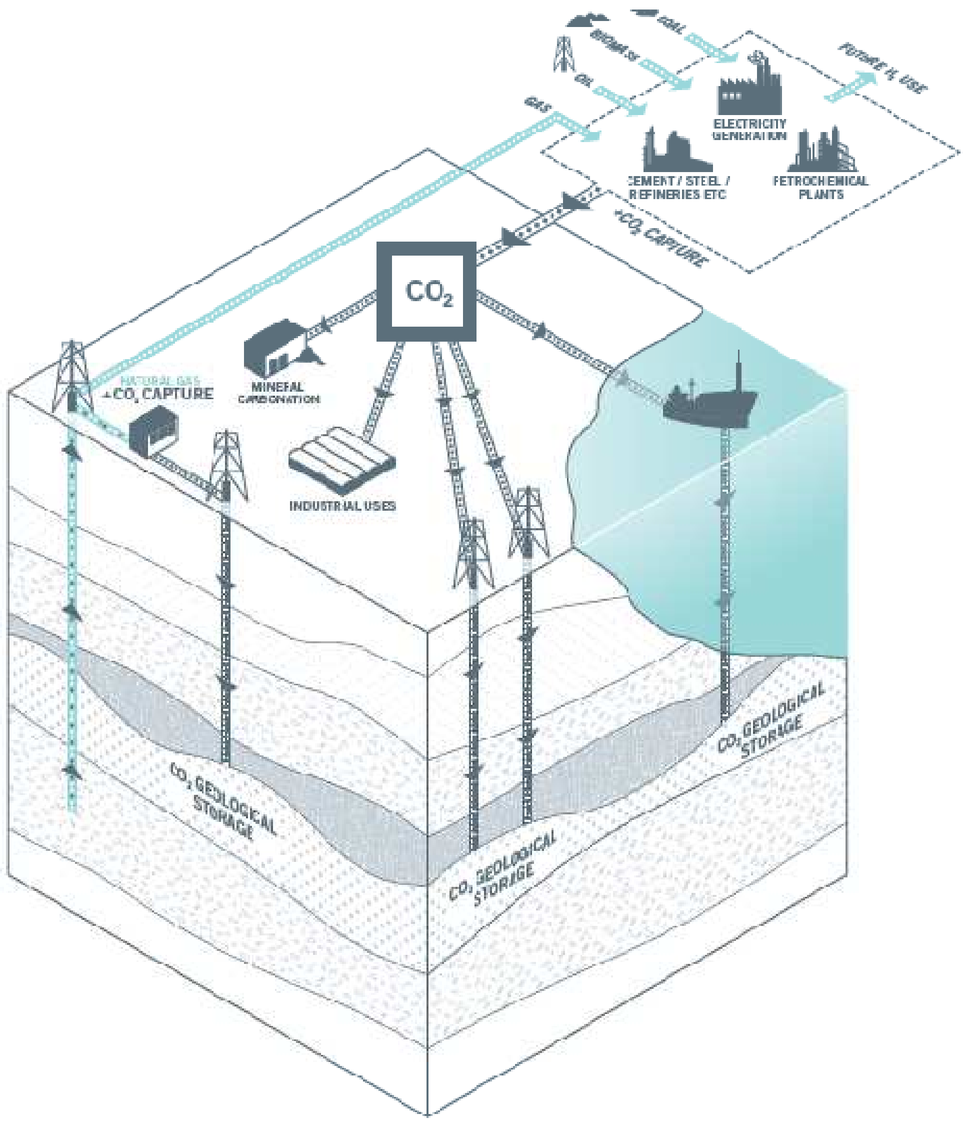


AFTER CO2CRC.

Contents

1. Introduction and Objective

Global climate change is arguably the most challenging environmental problem the world will be facing in coming decades and centuries. To curb the dramatic growth of greenhouse gases and its related consequences, a broad set of CO_2-limiting policies will be needed. The strictness and extent (global or not?) of such policies will play a significant role in decision process regarding future investments in different energy technologies. Whereas couple years ago CO2 capture and storage (CCS) was expected to play a significant role among other available options (see Figure 1), the rate of its deployment is nowadays seen a bit more skeptical.

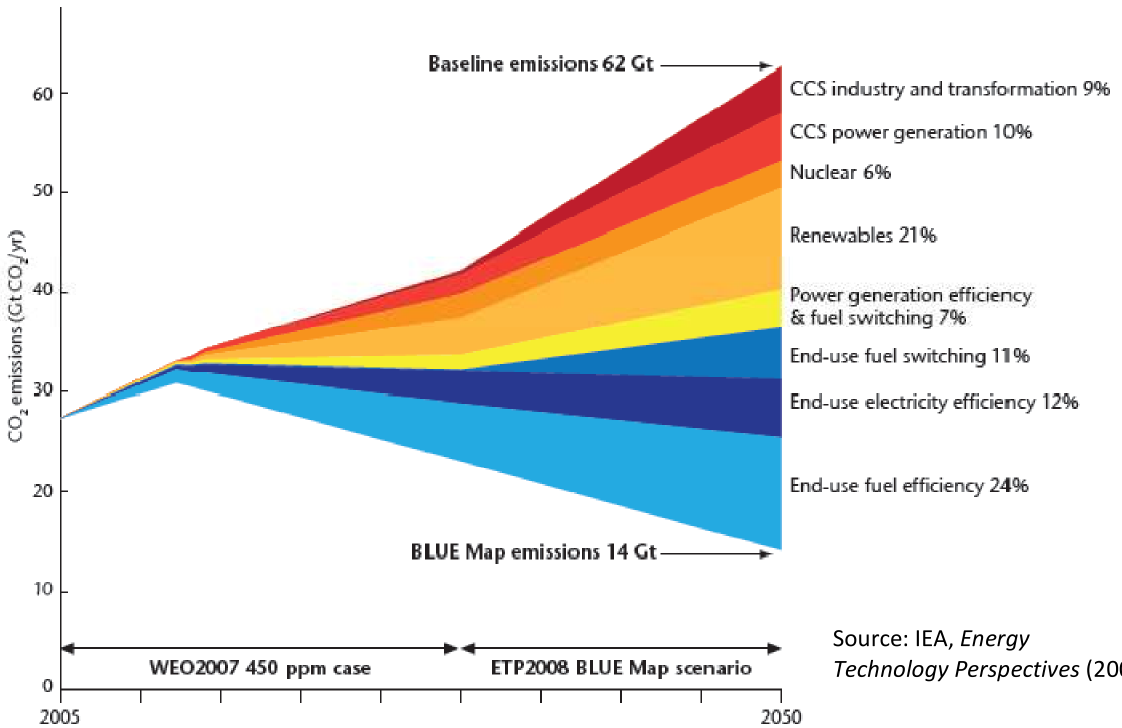
One of the key aspects of future deployment of CCS technologies are the expected future costs, allowing for more precise financial planning. The main purpose of this paper is to provide a reasonable estimate of these costs and discuss on their, and other, effects on future growth of CCS.

