Incorporating Carbon Capture and Geological Storage in an Integrated Assessment Model

Master's Thesis

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Abstract

Capture and storage of carbon emissions from large point sources (LPS) is assumed to play a key role in mitigation strategies to reduce carbon emissions to the atmosphere in the near future. This Master's thesis aims to contribute to the analysis of the potential of carbon capture and geological storage (CCS) regarding global and regional welfare, carbon energy use and temperature increase in the period 2005-2115. CCS has been incorporated as a carbon mitigation option in the "Regional Dynamic Integrated Model of Climate and the Economy" (RICE). In addition, average CCS costs for the regions included in the model have been calculated based on LPS data provided by the International Energy Agency (IEA). First, given the assumptions of the RICE framework, the results show that global and regional welfare is not increased due to the implementation of CCS. Second, carbon energy use is not considerably affected by the possibility to avoid the corresponding carbon emissions by the implementation of CCS. Third, neither optimal levels of CCS found in endogenous CCS scenarios nor exogenously determined levels of emission avoidance are sufficient to substantially mitigate the temperature increase in the period 2005-2115. Furthermore, the analysis of the sensitivity of the RICE model shows that the discounting of future welfare and the estimation of expected levels of market damage due to climate change are the most important issues regarding the economic analysis of CCS. However, whether CCS will deploy at large-scale might mainly depend on its inclusion in a legally-binding post-Kyoto agreement.

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Abbreviations

C	Carbon
°C	Degree Celsius
CCS	Carbon Capture and geological Storage
CDIAC	Carbon Dioxide Information Analysis Centre
CFC	Chloro Fluoro Carbon
CH_4	Methane
CO_2	Carbon Dioxide
DICE	Dynamic Integrated model of Climate and the Economy
ECBM	Enhanced Coalbed Methane recovery
EOR	Enhanced Oil Recovery
GDP	Gross Domestic Product
GHG	Greenhouse Gases
Gt	Gigaton
H_2	Hydrogen oxide
IAM	Integrated Assessment Model
IEA	International Energy Agency
IEA GHG	International Energy Agency Greenhouse Gas R&D Programme
IGCC	Integrated coal Gasification Combined-Cycle
IPCC	Intergovernmental Panel on Climate Change
IMO	International Maritime Organisation
Kt	Kiloton
LPG	Liquefied Petroleum Gas
LPS	Large Point Source of CO_2 emissions
MEA	Monoethanolamin
Mt	Megaton

NGCC	Natural Gas Combined-Cycle
N_2O	Nitrous Oxide
OECD	Organisation for Economic Co-Operation and Development
OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic
O_3	Ozone
PC	Pulverised Coal
RICE	Regional dynamic Integrated model of Climate and the Economy
TC	Technological Change
UN	United Nations
UNCLOS	United Nations Convention on the Law of the Seas
UNFCCC	United Nations Framework Convention on Climate Change

1 Introduction

Climate change is seen as a serious risk to the environment and the world economy. According to the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC), it is very likely that most of the increase in global mean temperature is due to the observed increase in anthropogenic greenhouse gases in the atmosphere (IPCC, 2007). In this context, the global use of carbon energy must be in the focus of any global policy regarding the mitigation of climate change. Pacala and Socolow (2004) state that the fundamental scientific and technical know-how to solve the carbon and climate problem in the next 50 years today already exists. In this context, carbon dioxide (CO_2) capture and storage (CCS) is seen as one of the major technologies applicable to arrive at lower global carbon emissions to the atmosphere and thus to mitigate climate change. CCS is a potential option to reduce net carbon emissions from large point sources of CO_2 emissions (LPS) such as fossil fuel power plants or large industrial facilities. A CCS system includes three major process steps: (1) separation and capture of CO_2 in flue-gases from power plants or industrial facilities with appropriate technological systems, (2) transport of CO_2 to a storage site located close to the point source and (3), injection of CO_2 in stable geological formations or in the deep ocean[1] (IPCC, 2005). The IPCC published a special report on carbon capture and storage (see IPCC, 2005) and the International Energy Agency (IEA) acting as energy policy advisor for the OECD members focuses on CCS within its greenhouse gas research and development program (see IEA GHG). According to the IPCC (2005), LPS account for around 60% of total global CO_2 emissions and CCS could provide 15% to 55% of a cumulative carbon mitigation effort up to 2100. Furthermore, the IEA proposes to capture and store up to 10 gigatons (Gt) CO_2 per year by the middle of the 21st century (IEA, 2009a).

Since CCS has not yet been implemented on a large scale, there is an urgent need for further research and demonstration projects in order to analyze whether the involved technologies can guarantee economic feasibility and environmental sustainability. To evaluate potential future benefits due to the implementation of CCS it is crucial to deal with cost-benefit analyses. Literature reports a wide range of CCS cost estimates due to variability of source- and site-

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[1] Since only geological storage is close to market maturity (IPCC, 2005), it is the only carbon storage option considered in this Master's thesis. Thus, the abbreviation CCS represents carbon capture and *geological storage* in the following sections and excludes any other storage option.

specific components (see e.g. Al-Juaied and Whitemore, 2009; Dahowski et al., 2009; Dooley et al., 2006 and 2008; IPCC, 2005, Wildenborg et al., 2005). Furthermore, the analysis of expected market damages caused by climate change must satisfy a certain reliability to allow an assessment of costs and benefits of CCS. Therefore, the key question concerning the future deployment of CCS is the expected level of climate damages in terms of costs per ton of carbon emitted to the atmosphere. These costs are known as social or shadow costs of carbon and are subject to an economic analysis of climate change.

1.1 Economics of climate change

From an economic view, global climate change is a problem of the public good. Public goods are defined as *"(…) collective consumption goods ($X_{n+1}, . . ,X_{n+m}$) which all enjoy in common in the sense that each individual's consumption of such a good leads to no subtraction from any other individual's consumption of that good, so that $X_{n+j} = X^i_{n+j}$, simultaneously for each and every i^{th} individual and each collective consumptive good"* (Samuelson, 1954). Taking Samuelson's definition, a correlation of manmade greenhouse gas emissions and climate change as well as the existence of social costs of carbon as a basis, a certain level of emission reduction seems to be urgent. Otherwise the climate system is facing the risk of not fulfilling Samuelson's condition for some regions and generations in the long-term. This again leads to the analysis of social costs of carbon. As an example, Nordhaus and Boyer (2000) focus on the following aspects of vulnerability to increasing temperature in order to estimate expected market damages due to climate change: agricultural production, settlement and ecosystems, human health, sea-level rise, vulnerable market sectors (amongst others water systems, energy systems and fisheries), non-market amenity impacts (e.g. leisure activities) and catastrophic impacts (amongst others the collapse of the West Antarctic Ice Sheet or a sharp rise in sea level). In a further step the social costs of carbon can be estimated by applying integrated assessment models including market damages due to climate change and a certain level of discounting (see sections 1.1.1 and 1.1.2). Tol (2008) presents a meta-analysis of 211 estimates of social costs of carbon concluding that despite a downward trend in the estimates of the economic impacts of climate change *"there is a fair chance that the annual climate liability exceeds the annual income of many people"*.

The conclusion of Tol (2008) and the classification of climate change and thus social costs of carbon as a public good problem raise the question about global equity and efficient policy.

The United Nations Framework Convention on Climate Change (UNFCCC) notes in article 3 that *"The Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities. Accordingly, the developed country Parties should take the lead in combating climate change and the adverse effects thereof"* (see UN, 1992). According to Stern (2008), there is a big difference between a stock and a flow notion of equity with regard to carbon emissions. Taking into account the total contribution to the atmospheric stock of carbon in the last 50 to 200 years, even global equalizing of per capita carbon flows by the year 2050 would be a week notion of equity. Proclaiming optimal per capita emissions of 2-2.5 tCO_2 per year, Stern postulates a "Global Deal" with the currently poor countries at its center. The design of an efficient policy should be based on a price mechanism leading to a carbon price following the path of the marginal costs of climate change abatement. In addition Stern's "Global Deal" contains elements in favor of developing countries such as lower emission reduction targets or compensation for increasing costs of development due to climate change.

However, based on integrated assessment modeling (see section 1.1.1) many economists conclude that equity and efficiency with regard to the abatement of climate change could be guaranteed by an emission trading- or alternatively a Pigouvian taxation-mechanism (see e.g. Nordhaus and Boyer, 2000; Manne and Stephan, 2005; Nordhaus, 2008; Tol, 2009). If the costs of climate change are expressed as pure market damages in terms of loss in GDP, equity would be assured by allocating emission rights to individual nations. International trade of these emission permits then leads to an efficient allocation of global emissions. Since the Pareto-efficient stock of atmospheric carbon is independent of the initial allocation of emission rights, no major changes in the historical ownership of labor, capital, and other conventional resources would occur (Manne and Stephan, 2005). A Pigouvian tax corresponds to the marginal damage cost of a unit of carbon emissions. Placed on the carbon price, this tax restores the market to an efficient solution by internalizing the shadow costs of carbon in the economy (Tol, 2009).

1.1.1 Integrated assessment modeling (IAM)

In the mid 80s integrated assessment modeling of global climate change emerged as a paradigm to combine science and policy with regard to complex environmental issues. By linking mathematical representations of the natural and the socio-economic system, cause-effect chains including feedbacks are represented in integrated assessment models (Böhringer et al., 2006). According to Stephan and Müller-Fürstenberger (2007), an IAM usually consists of three sub-models. An economic model represents the world economy at different spatial and temporal resolutions. A simple carbon cycle model is used as a proxy for the development of climate change and feedbacks from climate change to the economic sub-model are defined by an ecosystem-impact model (see Figure 1).

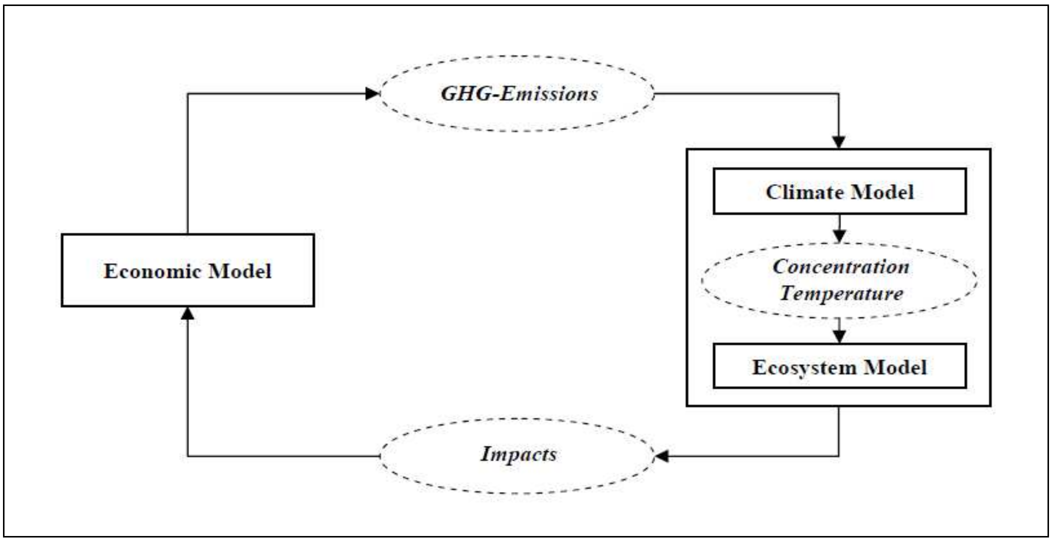

Figure 1: Schematic structure of an IAM of climate change (Böhringer et al., 2006)

These models vary widely in the complexity of the economic and climate sectors. In addition, the treatment of uncertainty which is a crucial concern in climate change policy, and the responsiveness of agents to climate change policies vary in IAMs (Böhringer et al., 2006). Weyant et al. (1996) and Kelly and Kolstad (1999) subdivide IAMs of climate change into policy optimization and policy evaluation models:

Policy evaluation IAMs

By applying policy evaluation IAMs the effect of a single exogenously specified policy option on the biosphere, climate and economic systems can be analyzed. Actions of agents representing the economy are taken as given (based on assumption, observation or expert opinion) in order to estimate costs and benefits of likely future decision paths. Therefore, the model results are subject to the decision predictions of the modeler and cannot readily be interpreted by the reader (Kelly and Kolstad, 1999). However, by avoiding optimization, policy evaluation models can contain greater modeling detail on biophysical, geophysical, economic or social aspects (Böhringer et al., 2006). Examples of policy evaluation models are the IMAGE Framework (see Rotmans, 1990) the PAGE-2002 Framework (see Hope, 2006) or the GIM Framework (see Mendelsohn and Williams 2004).

Policy optimization IAMs

Policy optimization models cover two different purposes: First, the target can be regulatory efficiency. This implies that an optimal policy is searched which trades off expected costs of climate change control and expected climate damages. Second, it is possible to seek for regulatory cost-effectiveness by minimizing the costs of achieving a particular goal, e.g. an emission threshold (Kelly and Kolstad, 1999). Assuming rationally behaving agents, policy optimizing IAMs are typically designed to maximize the discounted present value of welfare (see section 1.1.2) across all time periods and spatial areas covered by the models. In such models, emissions are defined as production input and are the driver of climate change. Due to increasing abatement costs, climate change reduces the production output available for consumption or capital investment. Since welfare is defined as a function of consumption, emission and savings rates are computed in order to guarantee optimal levels of production and abatement in each time period. Whereas the models respect market damages in terms of GDP losses, non-market goods such as ecosystems or human health are typically not considered for the optimization of welfare (Stanton et al., 2009).

Based on the spadework of Nordhaus et al. (DICE and RICE framework: see e.g. Nordhaus, 1991; Nordhaus and Yang, 1996; Nordhaus and Boyer, 2000; Nordhaus, 2008) and Manne and Richels (MERGE framework: see e.g. Manne and Richels, 1992; Manne and Richels, 2004) a broad variety of top-down and bottom-up policy optimizing IAMs has been developed. Bottom-up models focus on a disaggregated and detailed representation of the production sector of the economy, whereas the consumers are often represented by a single agent. In top-down models consumers are typically represented by several agents (regions), but the representation of economic production is simplified by using a centralized GDP production function for each region (Stephan and Müller-Fürstenberger, 2007).

1.1.2 Discounting

Discounting welfare accredits a current value to future benefits. A key element of the concept of discounting is the notion of optimality of investments and decisions. A standard first-order condition in optimal growth theory denotes that for each capital good (if there are no constraints between consumption and accumulation of the good in question) the social rate of return on investment should be equal to the social discount rate in terms of that good (Stern, 2008). Whereas the social rate of return on investment corresponds to the marginal productivity of a good at shadow prices, the social discount rate represents the social value of a unit of consumption at a specific time *t* relative to a unit of consumption at time *zero* (Stern, 2008).

The equation for the social discount rate as presented by Ramsey (1928) includes three components. A pure rate of time preference, the rate of growth of per capita consumption and a measure of inequality aversion influence the level of discounting of future welfare. The pure rate of time preference represents judgements about the relative importance of future well-being relative to the well-being of current generations. This so called time discounting is hard to defend regarding ethical considerations and must be handled with caution (Nordhaus, 1997). However, as decision processes often result in favor of present generations it would be unrealistic to negate the existence of a pure time preference. Moreover, growth discounting respects the rate of growth of per capita consumption over time. Since most global change models project continuing economic growth and increasing per capita consumption, it seems to be reasonable that future generations bear a greater part of the costs related to climate change abatement. In this context the measure of inequality aversion represents the decline of the marginal utility of per capita consumption in case of an increase in consumption. Hence, growth discounting gives less weight to later and wealthier generations relative to earlier generations (Nordhaus, 1997).

Although the concept of discounting is an issue controversially discussed in climate economics (see e.g. Stern, 2006; Weitzman, 2007; Nordhaus, 2007) *"it is well-known that the discount rate is crucially important for estimating the social cost of carbon, a standard indicator for the seriousness of climate change and desirable level of climate policy"* (Anthoff et al. 2009).

1.2 Economics of CCS

Even though CCS technologies are not yet market mature (IPCC, 2005), Zenghelis and Stern (2009) propose to scale-up the implementation of CCS in the medium term as a part of the "Global Deal" in order to address anthropogenic climate change. However, a growing body of economic literature points to significant economic potential of carbon capture and storage technologies (Dooley et al., 2003). On the one hand, research focuses on future costs of CCS. Costs of carbon transport and storage have been evaluated respecting regional storage potential and economies of scale (see e.g. Dahowski et al., 2009; Wildenborg et al., 2005; Dooley et al., 2004). In addition, carbon capture costs have been analyzed depending on the type of the emission source and the technologies applicable to capture CO_2 during industrial processes (see e.g. Al-Juaied and Whitemore, 2009; Dooley et al., 2006; IPCC, 2005). On the other hand, these cost estimates are used in energy-economic modeling. Economic modeling has been conducted in order to examine how CCS deployments would evolve assuming constraints in carbon energy use (IPCC, 2005). However, at present most economic analyses based on IAMs including CCS focus on regional energy sectors and on shifts to industrial technologies which allow the implementation of CCS (see e.g. Dooley et al., 2004 for the USA; Wildenborg et al., 2005 for the European Union).

Even though CCS is included in the MERGE framework (see Manne and Richels, 2004), only few studies dealing with global welfare effects of CCS implementation have been found (see e.g. McFarland, 2002 and 2006). As mentioned above, Pacala and Socolow (2004) postulate to mitigate climate change using current technologies. Thus, there seems to be a gap in the analysis whether CCS, at current cost estimates, is an appropriate method to mitigate harmful impacts of climate change on the global economy and the environment.

1.3 Outline of this Master’s thesis

The aim of this Master’s thesis is to examine, using CCS cost and capacity data, whether it is economically feasible to conduct global large-scale CCS. For the analysis of the potential of CCS the RICE-99 model, a policy optimizing IAM as presented by Nordhaus and Boyer (2000), has been chosen. CCS has been incorporated as a single emission mitigation option in the model framework. Whereas the CCS investments are in competition with consumption and capital investment within the economic sector, the emission reduction due to the implementation of CCS directly lowers the temperature increase by influencing the carbon cycle representation of the model. In one scenario group the agents representing the regions included in the RICE-CCS model determine individually an optimal amount of carbon captured and stored with respect to the maximization of global welfare. A second group of scenarios analyses exogenously determined (and thus arbitrary) CCS policies whereas all other decisions allowed by the model framework are left to the agents.

On the one hand, the analysis of the scenario results should give an answer to the questions whether a rational agent would implement CCS technologies and whether exogenous CCS deployment leads to changes in global or regional welfare within the next century. On the other hand, the impacts of the implementation of CCS on global carbon energy use and thus, on the economic and climate systems are the focus of this Master's thesis.

Chapter 2 gives an overview on the state of the art of CCS. A description of the RICE-99 model, the incorporation of CCS in the model and the data used for the computational procedures are provided in Chapter 3. Chapter 4 provides an overview of the exogenous and endogenous CCS scenarios and results are presented and discussed in Chapter 5. Finally the conclusions are presented in Chapter 6.

2 State of the Art CCS

A carbon capture and geological storage system (CCS) includes capturing of CO_2 at the emission source, transportation to a reservoir and injection into onshore or offshore underground geological formations. As an option to reduce CO_2 emissions from large point sources CCS systems use technologies already applied in common industrial processes. On the one hand, separation and capture techniques are known from ordinary gas purification processes. On the other hand, transport and underground injection systems are used in enhanced oil recovery (EOR) or enhanced coalbed methane recovery (ECBM) processes. Up to 45% of global fossil fuel CO_2 emissions are expected to be available for CCS by the year 2050 (IPCC, 2005). This chapter intends to give an overview of CCS regarding technological, cost, environmental and legal issues.

2.1 Large point sources of CO_2

Large point sources of CO_2 (LPS) are defined as stationary emission sources emitting more than 0,1 $MtCO_2$ per year. The major types of LPS are power plants based on fossil fuel combustion. Pulverised coal fired plants (PC), integrated coal gasification combined-cycle plants (IGCC) and natural gas combined cycle plants (NGCC) account for the major part of LPS emissions. PC and NGCC power plants provide about 40% of total global energy supply and the IGCC technique is seen to be a key technology in the near future. Further, cement manufactories and industrial facilities such as iron and steel, bioethanol or ammonia production factories are LPS with less relevance concerning CCS. In total, the power and industry sectors account for about 60% of total global CO_2 emissions and it is expected that this share will persist at a level of around 50% by the year 2050 (IPCC, 2005). Table 1 gives an overview of LPS which are theoretically available for CCS (based on data from the IEA; see IEA, 2009b). A total of 8'615 emission sources with an average annual emission rate of 1,7 $MtCO_2$ per source have been identified. Accounting for 15 $GtCO_2$ per year (see Table 1), the types of LPS considered in this Master's thesis cover around 90% of global LPS CO_2 emissions.

In order to assess the potential of CCS as an option to reduce global CO_2 emissions, the geographical distribution of LPS and their amenability to CO_2 capture and storage must be evaluated (IPCC, 2005). As shown in Figure 2, LPS are mainly clustered in the USA, Europe, Japan, India and eastern Asia. However, since each of these emission sources represents a substantial amount of carbon dioxide emitted to the atmosphere, CCS is an option to mitigate CO_2 emissions significantly in all regions of the world.

Table 1: Types and number of large point sources of CO_2 emission (data provided by the IEA, 2009b)

Emission Source	**Number of Sources**	**Emissions [$MtCO_2$]**	**Emissions/Source [$MtCO_2$ / Source]**	**Emissions [MtC]**	**Emissions/Source [MtC / Source]**
Ammonia Production	232	151	0.65	41	0.18
Cement Production	1'316	1'042	0.79	284	0.22
Hydrogen Production	106	25	0.24	7	0.07
Iron&Steel Production	504	705	1.40	192	0.38
Power Generation	5'217	11'833	2.27	3'227	0.62
Power Coal	2'138	9'198	4.30	2'508	1.17
Power Gas	1'875	1'560	0.83	425	0.23
Power Oil	1'120	977	0.87	266	0.24
Power div.	84	99.10	1.18	27.	0.32
Ethanol Production	587	534	0.91	146	0.25
Refineries	653	733	1.12	200	0.31
Total	**8'615**	**15'025**	**1.74**	**4'097**	**0.48**

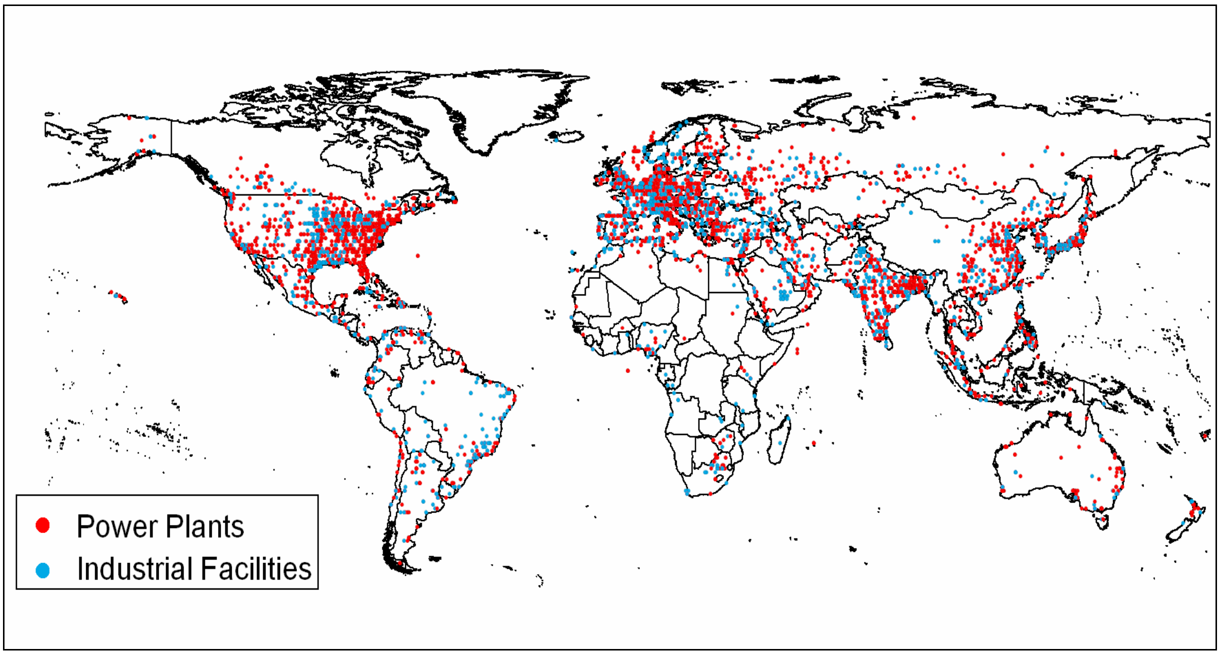

Figure 2: Geographical distribution of LPS of CO_2 emissions (this figure has been plotted using data provided by the IEA, 2009b)

2.2 CO_2 capture

In general, CO_2 capture can be defined as gas purification by separating CO_2 from other components in a flue gas (Kohl and Nielsen, 1997). Based on pre treatment of fossil fuels or air before and on chemical and physical separation processes after combustion, CO_2 from LPS can be captured using complex technological systems. Whereas the basic pre treatment and separation processes are well known and understood, most of the capture systems are not yet market-mature. Since capture of CO_2 is an energy-intensive procedure, the difference between CO_2 emissions captured and CO_2 emissions avoided must be considered. In addition, different processes could be applied to the same type of LPS. Thus, a detailed cost and performance analysis is required to determine an optimal separation process (IPCC, 2005). However, the separation processes and capture systems, described in this section, are of high relevance concerning a worldwide deployment of CCS.