One of the available methods for assessing the future costs is so called 'technological learning' which will be further focus of this paper. However, to make the reader familiar with the topic, the Carbon capture and storage (CCS) technologies will be first introduced, followed by the theoretical concept of 'technological learning'. Only thereafter the method of 'Technological learning' will be used to build up a case, through the help of which following four fundamental tasks will be addressed:

- **Calculate and critically comment on the difference between future costs obtained through the use of two different learning rates.**
- **Assess the possible magnitude of specific cost reductions in 2100 from scaling up a post-combustion CCS technology.**
- **Comment on strengths and weaknesses of technological learning methodology.**
- **Comment on possible opportunities and barriers of progressive expansion of CCS technologies and discuss the urgency of related policy actions.**

The paper is organized in a way that enough scientifically relevant data are collected in order to allow for a critical evaluation of these tasks in the very last section.

Figure 1: CCS delivers one-fifth of the lowest-cost GHG reduction solution in 2050

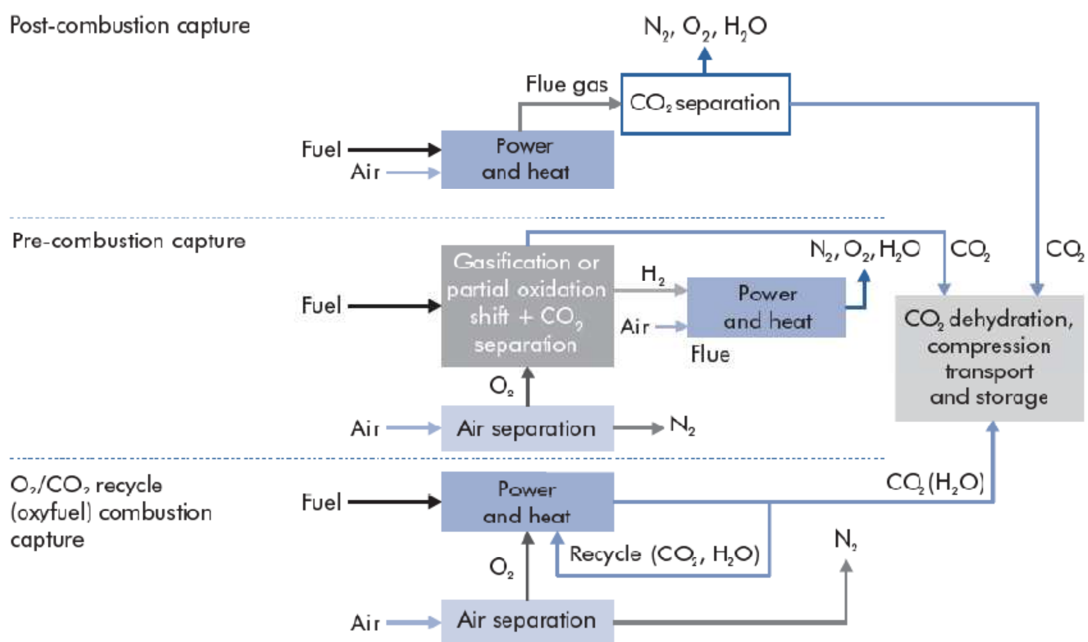


Source: IEA, *Energy Technology Perspectives* (2008).

2. Carbon Capture and Storage (CCS): A Short Overview

Carbon capture and storage (CCS) is a process consisting of the separation, transport and long-term isolation of carbon dioxide (CO2) from the atmosphere. At large point sources such as power stations or hydrogen production plants, carbon dioxide (CO2) is generated as one of the products of fossil fuels combustion. Through the use of rather complex and complicated capture technologies, CO2 can be separated from other byproducts, transported and captured by injection into storage reservoirs such as depleted oil and gas fields, deep saline aquifers or the deep ocean. It should be mentioned that there is always an energy penalty associated with CO2 capture, transport and storage since these processes consume additional energy, causing losses in overall efficiency of power plants or industrial processes.

Figure 2: Carbon Capture Technologies



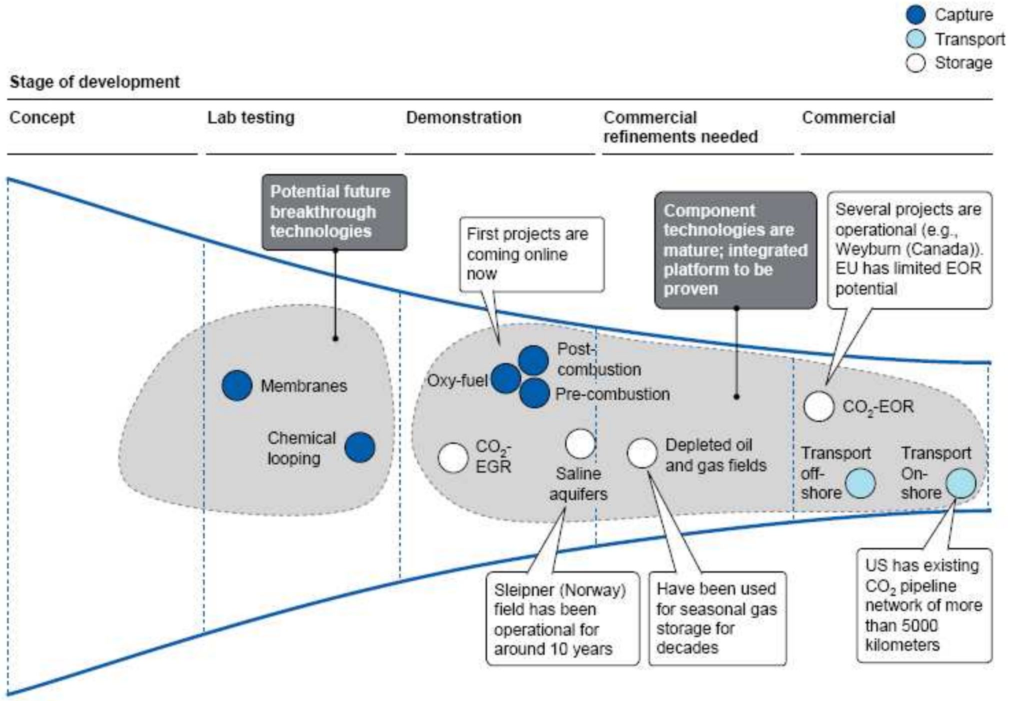
Source: IPCC, 2005.

We distinguish among four fundamental systems for capturing CO2:

- Capture from industrial process streams
- Post combustion capture
- Oxy-fuel combustion capture
- Pre combustion capture

The basic working principles and the current stages of maturity of these technologies are depicted in Figures 2 and 3, respectively. In section 3, the analysis of technological learning will be presented through the use of post combustion coal fired CCS power plant. In order to get the reader familiar with this technology, I will explain its working principle in next paragraph.

Figure 3: Stage of CCS Component Technologies

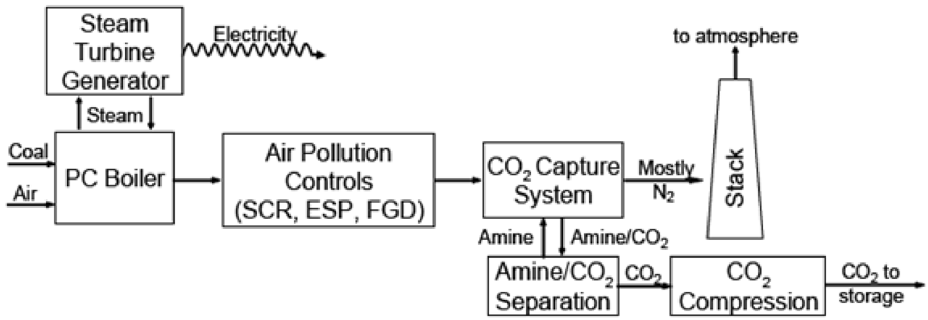


2.1. CO2 Capture by post-combustion

Post combustion systems separate CO2 from the flue gases produced by the combustion of a coal or natural gas with air. In commercial applications, an organic solvents, mostly monoethanolamine (MEA,) are used to capture a relatively small fraction of CO2 (3–15% of volumetric flow).

There are two main post-combustion power plant types: Natural gas combined cycle (NGCC) and ***pulverized coal plant (PC)***. The latter is used in section 4 as a reference plant for the analysis of technological learning and it consists of seven main parts as indicated in Figure 4. The capture process typically removes about 90% of the CO2 produced at the power plant. Once separated, the concentrated CO2 stream is compressed for transport and storage.

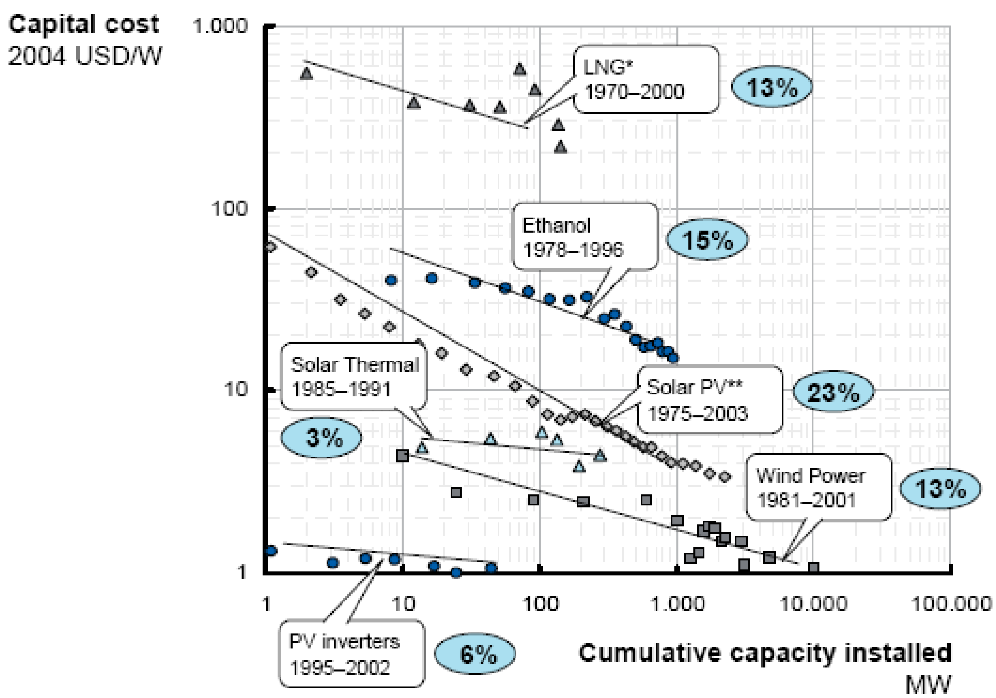
Figure 4: Pulerized coal (PC) post-combustion powerplant