2.2.1 Separation processes

CO_2 can be separated from hydrocarbons before combustion (pre treatment) or from flue gases after combustion (post treatment). Another approach is to remove nitrogen from air used for combustion which results in a flue gas of an optimal composition with regard to CO_2 separation processes. The following treatments can be distinguished:

a) Fossil fuel pre treatment processes

Basically fossil fuel pre treatment corresponds to converting the fossil fuel to CO_2 and hydrogen oxide (H_2). First, the fuel must be gasified. In a next process step the gasified fuel is oxidised by water vapour. Second, as a result of the oxidation, fixed carbon is converted to volatile CO_2 and thus available for separation whereas the heating value is available from pure H_2 (Rostrup-Nielsen, 2001). The advantage of this process called CO-shift is the low energy demand for CO_2 separation because of the high concentration of CO_2 in the resulting gas (Lyngfeldt et al., 1999).

b) Post treatment processes – separating CO_2 from flue gas

Capturing CO_2 from flue gases represents the removal of a vapour phase impurity from gas streams (Kohl and Nielsen, 1997). The main processes to separate CO_2 from flue gas are absorption with chemical solvents, separation with membranes and cryogenic distillation (see Figure 3). It depends on the mixture of the flue gas which processes are preferred to separate

CO_2 from other components in a gas. According to Kohl and Nielsen (1997), absorption with chemical solvents (see Figure 3a) refers to the transfer of a component of a gas phase to a liquid phase in which it is soluble. The separation is achieved by passing the flue gas through a liquid absorbent capable of capturing CO_2. In a so-called regeneration process the absorbent releases the CO_2 after being heated or compressed. The pure CO_2 can be captured and the absorbent is available for recycling (IPCC, 2005). According to Wallquist et al. (2008), monoethanolamin (MEA) is an appropriate absorbent for CO_2. Another possibility to separate CO_2 from flue gases is the permeation of the gas through a membrane (see Figure 3b). In this process polymeric membranes are used to separate gases by selective permeation from one side of a membrane to the other driven by a pressure gradient (Kohl and Nielsen, 1997). As noticed by the IPCC (2005) membrane separation has not yet been applied to capture CO_2 at a large scale. Furthermore, cryogenic distillation (see Figure 3c) is a process to separate CO_2 accomplishable for liquids. By compression or cooling, the phase of the flue gas is changed from gaseous to liquid. In the liquid phase the components can be separated in a distillation column and the CO_2 is available for capture (IPCC, 2005).

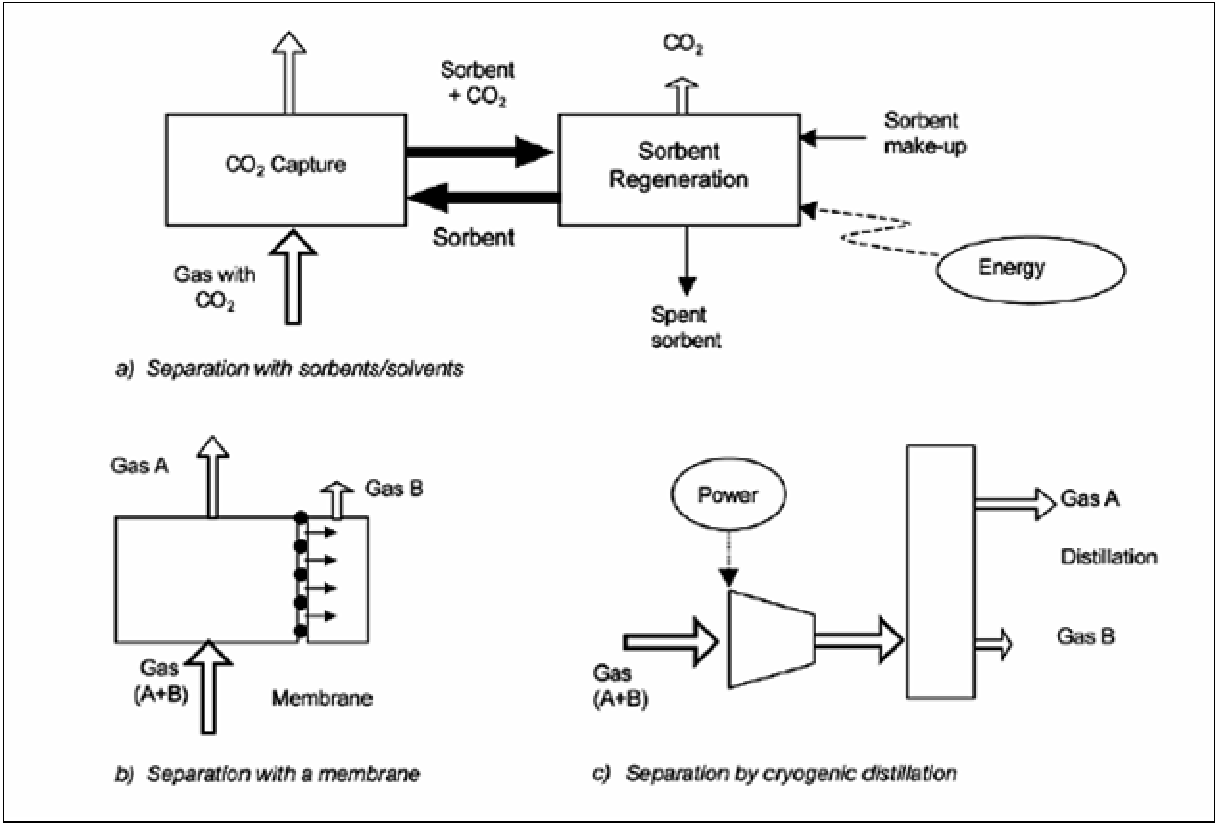

Figure 3: General schemes of post treatment processes relevant for CO_2 capture from flue gases (IPCC, 2005)

c) Removal of nitrogen from air

Instead of separating CO_2 from a flue gas containing mainly nitrogen after combustion with air, pure oxygen (O_2) is used for the combustion process to determine the mixture of the resulting flue gas. This implies that nitrogen must be separated from air in a first process step before combustion. The flue gas of this so called O_2/CO_2-firing consists solely of water vapour and CO_2. The separation can be executed by simple condensation and thus is significantly less energy intensive compared to common separation processes dealing with flue gases of a more complex structure (Lyngfeldt et al., 1999).

2.2.2 Capture systems

Regarding fossil fuel combustion, the three basic CO_2 capture systems applying the processes described in the previous section are known as pre combustion capture, oxy-fuel combustion capture and post combustion capture systems (IEA, 2007). Slightly different systems using the same technologies allow capturing CO_2 from industrial production processes such as ammonia or steel production (IPCC, 2005). Figure 4 gives an overview of the capture systems and their basic functionality described in this section.

a) Pre combustion capture

A pre combustion capture system is based on the CO-shift process. After the CO_2 is separated by physical or chemical absorption it is available for storage and the pure hydrogen can be used e.g. in gas turbines (see Figure 4). The pre-combustion capture technologies could be applied to IGCC power plants (Wallquist et al., 2008). It is expected that IGCC technologies will be deployed on a large scale in the late 2010s. Thus, the importance of pre-combustion capture is supposed to increase substantially (IEA, 2004).

b) Post combustion capture

At present “post combustion” is seen as the most mature CO_2 capture system. The CO_2 is separated from oxygen and nitrogen oxide by chemical absorption in a liquid amino solution after burning of fossil fuel (see Figure 4). As the fraction of CO_2 in the flue gas typically accounts for about 12-14% only, a huge amount of solvent is needed for the separation process. Recycling of the solvent is very energy intensive. Thus, it reduces the efficiency of a power plant considerably and increases the total energy requirement of a plant respectively. However, post-combustion technology has the advantage that it can be implemented to existing power plants without influence on the production processes. The additional facilities for such a capture system are of a considerable size. Therefore, the availability of sufficient space next to an LPS is a precondition (Wallquist et al., 2008). The post-combustion capture technology could be applied to NGCC and PC power plants (IPCC, 2005).

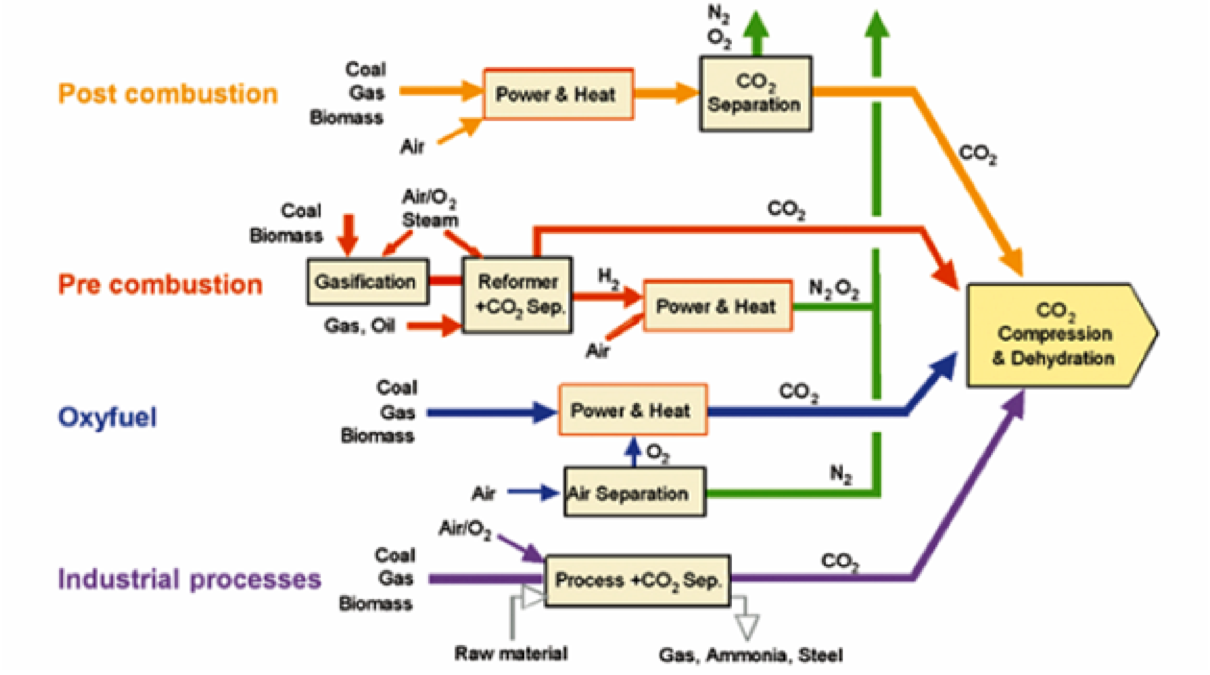

Figure 4: Overview of CO_2 Capture systems IPCC (2005)

c) Oxyfuel combustion capture

As shown in Figure 4, this capture system is based on the O_2/CO_2-firing process. The flue gas resulting resulting from this process consists of approximately 80% water vapour and 20% CO_2. Hence, water vapour can be separated from CO_2 by condensation without high energy input. Since the flame temperature of fuel burnt in pure oxygen is very high, parts of the CO_2 and water vapour rich flue gas must be recycled to the combustor. The main disadvantage of oxy-fuel combustion is the energy intensive production of pure oxygen (Wallquist et al., 2008). Oxy-fuel combustion capture systems could be implemented in NGCC and PC power plants (IPCC, 2005).

d) CO_2 capture from industrial processes

Systems capturing CO_2 during industrial process streams, like purification of natural gas or the production of hydrogen-containing synthesis gas for the production of ammonia, alcohols and synthetic liquid fuels, are already in operation today. However, mostly the CO_2 is released to the atmosphere again since the aim of the CO_2 separation is solely the purification of industrial gas streams. These current separation systems include similar techniques as applied for pre combustion capture. In addition, the implementation of post combustion capture systems in industrial process streams would allow capturing CO_2 from cement and steel production as well as from fermentation processes during food and drink production (IPCC, 2005).

2.2.3 Capture costs

CO_2 capture costs consist of capital and of operational costs. Capital costs include investments for capture facilities while operational costs mainly represent energy costs (IPCC, 2005). The total costs of CO_2 capture are subject to the type and size of an LPS, production technology and the concentration of CO_2 in the flue gases (Hendricks et al., 2004). Thus, literature shows a wide range of CO_2 capture costs from LPS (see e.g. IPCC, (2005); Dooley et al., (2006); Al-Juaied and Whitemore, 2009; Hendricks et al., 2004).

Table 2 shows cost estimates of CO_2 captured from different types of power plants in the range of US$13 to US$74 per ton of CO_2, respectively 20% to 69% increase in costs of electricity production. For other industrial facilities such as refineries, cement, steel or ammonia production the estimated capture costs are ranging from US$6 to US$55 per ton of CO_2. For this Master’s thesis the cost estimates of the IPCC (2005) and Dooley et al. (2006) were considered in all computational experiments.

Table 2: Cost estimates and calculations for CO_2 emissions avoided

Source	Low Range	High Range	Point Source Type	Details
IPCC (2005)	$13	$37	IGCC	Costs per ton CO_2 avoided [US$/t CO_2]. Representative value $23.
Dooley et al. (2006)	$25	$40	IGCC	Costs of CO_2 capture & compression [US$/t CO_2].
IPCC (2005)	20%	55%	IGCC	Increase in costs of electricity production. Representative value 33%.
IPCC (2005)	$29	$51	PC	Costs per ton CO_2 avoided [US$/t CO_2]. Representative value $41.
IPCC (2005)	42%	66%	PC	Increase in costs of electricity production. Representative value 57%.
Dooley et al. (2006)	$25	$60	Steam rankine power plants	Costs of CO_2 capture & compression [US$/t CO_2].

Source	**Low Range**	**High Range**	**Point Source Type**	**Details**
IPCC (2005)	\$37	\$74	NGCC	Costs per ton CO_2 avoided [US\$/t CO_2]. Representative value \$53.
IPCC (2005)	37%	69%	NGCC	Increase in costs of electricity production. Representative value 46%.
Dooley et al. (2006)	\$35	\$55	Refineries	Costs of CO_2 capture & compression [US\$/t CO_2].
Dooley et al. (2006)	\$35	\$55	Cement production	Costs of CO_2 capture & compression [US\$/t CO_2].
Dooley et al. (2006)	\$20	\$35	Steel production	Costs of CO_2 capture & compression [US\$/t CO_2].
Dooley et al. (2006)	\$6	\$12	Ammonia and ethanol production.	Compression costs only; no capture costs for pure CO_2 stream [US\$/t CO_2].

2.3 CO_2 transport

If an LPS is not located directly above a geological storage site, captured CO_2 must be transported to a geological storage reservoir. Today, commercial scale transport of gaseous and liquid CO_2 for EOR is conducted using pipelines (IPCC, 2005). Another possibility is transportation of CO_2 in road or rail tankers and ships. However, according to the economic analysis of Svensson et al. (2004), only pipeline systems and water carriers remain as economically feasible transport systems. Railway or road carriers are to expensive and lack capacity for large-scale transportation of CO_2 (IPCC, 2005).

2.3.1 Pipeline transportation

Since pipeline transportation of CO_2 is a market mature technology, this method is seen as the major option for large-scale CO_2 transport. The design of a pipeline system is determined by many different factors: mechanical design, optimal choice of the pipeline route considering topography, characteristics of the product mixture transported and challenges of very deep water or uneven seabed for offshore pipelines have to be considered (IPCC, 2005). Pipelines applicable for CO_2 transportation operate at ambient temperature and high pressure. CO_2 is transported in a phase near “triple point” corresponding to a phase with continuous progression from gaseous to liquid without a distinct phase (see Figure 5). Using a booster, gaseous CO_2 must be compressed to a pressure above 8bar in order to increase the density of the CO_2. The flow of CO_2 in the pipeline system is driven by pumps (IPCC, 2005). To ensure long term safety and economic feasibility of a pipeline system the removal of water from the transported fluid is crucial. Otherwise corrosion caused by the combination of CO_2 and free water might damage the pipeline system substantially. However, if the carbon dioxide stream is dry, pipelines can be constructed from materials already used for high-pressure pipelines in the oil and gas industries (Coleman, 2009).

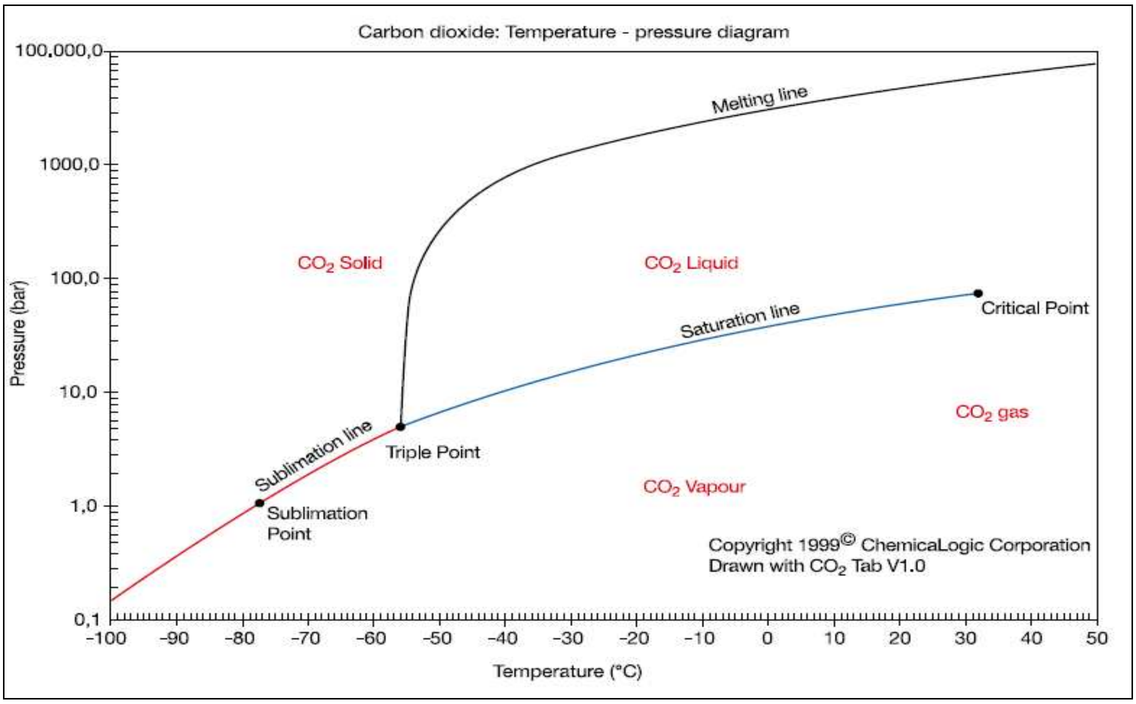

Figure 5: Phase diagram for CO_2 (IPCC, 2005)

2.3.2 Transportation by ship

In case of overseas transport, or generally if CO_2 has to be moved over large distances, transportation by ship is economically more attractive than using a pipeline system (IPCC, 2005). Large-scale transport of CO_2 by ship could be realized using established design of LPG (liquefied petroleum gas) carrier ships. CO_2 at pressure near “triple point” (see Figure 5) could be transported in vessels of around 20’000 m^3. Loading and unloading systems would be required to load the CO_2 at the required temperature and pressure on and off the carrier ships (Aspelund et al., 2006). The main disadvantage of CO_2 transportation by ship is that CO_2 has to be stored temporarily after capture due to the mismatch of continuous capture at the LPS and a discrete cycle of transportation by ship (IPCC, 2005).

2.3.3 Transport costs

Transport costs consist of three main components namely construction costs, operation & maintenance costs and administrative costs. Construction costs account for the major part of transport costs depending on the size of the pipeline system and on the amount of CO_2 transported. Operation & maintenance costs include expenses for monitoring, maintenance and energy whereas all other costs (design, project management, regulatory filling fees etc.) are summarized as administrative costs. In addition, steel costs contribute substantially to the total costs of a pipeline system. Thus, fluctuations in the steel price have a significant impact on total pipeline costs. Further, it must be considered that, compared to offshore transportation, an onshore pipeline system leads to lower costs per ton CO_2 transported since construction and maintenance is considerably less cost incentive (IPCC, 2005). Table 3 shows cost estimates of CO_2 transport ranging from US$0.2 to US$10 per ton of CO_2. The cost estimates of the IPCC (2005) and Wildenborg et al. (2004) are based on transport distance and mass flow rate whereas those of Dooley et al. (2006) and Hendricks et al. (2004) are based on transport distance and emission source only.

Table 3: Cost estimates and calculations for CO_2 transport

Source	Low Range ($ or € tCO_2^{-1})	High Range ($ or € tCO_2^{-1})	Details
IPCC (2005)	$ 1	$ 8	250 km pipeline or shipping with a mass flow rate of 5 to 40 $MtCO_2$/yr.
Dooley et al. (2006)	$ 0.2	$ 10	Distance, type and size of the emission source are the cost determining factors.
Wildenborg et al. (2005)	< € 1	€ 2.5	200 km pipeline transportation including booster stations.
Hendricks et al. (2004)	€ 1	€ 5	50 - 500 km pipeline transportation.

2.4 CO_2 storage

Geological storage is the most mature CO_2 storage method with a number of commercial projects in operation (IPCC, 2007b). CO_2 can be stored and onshore and offshore in different geological formations in the deeper underground (see Figure 6). Storage and monitoring techniques are similar to those routinely used by the oil and gas industries today. Being injected in geological formations at depths greater than 800m, CO_2 is compressed to the supercritical state (see Figure 5: “triple point”). This implies that the CO_2 has a liquid-like density and a gas-like viscosity (Dooley et al., 2006). Injection denotes that CO_2 is pumped into a well which infiltrates the storage zone in a deep geological formation. Perforations in the well or a permeable screen allow the CO_2 to enter the storage reservoirs. Since the pressure near the well is raised locally due to the injection of $CO_{2,}$ the pore space between grains and minerals is occupied and the in situ fluids in the storage formation are displaced. Storage is most effective if CO_2 is trapped either under a low permeable cap rock, converted to solid minerals, adsorbed on the surface of coal micro pores or through physical and chemical mechanisms (IPCC, 2005).

2.4.1 Principal trapping mechanisms

According to Dooley et al. (2006), the principal trapping mechanisms of deep geological CO_2 storage are hydrodynamic trapping, dissolution trapping, mineralization trapping and chemical adsorption in coals. They can be described as follows:

a) Hydrodynamic trapping

Hydrodynamic trapping can occur if CO_2 is injected below a caprock layer into geological formations. After having occupied the pore space in the formation CO_2 starts to migrate upwards due to its lower density in comparison to the in situ fluids. At the top of the geological storage formation CO_2 is trapped due to residual CO_2 saturation or in stratigraphic traps within the sealing formation (IPCC, 2005).

b) Dissolution trapping

If CO_2 dissolves in formation water, a process called dissolution or solubility trapping occurs. Dissolved CO_2 does not exist as a separate phase anymore which prevents it from migrating upwards due to buoyant forces. If salinity and temperature increase, the solubility of CO_2 in formation water decreases. Thus, the dissolution rate slows down and is controlled by diffusion and convection rates if the formation fluid is saturated with CO_2 (IPCC, 2005). Significant quantities of dissolved CO_2 start to migrate upwards through the low-permeable caprock with the groundwater. Since a caprock layer must have a thickness of several hundreds of meters the time to reach the surface can be millions of years for a fluid (Bachu et al., 1994 in IPCC, 2005).

c) Mineralization-based trapping

Mineralization-based trapping includes dissolved CO_2 reacting with minerals in the rock of the storage layer. Ionic species are formed due to the decomposition of the rock causing a rise in the pH value. In the end of this process parts of the dissolved CO_2 are trapped in stable carbonate minerals (IPCC, 2005). These chemical reactions produce non-reactive minerals and are not reversible without a change in external conditions. Thus, CO_2 is trapped permanently and cannot be released to the atmosphere (Dooley et al., 2006).

d) Chemical adsorption in coals

Methane molecules are attached to the surface of coal by chemical bonding. The surface of the coal molecules has a chemical preference for CO_2. Thus, methane is replaced after injection of CO_2 in a coaly geological formation. The CO_2 adsorption capacity varies depending on the chemical composition of the coal. However, coals of a specific chemical composition are able to adsorb multiple CO_2 molecules for each methane molecule released (Dooley et al., 2006).

2.4.2 Geological storage locations

Figure 6 shows the different man-made geological storage sites and the geological structures applicable to the storage of CO_2. In general, most CO_2 storage reservoirs are porous layers in the deep underground which are separated from the surface or from sources of fresh water by layered rock. The following geological formations can be discriminated:

a) Deep saline formations

Deep saline formations are underground, water-filled layers and are distributed widely below all continents and oceans (see Figure 6: 3 and 4). They consist mainly of sandstone and carbonate rocks and the void spaces between the mineral grains are occupied by large amounts of saline water. This saline water can be readily replaced by injected CO_2. However, it is crucial that a caprock layer prevents the CO_2 from migrating to the surface and prohibits its release to the atmosphere. The injection of CO_2 in such geological structures seems to be technically feasible since storage of waste fluids in saline formations is already a common practice today (Dooley et al., 2006).

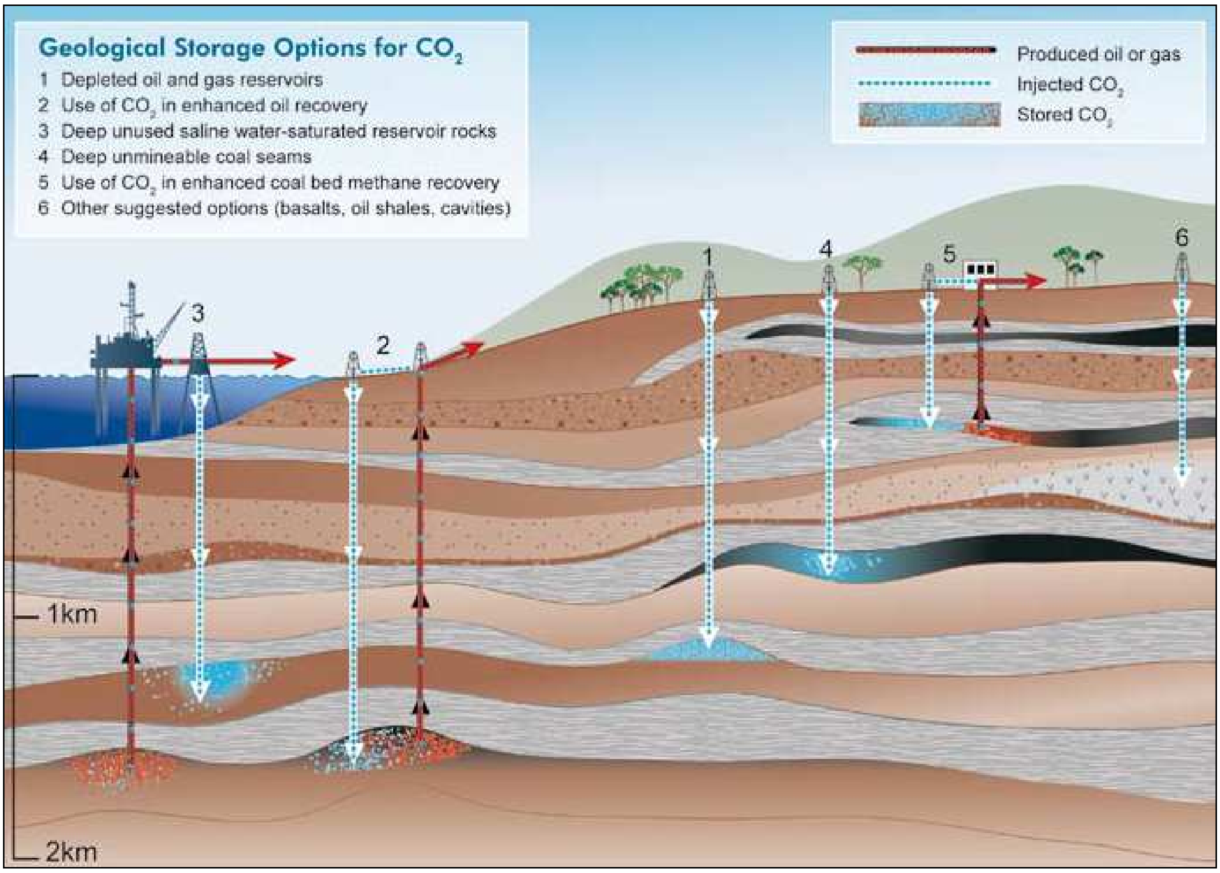

Figure 6: Geological reservoirs available for CO_2 storage (Dooley et al., 2006, by courtesy of CO2CRC)

b) Depleted oil and natural gas reservoirs

Once the fossil resources in an oil or natural gas reservoir have been exploited, CO_2 can be stored in the pore space which has been occupied by gas or oil before extraction. Injection of liquids in such formations is already in operation in current industries. Whereas depleted natural gas formations are used as storage reservoir for natural gas, injection of CO_2 is a common procedure to increase the pressure in depleted oil reservoirs with the aim to extract additional oil. This so called enhanced oil recovery (EOR, see Figure 6: 2) is in operation for more than 30 years in Northern America and provides valuable empirical knowledge of CO_2 injection into depleted oil fields. However, there has been little focus on long term storage of CO_2 and prevention from leakage out of the storage reservoirs (Dooley et al., 2006).

c) Deep unmineable coal seams

After injection of CO_2 in coal seams, methane is replaced due to the principle of chemical adsorption of CO_2 on coal molecules. Enhanced coalbed methane recovery (ECBM see Figure 6: 5) including simultaneous storage of CO_2 is seen as an upcoming technology for the present. Hence, the large-scale adsorption of CO_2 leads to a release of methane which is available for industrial purpose (Dooley et al., 2006).

d) Deep saline-filled basalt formations:

Dooley et al. (2006) propose that CO_2 could be injected into porous zones in basalt formations. Impermeable layers must prohibit CO_2 from migrating upwards. Since basalt formations are rich in elements that allow for the inclusion of CO_2, their potential for mineralization- based trapping and permanent CO_2 storage is supposed to be high.

2.4.3 Potential geological storage capacity

Estimates of worldwide geological storage capacity are of high relevance for governments and the industry. The actors need this data to assess viability of geological storage in their jurisdictions and as an input for business decisions such as site selection and development. Existing capacity estimates are of high variability or even contradictory. Thus, it is crucial to clearly state limitations concerning data, time and knowledge with the aim to prevent negative impacts on future scientific work based on capacity estimates (Bradshaw et al., 2007).

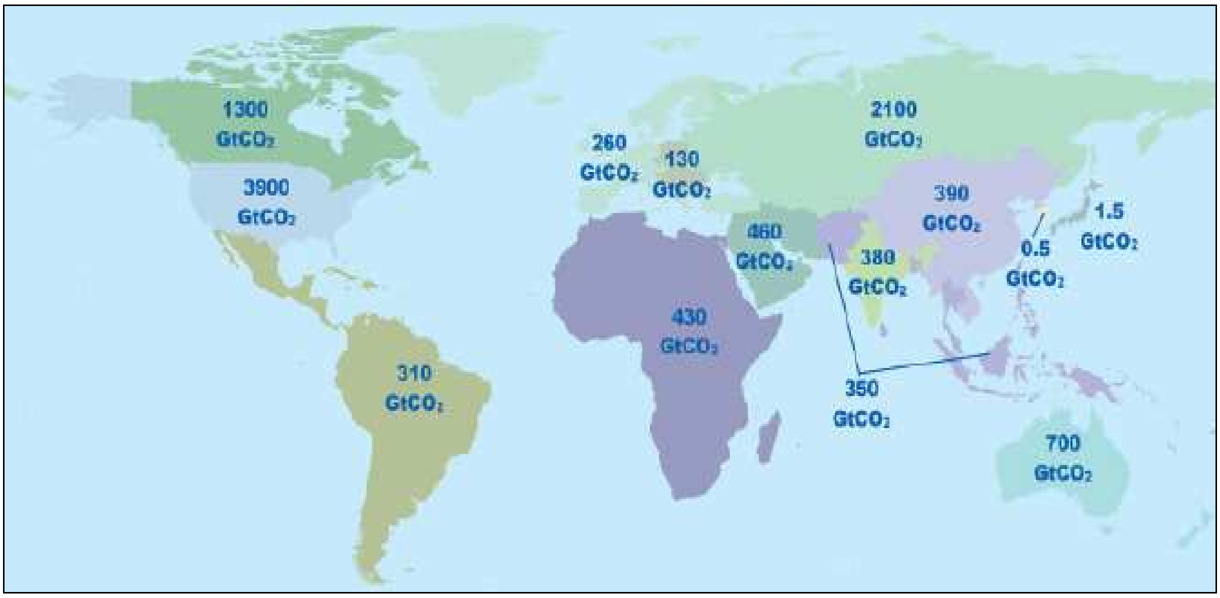

Figure 7: Geological storage potential in GtC (Dooley et al., 2006)

Figure 7 shows the global geological storage potential summed up from all types of storage reservoirs. According to Dooley et al. (2006), the storage capacity in deep saline formations is estimated to be around 9’500 $GtCO_2$, depleted oil and gas reservoirs account for 820 $GtCO_2$ and deep unminable coal seems for 140 $GtCO_2$. Hendricks et al. (2004) contend that the potential storage capacity won’t be entirely available for CO_2 storage. As more research and a more consistent methodology will be applied globally, capacity estimates are expected to mature over time. However, *“there is more than enough theoretical CO_2 storage capacity in the world to meet likely storage needs for at least a century, and in many key regions the storage capacity is in the right places to meet current and future demand from nearby LPS”* (Dooley et al., 2006).

2.4.4 Storage costs

Storage costs include capital as well as operational costs and depend on site-specific characteristics. Capital costs consist of site development costs, drilling costs and in case of offshore storage expenses for ocean platform facilities. Operational costs are returning and include maintenance and monitoring costs (Wildenborg et al., 2005). As technologies and equipment required for CO_2 storage are already applied in the oil and gas industries, the cost estimates are of a high reliability. However, there is a significant variability in storage costs due to site-specific aspects (IPCC, 2005). If CO_2 is injected for EOR or ECBM purposes, the profits gained due to the extraction of gas or oil must be subtracted from total storage costs. Hypothetically, this could result in very low or even negative net storage costs depending on fossil fuel prices (Hendricks et al., 2004). Table 4 shows different cost estimates of CO_2 storage including capital and operational costs in the range of \$-18 to €11.4 per ton of CO_2.

Table 4: Cost estimates and calculations for CO_2 storage

Source	Low Range (\$ or € tCO_2^{-1})	High Range (\$ or € tCO_2^{-1})	Details
IPCC (2005)	\$ 0.6	\$ 8.3	Cost estimates for carbon storage in saline formations or depleted oil and gas fields
Dooley et al. (2006)	\$ -18	\$ 12	Cost estimates for carbon storage including EOR.
Wildenborg et al. (2005)	€ 0.6	€ 6	Cost estimates for carbon storage in saline formations (onshore and offshore).
Hendricks et al. (2004)	€ 2.7 (onshore) € 7.3 (offshore)	€ 2.7 (onshore) € 11.4 (offshore)	Cost estimates for carbon storage in saline formations (onshore and offshore).

2.5 Environmental impacts and risks

Leakage from storage sites is the major risk affiliated with CCS and might have impacts on a local or on a global scale. On a global scale, leakage of CO_2 contributes to climate change in the same way as any other carbon emission. Appropriately selected and managed reservoirs are expected to retain a fraction of 99% of the stored CO_2 over 1000 years. In addition, existing pipelines and marine transportation systems for gas and oil show a good safety record. Thus, the global risk of CCS is considered to be very low (IPCC, 2005).

On a local scale, impacts of leakage might be more severe especially in the case of leakage from an onshore storage reservoir. Humans and ecosystems would be affected directly by CO_2 leaking out of a storage reservoir or a pipeline. On the one hand, a sudden release of CO_2 due to a failure in a pipeline or injection system could cause dangers to human health as a consequence of a local concentration greater than 7-10% of CO_2 in the air. However, such an incident is likely to be detected and could be resolved by applying techniques which are in operation to stop containing well blow-outs in the oil and gas industries today. On the other hand, CO_2 released by constant and undetected leakage would mainly threaten drinking water aquifers and underground ecosystems. In this context acidification of soils and displacement of oxygen are possible risks. If leakage to the atmosphere were to occur in areas with a geomorphology promoting an accumulation of CO_2 nearby the surface, all live in this area would be threatened. However, such hazards from constant leakage could be avoided by an accurate design of the CCS system and the implementation of appropriate monitoring systems (IPCC, 2005).

2.6 Legal aspects concerning CCS

According to Robertson et al. (2006), the main legal and regulatory issues critical to the future success of CCS development and deployment are regulation of CO_2 storage, property rights and the regulation of CCS monitoring and liability. CO_2 storage is supposed to be the main new legal issue within the CCS framework whereas capture and transport are subject to regulatory requirements designed for analogue processes in current industries. Thus, international legal frameworks are relevant primarily for offshore storage whereas onshore storage must be subject to national legal frameworks (IEA, 2005). As a consequence, legal aspects of CCS have to be regarded as a concern of national and international legal policy.

2.6.1 CCS subject to national legal frameworks

Only few countries have developed legal and regulatory frameworks for onshore CO_2 storage at present (IPCC, 2005). The IEA report on legal aspects of storing CO_2 (2005) includes, an analysis of five countries (USA, UK, Japan, Canada and Australia) of which solely the USA and the UK have a substantial regulatory framework regulating or at least partly covering the legal aspects of CCS. In Japan, Canada and Australia additional regulations would have to be adopted to create a legal basis for large CCS projects. In general, legal and regulatory conditions vary considerably from one country to another. Therefore, a detailed analysis would be beyond the scope of this Master's thesis.

2.6.2 CCS subject to international legal frameworks

The main international legal frameworks relevant for the remaining offshore carbon storage activities are the United Nations Convention on the Law of the Seas (UNCLOS, see UN 1958), the marine environmental protection framework and the climate change framework (see Table 5). The UNCLOS is an overarching legal convention not containing detailed operative provisions on most maritime issues. However, according to the IEA (2005), it provides a basis for regulations and specified agreements concerning all aspects of marine protection. Furthermore, the purpose of the London Convention (see IMO, 2007) is to prevent the marine environment from pollution through dumping of waste. In principle, the London Convention would only prohibit carbon storage in the water column if CO_2 is considered as an industrial waste (IEA, 2005). Since the year 2007 carbon storage in sub-seabed geological formations is allowed within the London Convention if permitted by a national authority.

Table 5: International conventions concerning CCS (IEA, 2005)

Convention	Subject	Signature
UNCLOS	Marine Jurisdictions and deep Ocean mineral Resource Exploitation	1982
London Convention	Marine Environmental Protection	1972
OSPAR Convention	Marine Environmental Protection	1992
UNFCCC	Climate Change	1992
Kyoto Protocol	Climate Change	1997

Concerning the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR, see UN 1992a), the emphasis must be placed on methods and intentions of CO_2 storage. The use of CO_2 captured from offshore oil or natural gas extraction would be allowed, since CO_2 injection for industrial purposes is not considered dumping of waste. Furthermore, the storage of CO_2 captured on land and transported by pipeline to an offshore storage site would not be subject to the OSPAR (Wall et al., 2005).

CCS is neither clearly included nor excluded as an option to reduce emissions in the UNFCCC (see UN, 1992) as well as in the Kyoto Protocol (see UN, 1997). Concerning CCS, the crucial question to answer for a post-Kyoto commitment is whether CCS emission reductions are entitled to provide emission rights in an emission trading system. In this context greenhouse gas accounting issues must be addressed, before CCS activities can be included in the portfolio of climate change mitigation mechanisms (IEA, 2005).

2.6.3 Outlook on legal aspects

Wall et al. (2005) summarize that the international legal rules surrounding the concept of CO_2 storage are fragmentary. The conclusion of the IEA (2005) is that national and international regulations are not fitted to large-scale CCS projects and urgent legislative work is needed to keep pace with technological progress. Primary, governments should ensure a national legal and regulatory framework for storage demonstration projects in the short-term to achieve empirical knowledge of conditions and risks related to CCS. Based on these experiences, legal frameworks for CCS must be developed to ensure a basis for worldwide CCS deployment (IEA, 2005).

2.7 Worldwide CCS projects

According to the IEA (2009), only four large-scale CCS Projects are in commercial operation today (see Table 6). The ‘Sleipner’ and ‘Snohvit’-projects in Norway and the ‘In Salah’-project in Algeria inject CO_2 deriving from natural gas production in underground sandstone formations. The ‘Weyburn-Midale’-project in Canada injects CO_2 captured from a coal gasification plant in North Dakota, USA in underground carbonate formations. Besides these commercial projects an increasing number of small scale demonstration projects are in operation or at least planed at present (IPCC, 2005). Latest action concerning CCS was taken at the

G8 summit in Hokkaido Toyako in Japan (July 2009). The G8 leaders announced the aim of 20 large-scale CCS demonstration projects by 2010 and the beginning of worldwide CCS deployment by 2020. Besides the International community, most of the major economies have focused on CCS and set it on the political agenda. Australia, Brazil, Canada, the European Union, Norway, South Africa, the United Arab Emirates, the USA and a consortium of companies in China are developing national CCS projects (IEA, 2009).

However, if CCS should be the key option to reduce CO_2 emissions to the atmosphere considerably there are hundreds, and perhaps even thousands, of large-scale commercial geological storage projects required (IPCC, 2005).

Table 6: Current large-scale CCS projects according to the IEA (2009) and the IPCC (2005)

Country	**Project**	**Average daily Injection Rate [$KtCO_2$/day]**	**Total Storage Capacity [$MtCO_2$]**	**Storage Reservoir**
Norway	Sleipner	2	20	Deep Saline Formation (offshore) - Sandstones
Norway	Snohvit	3	N/A	Deep Saline Formation (offshore) - Sandstones
Algeria	In Salah	3-4	17	Depleted Hydrocarbon Reservoirs - Sandstones
Canada	Weyburn-Midale	3-5	20	Depleted Oil Field (EOR) - Carbonates

3 Methods and Data

3.1 The RICE framework

The “Regional Dynamic Integrated Model of Climate and the Economy” (RICE) is a policy optimizing IAM developed by Nordhaus and Boyer (2000). In the version of the RICE model used for this Master’s thesis (RICE-99), the world is divided in 13 sovereign regions[2]. These regions are classified as high-, middle- or low-income regions based on GDP per capita. Each region is represented by a single agent acting as a central planner. Covering a period of 200 years, with a temporal resolution of 10 years, an optimal path of carbon energy input, capital investment and consumption is sought in order to maximize welfare net of climate damage within each region and time period. In the RICE-99 model, welfare is subject to the discounted present value of per capita consumption. In this context, a discount factor determines the weight of future generation’s welfare. On the one hand, the input of carbon energy in the production function of the model leads to output in terms of GDP available for consumption or capital investment. On the other hand, market damages due to increasing climate change reduce the possibilities of consumption or capital investment and thus lead to a decrease in welfare. Therefore, an “optimal” level of economically harmful climate change is determined in order to guarantee certain equity between generations and regions (Nordhaus and Boyer, 2000).

3.1.1 Description of the RICE model including CCS

The mathematical structure of the RICE model can be subdivided in an economic and a climate-related sector with a damage function representing the impacts from climate change on the economic sector. To incorporate CCS in the RICE framework, the model has been extended by a possibility to invest in the implementation of CCS. Whereas the only option to

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[2] *High-income regions*: USA (United States of America), EUROPE (OECD Europe, Abbreviation: EU), JAPAN (Abbreviation: JAP), OHI (other high income countries; amongst others Canada and Australia).
Middle-income regions: EE (Eastern Europe), RUSSIA (Russian Federation, Abbreviation: RU), HIO (high income OPEC countries), MI (middle income countries; amongst others Brazil, South Korea, Argentina), LMI (lower middle income countries; amongst others Mexico, Chile).
Low-income regions: CHINA (Abbreviation: CHI), INDIA (Abbreviation: IND), LI (low income countries; amongst others; Pakistan, Egypt), AFRICA (sub-Saharan Africa, Abbreviation: AFR)
See Appendix B for details on a country level.

prevent climate change in the original RICE model is the reduction of carbon energy input, the agents are now allowed to use their production output to avoid carbon emissions by the implementation of CCS[3]. This extension of the original model theoretically offers a possibility to increase carbon energy input in the production function without increasing economically harmful carbon emissions to the atmosphere. Considering the costs of CCS and the impacts of increasing temperature on the economy, the agents choose an optimal path of carbon emission avoidance over time in order to maximize global welfare.

Exogenous parameters and their derivation were not changed and are not discussed in detail in this section; see Nordhaus and Boyer (2000) for a detailed description and Appendix C for the original mathematical framework.

Economic sector

The economic sector of the RICE model is an extension of the Ramsey model (Ramsey, 1928), including investments in the environment. The objective function to be maximized for all regions *J* and time periods *t* is the welfare function given by:

$$W = \sum_{t} \sum_{J} w_J(t)\ U[c_J(t),L_J(t)]\ R(t), \tag{1}$$

where $U[c_J(t),L_J(t)]$ is the utility of consumption of region *J* at time *t*. The flow of per capita consumption as chosen by the agents is represented by $c_J(t)$. $L_J(t)$ corresponds to the population level determined by an exogenous population growth function and $R(t)$ is the discount rate. Furthermore, Nordhaus and Boyer (2000) included a modification of Negishi-weights in the welfare function (see Negishi, 1960). The time-varying welfare weight $w_J(t)$ corresponds to the marginal product of carbon in region *J* at time *t*. The utility of consumption measures the willingness to reduce the welfare of generations with high-consumption to increase the welfare of generations with low-consumption and is represented by the Bernoullian utility function:

$$U[c_J(t),L_J(t)] = L_J(t)\{\log[c_J(t)]\}. \tag{1a}$$

The utility is discounted by the factor $R(t)$ subject to the pure rate of time preference $\rho(t)$:

$$R(t) = \prod_{v=0}^{t} [1+\rho(t)]^{-10}. \tag{1b}$$

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[3] All cost estimates used for the computational experiments include the carbon energy requirement of the CCS processes. Thus in the following, the term “CO_2 emissions captured and stored”, as used in the previous chapters, is replaced by the term “carbon emissions avoided”.

The pure rate of time preference $\rho(t)$ is a choice parameter closely connected with the marginal rate of production and the savings rate. Since the rate is assumed to be positive, future generations welfare is discounted compared to the present. Due to decreasing impatience, $\rho(t)$ is assumed to decline over time.

GDP production is represented by a Cobb-Douglas production function including the inputs of labor [$L_J(t)$], carbon energy [$ES_J(t)$] and capital [$K_J(t)$]:

$$Q_J(t) = [A_J(t)K_J(t)^{\gamma}L_J(t)^{(1-\gamma-\beta)}ES_J(t)^{\beta_J} - c^E{}_J(t)E_J(t) - t^C(t)E^H{}_J(t)]\Omega_J(t), \qquad (2)$$

where γ, β_J and the term $[1- \gamma-\beta_J]$ are the elasticities of output with respect to the production inputs. $A_J(t)$ characterizes the level of Hicks-neutral technological change and is determined exogenously for each region. Hicks-neutrality of $A_J(t)$ implies that the balance of labor, capital and carbon energy is not affected by a change in total factor productivity due to technological change. $ES_J(t)$ represents carbon energy services derived from all types of fossil fuels in terms of carbon emission units:

$$ES_J(t)^{\beta_J} = \varsigma_J(t)E_J(t), \qquad (2a)$$

All non-fossil fuel energy is assumed to be generated from a combination of capital and labor inputs. Equation (2a) determines the relationship between fossil fuel input $E_J(t)$ and the corresponding level of energy services $ES_J(t)$. Technological change in the energy sector leads to increasing energy output per unit of carbon emission and is subject to the exogenously determined parameter ς_J. The costs of carbon-energy per unit of carbon emission correspond to:

$$c^E{}_J(t) = q(t) + markup^J \qquad (2b)$$

where $q(t)$ is the wholesale price of carbon energy exclusive of the Hotelling rent and $markup^J$ is a markup on energy costs given by region specific differences. The markup on energy costs is different for all regions and is assumed to be constant over time. The wholesale price $q(t)$ is equal for all regions and depends on cumulative carbon extraction over time:

$$q(t) = \xi_1 + \xi_2[CumC(t)/CumC^*]^{\xi_3}. \qquad (2c)$$

Considering the cumulative use of carbon energy $CumC(t)$ and given the parameters ξ_1, ξ_2, ξ_3 and $CumC^*$, $q(t)$ corresponds to the global supply price of carbon energy. The total costs of carbon energy use, subtracted from the production output, are given by the term [$c^E{}_J(t)\ ES_J(t)$]. Furthermore, the term [$t^C(t)E^H{}_J(t)$] represents carbon taxation in the production function. The carbon tax $t^C(t)$ only becomes due for the share of emissions $E^H{}_J(t)$ exceeding a threshold. The tax revenue is invested in CCS as shown by equation (6). Finally, $\Omega_J(t)$ determines the level of market damage in terms of GDP losses caused by increasing temperature and is described by equations (10) and (10a).

The possibility of investment in CCS has been added to the equation representing the constraints on regional expenditures:

$$Q_J(t) = C_J(t)+I_J(t)+I^{CCS}{}_J(t)+I^F{}_J(t). \tag{3}$$

By maximizing welfare, optimal levels of consumption $C_J(t)$, capital investment $I_J(t)$, investment in CCS $I^{CCS}{}_J(t)$ and investment in future CCS $I^F{}_J(t)$ are chosen. $I^{CCS}{}_J(t)$ is defined by:

$$I^{CCS}{}_J(t) = c^C{}_J(t)E^C{}_J(t), \tag{3b}$$

where the price per emission unit avoided is $c^C{}_J(t)$ and $E^C{}_J(t)$ is the optimal level of CCS determined by the agents. Capital investments $[I_J(t)]$ contribute to the evolution of the regional capital stocks used as production input as given by:

$$K_J(t) = K_J(t-1)(1-\delta_K)^{10} + 10 \times[I_J(t-1)], \tag{4}$$

where δ_K is the annual rate of capital depreciation. The capital stock $[K_J(t)]$ is determined by capital investment $I_J(t)$. The scalar 10 is introduced in equation (4) to adjust the different temporal resolutions of the variables.

Climate sector

Greenhouse gases affect the climate due to their radiative forcing. In the RICE model only industrial CO_2 emissions are determined endogenously by the agents. All other greenhouse gas emissions, including carbon emissions from land-use change, are determined exogenously. A simple linear sub-model is used to simulate the effects of carbon emissions on the global mean temperature. On the one hand, a simple three-reservoir carbon cycle sub-model represents transportation and accumulation of carbon dioxide in the atmosphere, the upper ocean and the lower ocean. The coefficients included in the equations of this sub-model derive from calibration to established carbon cycle models. On the other hand, an equation representing radiative forcings of all greenhouse gases is used to simulate the impacts of natural and anthropogenic greenhouse gases on the global mean temperature. For this Master's thesis the climate sub-model presented by Nordhaus (2008a) was applied. Furthermore, emission avoidance by the implementation of CCS reduces the total emissions to the atmosphere deriving from economic production and land-use change.

Total global emissions to the atmosphere are represented by:

$$ET(t) = \sum_{J} [E_J(t) + LU_J(t) - CCS_J(t)], \tag{5}$$

where the industrial carbon emissions $E_J(t)$ derive from equation (2a) and $LU_J(t)$ represents exogenously determined carbon emissions from land use change. $CCS_J(t)$ corresponds to the total level of CCS and is given by:

$$CCS_J(t) = E^C{}_J(t) + [(I^F{}_J(t-1) + t^C(t)\ E^H{}_J(t)) / c^C{}_J(t)]. \tag{6}$$

$E^C{}_J(t)$ corresponds to the optimal level of emission avoidance in period *t*. CCS triggered by investment in future CCS (see equation 3) and/or the carbon tax revenue at time *t-1* (see equation 2) is represented by the term $[(I^F{}_J(t-1) + t^C(t)\ E^H{}_J(t)) / c^C{}_J(t)]$.

The end of period stocks of carbon in the different reservoirs evolve over time determined by the subsequent equations:

$$M_{AT}(t) = 10 \times ET(t) + \Phi_{11}M_{AT}(t-1) - \Phi_{12}M_{AT}(t-1) + \Phi_{21}M_{UP}(t-1), \tag{7}$$

$$M_{UP}(t) = \Phi_{22}M_{UP}(t-1) + \Phi_{12}M_{AT}(t-1) – \Phi_{21}M_{UP}(t-1) + \Phi_{32}M_{LO}(t-1)\ \Phi_{23}M_{UP}(t-1), \tag{7a}$$

$$M_{LO}(t) = \Phi_{33}M_{LO}(t-1) - \Phi_{32}M_{LO}(t-1) + \Phi_{23}M_{UP}(t-1). \tag{7b}$$

$M_{AT}(t)$ corresponds to the carbon stock in the atmosphere, $M_{UP}(t)$ to the mass of carbon in the biosphere and the upper oceans and $M_{LO}(t)$ represents the lower ocean carbon stock. The coefficients Φ_{ij} determine the transfer between the reservoirs and are calibrated against climate models.