3. Technological Learning

The concept of 'technological learning' first emerged more than 60 years ago, when a quantitative model describing time and cost savings in rapidly growing aircraft manufacture was introduced by Wright (1936). Since then, the method of 'learning by doing', when manufacturers improve their knowhow, and 'learning by using', when customers become familiar with the technology, was an object of intensive research. Its historical development proved that it was applicable for a wide range of manufacturing activities, including variety of energy technologies (Nakicenovic et al. 1998; McDonald and Schrattenholzer 2001). Figure 5 shows an example of learning curves for various renewable energy technologies. Methodology of 'technological learning' has also been increasingly incorporated in various large scale energy-economic models dealing with an assessment of long term energy strategies and related environmental performance.

Figure 5: Technological learning of selected energy-related technologies



The experience curve can be generally expressed as:

This equation represents an empirical function where Y denotes the specific investment cost of the x^{th} unit, a is the cost of the first unit, and b (b > 0) is a parametric constant. After substituting for the variables, following expression is obtained:

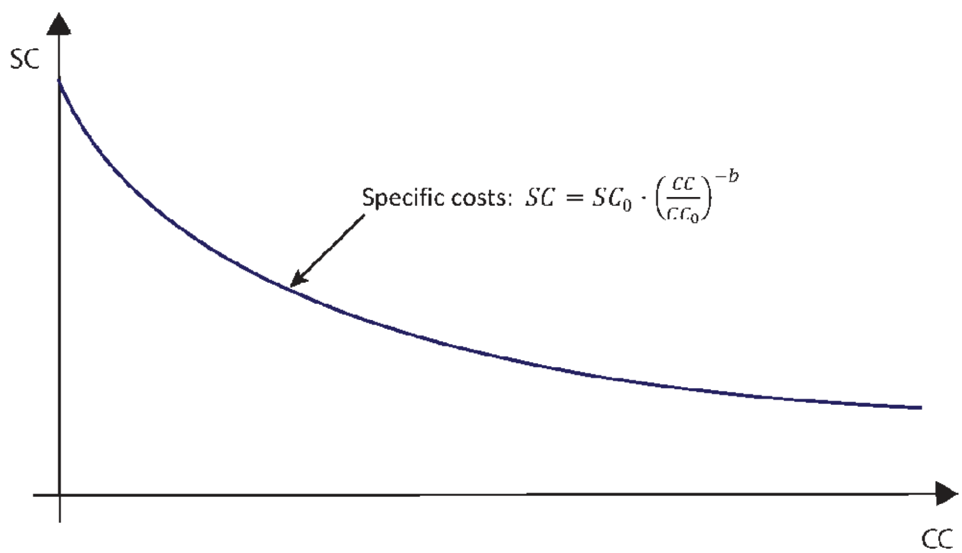
—

where TSC stands for a total specific cost, CC for the cumulative capacity, CC_O for initial capacity, FC for FC floor (base) costs and b expresses the learning index.

Further, I also define so called learning rate (LR) as:

where quantity 2^{-b} is generally defined as *progress ratio (PR),* which implies that each doubling of cumulative capacity results in a cost savings of $(1 - 2^{-b})$. For example, by doubling a capacity of a technology with learning rate of 20%, the initial specific costs are reduced to 80% of their starting value.

Figure 6: Technology learning curve



In my model the Cumulative Capacity (CC) covers all variables contributing to cost reductions (e.g. R&D expenditures) and the floor costs (FC) include all the costs that cannot be reduced by technology learning (e.g. expenditures for planning, installation or energy used for manufacture).

4. Building a Case

As it has already been mentioned, one of the goals of this paper is to calculate the future specific costs (SC) of deployment of CCS technologies with the use of 'technological learning'. To do so, five variables need to be determined. The inputs for these five variables are summarized in table 1, together with short description of how the values were derived and the page number of further reference.

Table 1: Summary of input parameters

	Value		Source	Described on page
Cumulative capacity (CC)	243 GtC	137 GtC	Riahi (2004)	15
Learning rate 1 (lr_1)	12%		Derived from flue gas desulfurization (FGD) systems	11
Learning rate 2 (lr_2)	20%		IEA (2004)	11
Initial capacity (CC_0)	500 ktC		ETH Zurich, Renewable energy I, Lecture materials	
Initial specific costs (SC_0)	168 $\$/tC$		Riahi (2004)	14
Floor costs (FC)	28 $\$/tC$		Riahi (2004)	14

4.1. Estimating Learning Rate – Different Perspectives

In order to set a reasonable estimate of a learning rate, which will be later used for a calculation of future cost of CCS, I consulted frequently cited research papers dealing with this topic (Rubin et al. 2004; Yeh et al. 2005; Colpier and Cornland 2002; Rubin et al. 2006). Authors of these research studies used two-step approach to determine learning rate values. Firstly, the significance of historical cost reductions for particular energy process technology is assessed. Findings obtained are then used to estimate achievable cost reductions for future scaling up of the cumulative capacity. Some of these findings are summarized in Table 2 and their detailed description is to be found in Rubin et al. (2006).