Radiative forcings are represented by:

$$F(t) = \eta\{\log[M_{AT}(t)/M_{AT}{}^{PI}]/\log(2)\} + O(t). \tag{8}$$

$F(t)$ denotes the increase in radiative forcing since 1990 in Watts per square meter. $M_{AT}{}^{PI}$ is the pre-industrial carbon level taken to be 280ppm. $O(t)$ represents forcings of other green house gases such as CFCs, CH_4, N_2O, O_3 or aerosols and is determined exogenously. Radiative forcing leads to an increase in global mean temperature and due to heat flows the upper and lower oceans are gradually warmed too. The change in the mean atmospheric and deep ocean temperature compared to the 1990 temperature level is given by:

$$T(t) = T(t-1) + \sigma_1\{F(t) – \lambda T(t-1) – \sigma_2[T(t-1) – T_{LO}(t-1)]\}, \tag{9}$$

and $$T_{LO}(t) = T_{LO}(t-1) + \sigma_3[T(t-1) – T_{LO}(t-1)]. \tag{9a}$$

Both temperature equations depend on the feedback parameter λ, the transfer coefficients σ_i and the increase in radiative forcing represented by F(t).

Damage function

$\Omega_J(t)$ is the function incorporating the level of market damage caused by climate change to the economic sector (see equation 2) and is given by:

$$\Omega_J(t) = 1/[1 + D_J(t)] \tag{10}$$

$D_J(t)$ represents the relationship between global temperature increase and market damages in terms of GDP loss:

$$D_J(t) = \theta_{1,J}T(t) + \theta_{2,J}T(t)^2 \tag{10a}$$

$\theta_{1,J}$ and $\theta_{2,J}$ are coefficients which specify the sensitivity of the economy to a temperature increase for each region *J* individually. Damages due to temperature increase include changes in agricultural production, impacts on other vulnerable markets, health effects as well as aspects concerning coasts and settlements (see Nordhaus and Boyer, 2000). Due to the derivation of the damage function, market damages related to climate change increase exponentially in case of increasing temperature.

The results of the RICE model satisfy the following conditions:

- The savings rates are optimized for each region and time period.
- The industrial emissions satisfy the market equilibrium.
- The Hotelling rent equals the scarcity rent.
- The present value of the impact of a marginal carbon extraction on the carbon price equals the Hotelling rent.

3.2 Data used for the computational procedures

This section provides an overview of all data used for the RICE-CCS model runs. Since for certain regions considered in the RICE-CCS model not much data on large point sources are available, several estimates must be made.

3.2.1 Data of large point sources of CO_2

In order to assess the potential of CCS, the IEA Greenhouse Gas Research and Development Program (see IEA GHG) has developed a global LPS database published in the year 2002. Since the first publication, the IEA has progressively improved and updated the emission source data removing all entries concerning LPS with emissions smaller than 100Kt of CO_2 per year. The latest version of the database includes data of around 14'000 emission sources categorized among others by country, industries and fossil fuel class. The database is available on request from the IEA (see IEA, 2009b).

As shown in Table 7, 8193 LPS, which are theoretically adaptable to CCS, are assigned to the RICE-regions and have been selected for this Master's thesis. It is assumed that this data represents the distribution of the types of LPS in a region. This proxy of the structure of the regional economies was then used to calculate average CCS costs for each RICE-region (see section 3.2.2: Table 8).

Table 7: Number of emission sources (>0.1MtC/year) located in the RICE-regions (based on data from the IEA)

Source Definition	**Number of Emission Sources per RICE Region**													
	USA	**EU**	**JAP**	**CHI**	**IND**	**RU**	**EE**	**OHI**	**HIO**	**MI**	**LMI**	**LI**	**AFR**	**Total:**
Power Total	1'073	813	259	462	410	284	277	237	184	284	426	301	79	5'089
Power Coal	514	335	77	370	303	89	161	74	0	43	95	64	8	2'133
Power Gas	466	278	50	7	88	171	77	103	102	144	198	108	34	1'826
Power Oil	73	152	132	85	8	24	39	60	82	97	133	129	37	1'051
Power div.	20	48	N/A	N/A	11	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	79
Ammonia Total	19	42	5	62	25	13	17	9	1	4	15	15	4	231
Ammonia (Pure CO_2)	19	26	5	62	7	13	17	9	1	4	15	15	4	197
Ammonia (Flue Gas)	N/A	16	N/A	N/A	18	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	34
Cement	106	227	42	70	157	49	82	37	26	108	191	147	36	1'278
Hydrogen Total	30	19	16	N/A	2	0	1	14	7	7	9	1	N/A	106
Hydrogen (Pure CO_2)	25	13	15	N/A	1	N/A	N/A	11	6	5	N/A	N/A	N/A	76
Hydrogen (Flue Gas)	5	6	1	N/A	1	0	1	3	1	2	9	1	N/A	30
Iron & Steel	44	232	12	23	50	9	54	15	3	27	20	7	3	499
Ethanol	90	55	13	21	14	11	14	15	11	44	20	22	12	342
Ethanol (Pure CO_2)	7	3	0	N/A	1	N/A	N/A	2	2	1	N/A	N/A	N/A	16
Ethanol (Flue Gas)	83	52	13	21	13	11	14	13	9	43	20	22	12	326
Refineries	135	101	35	50	31	32	33	38	21	37	66	45	24	648
Total	1'497	1'489	382	688	689	398	478	365	253	511	747	538	158	8'193

3.2.2 Cost estimates of CCS

Transport and storage costs

Following the approach of Dooley et al. (2008), carbon transport and storage costs (including measurement and monitoring) are assumed to be \$15/tCO_2 (\$55/tC^{-1}) for all types of LPS and RICE-regions.

Capture and compression costs

For the different types of LPS, the capture costs estimated by the IPCC (2005) and Dooley et al. (2006) were used to determine individual regional CO_2 capture cost levels. The average capture costs for the RICE-regions were determined by weighting the proportion of different types of LPS. Compression costs are assumed to be the same for all types of emission sources whereas capture costs vary widely. CO_2 capture from power plants, cement manufactories or iron&steel production facilities is generally more cost intensive than CO_2 capture from pure CO_2 gas streams which result from high technology ammonia, ethanol or hydrogen production. Thus, regions including many LPS with high CO_2 capture costs have to deal with higher average CCS costs (see section 2.1: Table 2; section 3.2.1: Table 7; Appendix B).

Table 8 shows the estimated regional CCS costs used for the computational experiments. The costs range from 53\$ (CHINA) to 63\$ (HIO) per tCO_2 (193\$ to 231\$ per tC).

Table 8: Estimated average costs of CCS for the RICE-regions in \$US (including Capture & Compression, Transport, Storage and Monitoring Costs)

Total CCS Costs (including Capture & Compression, Transport, Storage and Monitoring Costs)	**RICE-Region**												
	USA	**EU**	**JAP**	**CHI**	**IND**	**RU**	**EE**	**OHI**	**HIO**	**MI**	**LMI**	**LI**	**AFR**
Power Generation [\$ per tCO_2]	62	61	62	56	59	64	60	63	68	65	64	64	66
Power Generation [\$ per tCO]	226	225	61	206	215	234	220	231	249	239	235	233	241
Other Industry (estimated) [\$ per tCO_2]	47	49	223	45	52	51	50	48	49	49	54	54	52
Other Industry (estimated) [\$ per tCO]	171	178	178	166	191	188	184	174	181	181	198	197	191
Weighted Average CCS Costs [\$ per tCO_2]	57	56	57	53	56	60	56	58	63	58	60	59	59
Weighted Average CCS Costs [\$ per tC]	211	204	208	193	205	221	205	211	231	214	219	217	216

3.2.3 GDP and emission data

Table 9 shows initial regional GDP and emission data of the year 2005 used for the calibration of the RICE-CCS model. National GDP data was used as provided by the United Nations Statistics Division[4]. The physical capital stock of the RICE-regions for the year 2005 was estimated based on GDP data of the period from 1960 to 2005, assuming savings rates of 20% and capital discount rates of 10% per year (see Appendix B for details on a national level). All emission data has been used as provided by the CDIAC[5]. The emission cap used for scenarios including carbon penalty taxation (see section 4.3) equals the 1990 CO_2 emission level for the high income RICE-regions (EU, USA, Japan and OHI). For the middle and low income RICE-regions (EE, RUSSIA, CHINA, INDIA, HIO, MI, LMI, LI and AFRICA), the emission cap corresponds to the 2005 emission level assuming that these regions agree to take action regarding the mitigation of climate change in the entire period covered by the model runs.

Table 9: Initial Data used for the Computational Experiments

Data	**RICE-Region**													
	USA	**EU**	**JAP**	**CHI**	**IND**	**RU**	**EE**	**OHI**	**HIO**	**MI**	**LMI**	**LI**	**AFR**	**Total:**
CO_2 Emissions[5] **2005** [GtC]	1.57	0.96	0.35	1.66	0.41	0.43	0.34	0.31	0.21	0.31	0.74	0.34	0.05	7.69
Emission Cap[5] [GtC]	1.33	0.83	0.32	1.66	0.41	0.43	0.34	0.24	0.21	0.31	0.74	0.34	0.05	7.21
GDP 2005[4] [trillion US$ 2000]	11.05	9.13	4.99	1.89	0.64	0.35	0.58	2.05	0.46	1.88	2.10	0.81	0.21	36.15
Capital Stock 2005[4] [trillion US$ 2000]	17.34	15.32	8.59	2.12	0.83	0.48	0.83	2.49	0.65	2.85	3.20	1.16	0.34	56.22

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[4] GDP data (at market prices, constant US$ 2000) as provided by the United Nations Statistics Division. Available at: http://data.un.org/

[5] Sum of national CO_2 emissions as provided by the “Carbon Dioxide Information Analysis Centre” (CDIAC). Available at: http://cdiac.ornl.gov/

4 Scenarios

The incorporation of CCS in the RICE model is in the focus of the scenarios described in this section. In one scenario group the agents determine individually the optimal amount of carbon emissions avoided with respect to the maximization of welfare. A second group of scenarios includes exogenous CCS policies whereas all other decisions allowed by the model framework are entrusted to the agents. In addition, general assumptions concerning CCS and a reference scenario used as benchmark for the scenario analysis are described in this chapter.

4.1 Optimal scenario

The optimal scenario as given by the RICE-99 model excluding CCS (see Nordhaus and Boyer, 2000a) is used as a benchmark. This scenario includes a regional climate damage function internalizing shadow costs of carbon emissions in the economic sector of the model. Thus, carbon energy use and savings rates are optimized with respect to the expected social costs of carbon in terms of market damages. The agents have the possibility to compensate carbon energy used for production by increasing the savings rates in order to change the physical capital stock available for production. In the optimal scenario, carbon energy use is reduced in comparison to a “business as usual” (BAU) scenario neglecting the impacts of carbon emissions on the economic system. Therefore, the optimal scenario has been chosen as a benchmark since CCS would not be implemented in a BAU scenario. The aim of the comparison of the scenarios including CCS with the optimal scenario is to quantify the effects of CCS on regional and global welfare as well as on the climate system.

4.2 Endogenous CCS scenarios

In the endogenous scenarios, the agents have the possibility to avoid up to 30% or 0.5 GtC of their annual carbon emissions. The 30% threshold has been chosen since the IPCC (2005) projects that 21-45% of total global emissions could be avoided by CCS in 2050. Depending on benefits gained by lowering the damages caused by increasing temperature, the agents determine an optimal amount of carbon emissions avoided. CCS is defined as an investment in emission reduction and the share of total output used for CCS is not available for other purposes anymore. Thus, CCS investment is in competition with capital investment and consumption. Since the shadow costs of carbon and the costs of CCS vary between the RICE-regions, the agents have different incentives to reduce their carbon emissions to the atmosphere by conducting CCS. In general, a rational agent will implement CCS technologies as long as the marginal welfare of an emission reduction is higher than the welfare loss due to the costs of CCS. The following endogenous CCS scenarios have been designed:

a) Scenario ENDO-REG:

In the ENDO-REG scenario, an optimal amount of CCS is determined individually for all regions and time periods. Based on regional CCS cost estimates and the expected level of market damages due to climate change, an optimal path of regional CCS implementation in order to maximize global welfare is sought.

b) Scenario ENDO-GLOBAL:

The result of the ENDO-GLOBAL scenario is an optimal path of global CCS conduction assuming that all regions avoid equal amounts of carbon emissions per capita in all time periods. The per capita allocation of global CCS leads to a burden sharing avoiding the possibility to free ride on the CCS emission reductions of regions with higher shadow costs of carbon or a lower welfare weight in the objective welfare function of the RICE model.

c) Scenarios ENDO-REG-TC and ENDO-GLOBAL-TC

In addition, both scenarios described above were computed including exogenously driven technological change in CCS. The level of technological change has been set arbitrary in order to show effects of a possible decrease in CCS costs. The design is analogue to the exogenous level of technological change influencing the total factor productivity in the RICE model (see Nordhaus and Boyer, 2000). Since free deployment of CCS technology is assumed (see section 4.4), the level of technological change is equal for all regions and leads to a decrease in CCS costs over time. The minimum costs of CCS are assumed to be US$120 per ton of carbon avoided and are mainly driven by economies of scale and an expected shift to IGCC technologies which have an optimal applicability of CCS (see e.g. Al–Juaied et al., 2009; IEA, 2009a).

4.3 Exogenous CCS Scenarios

The evaluation of the economic and environmental effects of different exogenous CCS policies is in the focus of these scenarios. The agents have the possibility to optimize savings rates and consumption levels given a non optimal level of CCS. Since the level of CCS is determined exogenously, these scenarios are normative by definition. The following exogenous CCS scenarios have been designed:

a) Scenarios EXO and EXO-ANNEX B:

In the EXO scenario the level of carbon emissions avoided is defined as a percentage of the 2005 carbon emission level. The level of CCS increases linearly reaching the maximum percentage by the year 2055. Two levels of CCS have been considered for the computational experiments: 15% (EXO-15 scenario) and 30% (EXO-30 scenario) of the 2005 carbon emission level. 30% of the 2005 emission level corresponds to 2186 MtC. The IEA Technology Roadmap (see IEA, 2009a) postulates a target of 2730 MtC (10 $GtCO_2$) emissions avoided by the implementation of CCS by the year 2050. Thus, the maximum exogenous level of CCS chosen for the computational experiments seems to be defensible. Based on the geographic analysis of the number of LPS the regions AFRICA and LI are excluded from CCS conduction (see section 2.1; Figure 2). This approach was chosen to guarantee a certain level of inter-regional equity. On the one hand, the high-income regions at present have high per capita emissions and thus will have constant high per capita CCS in the future. On the other hand, the low-and middle-income regions will only suffer from slight constraints in their economic development. Since carbon emissions increase as a consequence of economic growth, the share of total carbon emissions to be avoided will decrease over time. In addition per capita CCS will decrease due to a growth in population which is expected especially in the low-and middle-income regions.

The EXO-ANNEX B scenarios (EXO-ANNEX B-15 and EXO-ANNEX B-30) are designed similarly to the EXO scenarios, but only those regions listed in the ANNEX B of the Kyoto Protocol (EUROPE, JAPAN, USA and OHI) are obliged to conduct CCS (see UN, 1997).

b) Scenario EXO-TAX and EXO-ANNEX-B-TAX:

In the EXO-TAX scenario, a penalty tax-mechanism is used to determine the amount of carbon emissions avoided by the implementation of CCS. If a region emits more carbon than allowed by the emission cap (see section 3.2.3; Table 9), a tax is put on the emission share exceeding the threshold. The sum of the tax revenue is invested directly in the implementation of CCS in the region paying the tax. If a region does not emit as much carbon as allowed by the emission cap, an extra income is provided due to a “negative” taxation of the gap between actual carbon emissions and the emission threshold. The tax mechanism has a design ensuring that no tax income is achievable if total global emissions undercut the sum of the regional emission caps. Following the approach of McFarland et al. (2002), carbon taxation is implemented by the year 2015 and increases linearly over time. The maximum tax, put on carbon energy services exceeding the regional emission threshold, is 50US$ per ton of carbon (14US$ per ton of CO_2) and is reached by the year 2055.

The EXO-ANNEX B-TAX scenario is designed similarly to the EXO-TAX scenario. Though, carbon taxation is only assigned to regions including high-income countries listed in the ANNEX B of the Kyoto Protocol (see UN, 1997) namely the regions EUROPE, JAPAN, USA and OHI.

4.4 Assumptions concerning CCS

To simplify the incorporation of CCS in the RICE-99 framework several assumptions have been respected in all scenarios:

- The agents are not allowed to increase the amount of carbon emissions avoided in one time step by more than a factor 2.
- Geophysical and legal restrictions concerning CCS are neglected.
- Market damages due to leakage from storage sites or transport systems are assumed to be zero.
- The carbon storage capacity is not limited since the estimated global storage capacity is a multiple of total global emissions in the time period covered by the model runs. As a consequence, CCS costs are not increasing due to scarcity of the storage capacity.
- Free access to perfect knowledge concerning deployment and implementation of CCS technologies is assumed.
- The share of LPS in total carbon emissions is taken to remain constant at a level of around 60% in the time period covered by the model runs.

5 Results and Discussion

The results of the scenarios described in chapter 4 are presented and discussed subsequently. All computations were carried out using non linear programming (NLP) with the "General Algebraic Modeling System" (GAMS). The GAMS code for the RICE-CCS model was designed based on the "RICE-99 GAMS code" as provided by Nordhaus and Boyer (2000a). All exogenous parameters, trend data and elasticises included in the RICE-CCS model were used as provided by Nordhaus and Boyer (2000a). Results are reported till 2115 but computations are carried out till 2205 to reduce end-of-time-horizon effects. Following the approach of Nordhaus and Boyer (2000), global welfare is defined as the sum across regions of the present value of consumption in the entire period of observation.

Efficiencies guaranteed by the RICE model

According to Nordhaus and Boyer (2000), the results from solving the RICE model satisfy the following types of efficiency:

- "How-efficiency" denotes efficient strategies to achieve emission reductions in a given year and region. For this Master's thesis, it is assumed that how-efficiency can be attained by choosing optimal levels of CCS and carbon emissions regarding market damages due to climate change.
- "Where-efficiency" refers to an efficient allocation of emission mitigation efforts across regions in order to maximize global welfare. The population level and the marginal product of carbon energy are the key factors determining where-efficiency.
- "When-efficiency" denotes allocating emissions over time. A when-efficient policy seeks an emissions path which minimizes the present value of the costs of emission reductions.
- "Why-efficiency" refers to balancing the costs of abatement and the benefits of reducing market damages due to climate damage.

The optimal scenario (used as a benchmark) and the endogenous CCS scenarios satisfy all types of efficiency mentioned above. In contrast, the exogenous scenarios are in parts when-efficient (with respect to the degree of freedom left to the agents). Since the levels of emission avoidance are chosen arbitrarily the results do not satisfy how-, where-and why-efficiency.

5.1 Optimal scenario

The optimal scenario provides results with respect to the level of expected market damage due to climate change. There are substantial differences between the optimal scenario including impacts of the climate system on the economy and a “BAU” scenario not respecting climate damages. All regions except OHI and RUSSIA suffer from a net loss in welfare due to increasing temperature. The net benefit of OHI and RUSSIA is mainly explained by an increase in agricultural production (see Nordhaus and Boyer, 2000). Table 10 provides an overview of selected variables which vary beeing influenced by climate change. In the period from 2005 to 2115 the internalization of the shadow costs of carbon leads to a decrease of 0.64% in global welfare and 0.81% in discounted global GDP respectively. On a regional scale, the changes in welfare show a range of +0.8% (OHI) to -4.38% (INDIA). In terms of regional discounted per capita GDP results ranging from +0.89% (OHI) to -3.9% (INDIA) have been found. Since a decrease in GDP leads to changes in the savings rates, a lower income does not necessarily cause an analogue decrease in welfare.

Table 10: Optimal scenario: Changes in economic and environmental variables due to the internalization of climate damage in the economic sector of the RICE model in comparison to a “business as usual” scenario (period 2005-2115)

	Global Consumption	**Global GDP**	**Global Emissions**	**Temperature Increase**
Global Impact of Climate Damage	- 0.64%	- 0.81%	2005: -4.57% 2115: -81.57%	2115: -0.42°C
Regional Impact of Climate Damage	Max: -4.38% Min: +0.8%	Max: -3.9% Min: +0.88%	n/a	n/a

Furthermore, the incorporation of climate damage leads to a significant mitigation of carbon emissions. The reduction can be explained by substitution of carbon energy by capital in the production function. Thus, by the year 2005, carbon emissions are increased by 4.57% compared to the level of emissions found in a scenario excluding impacts of climate change on the economic sector of the RICE model. The emission reduction increases over time reaching a maximum of 81.57% by the year 2115. At the end of the period of observation, the temperature increase is reduced by 0.42°C amounting to 2.639°C above the pre-industrial level compared to 3.06°C in a scenario assuming “business as usual” carbon emissions (see Table 10).

5.2 Endogenous CCS scenarios

As described in chapter 4 the endogenous scenarios expand the optimal scenario by the possibility of avoiding carbon emissions by the implementation of CCS. Thus, carbon emissions could be reduced not affecting the level of carbon energy services used for economic production. On the one hand, the endogenous scenarios seek for optimal levels of regional CCS emission avoidance (scenario ENDO-REG). On the other hand, an optimal level of global per capita CCS is computed (scenario ENDO-GLOBAL). In this section the findings of all endogenous scenarios are presented on global and on regional scale. Since the agents do not invest in future CCS (see section 3.1: Equations 5 + 6) in all endogenous scenarios, this aspect is not included in the discussion of the scenario results. All findings regarding economic and environmental variables are presented and discussed in comparison to the optimal scenario.

5.2.1 Endogenous CCS scenarios - global analysis

a) Global CCS, carbon emissions and temperature

Overall, no considerable changes in carbon energy use (and thus in carbon emissions) have been observed in the analysed time horizon. On a global scale, the scenarios show a decrease of 0.06% (ENDO-REG) and 0.24% (ENDO-GLOBAL) respectively. As shown in Figure 8, there are almost no carbon emissions avoided by the implementation of CCS until the year 2055. However, in the period from 2055 to 2115 the results show different paths of CCS deployment for both the ENDO-REG and the ENDO-GLOBAL scenarios. On the one hand, the implementation of CCS increases exponentially in the period from 2055 to 2115 in the ENDO-REG scenario. A maximum of 672 MtC or 6.62% of annual global carbon emissions are avoided by the year 2115 (see Figure 8). The observed temperature increase is 2.634°C in comparison to the pre-industrial level and is reduced by 0.05°C in comparison to the optimal scenario (2.639°C). On the other hand, only a marginal amount of the global carbon emissions is avoided by the implementation of CCS in the ENDO-GLOBAL scenario. As shown in Figure 8, emission avoidance does not emerge until the year 2085 and reaches a maximum of 25 MtC by the year 2115 (see Figure 8). This global maximum is equivalent to 2,3kgC avoided per capita and 0.25% of annual global carbon emissions respectively. In comparison to the optimal scenario, the temperature increase amounts to 2.638°C by the year 2115 and is reduced by 0.001°C. For both endogenous CCS scenarios, the negligibility of the changes in temperature at the end of the period of observation can be explained by the time lag between the reduction in global carbon emissions and the change in global mean temperature determined by the climate sub-model of the RICE-CCS model.

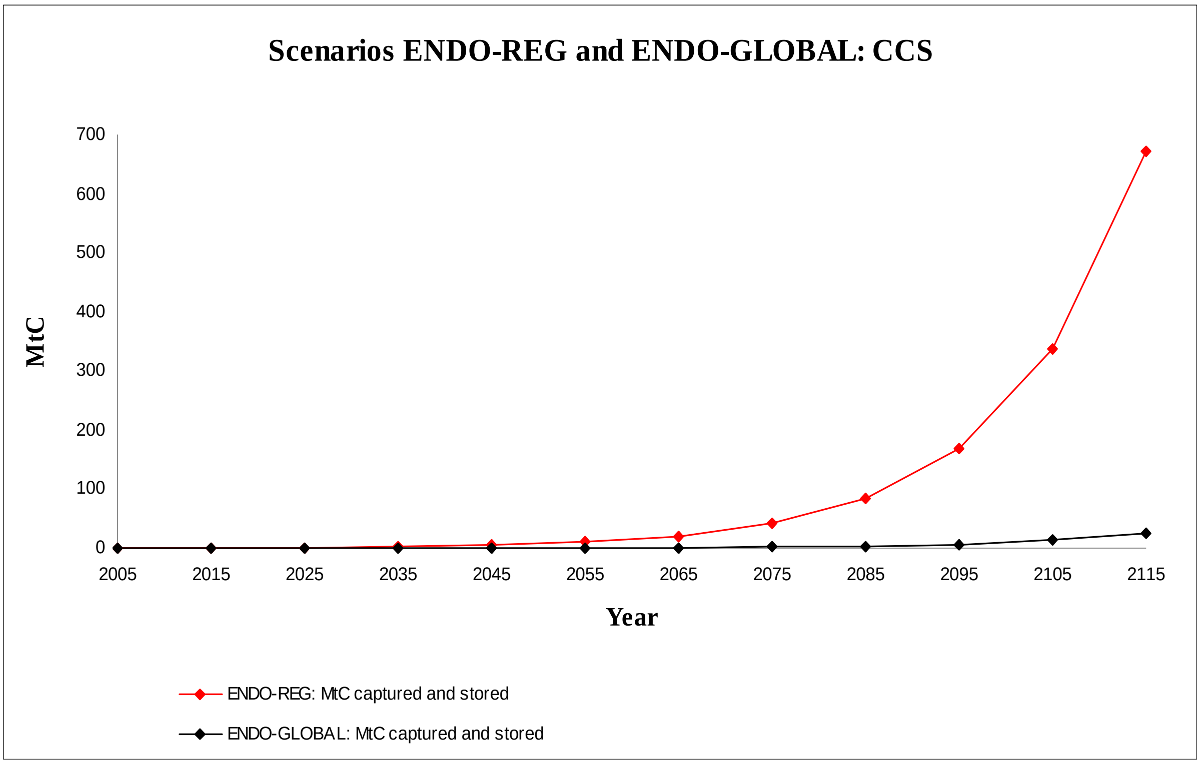

Figure 8: Scenarios ENDO-REG and ENDO-GLOBAL: MtC of global emissions avoided (period 2005-2115)

b) Global welfare, GDP and savings rates

Table 11 shows global economic impacts of the implementation of CCS in the period from 2005 to 2115 in comparison to the optimal scenario. The changes in the economic variables are very small. On a global scale, the RICE-CCS model finds changes in welfare of -12US$ billion (ENDO-REG) and -4US$ billion (ENDO-GLOBAL). In terms of global GDP, the results show a range of +3US$ billion (ENDO-REG) and -13US$ billion (ENDO-GLOBAL). The average global savings rates of the period from 2005 to 2115 persist almost at the level of the optimal scenario in both endogenous CSC scenarios. However, they can be used to explain the difference between changes in welfare and GDP since savings reduce the fraction of the GDP available for consumption. The global savings rates are slightly reduced in the ENDO-GLOBAL scenario and slightly enhanced in the ENDO-REG scenario respectively. Corresponding to this finding, the ENDO-REG scenario reports an increase in GDP whereas the ENDO-GLOBAL scenario shows an inverse result. As mentioned above, no considerable decrease in global mean temperature has been observed. Thus, potential benefits of an emission reduction occur after the time period of observation. Based on this consideration the insubstantial changes in welfare and GDP due to the implementation of CCS are intuitively comprehensible.

Table 11: Endogenous CCS scenarios: Changes in economic variables due to the implementation of CCS in comparison to the optimal scenario (period 2005-2115)

Scenario	**Global Consumption** [US$ billion]	**Global GDP** [US$ billion]	**Change in Average Global Savings Rate** (2005-2115)
ENDO-REG	- 12	+ 3	+ 0.01%
ENDO-GLOBAL	- 4	- 13	- 0.02%

5.2.2 Scenario ENDO-REG – regional analysis

a) Regional CCS and investment in CCS

Figure 9 shows the development of regional CCS deployments in the period 2005-2115. Only minor parts of regional carbon emissions are avoided until the year 2055. Though, in the second half of the 21st century the level of CCS increases exponentially. The regions avoiding parts of their emissions are EE, RUSSIA, CHINA, INDIA and LI. Since the marginal product of carbon is represented by a welfare weight in the objective function of the RICE model, the regions having a low GDP/carbon emission ratio are foremost “forced” to implement CCS. This effect dominates the incentive to implement CCS due to the level of regional climate damages. Thus, the region EUROPE, which is supposed to have greater negative impacts from temperature increase than CHINA, RUSSIA and EE, does not conduct CCS. However, CHINA and INDIA are the only regions which are willing to capture and store a substantial part of the regional carbon emissions: CHINA avoids a maximum of 30% (502 MtC) and INDIA of 16% (141 MtC) of by the year 2115. As shown in Figure 10, the willingness to invest in CCS is increasing over time but does not exceed 0.3% of annual GDP for all regions and time periods. CHINA (0.28%) and INDIA (0.25%) are the only regions investing more than 0.1% of their annual GDP in CCS by the end of the period of observation.

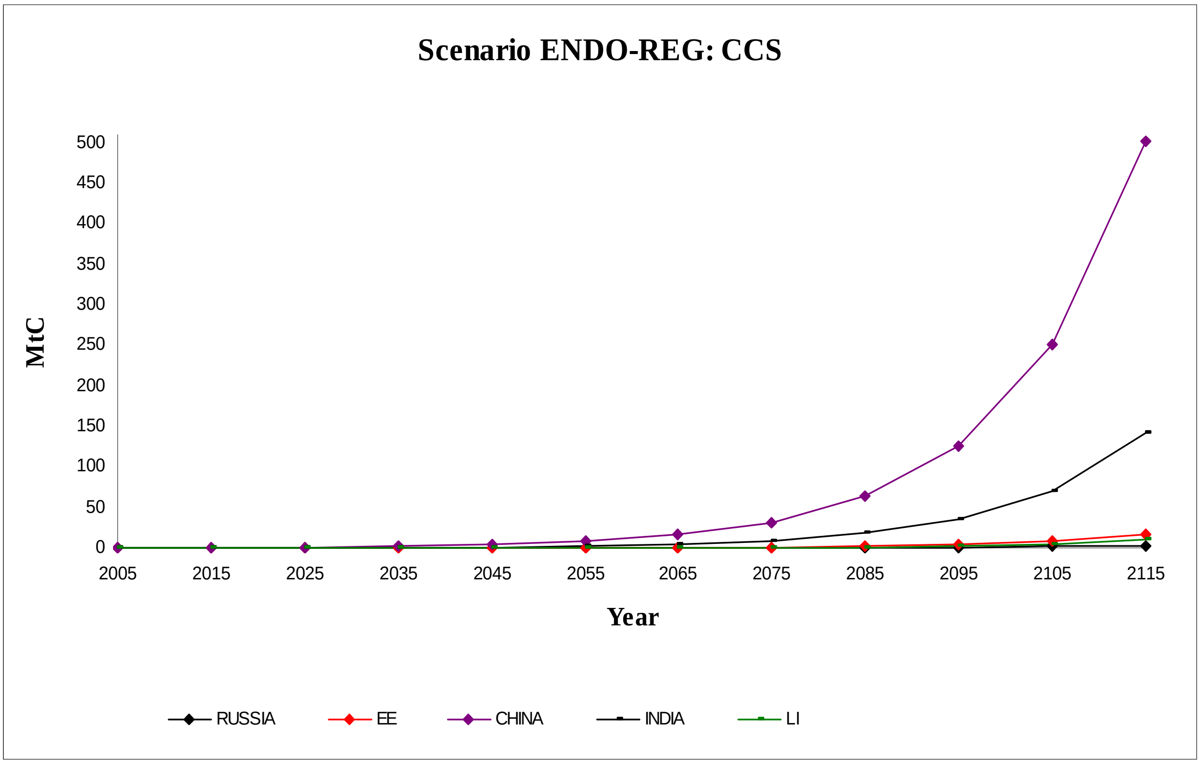

Figure 9: Scenario ENDO-REG: MtC of regional emissions avoided (period 2005-2115)

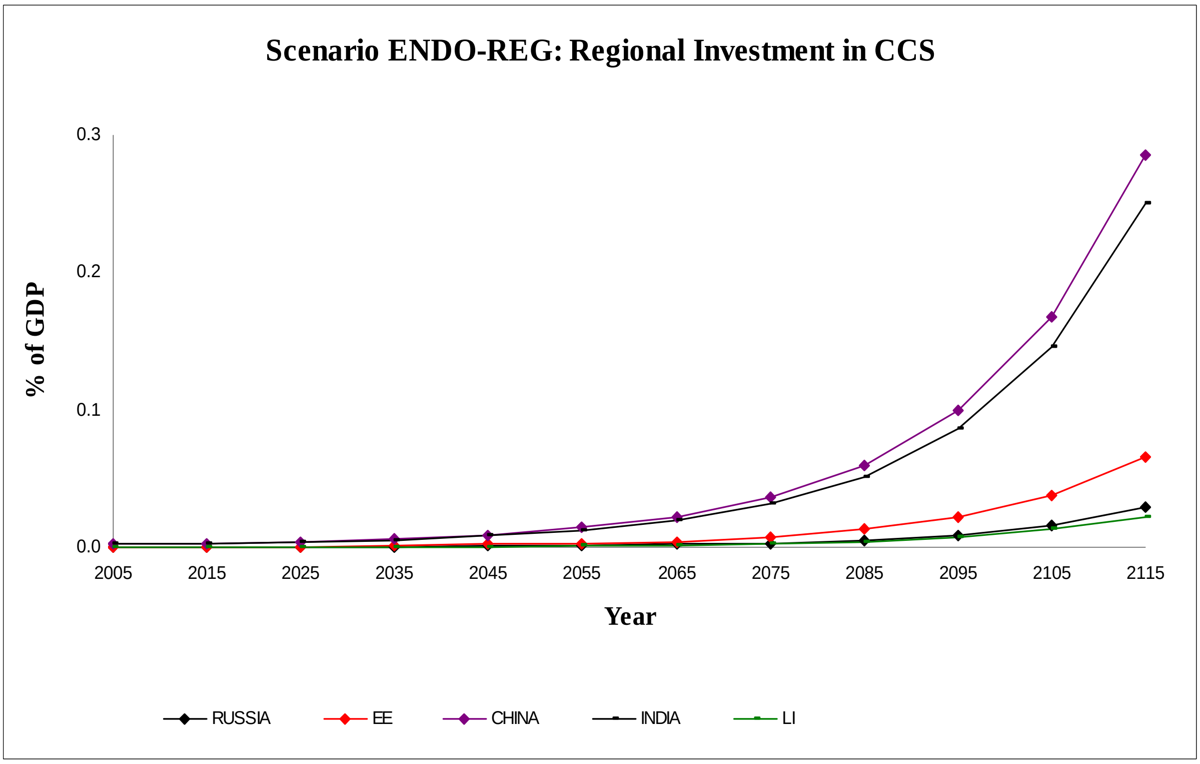

Figure 10: Scenario ENDO-REG: Investment in CCS as a percentage of annual GDP (period 2005-2115)

b) Regional Welfare, GDP and savings rates

As mentioned before, no substantial changes in temperature increase have been observed in the period of observation compared to the optimal scenario. Thus, for regions not conducting CCS, the occurrence of free riding on emission abatement can be excluded. Table 12 gives an overview on total changes in economic variables compared to the optimal scenario of those regions avoiding parts of the regional carbon emissions by the implementation of CCS. The results do not show considerable changes in welfare in the period from 2005 to 2055. From 2055 to 2115, regional welfare losses increase over time reaching a maximum in the range of 0.82% (LI) to 1.37% (INDIA) by the year 2115. Overall, the findings show varying levels of decrease in welfare and per capita GDP. RUSSIA, EE and LI suffer from a minor decrease in welfare which corresponds to the loss in regional per capita GDP. However, CHINA and INDIA loose 0.1% of their total regional welfare. In addition, the greatest changes in the average savings rate have been observed for these regions. Thus, the gap between welfare loss and reduction in regional GDP of 0.09% for CHINA and 0.06% for INDIA can be explained.

Table 12: Scenario ENDO-REG: Changes in economic variables due to the implementation of CCS (period 2005-2115; percentages in relation to the optimal scenario)

Region	**Change in Global Consumption**	**Change in GlobalGDP**	**Change in Average Savings Rate** (2005-2115)
RUSSIA	- 0.04%	- 0.03%	- 0.001%
EE	- 0.04%	- 0.02%	+ 0.009%
CHINA	- 0.1%	- 0.01%	+ 0.033%
INIDIA	- 0.1%	- 0.03%	+ 0.056%
LI	- 0.06%	- 0.04%	- 0.007%

5.2.3 Scenario ENDO-GLOBAL – regional analysis

a) Regional investment in CCS

In the ENDO-GLOBAL scenario, the willingness to pay for CCS is increasing over time but does not exceed 0.04% of annual GDP in any region until the year 2115 (see Figure 11). By the year 2115 AFRICA (0.038%) and LI (0.011%) must invest the highest percentage of their

GDP in CCS to guarantee the demanded level of per capita CCS. The high-and middle-income regions, as represented by the USA in Figure 11, invest less than 0.003% of their annual GDP in the abatement of carbon emissions by implementing CCS. In comparison to the ENDO-REG scenario the results show, that those regions not suffering significantly from climate damage suppress the global willingness to invest in CCS.

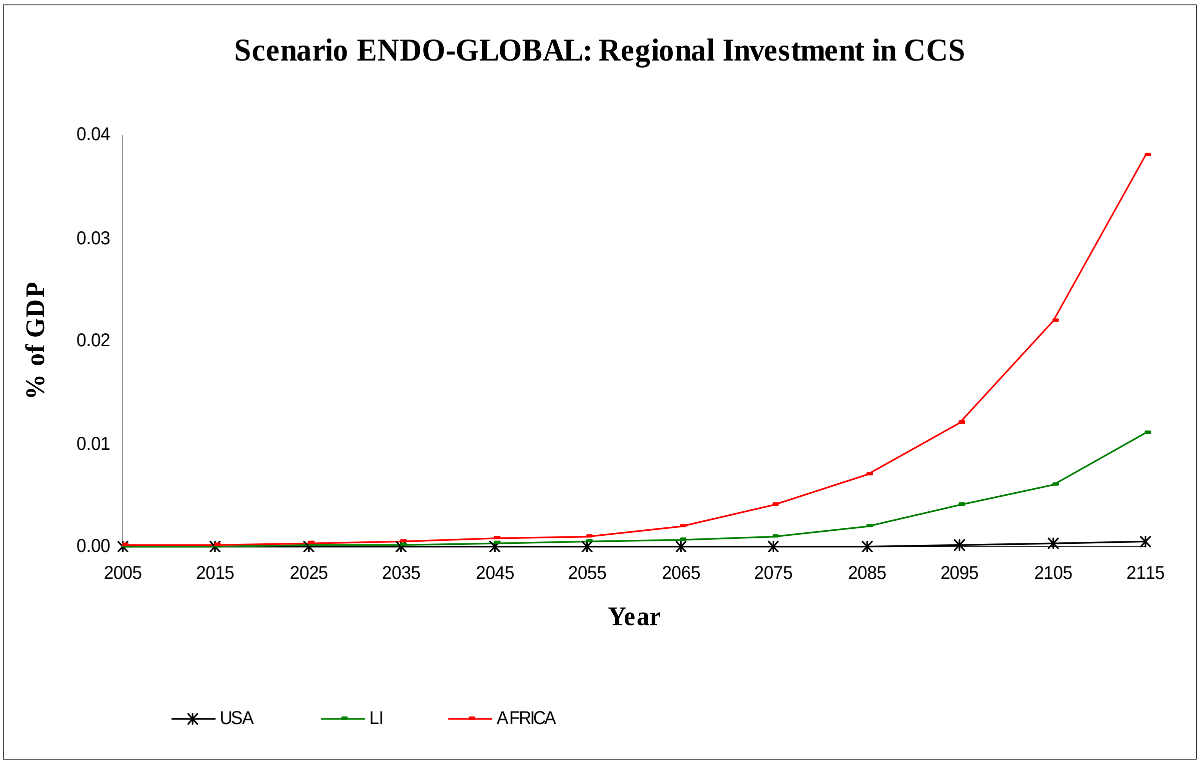

Figure 11: Scenario ENDO-GLOBAL: Investment in CCS as a percentage of annual GDP (period 2005-2115)

b) Regional Welfare, GDP and savings rates

In comparison to the optimal scenario, the global implementation of equal per capita CCS does not lead to considerable changes in the regional economic variables considered for the economic analysis. This finding is explained by the fact that only minor amounts of carbon emissions are avoided and thus, no substantial changes in comparison to the optimal scenario are observed. AFRICA suffers from the greatest loss in welfare (0.04%) and per capita GDP (0.04%). For all other regions neither an increase nor a decrease greater than 0.01% in welfare or per capita GDP has been observed.

5.2.4 Endogenous CCS scenarios expanded by technological change

In this section the impacts of technological change in CCS technologies on the presented endogenous scenarios is analyzed. Figure 12 shows the CCS cost curves of the regions HIO and CHINA. HIO derives the major part of its electricity from gas power plants and thus has the highest initial CCS costs. CHINA on the contrary, has the lowest initial CCS costs of all RICE-regions, depending mainly on energy services derived from coal combustion (see section 3.2.1; Table 7). The CCS cost curves of all other regions run between those of CHINA and HIO.

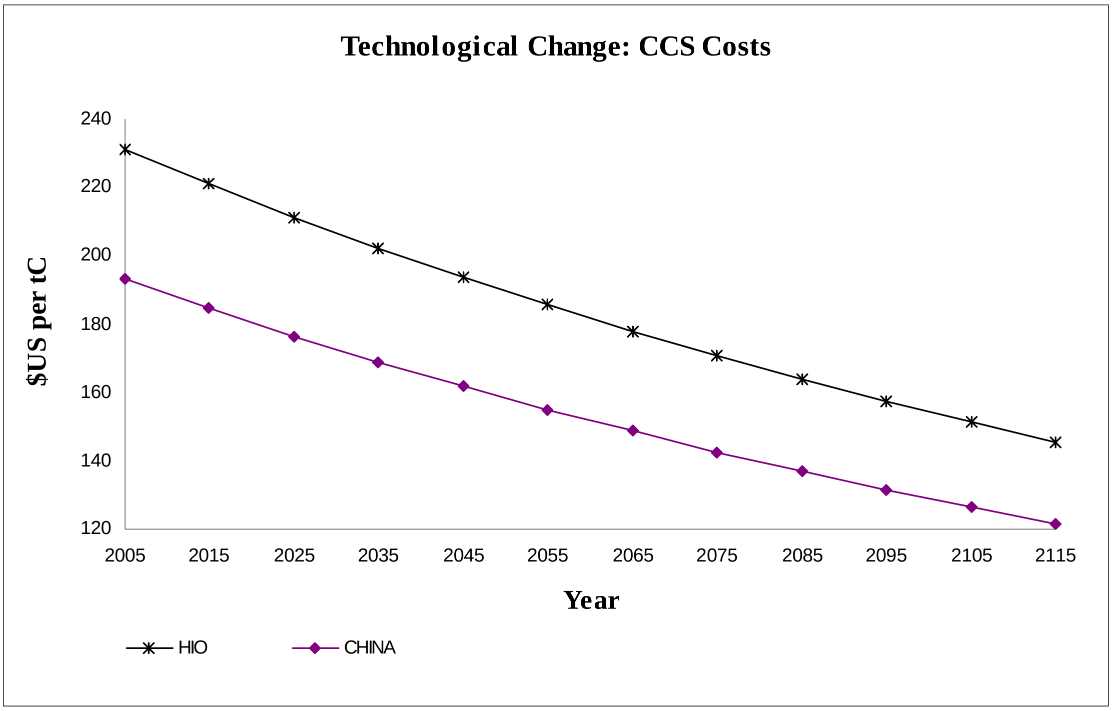

Figure 12: CCS cost curves for the regions HIO and China (period 2005-2115)

a) Global CCS, carbon emissions and temperature

The results of the scenarios ENDO-REG-TC and ENDO-GLOBAL-TC are discussed in comparison to the corresponding CCS scenario excluding technological change as well as to the optimal scenario. Figure 13 shows the amount of carbon captured and stored in the endogenous scenarios including and excluding a decrease in CCS costs. For both the ENDO-REG and the ENDO-GLOBAL scenarios, the incorporation of technological change leads to a substantial increase in the deployment of CCS. However, the global level of emission avoidance as sought in the ENDO-GLOBAL scenario is affected much more by the introduction of technological change than the sum of the regional emission avoidance as sought in the ENDO-REG scenario.

In the ENDO-REG scenario, the deployment of CCS starts 20 years earlier due to the incorporation of technological change. The percentage of total carbon emissions avoided is increasing over time from 0.03% in the year 2015 to 11.2% by the year 2115. In terms of MtC emissions avoided, technological change leads to an increase from 673 MtC (ENDO-REG) to 1169 MtC (ENDO-REG-TC) at the end of the period of observation. Overall, 3.1% of the global carbon emissions are avoided by the implementation of CCS in the period 2005-2115 compared to 1.16% in the scenario ENDO-REG excluding technological change (+ 74%). The temperature increase amounts to 2.62°C by the year 2115. This finding corresponds to a mitigation of 0.015°C compared to the ENDO-REG scenario and 0.02°C regarding the optimal scenario.

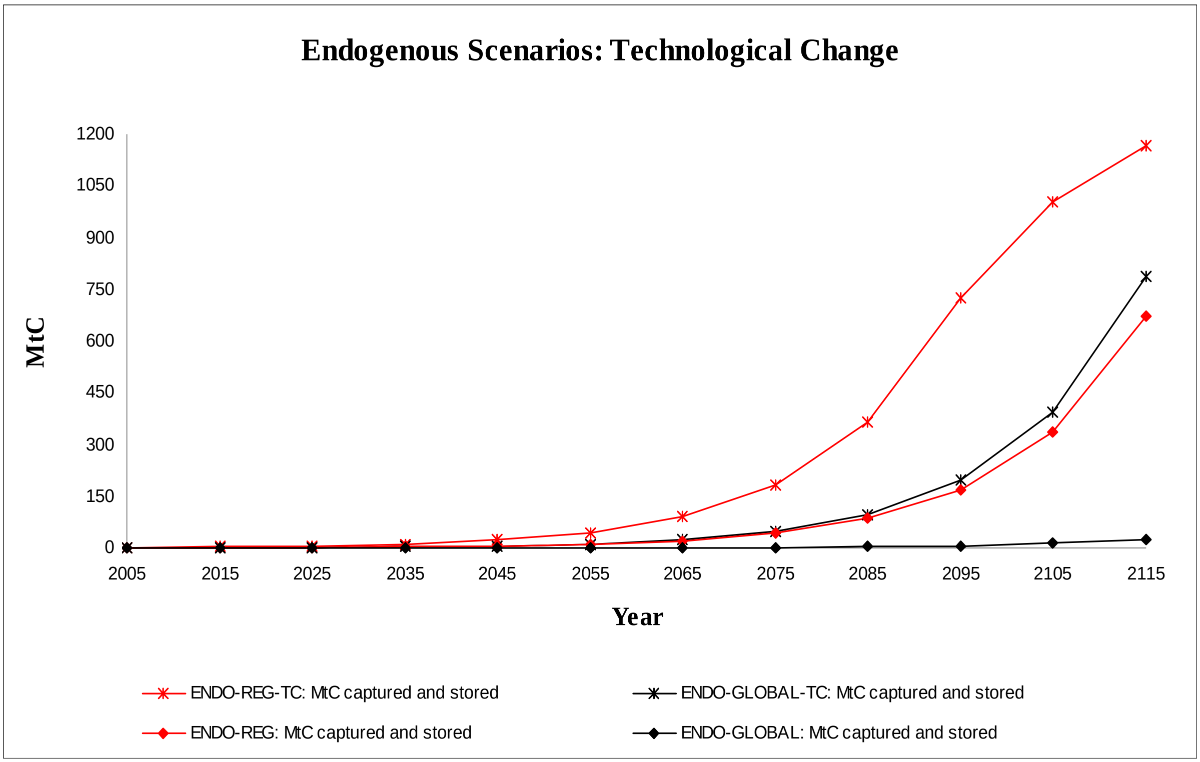

Figure 13: Endogenous CCS scenarios including technological change: MtC of total global emissions avoided (period 2005-2115)

In the ENDO-GLOBAL-TC scenario, CCS emerges by the year 2055 and increases exponentially until the end of the period of observation (see Figure 13). The maximum optimal amount of per capita CCS corresponds to 72.2kg by the year 2115 compared to 2.3kgC per capita in the scenario ENDO-GLOBAL excluding technological change. Emission abatement increases from 25 MtC (ENDO-GLOBAL) to 785 MtC (ENDO-GLOBAL-TC) by the year 2115. In terms of total global emissions the results correspond to an avoidance of 1.36% (ENDO-GLOBAL-TC) compared to 0.04% (ENDO-GLOBAL) in the period 2005-2115. By the year 2115, the temperature increase amounts to 2.63°C and is diminished by 0.08°C compared to the ENDO-GLOBAL scenario and by 0.09°C regarding the optimal scenario.

b) Global Welfare, GDP and savings rates

Table 13 shows global economic impacts of the incorporation of technological change in the RICE-CCS model. Compared to the endogenous CCS scenarios excluding technological change, the increase in emission avoidance leads to a welfare loss of 18US$ billion (ENDO-REG-TC) and 12US$ billion (ENDO-GLOBAL-TC) in the period of observation. In comparison to the optimal scenario, the characteristics of the changes in welfare, global GDP and savings rates remain mostly the same and but are slightly enhanced. The ENDO-REG scenarios both show an increase in GDP due to the change in the savings rates whereas for the ENDO-GLOBAL scenarios the savings rates are slightly reduced and thus diminish the effect of a decrease in GDP on welfare.

Table 13: Endogenous CCS scenarios including and excluding technological change: Changes in economic variables due to the implementation of CCS in comparison to the optimal scenario (period 2005-2115)

Scenario	Global Consumption [US$ billion]	Global GDP [US$ billion]	Change in Average Global Savings Rate (2005-2115)
ENDO-REG	- 12	+ 3	+ 0.001%
ENDO-REG-TC	- 30	+ 22	+ 0.002%
ENDO-GLOBAL	- 4	- 13	- 0.003%
ENDO-GLOBAL-TC	- 16	- 47	- 0.022%

c) Scenario ENDO-REG-TC: Regional CCS investment

As shown in Figure 14, all regions except EUROPE, USA, OHI and JAPAN conduct CCS in the ENDO-REG-TC scenario. However, besides CHINA and INDIA only the regions

RUSSIA (15%) and EE (14.7%) avoid a substantial part of their carbon emissions by the year 2115. All other regions capture and store emissions within the range of 0.6% (HIO) and 7.6% (LMI). Furthermore, the paths of CCS deployment for CHINA and INDIA both show a peak at the end of the period of observation (see Figure 14). This effect is triggered by the fact that CHINA and INDIA reach the maximum ratio of emission avoidance (30% of the annual regional emissions) by the year 2095 (CHINA) and by the year 2105 (INDIA) respectively. Since the results for CHINA show a decrease in total carbon emissions in the last time step, the findings correspond to an absolute decrease in CCS. For INDIA on the contrary, only a decrease in the growth rate of CCS is observed in the last time step of the period of observation since the total regional emissions are increasing over the entire period of observation.