Table 2: Learning rates of various energy technologies

Technology	Learning Rate*		Cost Increase During Early Commercialisation
	Capital Cost	O&M cost	
Flue gas desulfurisation (FGD)	0.11	0.22	Yes
Selective catalytic reduction (SCR)	0.12	0.13	Yes
Gas turbine combined cycle	0.10	0.06	Yes
Pulverised coal boilers	0.05	0.07 0.30	n/a
LNG production	0.14	0.12	Yes
Oxygen production	0.10	0.05	n/a
Hydrogen production (SMR)	0.27	0.27	n/a

Among all the technologies mentioned in Table 2, it is the **flue gas desulfurization (FGD) systems,** which the future deployment of CCS technology is often referred to. These sulfur dioxide (SO2) emissions reducing technologies (commonly known as SO2 ''scrubbers'') have being installed since more than 30 years at coal-fired power plants all around the world and a historical development of their investment costs and cumulative capacities are well understood. Thus, the future deployment of CCS technology can generally be estimated based on historical performance of FGD systems. All studies on this topic estimate the learning rate of FGD systems between 11 and 13%. For my calculations, I take a middle value and set . The historical growth in installed capacity of FGD is shown in Figure 6.

In my analyses, I use two different learning rates, results of which will be then compared with each other. To set a value of the second learning rate, I refer to two scientific studies. McDonald and Schrattenholzer (2001) found that the cost for each doubling of cumulative installed capacity of energy-related technologies was reduced by 0–34% (with a median rate of 14%). Another recent and extensive study (IEA 2004) suggested a learning rate of 20% as a general cost reduction factor of engineered processes. I use this value as my second learning rate and set: .

To conclude this section, I would like to emphasize that my selection of the learning rates is based on scientific papers published more than five years ago. Since then, there have been increasing indications of move of industry away from long-term investments in CCS towards renewable energies. In the light of this fact, the learning rates I have been using can already be slightly overestimated.

Figure 6: Historical growth in installed capacity of desulfurization systems (FGD)

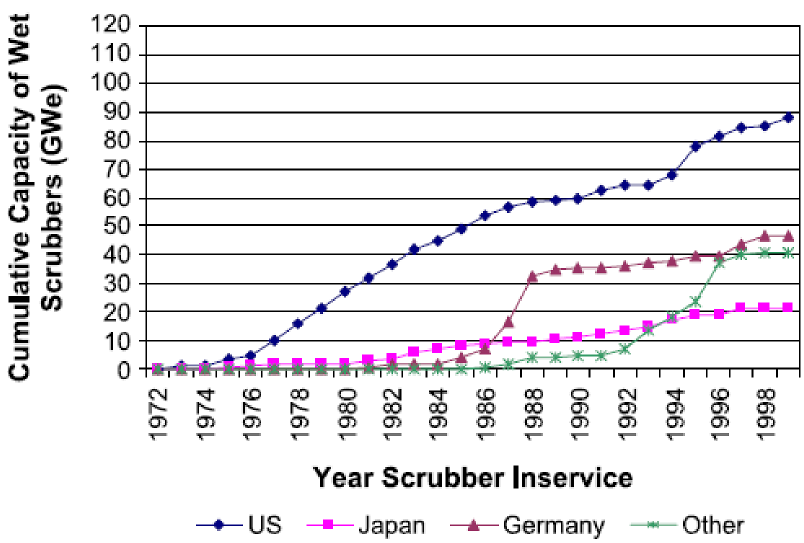
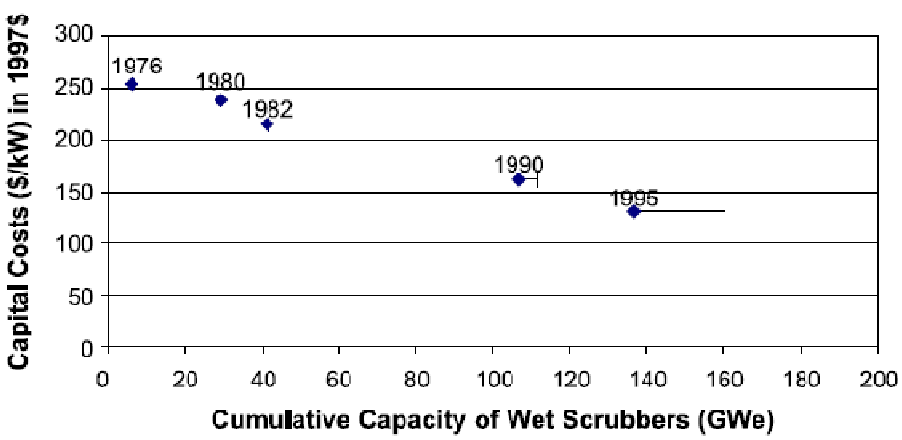
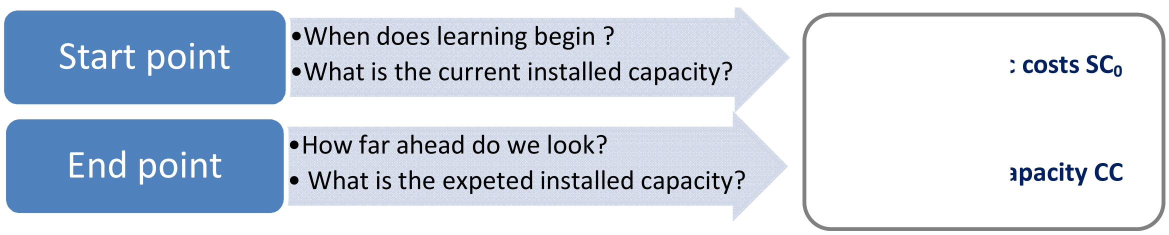


Figure 7: 'technological learning' in desulfurization systems (FGD)



4.2. Current Specific Costs (SC_0)

After rather general task of determining the learning rates was achieved, the choice of remaining two parameters (Current specific costs SC_0 and Expected cumulative capacities CC) is far more complex and plays a crucial role in obtaining representative results, i.e. values of future specific costs. In following scheme, I pose four significant questions which need to be thoroughly considered, before the parameters on right will be derived.