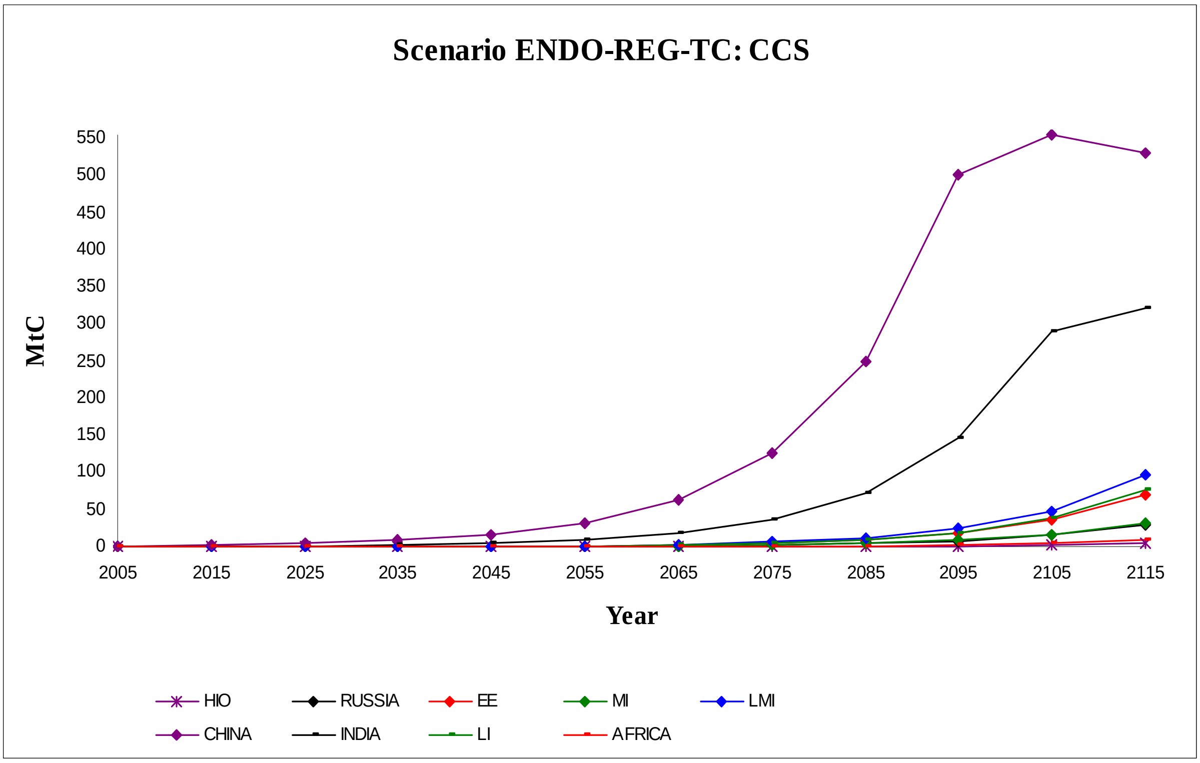

Figure 14: Scenario ENDO-REG-TC: MtC of regional emissions avoided (period 2005-2015)

As shown in Figure 15, the willingness to invest in CCS is increased due to technological change. In contrast to the scenario ENDO-REG excluding technological change, the regions HIO, LMI and MI introduce CCS in the period of observation. In addition, CHINA, INDIA, EE, RUSSIA and LI invest more than 0.1% of their annual GDP in the avoidance of regional carbon emissions by the year 2115. The results show constantly increasing deployment of emission avoidance for most of the regions implementing CCS. Thus, the percentage of GDP invested in emission abatement is increasing despite technological change (except for the regions CHINA and INDIA). CCS investments of CHINA and INDIA show a peak after having reached the maximum percentage of emission avoidance (30%) allowed within the RICE-CCS model. For these two regions, due to the level of economic growth, the findings correspond to a decrease in the percentage of GDP invested in emission abatement in spite of an absolute increase of carbon captured and stored in the end of the period of observation.

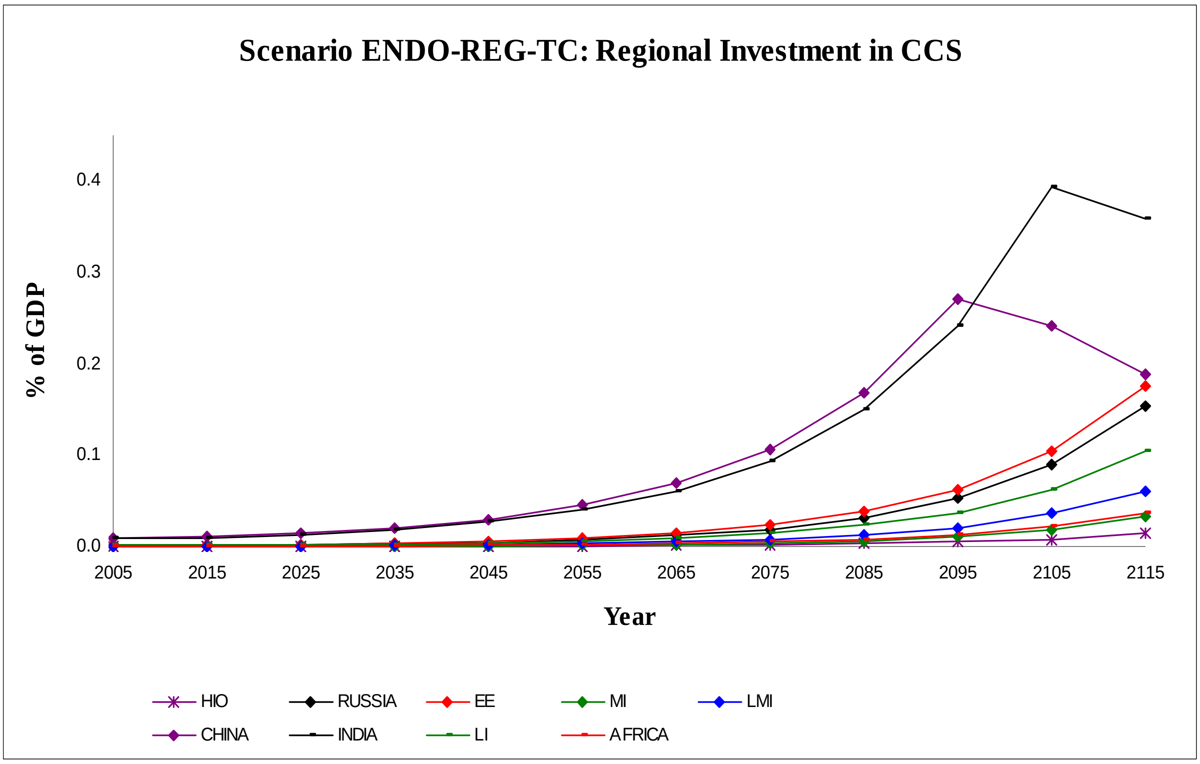

Figure 15: Scenario ENDO-REG-TC: Investment in CCS as a percentage of annual GDP (period 2005-2115)

d) Scenario ENDO-REG-TC: Regional welfare, GDP and savings rates

Compared to the ENDO-REG scenario excluding technological change, no major changes in the economic variables have been observed. Despite the increase in emission avoidance, the benefits due to decreased climate damages still occur after the period of observation. Thus, the welfare of the high-income regions not avoiding carbon emissions is not affected by technological change in CCS. CHINA (0.11%) and INDIA (0.13%) are the only regions suffering from a welfare loss higher than 0.05%. The changes in the savings rates correspond to the changes in GDP and welfare for all regions conducting CCS.

e) Scenario ENDO-GLOBAL-TC: Regional CCS investment

Even though the willingness to pay for CCS is increased in the ENDO-GLOBAL-TC scenario, the findings show that the low-income regions must invest a greater part of their annual GDP than the high-and middle-income regions to fulfil the global CCS goal. As shown in Figure 16, AFRICA (0.75%) and LI (0.2%) must employ considerable financial resources whereas the other regions (as represented by the USA in Figure 16) invest less than 0.06% of their annual gross income in carbon emission avoidance.

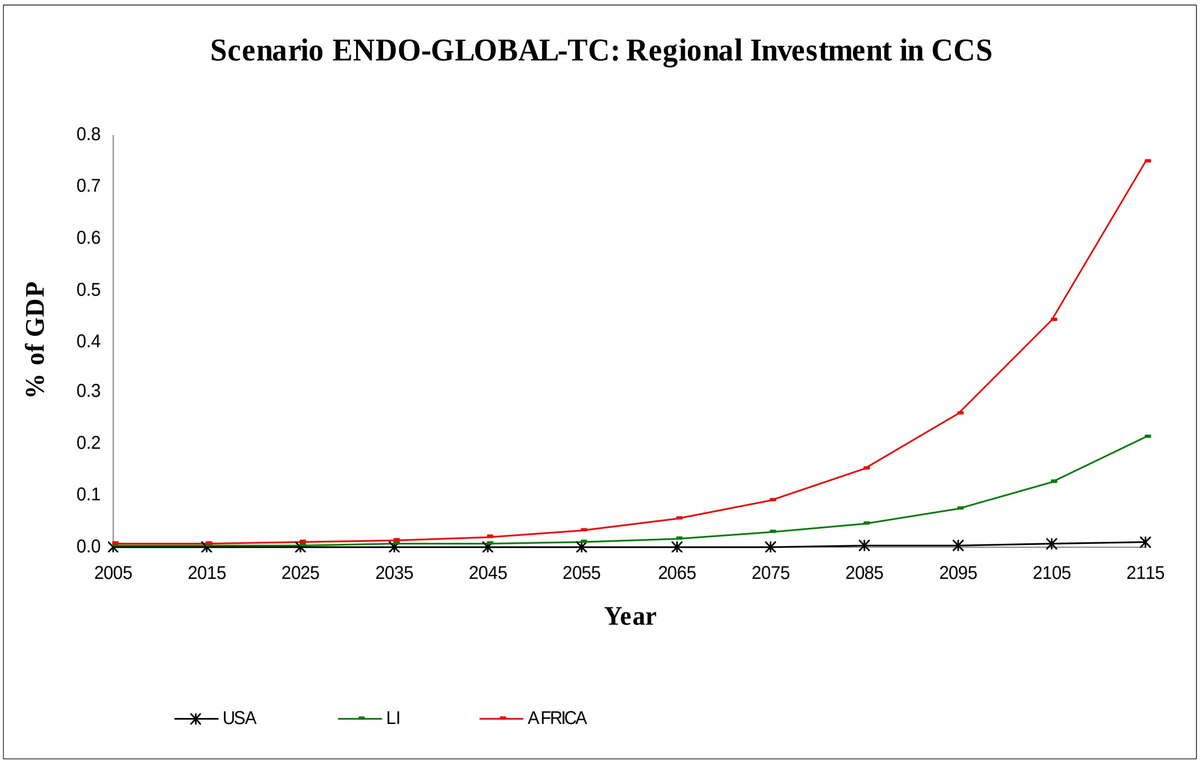

Figure 16: Scenario ENDO-GLOBAL-TC: Investment in CCS as a percentage of annual GDP (period 2005-2115)

f) Scenario ENDO-GLOBAL-TC: Regional welfare, GDP and savings rates

For the high- and middle-income regions no major changes in the economic variables could be observed in comparison to the scenario ENDO-GLOBAL excluding technological change. The only region showing a considerable decrease in welfare is AFRICA. Its investments in CCS lead to a decrease in total regional welfare of 0.18% in the period of observation. In addition, no substantial welfare effects due to a decrease in climate damage have been observed for this scenario.

5.3 Exogenous CCS scenarios

In this section the results of the exogenous CCS scenarios as described in Chapter 4 are presented on global and on regional scale. All results are presented and discussed in comparison to the optimal scenario.

5.3.1 Exogenous CCS scenarios - global analysis

a) Global CCS, carbon emissions and temperature

Compared to the optimal scenario, the global use of carbon energy for production is slightly increased in all exogenous CCS scenarios excluding carbon taxation. However, the maximum increase observed for the EXO-30 scenario (30% of regional carbon emissions avoided by 2055) corresponds to negligible 0.38% of global carbon energy use in the period of observation. As shown in Figure 17, the levels of emission avoidance by the implementation of CCS increase linearly over time in the exogenous scenarios excluding a tax mechanism (red and black lines). The maximum avoidance is reached by the year 2055 and held constant for the rest of the period of observation. In the EXO-15 scenario (15% of regional carbon emissions avoided by 2055), a maximum of 1093 MtC are captured and stored (EXO-ANNEX B-15: 478 MtC - only ANNEX B countries forced to conduct CCS) whereas the values are doubled in the scenarios EXO-30 (2186 MtC) and EXO-ANNEX B-30 (956 MtC - only ANNEX B countries forced to conduct CCS). For the EXO-15, scenario these values correspond to an avoidance of more than 8% of total global emissions in the period 2005-2115 (EXO-ANNEX B-15: 3.5%). For the EXO-30 scenario, the level of CCS accounts to 16% of global carbon emissions to the atmosphere (EXO-ANNEX B-30: 7%). The temperature increase is diminished by 0.106°C by the year 2115 in the EXO-15 scenario (EXO-ANNEX-B-15; 0.047°C) respectively 0.215°C in the EXO-30 scenario (EXO-ANNEX B-30; 0.094°C).

In the EXO-TAX scenarios (green lines in Figure 17), emission avoidance reaches a maximum of 399 MtC by the year 2095 (EXO-TAX) respectively 91 MtC by the year 2035 (EXO-ANNEX B-TAX). Only 3% of global carbon emissions in the period of observation are avoided by the implementation of CCS in the EXO-TAX scenario (EXO-ANNEX B-TAX; 0.55%). However, compared to the optimal scenario, the penalty tax-mechanism leads to a substantial decrease of 6.33% (EXO-TAX) and 2.78% (EXO-ANNEX-B-TAX) in global carbon energy use in the period of observation. This finding explains why the reduction in temperature increase observed for the EXO-TAX scenario does not correspond to the low level of emission avoidance by the implementation of CCS. By the year 2115, the temperature increase is diminished by 0.136°C in comparison to the optimal scenario (EXO-ANNEX B-TAX; 0.04°C).

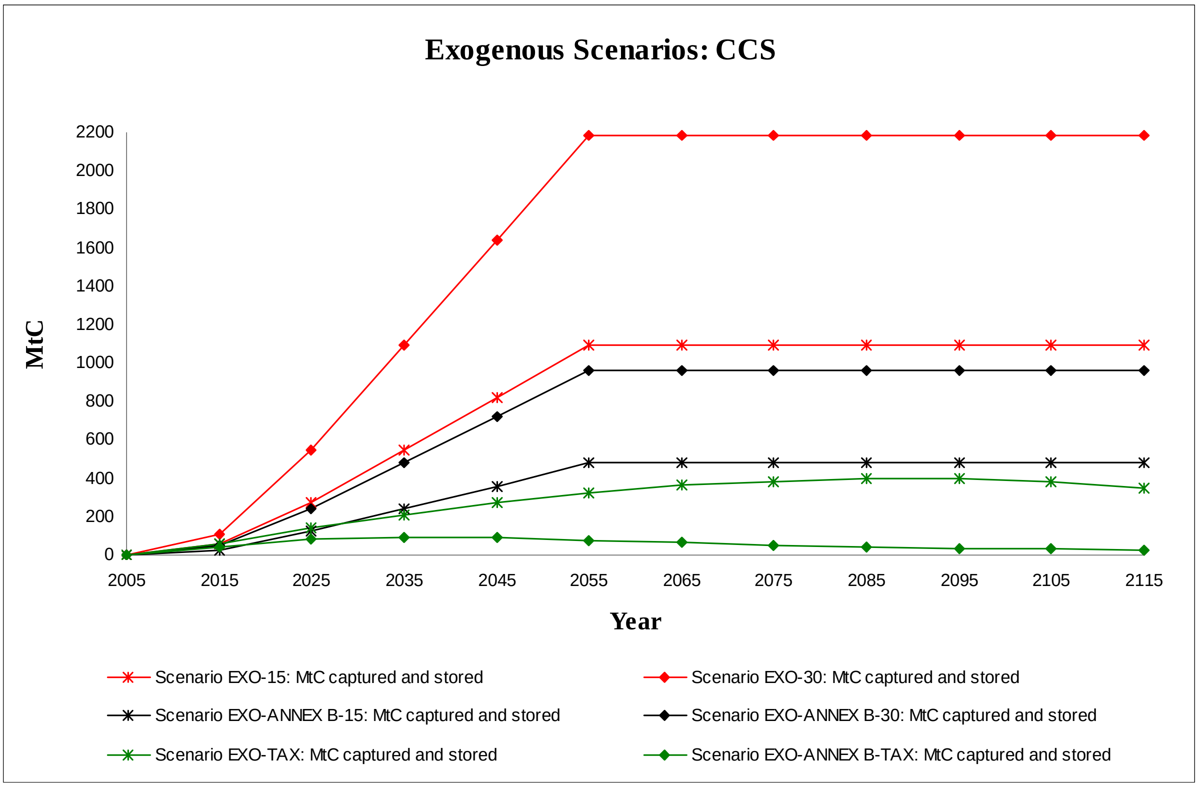

Figure 17: Exogenous CCS scenarios: MtC of global emissions avoided (period 2005-2115)

b) Global welfare, GDP and savings rates

As shown in Table 14, all exogenous CCS scenarios lead to a net loss in global welfare in comparison to the optimal scenario. Since the investments in CCS as well as the expenses for carbon taxation are in competition with investments in productive capital, this finding is expectable. The greatest loss in welfare in the scenarios excluding carbon taxation is observed for the EXO-30 scenario. Compared to the optimal scenario, the welfare loss amounts to 596 US$ billion despite the decrease in climate damage due to a diminished temperature increase as described above. The global savings rates are slightly increased in the first and reduced in the second half of the period of observation. However, changes in the savings rates can explain the gap between welfare losses and the changes in global GDP as observed for all exogenous CCS scenarios excluding carbon taxation.

Table 14: Exogenous CCS scenarios: Changes in economic variables due to the implementation of CCS in comparison to the optimal scenario (period 2005-2115)

Scenario	**Global Consumption** [US$ billion]	**Global GDP** [US$ billion]	**Change in Average Global Savings Rate** (2005-2115)
EXO-15	- 311	+ 68	+ 0.003%
EXO-30	- 596	+ 174	+ 0.015%
EXO-ANNEX B-15	- 152	+ 11	0%
EXO-ANNEX B-30	- 278	+ 64	+ 0.015%
EXO-TAX	- 228	- 414	- 0.1%
EXO-ANNEX B-TAX	- 99	- 206	- 0.073%

In comparison to the optimal scenario, the results of the EXO-TAX scenarios show less reduction in welfare but greater decrease in GDP than the exogenous CCS scenarios excluding carbon taxation (see Table 14). In the EXO-TAX scenario global welfare is reduced by 278 US$ billion (EXO-ANNEX B-TAX; 99 US$ billion) and global GDP by 414 US$ billion (EXO-ANNEX B-TAX; 206 US$ billion). On the one hand, the reductions in global GDP can be explained by the decrease in carbon energy use due to taxation. On the other hand, the gap between GDP and welfare loss is caused by decreased savings rates leading to an increase in present welfare which is weakly discounted in comparison to the welfare losses of future generations.

5.3.2 Scenarios EXO and EXO-ANNEX-B – regional Analysis

a) Regional investment in CCS

Figure 18 shows the regional amounts of carbon emissions avoided by the implementation of CCS for the EXO-15 scenario. Corresponding to the level of carbon emissions in the year 2005, CHINA (249 MtC) and the USA (235 MtC) must fulfil the highest level of emission avoidance by the year 2055 followed by EUROPE (144 MtC) and LMI (111 MtC). All other regions capture and store a maximum of their carbon emissions ranging from 32 MtC (HIO) to 65 MtC (RUSSIA). For the EXO-30 scenario, the values are doubled whereas in the EXO-

ANNEX B-15 and EXO-ANNEX B-30 only the regions USA, EUROPE, JAPAN and OHI are forced to conduct the corresponding level of emission avoidance.

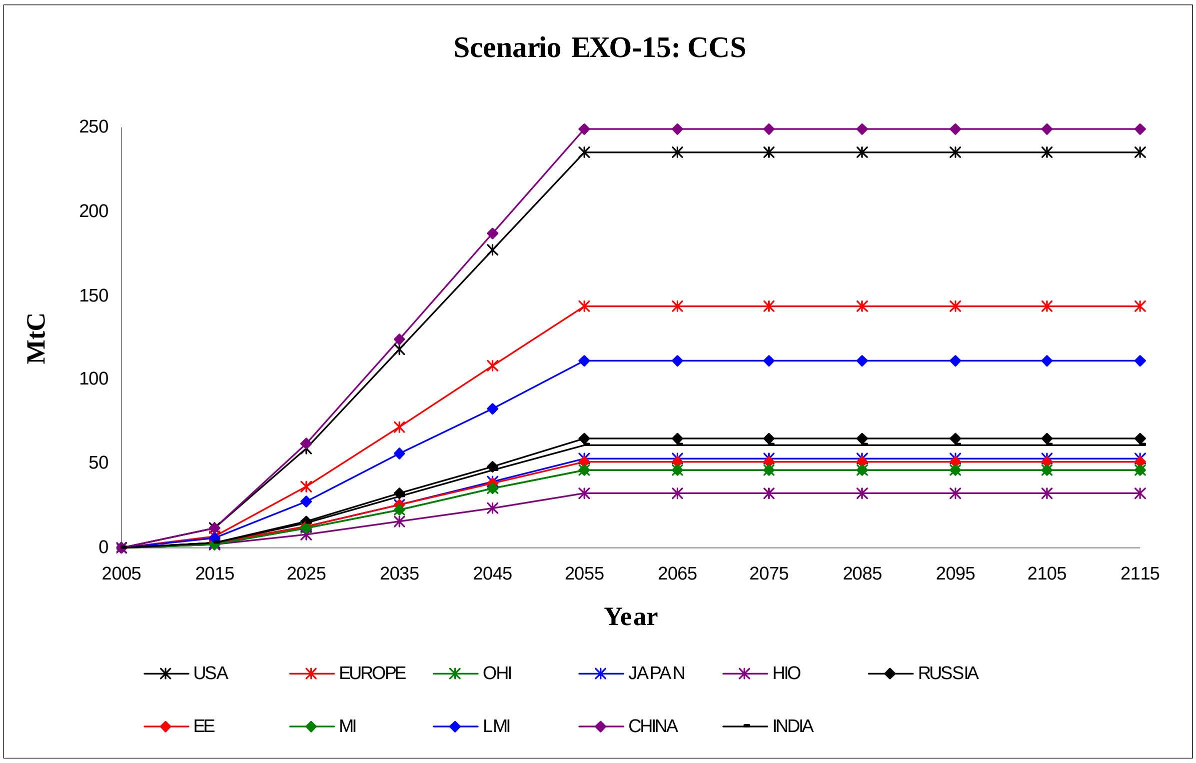

Figure 18: Scenario EXO-15: MtC of regional emissions avoided (period 2005-2015)

As shown in Figure 19, the development of the CCS investments over time is similar for the EXO-15 and the EXO-30 scenario. Since the level of emission avoidance is increasing until the year 2055, the percentage of annual GDP spent to fulfil the demanded level of CCS implementation is increasing too. Until the year 2055 economic growth leads to a nonlinear increase in CCS investment although the level of emission avoidance increases linearly. However, in the period 2055-2115 economic growth leads to a net decrease in the percentage of GDP invested in CCS. RUSSIA is the region investing the greatest percentage of annual GDP in emission avoidance (1.24% in the EXO-15 and 2.47% in the EXO-30 scenario by the year 2055). This finding can be explained by the fact that RUSSIA has a very low carbon energy/GDP ratio. On the contrary the regions JAPAN and MI spend less than 0.16% of their annual GDP in the EXO-15 and less than 0.27% in the EXO-30 scenario. For JAPAN the results can be explained by a very high carbon energy/GDP ratio whereas the region MI benefits from its considerable economic growth as found by the RICE-CCS model. The regions which are not discussed above invest a maximum percentage ranging from 0.22% (JAPAN) to

0.52% (EE) in the EXO-15 scenario and from 0.43% (JAPAN) to 1% (EE) in the EXO-30 scenario of their regional GDP in CCS by the year 2055.

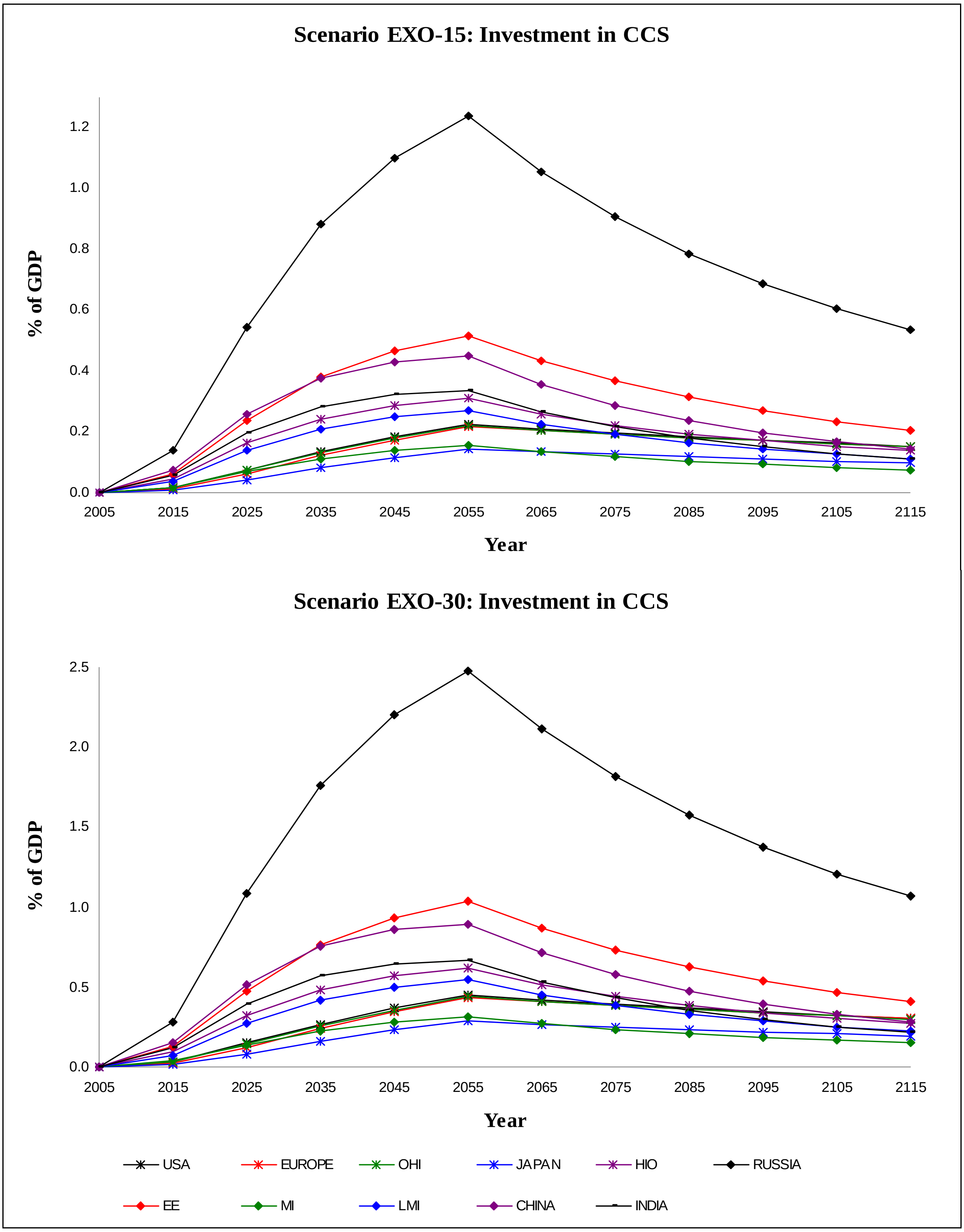

Figure 19: Scenarios EXO-15 & EXO-30: Investment in CCS as a percentage of annual GDP (period 2005-15)

In the EXO-ANNEX B-15 and EXO-ANNEX B-30 scenarios, the investments in CCS of the high-income regions are not changed compared to the corresponding EXO scenarios including the non-high-income regions. Therefore, JAPAN still has the lowest expenses for CCS. As shown in Figure 19, the regions USA, EUROPE and OHI invest almost the same fractions of their GDP in CCS with a maximum of 0.22% (EXO-ANNEX B-15: USA) and 0.45% (EXO-ANNEX B-30: USA) by the year 2055.

b) Regional welfare, GDP and savings rates

The implementation of CCS leads to an increase in the regional savings rates in the first half of the time period of observation in all exogenous scenarios excluding carbon taxation. Therefore, regional GDP is slightly enhanced for all regions in comparison to the optimal scenario. However, regional welfare is negatively affected by the increasing savings (see Table 15). RUSSIA, EE and CHINA show the greatest changes in welfare in the EXO-15 and the EXO-30 scenario. RUSSIA looses a maximum of 1.71%, EE 0.73% and CHINA 0.64% of total welfare in the period from 2005 to 2115 in the scenario EXO-30. The findings can be explained by the fact that these regions invest the highest percentage of their annual GDP in CCS (see Figure 19) thus reducing the fraction of GDP available for consumption. For all other regions which avoid parts of their carbon emissions, welfare losses smaller than 0.32% are observed in all exogenous scenarios excluding taxation. Even though only the high-income regions are forced to implement CCS in all exogenous CCS scenarios, there are moderate losses in regional welfare observed. Compared to the optimal scenario, a maximum decrease in welfare is found for all high-income regions in the EXO-ANNEX B-30 scenario. For EUROPE and JAPAN, the observed difference in welfare loss between the EXO and the EXO-ANNEX B scenarios can be explainable by positive impacts of the temperature increase on the regional economic sector. Thus, EUROPE and JAPAN have a very small profit from the emission avoidance of the other regions in the EXO-15 and EXO-30 scenarios. On the contrary the USA and OHI do not have the same vulnerability towards climate change and therefore show almost the same decrease in welfare in the EXO and the EXO-ANNEX B scenarios. Furthermore, for both EXO-ANNEX B scenarios, the benefits of the low-and middle-income regions due to the emission avoidance of the high-income regions are negligible. EE and RUSSIA suffer from minor welfare losses since a positive impact from temperature increase on the regional economic system is assumed. The results for the other regions show changes in welfare ranging from 0% (EXO-ANNEX B-15: MI and LMI) to +0.04% (EXO-

ANNEX B-30: AFRICA). Even though LI and AFRICA are excluded from the implementation of CCS in all scenarios, the maximum benefit observed amounts to only 0.13% (LI) and 0.1% (AFRICA) in the scenario EXO-30 (see Table 15).

Table 15: Exogenous CCS scenarios excluding carbon taxation: Regional changes in welfare due to the implementation of CCS (period 2005-2115; percentages in relation to the optimal scenario)

Region	**Scenario EXO-15**	**Scenario EXO-30**	**Scenario EXO-ANNEX B-15**	**Scenario EXO-ANNEX B-30**
USA	- 0.14%	- 0.27%	- 0.14%	- 0.28%
EUROPE	- 0.09%	-0.18%	- 0.12%	- 0.23%
JAPAN	- 0.08%	- 0.15%	- 0.09%	- 0.17%
OHI	- 0.14%	- 0.26%	- 0.14%	- 0.27%
HIO	- 0.2%	- 0.41%	0%	+ 0.01%
RUSSIA	- 0.87%	- 1.71%	- 0.03%	- 0.01%
EE	- 0.38%	- 0.73%	- 0.01%	- 0.01%
MI	- 0.09%	- 0.18%	0%	+ 0.01%
LMI	- 0.18%	- 0.32%	0%	+ 0.01%
CHINA	- 0.33%	- 0.64%	+ 0.01%	+ 0.01%
INDIA	- 0.17%	- 0.29%	+ 0.02%	+ 0.1%
LI	+ 0.02%	+ 0.13%	+ 0.01%	+ 0.02%
AFRICA	+ 0.03%	+ 0.1%	+ 0.03%	+ 0.04%

5.3.3 Scenarios EXO-TAX and EXO-ANNEX-B-TAX – regional analysis

a) Regional investment in CCS

In the EXO-TAX scenario, carbon taxation leads to different individual paths of CCS deployment over time (see Figure 20). RUSSIA and EE do not exceed the emission cap in the period of observation and thus not implement CCS emission avoidance at all. EUROPE and JAPAN must avoid carbon emissions only until the year 2035 and CHINA is forced to capture and store varying parts of its emissions until the year 2095. From those regions implementing CCS (or paying carbon taxation respectively) over the entire period, OHI and the USA show a similar path of CCS deployment. Emission avoidance reaches a maximum by the year 2045 and decreases slightly until 2115. For INDIA, a constant increase in CCS until the year 2105 followed by a minor decrease in the last time step is observed. HIO, MI and LMI show an increase in the amount of carbon captured and stored over the entire period of observation. Overall, the USA have the highest level of CCS implementation until the year 2045 avoiding up to 95 MtC or 5.45% of the regional carbon emissions by the year 2045. By then INDIA outruns the USA followed by the regions LMI, MI and HIO. At the end of the study period HIO is avoiding the largest part of its carbon emissions (134 MtC or 16.16% of regional carbon emissions by the year 2115) of all regions (see Figure 20).

In the EXO-ANNEX B-TAX scenario, the level of emission avoidance of the high-income regions USA, EUROPE, OHI and JAPAN is not changed compared to the EXO-TAX scenario. Since no interregional trade is allowed and these regions have a high welfare weight in the objective function of the RICE-CCS model, their choices of carbon energy use and carbon emission avoidance is not considerably influenced by the behaviour of the other regions.

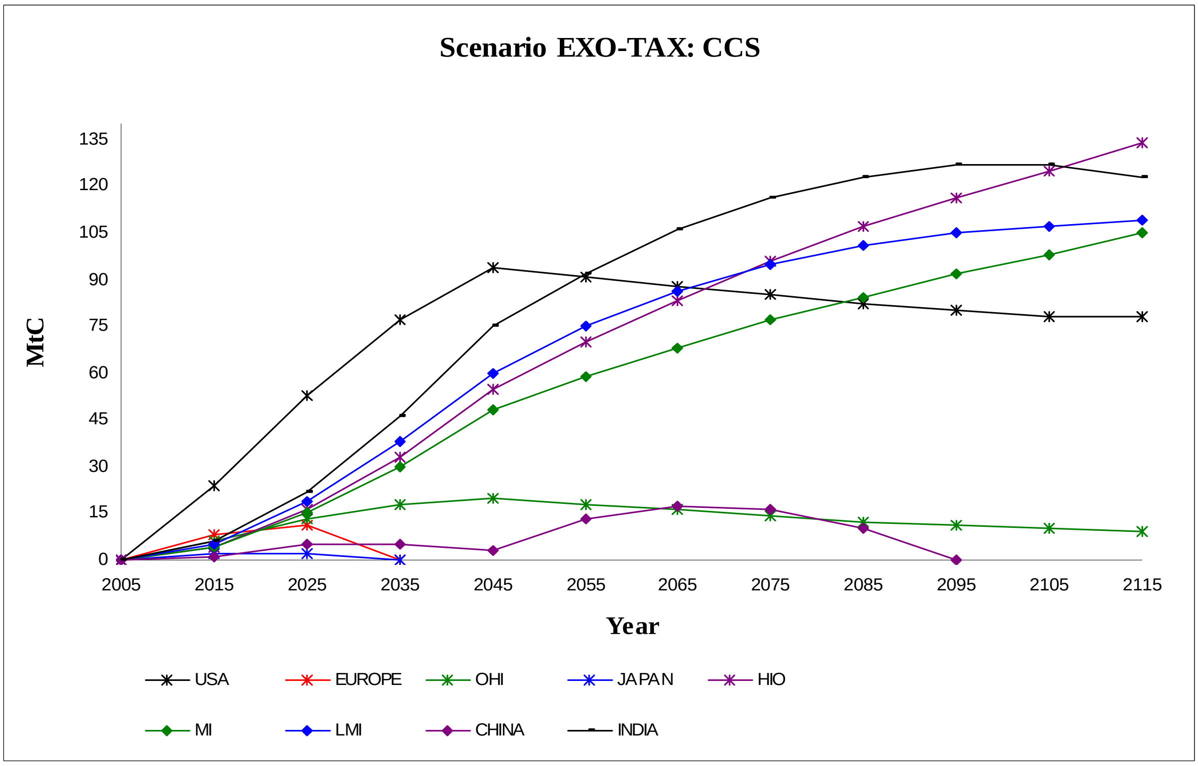

Figure 20: Scenario EXO-TAX: MtC of regional emissions avoided (period 2005-2015)

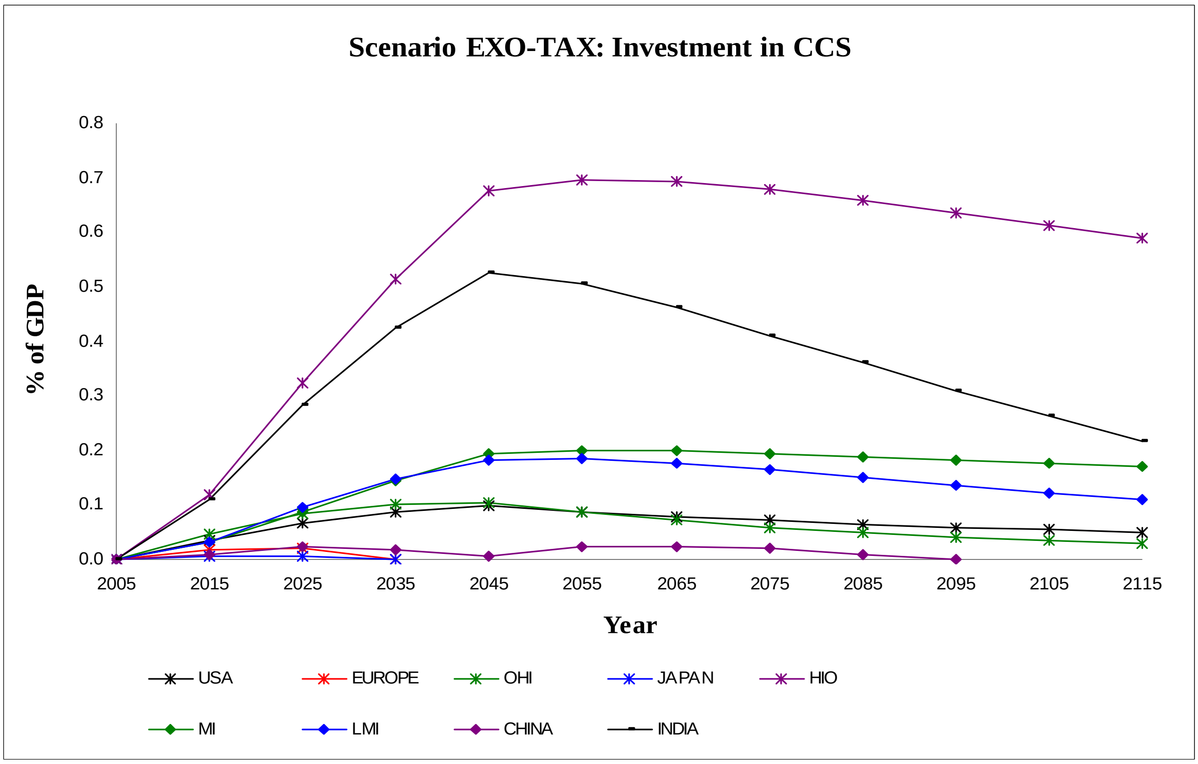

Figure 21: Scenario EXO-TAX: Investment in CCS as a percentage of annual GDP (period 2005-2115)

Figure 21 shows the regional investments in CCS for the EXO-TAX scenario as a percentage of regional annual GDP. Investment in CCS is determined by taxation on emissions exceeding the emission cap (see section 3.2.3: Table 9). By the year 2045, the regions HIO and INDIA loose up to 0.7% (HIO) and 0.5% (INDIA) due to the carbon taxation. In the case of INDIA, MI and LMI, the decrease in investment towards the end of the study period can be explained by economic growth and diminished increase in regional emissions. The regions OHI, USA, JAPAN, EUROPE and CHINA use less than 0.1% of their annual GDP to satisfy the carbon taxation in the entire period of observation.

As shown in Figure 22, the regions RUSSIA and EE gain a net income due to “negative” carbon taxation in the entire period of observation in the EXO-TAX scenario. Since the regional levels of carbon emissions undercut the emission cap, these regions receive compensation out of the global carbon taxation pool. By the year 2045, RUSSIA and EE derive a maximum of 0.87% (RUSSIA) and 0.23% (EE) of their annual GDP from compensation for reductions in regional emissions. Furthermore, carbon emissions of the regions EU and JAPAN fall below the emission threshold by the year 2035. Thus, these regions receive a net income in the period 2035-2115. In addition, CHINA is compensated for undercutting the emission cap in the last three time steps of the period of observation. Overall, the compensations paid to the regions undercutting the emission caps account to 13.8% of the global tax pool fed by regional carbon taxation in the period of observation.

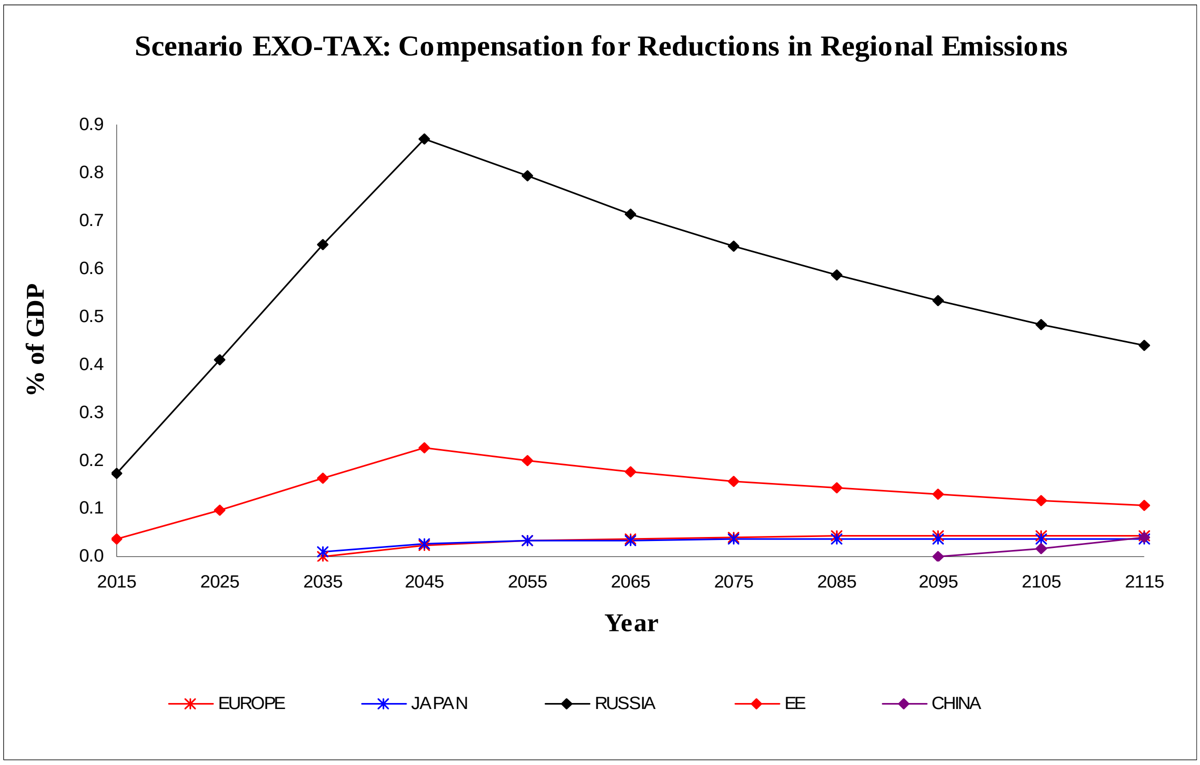

Figure 22: Scenario EXO-TAX: Compensation for reductions in regional carbon emissions as a percentage of annual GDP (period 2005-2115)

In the EXO-ANNEX-B-TAX scenario, the compensation for emission reductions leads to a considerable decrease in the global implementation of CCS. Due to the decrease in regional carbon emissions observed for the regions EUROPE and JAPAN, the fraction of the carbon taxation pool used for compensation instead of investment in CCS is increasing in the period from 2035 to 2115. A maximum of 69.3% of the tax pool fed by the USA and OHI is used to compensate the emission reductions of EUROPE and JAPAN by the year 2115.

b) Regional welfare, GDP and savings rates

In the EXO-TAX scenario, the results for EUROPE, JAPAN, RUSSIA, EE, AFRICA and LI show a net benefit in welfare for the study period in comparison to the optimal scenario (see Table 16). Since AFRICA and LI are excluded from carbon taxation, the increase in regional consumption of 0.13% (LI) and 0.1% (AFRICA) can be explained by a decrease in the market damages due to climate change. On the contrary, the increase in welfare of the regions EUROPE, JAPAN, RUSSIA and EE is based on the compensation for the regional emission reductions. However, RUSSIA is the only region showing a considerable benefit in welfare in the period of observation in the EXO-TAX scenario (0.27%). From those regions for which a net loss in welfare is observed due to the introduction of carbon taxation, HIO (0.77%) and INDIA (0.46%) are suffering the most. Since the results show a strong increase in carbon emissions over time for HIO and INDIA, they must reduce consumption in order to finance the carbon taxation. As shown in Table 16, all other regions loose welfare in the range of 0.09% (USA) and 0.26% (CHINA) in the EXO-TAX scenario.

Table 16: Exogenous CCS scenarios including carbon taxation: Changes in welfare due to the implementation of CCS (period 2005-2115; percentages in relation to the optimal scenario)

Region	Scenario EXO-TAX	Scenario EXO-ANNEX B-TAX
USA	- 0.09%	- 0.11%
EUROPE	+ 0.05%	0%
JAPAN	+ 0.02%	0%
OHI	- 0.11%	- 0.12%
HIO	- 0.77%	0%
RUSSIA	+ 0.27%	- 0.03%
EE	0%	- 0.01%
MI	- 0.18%	0%
LMI	- 0.24%	0%
CHINA	- 0.26%	- 0.11%
INDIA	- 0.46%	- 0.07%
LI	+ 0.13%	+ 0.02%
AFRICA	+ 0.1%	+ 0.03%

In the EXO-ANNEX B-TAX scenario, carbon taxation leads to an income-shift from the regions USA and OHI to EUROPE and JAPAN. EUROPE receives a maximum income of 8.5US$ billion by the year 2115 undercutting its emission cap by 170 MtC. Furthermore, JAPAN earns 4.1US$ billion reducing its emissions by 82 MtC compared to the emission cap at the end of the period of observation. Overall, the regions USA and OHI loose 0.09% (USA) and 0.11% (OHI) of their regional welfare whereas the tax income leads to an increase in welfare of 0.05% for EUROPE and 0.02% for JAPAN respectively. As shown in Table 16, there are no substantial benefits observed for the low-and middle-income regions excluded from carbon taxation in the EXO-ANNEX B-TAX scenario. RUSSIA, EE, CHINA and INDIA even suffer from a decrease in welfare in comparison to the optimal scenario. Whereas for RUSSIA and EE only a marginal decrease in welfare is observed, CHINA and INDIA loose 0.11% (CHINA) and 0.07% (INDIA) of the regional welfare due to an increase in the average regional savings rate in the period of observation.

5.4 Analysis of the sensitivity of the RICE-CCS model

This section focuses on the analysis of the sensitivity of the RICE-CCS model regarding the choice of the discount rate and the level of market damage due to climate change. Since the results for all scenarios show similar changes in case of a change in these key parameters, only the results regarding the ENDO-GLOBAL scenario are presented in this section. First, the scenario has been computed assuming a doubling of climate damages. Second, the discount factor has been changed from 3% to 1.5%. The results are discussed in comparison to the optimal scenario.

a) Variations in the scenario ENDO-GLOBAL: CCS, carbon emissions and temperature

As shown in Figure 23, the willingness to conduct CCS increases considerably due to a change in the discount rate or an increase in the level of climate damage. Reducing the discount factor by 50% leads to a CCS emission avoidance of 2.45 GtC at the end of the period of observation. The results of the model run assuming a doubling of regional climate damages show an emission avoidance of 2.187 GtC by the year 2115. Furthermore, global carbon energy use in the study period is reduced by 15.5% (change in discount factor) and 18.1% (doubled climate damage) respectively in comparison to the optimal scenario.

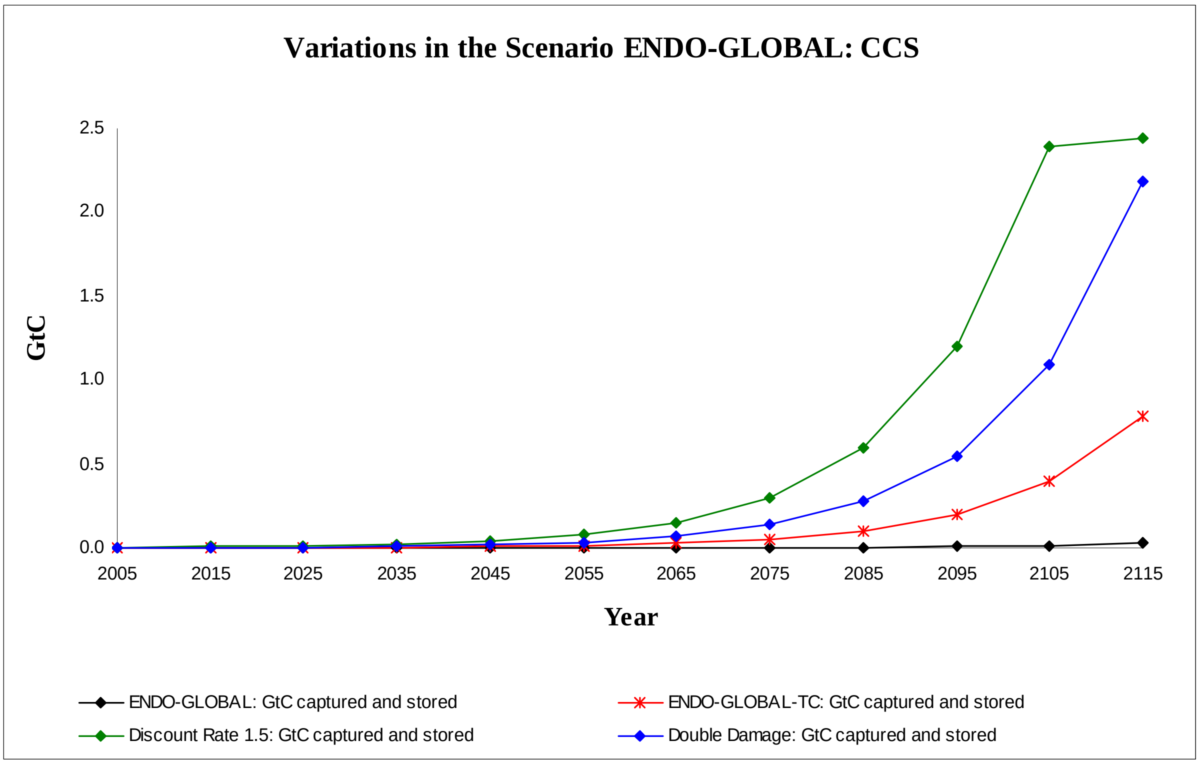

Figure 23: Variations of the scenario ENDO-GLOBAL: GtC of global emissions avoided (period 2005-2015)

In comparison to the standard ENDO-GLOBAL scenarios including and excluding technological change, the level of carbon emission avoidance is increased. Nevertheless, CCS does not start to deploy considerably earlier on a global scale (see Figure 23). The findings show that the maximum percentage of global emission avoidance (30%) is reached by the year 2105 in case of a reduction in discounting and by the year 2115 respectively if a doubling in climate damages is assumed. However, the enhancement of climate damage leads to a greater reduction of total global carbon emissions than the change in the discount factor. Thus, the absolute amount of emissions avoided by CCS at the end of the period of observation is higher in case of a change in the discount factor. Compared to the optimal scenario, the temperature increase by the year 2115 is mitigated by 0.25°C (doubling of climate damage) and 0.24°C respectively (decrease in discount rate).

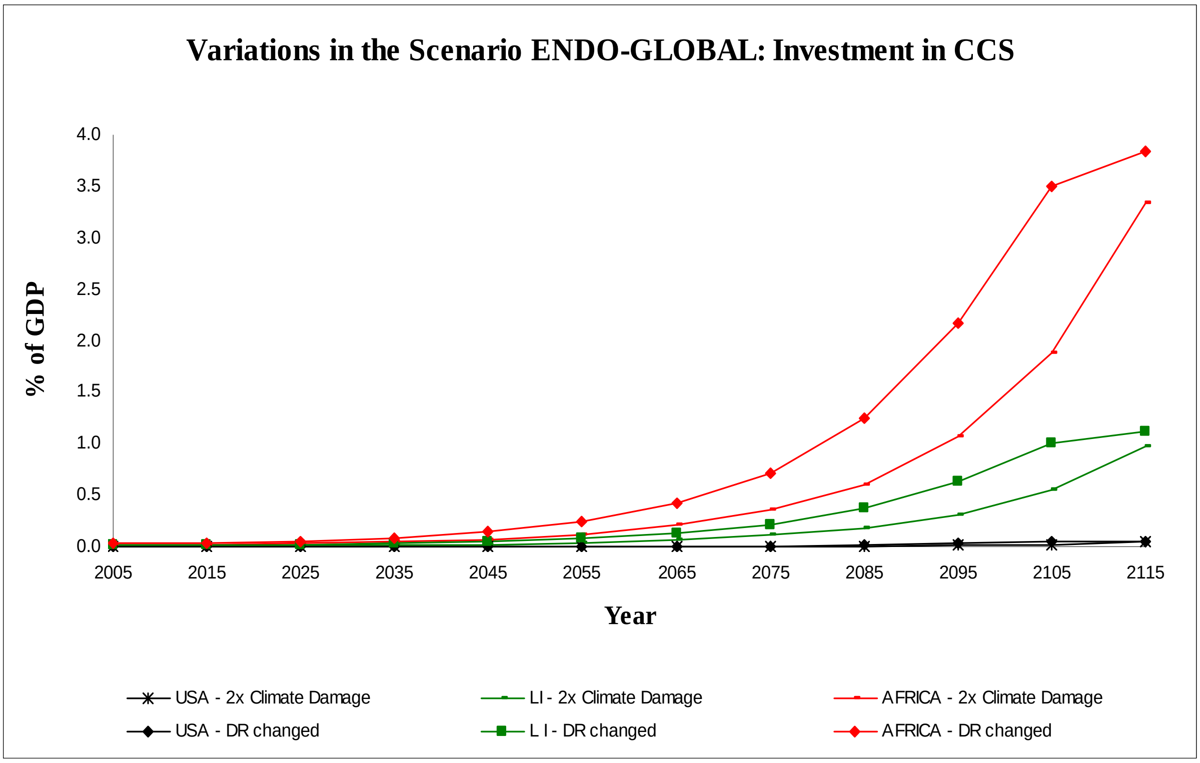

Figure 24: Scenario ENDO-GLOBAL: Investment in CCS as a percentage of annual GDP in case of a change in the discount rate or a doubling of regional climate damages (period 2005-2115)

As shown in Figure 24, he gap in investment between the low-income regions and the rest t of the world is increased compared to the standard ENDO-GLOBAL scenario. Assuming a 50% reduction of the discount factor, AFRICA must invest 3.8% of its annual GDP to reach the level of global per capita CCS by the 2115. In the same scenario, the USA spend only

0.05% of annual GDP to fulfil the same contract. The investment curves of all other regions run between those of LI (1.13% by the year 2115) and the USA. The bends in the investment curves for AFRICA and LI at the end of the study period can be explained by the fact that the optimal amount of per capita CCS is higher than the maximum regional carbon emission avoidance (30%) by the year 2115. Thus, the increase in CCS investment from 2105 to 2115 is solely driven by an increase in regional carbon emissions.