Estimation of current specific costs of highly complicated technology, where only individual commercial projects at a sufficiently large scale exist, is a challenge indeed.

To obtain a value of Current specific costs SC_0 for my model, I refer to Table 3 published in Riahi (2004). Firstly, it provides cost break-down of building up a new standard coal power plant without CCT (Carbon capture technology), secondly, it estimates the parameters’ values for erection of corresponding plant equipped with carbon capture. It is assumed that CO2 is captured from flue gas by currently available chemical absorption systems, which means, by mean of post combustion technology (as it was described in detail in paragraph 2.1).

Table 3: Reference for estimating current specific costs (SC0)

	Unit	Coal	
		Reference technology	
		Standard coal power plant	Incl. CCT
Investment costs	$/kW	1000	1749
Fixed O&M costs	$/kW	27	20.7
Variable O&M costs	$/kW year	n.a.	188.7
Efficiency	%	40	30.4
Plant life	years	30	30
Plant factor	%	65	65
Fuel cost	$/GJ	1.75	1.75
Levelized investment costs	mills/kW h	11.8	20.6
Levelized O&M costs	mills/kW h	4.8	30.4
Levelized fuel costs	mills/kW h	15.7	20.7
Electricity generation costs	mills/kW h	32.3	71.8
Carbon emissions	g C/kW h	232	30
Total carbon reduction costs	$/t C	–	196

At the bottom of table 3, the desired reference value for calculation of Current specific costs SC_0 is to be found and reads 196 US$/tC. As mentioned in Section 3, there is always some portion of this reference cost that does not participate in the 'technological learning' ; the so called 'Floor cost' (FC). In terms of CCT, only technologies related to CO_2 capturing are generally considered to undergo the learning process. As a rule of thumb, the capturing of CO2 accounts for about three- fourths of the total cost of a carbon capture, transport, and storage system (IEA 2004). This portion can, however, differ quite significantly with the difference in distance needed to transport CO_2 between power plant and the storage site.

Floor cost (FC) for my model was determined by consulting Riahi (2004) where he states that "the cost for CO2 *transportation is based on estimates from the IEA (1999), assuming originally a distance of 500 km at US$45/t C. Here, half the distance and an economy of scale factor of 2/3, which results in US$28/t C of transport plus disposal cost, is assumed. "And* so initial costs for my analysis reads:

$$FC = 28 \frac{US\,\$}{tC}$$

$$SC_0 = (196 - 28) \frac{US\,\$}{tC} = 168 \frac{US\,\$}{tC}$$

4.3. Cumulative Capacity

Estimating a Future Cumulative capacity (CC) of, in these days still immature CCS technologies, is a very challenging task. It generally involves significant amount of scientific knowledge and experience, since very complex Integrated Assessment Models (IAMs) are to be used. These modeling tools integrate the simulation of climate change dynamics with the modeling of energy and economic systems using a set of various input parameters. As an output large numbers of possible futures organized in so called ‘baseline scenarios’ are obtained.

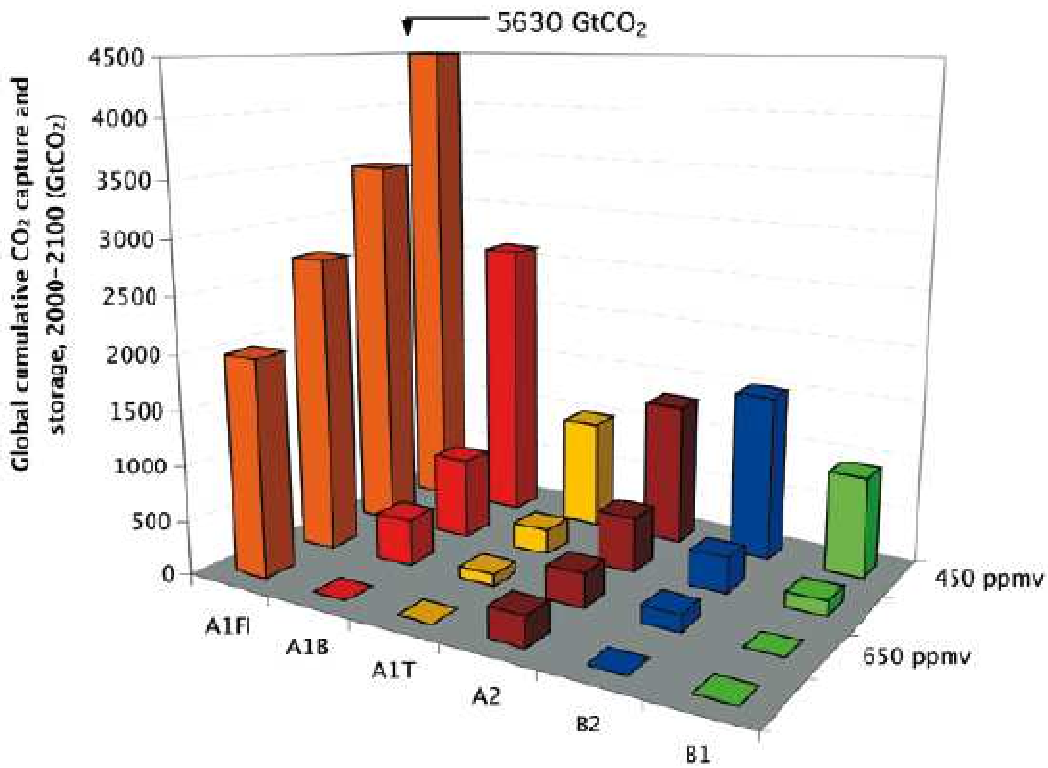
By use of these methodologies a famous illustrative scenario groups A1FI, A1B, A1T, A2, B1, B2 were acquired (SRES, 2000). Each of these groups represents different combinations of technological and socio-economic developments which also derives different implications for the potential use of CCT. Such potential depends primarily on the carbon intensity of the baseline scenario and the stringency of the assumed climate stabilization target. From this description it becomes clear that an estimate of Future Cumulative capacity (CC) heavily depends on boundary conditions under which it is to be estimated. For purpose of my analysis I make use of two Cumulative capacities which were derived under two different SRESS scenarios, namely A2 and B2, both assuming a stabilization target of 550 ppmv (Riahi 2004). To provide a reader with an idea how much the cumulative capacities differ when computed under different scenario and stabilization target settings I refer to figure 8 (IPCC 2005).

Cumulative carbon sequestration (Gt C) 1990–2100:

Scenario I: $A2 - 550t \rightarrow \quad CC = 243\ GtC$

Scenario II: $B2 - 550t \rightarrow \quad CC = 137\ GtC$

Figure 8: Global cumulative CO2 storage (2000–2100) in the IPCC mitigation scenarios



Source: IPCC, 2005

4.4. Calculations

Learning rate lr_1=12%

Learning rate lr_2= 20%

Figure 5: Overview of input parametries for two studied scenarios

		Scenario I			Scenario II	
Cumulative capacity (CC)		243 GtC			137 GtC	
Learning index (b_1, b_2)		0.184	0.322		0.184	0.322
Initial capacity (CC_0)		500 ktC			500 ktC	
Initial specific costs (SC_0)		168 $\$/tC$			168 $\$/tC$	
Floor costs (FC)		28 $\$/tC$			28 $\$/tC$	

Total Specific Costs (TSC):

$$\mathrm{TSC} = \mathrm{SC_0}\left(\frac{\mathrm{CC}}{\mathrm{C_0}}\right)^{-\mathrm{b}} + \mathrm{FC}$$

Scenario I:

$$TSC\,{}^{A2}_{0.184} = 168\left[\frac{US\$}{tC}\right].\left(\frac{243\;10^6\left[\frac{ktC}{GtC}\right]}{500[ktC]}\right)^{-0{,}184} + 28\left[\frac{US\$}{tC}\right] = 43.10\left[\frac{US\$}{tC}\right]$$

$$TSC\,{}^{A2}_{0.322} = 168\left[\frac{US\$}{tC}\right].\left(\frac{243\;10^6\left[\frac{ktC}{GtC}\right]}{500[ktC]}\right)^{-0{,}322} + 28\left[\frac{US\$}{tC}\right] = 30.48\left[\frac{US\$}{tC}\right]$$

Scenario II:

$$TSC\,{}^{B2}_{0.184} = 168\left[\frac{US\$}{tC}\right].\left(\frac{137\;10^6\left[\frac{ktC}{GtC}\right]}{500[ktC]}\right)^{-0{,}184} + 28\left[\frac{US\$}{tC}\right] = 44.78\left[\frac{US\$}{tC}\right]$$

$$TSC\,{}^{B2}_{0.322} = 168\left[\frac{US\$}{tC}\right].\left(\frac{137\;10^6\left[\frac{ktC}{GtC}\right]}{500[ktC]}\right)^{-0{,}322} + 28\left[\frac{US\$}{tC}\right] = 30.98\left[\frac{US\$}{tC}\right]$$

Factor and percentage of Specific Cost reduction:

Scenario I:

$$f\,{}^{A2}_{0.184} = \frac{196}{43.10}\left[\frac{US\$}{tC}\right] = 4.55 \qquad f\,{}^{A2}_{0.322} = \frac{196}{30.48}\left[\frac{US\$}{tC}\right] = 6.43$$

$$p\,{}^{A2}_{0.184} = 1 - \frac{43.10}{196}\left[\frac{US\$}{tC}\right] = 0.78 = 78\% \qquad p\,{}^{A2}_{0.322} = 1 - \frac{30.48}{196}\left[\frac{US\$}{tC}\right] = 0{,}84 = 84.4\%$$

Scenario II:

$$f\,{}^{B2}_{0.184} = \frac{196}{44.78}\left[\frac{US\$}{tC}\right] = 4.38 \qquad f\,{}^{B2}_{0.322} = \frac{196}{30.98}\left[\frac{US\$}{tC}\right] = 6.33$$

$$p\,{}^{A2}_{0.184} = 1 - \frac{44.78}{196}\left[\frac{US\$}{tC}\right] = 0.772 = 77.2\% \qquad p\,{}^{A2}_{0.322} = 1 - \frac{30.98}{196}\left[\frac{US\$}{tC}\right] = 0.842 = 84.2\%$$

4.5. Results obtained

Table I: Total Specific Costs

US$/tC	**Scenario I**	**Scenario II**
b_1=0,184	43.10	44.78
b_2= 0,322	30.48	30.98

Table II: Factor of Specific Cost reduction

	Scenario I	**Scenario II**
b_1=0,184	4.55	4.38
b_2= 0,322	6.43	6.33

Table III: Percentage of Specific Cost reduction

%	**Scenario I**	**Scenario II**
b_1=0,184	78%	77,2%
b_2= 0,322	84.4%	84.2%

Table IV: Percentage difference b_2-b_1

b_2-b_1	**Scenario I**	**Scenario II**
b_1=0,184	+6.4%	+7%
b_2= 0,322		

5. Discussion on Results and Method used

Calculate and critically comment on the difference between future costs obtained through the use of two different learning rates.

The impact of learning rate's (LR) value estimate on final results is observable in table I-IV. It is evident that the higher learning rate leads to the lower costs at the end point. I conclude that the impact of learning rate on finally obtained results is of a rather intermediate significance.

Assess the possible magnitude of specific cost reductions in 2100 from scaling up a post- combustion CCS technology.

The outcome of scaling up the studied CCT as far ahead as 2100 is shown in tables I-III. It is to be emphasized that there is a rapid drop of future specific costs and a reduction of factor of 4 – 6 could be theoretically achieved. Expressed in relative numbers, prices could drop by as much as 78 – 84% compared to the starting point. Such findings are comparable with Riahi (2004), where the same boundary conditions were used.

It has also been proved that the more ambitious long-term carbon emission reduction potential of 243 GtC ('Scenario I') would result in lower future costs compared to those obtained for potential of 173 GtC ('Scenario II'). Nevertheless, this difference between scenarios I and II is suspiciously low and for the lack of data, it could not unfortunately be compared with studies under similar boundary conditions.

Here, it should be mentioned again that results obtained for 'technological learning' strictly depend on the boundary conditions at the start and end point. For my calculations, the future cumulative capacity (CC) was derived under two SRESS scenarios, A2 and B2 (IPCC), assuming a stabilization target of 550 ppm. Should the end point be identified by different SRESS scenarios or stabilization targets, very different results could be obtained.

Comment on strengths and weaknesses of 'technological learning' methodology.

Learning curves are increasingly used in large scale energy-economic models and various environmental scientific studies. The methodology I used, is rather straightforward calculation assuming that all inputs are either "reasonably" estimated (learning rate) or available as outcomes of simulations carried out with the help of complex economic modeling tools.

Generally, more precised results of the concept of "learning by doing and using" would be achieved by dividing the system, e.g. post-combustion power plant, into its major subsystems. After such a decomposition, the method of 'technological learning' could be applied to all these subsystems separately. This approach would take into account differences in the technological maturity of each subsystem and would allow them to develop at different rates. Moreover, the contribution of each component to the total capital and O&M costs could be addressed. On the contrary, neither this approach is completely accurate, since it does not take into account variation in cost resulting from the growth of system's complexity. Herzog (1999) provides further details on this.

Comment on possible opportunities and barriers of progressive expansion of CCS technologies and discuss the urgency of related policy actions.

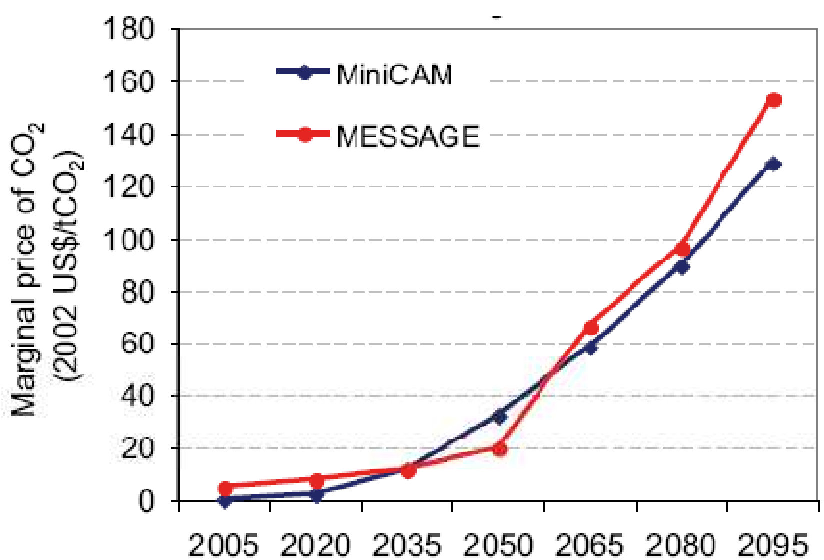
Regarding opportunities and barriers, **I identify the marginal value of CO2 emission reduction permits as a crucial variable for scaling up and further deployment of CCS technologies.**

The higher marginal carbon values, the faster and more extensive diffusion of CCT into the energy markets can be expected.

Furthermore, the **strictness and extent of CO_2-related policies will be of a significant importance**. Only an explicit, and possibly world-wide, policy or regulatory regime significantly limiting the amount of released greenhouse gas emissions would drive the expansion of CCT ahead. Nevertheless, putting such policies into effect seems to take much more time than it had been expected even couple years ago. Despite an enormous effort of number of scientists, politicians or general public, invested in reaching a global CO_2-limiting policy, only a qualified success was achieved in last 20 years. Moreover, the fiasco of 'Copenhagen' (2009 United Nations Climate Change Conference) further emphasized the failure to find a global agreement to a post-Kyoto regime. In the light of these facts, it seems very unlikely that CCS technologies would see a rapid growth within next few decades. Such a conclusions is also stressed in various scientific studies (Edmonds *et al*. 2003; Edmonds and Wise 1998; Riahi *et al*. 2003) stating, for instance, that "*while there is significant penetration of CCS systems over the decades to come, the majority of CCS deployment will occur in the second half of this century."* (Riahi et al. 2003)

Such a time estimate of CCS deployment can also be derived numerically, for example by statement, that "***most energy and economic modeling done to date suggests that CCS systems begin to deploy at a significant level when carbon dioxide prices begin to reach approximately 25–30 US$/tCO2 (90–110 US$/tC)"*** (IEA 2004; Johnson and Keith 2004; Wise and Dooley 2004; McFarland *et al*. 2004). Referring to Figure 9 one can observe that an above-mentioned threshold value of 30 US$/tCO2 is unlikely to be reached before 2040.

Figure 9: Projections of marginal CO_2 prices 2000 - 2100



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