In case of a doubling of regional climate damages, AFRICA must invest 3.3% (LI 0.97%) of its annual GDP whereas the USA spend only 0.045% of their gross income for CCS by the year 2115. Since the maximum ratio of total emissions avoided is not reached within the period of observation, the results show constantly increasing CCS investment for all regions until the year 2115.

b) Variations in the scenario ENDO-GLOBAL: Welfare, GDP and savings rates

In order to allow comparison, the results deriving from the scenario variation assuming a lower discount factor have been prepared using the standard discount rate of the optimal scenario. As shown in Table 17, the greater weight put on future generations in the computational experiments leads to a remarkable increase in the average global savings rate of 14.42%. Therefore, the increased investment in productive capital can explain the huge difference of +13.134US$ trillion in global GDP in comparison to the optimal scenario. Furthermore, since much more of the additional GDP is saved instead of consumed, global welfare increases by comparably moderate 72US$ billions or 0.04% for the period of observation. On a regional scale, welfare is reduced by more than 5% for all regions in the first time step. Overall, the findings correspond to regional changes in welfare ranging from -1.39% (AFRICA) to +0.22% (EUROPE). On the one hand, the regions EUROPE, OHI, JAPAN, EE and MI show an increase in total welfare in the period of observation in comparison to the optimal scenario. On the other hand, the welfare losses show a range of -0.09% (USA) to -1.39% (AFRICA) for the other regions. AFRICA though suffers by far the most due to the investment of up to 3.8% of annual GDP in CCS in the period 2085-2115.

The decrease in total welfare due to a doubled level of regional climate damages corresponds to 1.793US$ trillion or 0.9% in the period of observation compared to the optimal scenario (see Table 17). Because of the relation between temperature increase and climate damages, the observed losses in welfare increase over time starting with 0.08% in the year 2005 and reaching 2.55% by the year 2115. Overall, global discounted per capita GDP is reduced by 0.96% (2.51 US$ trillion) with a path beginning at 0.17% for the year 2005 and leading to a maximum of 2.27% by the year 2115. The changes in the average savings rate (-0.28%) for the period 2005-2115 can explain the gap between welfare loss and reduction in GDP. On a regional scale, INDIA suffers from the greatest decrease in welfare (2.28%) whereas the USA and MI only loose 0.4% of their total consumption in the period of observation. Due to its vulnerability to climate change, INDIA shows a maximum loss in welfare of 6.07% by the year 2115 in comparison to the optimal scenario. For the other regions except AFRICA, welfare loss constantly increases from less than 0.2% in the year 2005 to a maximum in the range of -1.98% (MI) to -5.27% (RUSSIA) by the year 2115. Due to its investment in CCS (see Figure 24) the welfare loss of AFRICA grows from 0.8% by the year 2005 to 5.5% by the end of the period of observation. However, neglecting CCS investments AFRICA would be less affected by a doubling in climate damages than the other low-income regions INDIA, CHINA and LI.

In general, the analysis of the sensitivity of the ENDO-GLOBAL scenario towards changes in the level of climate damages and discounting shows clearly that these are the key issues to deal with in integrated assessment modeling. Thus, discounting and market damage estimates must be handled with particular diligence regarding the analysis of potential benefits due to the implementation of CCS.

Table 17: Variations in the ENDO-GLOBAL scenario: Changes in economic variables due to changes in the discount rate and the level of climate damages compared to the optimal scenario (period 2005-2115)

Change in Scenario ENDO-GLOBAL	**Global Consumption** [US$ trillion]	**Global GDP** [US$ trillion]	**Change in Average Global Savings Rate** (2005-2115)
No Changes (original scenario)	- 0.004	-0.013	- 0.003%
Climate Damage	- 1.793	- 2.510	- 0.28%
Discount Rate	+ 0.072	+ 13.134	+ 14.42%

5.5 Key findings

This section intends to give a brief summary of the impacts of the incorporation of emission avoidance by the implementation of CCS in the RICE model. The effects on global welfare, global carbon energy use and temperature increase in the period 2005-2115 are discussed in comparison to the optimal scenario.

a) Endogenous scenarios

No considerable changes in global or regional carbon energy use have been observed for the ENDO-REG and ENDO-GLOBAL scenarios in comparison to the optimal scenario. The results show changes in a range of -0.33% (ENDO-GLOBAL-TC scenario) to +0.45% (ENDO-REG-TC scenario) in global carbon energy use for production purposes in the period of observation (see Table 18). On a regional scale, CHINA and INDIA are the only regions showing a slightly increased use of carbon energy. Since for all endogenous CCS scenarios emission avoidance due to the implementation of CCS does not evolve substantially until the year 2055, the temperature increase is not considerably mitigated by the year 2115. Thus, potential benefits of a decrease in the level of climate damages occur after the period of observation. Overall, the implementation of CCS leads to moderate losses in global welfare in the range of 4US$ billion (ENDO-GLOBAL scenario) to 30 US$ billion (ENDO-REG-TC scenario) for the endogenous CCS scenarios (see Table 18).

In summary, the results indicate that the implementation of large-scale CCS is not necessarily an optimal choice at current CCS cost- and climate damage estimates. Given the elasticities of the production inputs (as given by Nordhaus and Boyer, 2000), carbon emissions are reduced substantially by substitution of carbon energy by capital. Therefore, only minor additional carbon emission avoidance by the implementation of CCS is required in order to optimize global welfare. In the ENDO-REG scenario, the derivation of the objective welfare function causes disproportionate expenses for the implementation of CCS for the low income regions (especially for CHINA and INDIA) compared to the middle- and high-income regions. The inclusion of the carbon energy/GDP ratio in the welfare function leads to an allocation of optimal global CCS deployment in favour of those regions generating high production output per unit of carbon energy input. Furthermore, the regions having a high per capita GDP suffer less from fulfilling the global contract if equal per capita emission avoidance is aspired on a global scale (as it is in the case of the ENDO-GLOBAL scenarios).

Table 18: CCS scenarios: Changes in economic and environmental variables due to the implementation of CCS in comparison to the optimal scenario (period 2005-2115)

Scenario	**Global Consumption** [US$ billion]	**Global Use of Carbon Energy** [period 2005-2115]	**Change in the Increase in Global mean Temperature** [by the year 2115]
ENDO-REG	- 12	- 0.06%	- 0.005°C
ENDO-REG-TC	- 30	+ 0.45%	- 0.02°C
ENDO-GLOBAL	- 4	- 0.24%	- 0.001°C
ENDO-GLOBAL-TC	- 16	- 0.33%	- 0.009°C
EXO-15	- 311	+ 0.16%	- 0.106°C
EXO-30	- 596	+ 0.38%	- 0.215°C
EXO-ANNEX B-15	- 152	+ 0.03%	- 0.047°C
EXO-ANNEX B-30	- 278	+ 0.07%	- 0.094°C
EXO-TAX	- 228	- 6.33%	- 0.136°C
EXO-ANNEX B-TAX	- 99	- 2.78%	- 0.039°C

b) Exogenous scenarios

In the exogenous CCS scenarios excluding carbon taxation, global carbon energy use is not affected significantly in comparison to the optimal scenario: a maximum increase of 0.38% is observed for the EXO-30 scenario (see Table 18). Overall, the results of these scenarios show limited potential of CCS to mitigate climate change substantially. As shown in Table 18, the temperature increase is reduced by 0.047°C to 0.215°C by the year 2115. However, the global mean temperature is increased by at least 2.42°C by the year 2115 compared to the pre-industrial level for all scenarios. Therefore, the regions which are not obliged to implement CCS do not benefit substantially from global carbon emission avoidance. The fulfilment of the exogenous CCS contracts leads to global welfare losses in a range of 152US$ billion (EXO-ANNEX B-15 scenario) to 596US$ billion (EXO-30 scenario) in the period of observation. Furthermore, the results show that even substantial emission avoidance by the ANNEX

B countries does not compensate the increase in carbon emissions of the middle-and low-income regions which is expected due to economic growth.

No substantial emission avoidance has been observed in the scenarios using carbon taxation to determine the level of regional CCS implementation. In comparison to the optimal scenario, the decrease in global mean temperature is mainly triggered by a reduction in global carbon energy use due to taxation and not due to avoidance of carbon emissions by the implementation of CCS. As indicated by the changes in global and regional welfare, the negative economic effects due to non-optimal carbon taxation (see Table 18) cannot be compensated by benefits of substitution of energy by capital in the production function on the one hand and reductions in climate damages due to the implementation of CCS on the other.

6 Conclusions

The goal of this Master's thesis was to incorporate CCS in the RICE-99 model in order to examine the potential of CCS to contribute to the mitigation of global climate change in the period 2005-2115. On the one hand, an endogenous optimal level of CCS deployment was pursued on a regional and on a global scale. On the other hand, impacts from exogenously determined levels of CCS emission avoidance on the economy and on the climate system were analyzed. The following conclusions regarding the economic and environmental potential of CCS are based on the results presented and discussed in Chapter 5.

Overall, the low optimal levels of emission avoidance found in the endogenous CCS scenarios do not compensate the increase in global emissions due to increasing carbon energy use. Therefore, the temperature increase is not substantially mitigated in the period 2005-2115. In fact, the findings show that the CCS costs per ton of carbon are only weakly competitive against the marginal market damages per ton of carbon emitted, especially in the first half of the 21st century. Further, due to the elasticities of the production inputs in the RICE model, most of the carbon emission mitigation effort, in comparison to a "business as usual" world not respecting climate damages, is provided by substitution of carbon energy by capital in the production function and not by CCS. Regarding the exogenous implementation of CCS, the findings allow the conclusion that even a considerable level of CCS emission avoidance is not sufficient to substantially mitigate climate change. In addition, it has been shown that exogenously driven CCS in the countries included in the ANNEX B of the Kyoto protocol (UN, 1997) is not likely to compensate the increase in carbon emissions of the developing low-and middle-income regions in the 21st century.

Regarding welfare and GDP, the impacts from endogenous and exogenous implementation of CCS differ substantially. The endogenous implementation of CCS, does not lead to considerable changes in global or regional welfare and GDP in comparison to a scenario excluding CCS. Thus, from an economic view, the question whether CCS is a reasonable option to mitigate carbon emissions cannot be clearly answered. On a regional scale, the inclusion of welfare weights in the objective function of the RICE model leads to a disproportionate allocation of total CCS implementation to low-income regions. On the one hand, CCS emission avoidance is allocated to those regions having low output per input of a unit of carbon energy. On the other hand, if equal per capita CCS is established on a global scale, the regions with a low GDP per capita suffer more from the enforcement to conduct CCS. Thus, it can be concluded that a single agent representing a low-income region would not likely implement CCS at large-scale given the levels of climate damages included in the RICE framework.

On a global scale, the exogenous implementation of CCS leads to relatively small welfare losses compared to a standard scenario excluding CCS. These losses can be explained by the expenses of the regions forced to mitigate parts of their carbon emissions by conducting CCS. Further, on a regional scale, no major benefits have been observed for those regions which are not forced to conduct CCS. Therefore, given the assumptions of the RICE model, one can conclude that even the regions not implementing CCS do not profit considerably from the carbon mitigation effort of the others.

A further part of the analysis of CCS within the RICE model was the incorporation of technological change in the endogenous CCS scenarios. As expected, a decrease in CCS costs due to exogenous technological change leads to a slightly earlier deployment of endogenously driven CCS implementation. In addition, the amounts of carbon emissions mitigated by the implementation of CCS are substantially increased. However, due to the time lag between emission reductions and mitigation of the temperature increase, the assumption of technological change does neither lead to a substantial mitigation of climate change nor to considerable changes in welfare and GDP compared to the scenarios excluding technological change.

Finally, a sensitivity analysis of the RICE-CCS model showed that discounting and the levels of market damage due to climate change are the key issues influencing the results of the model runs regarding CCS.

In summary, the key role of CCS in the climate change abatement strategies, as proposed e.g. by the IEA (2009a), Stern (2008) or the IPCC (2005), cannot be proven by this analysis using the RICE model. At current CCS cost estimates, the internalization of shadow costs of carbon in the economies of the regions covered by the RICE model does not lead to near-term economic viability of CCS. Thus, the role of CCS is likely to depend on future policy constraints on carbon dioxide emissions. In this context, it is crucial whether CCS will be accredited to account for emission reductions in a post-Kyoto agreement or not. However, since considerable uncertainties concerning market damages due to climate change exist, CCS could be seen as an option to mitigate carbon emissions not affecting global GDP and welfare substantially.

Overall, there is need for ongoing research on the economic analysis of CCS based on integrated assessment modeling. The reliability of data concerning CCS costs is assumed to increase due to experience derived from large-scale demonstration projects. In addition, the evaluation of the global carbon storage capacity will allow a detailed analysis of regional CCS potential. Based on this research, those countries should be identified which could profit from CCS. However, it is crucial that the economic analysis of CCS will keep pace with future research on discounting and market damages due to climate change.

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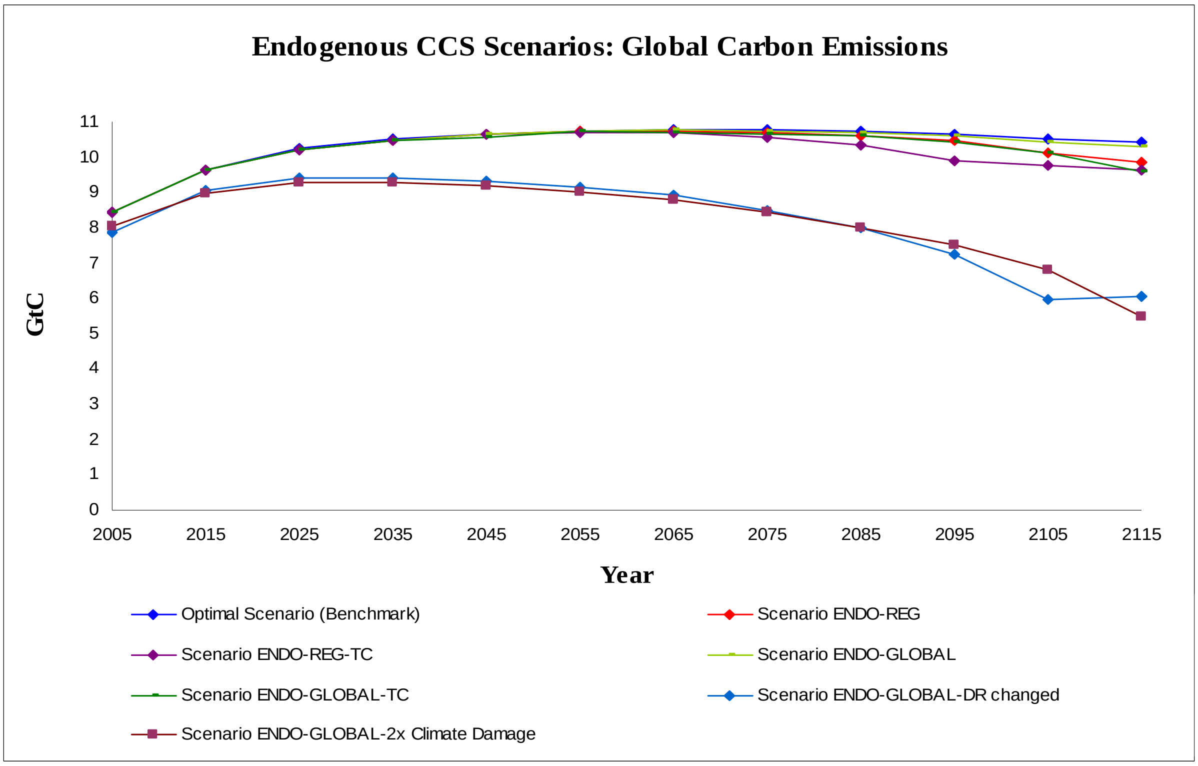
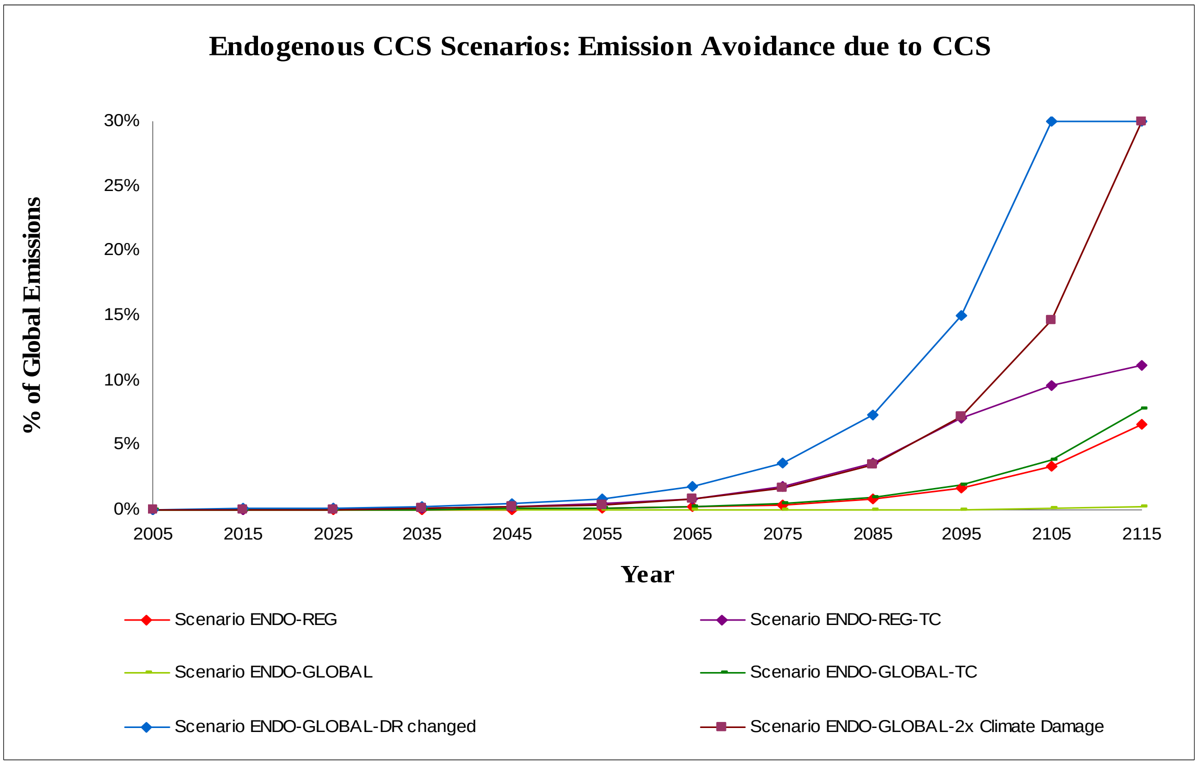
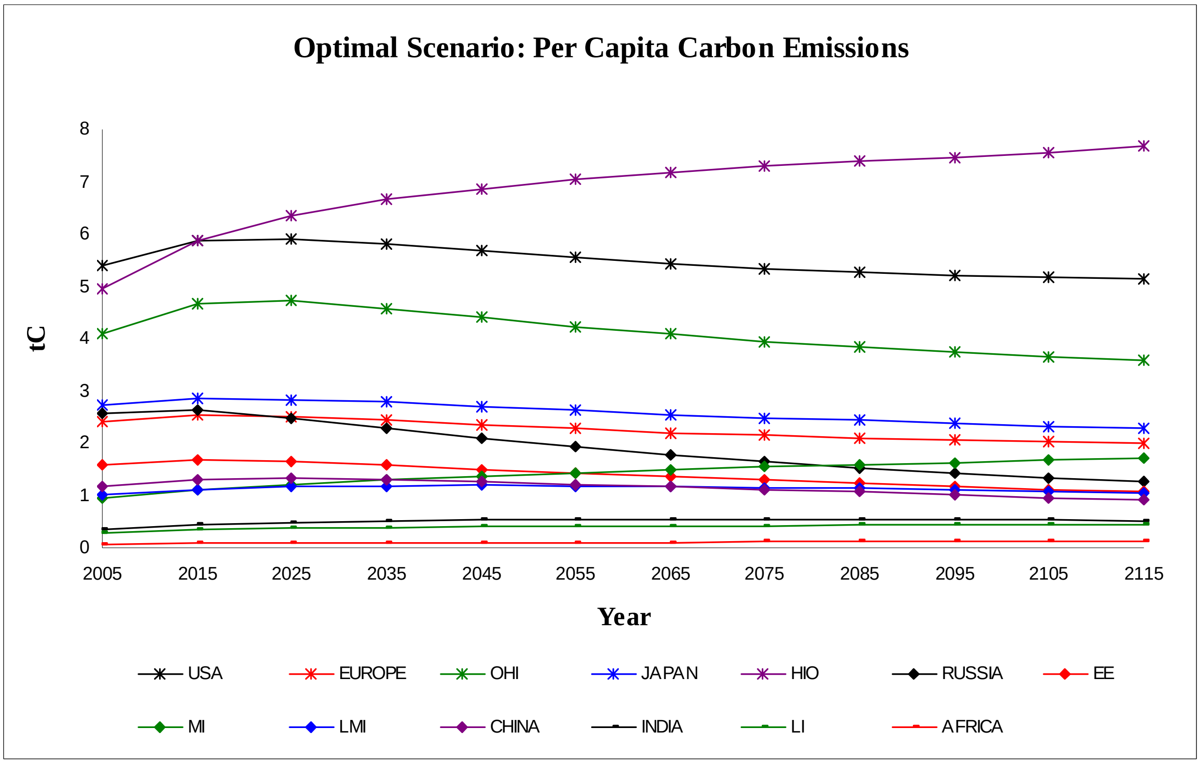
Appendix A – Results



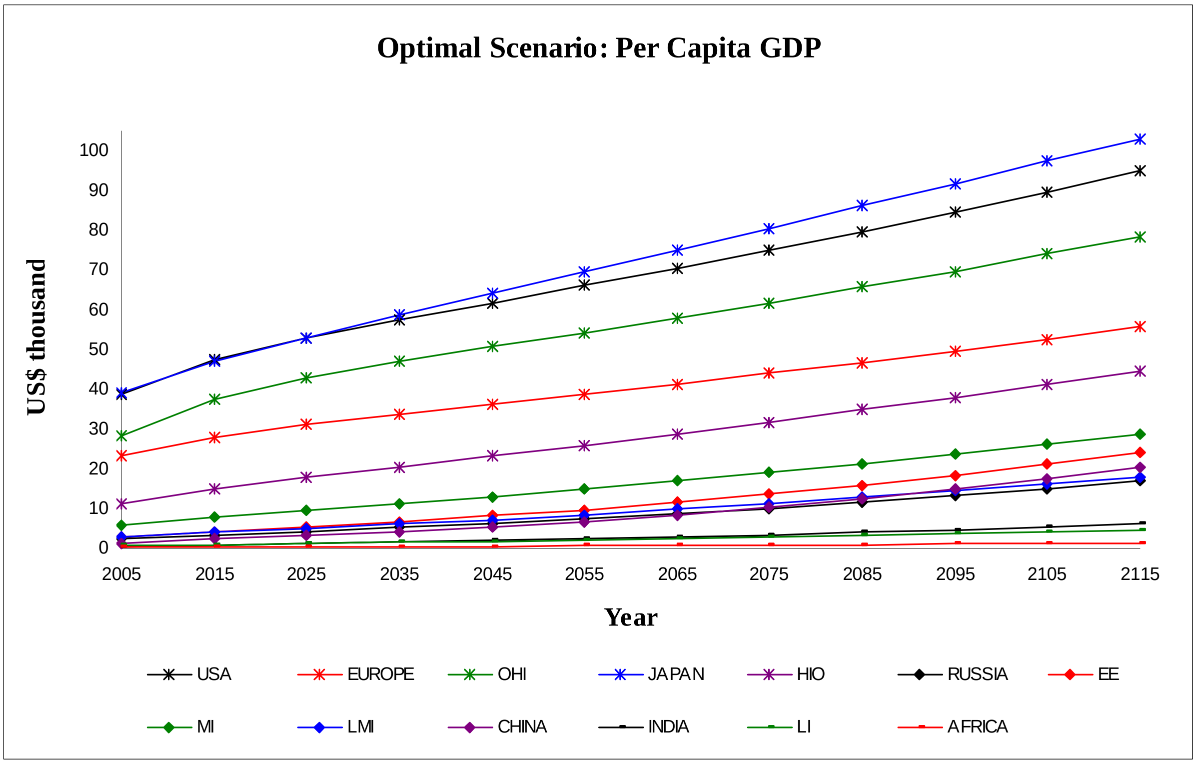
A - Figure 1: Endogenous CCS Scenarios – global carbon emissions (2005-2115)



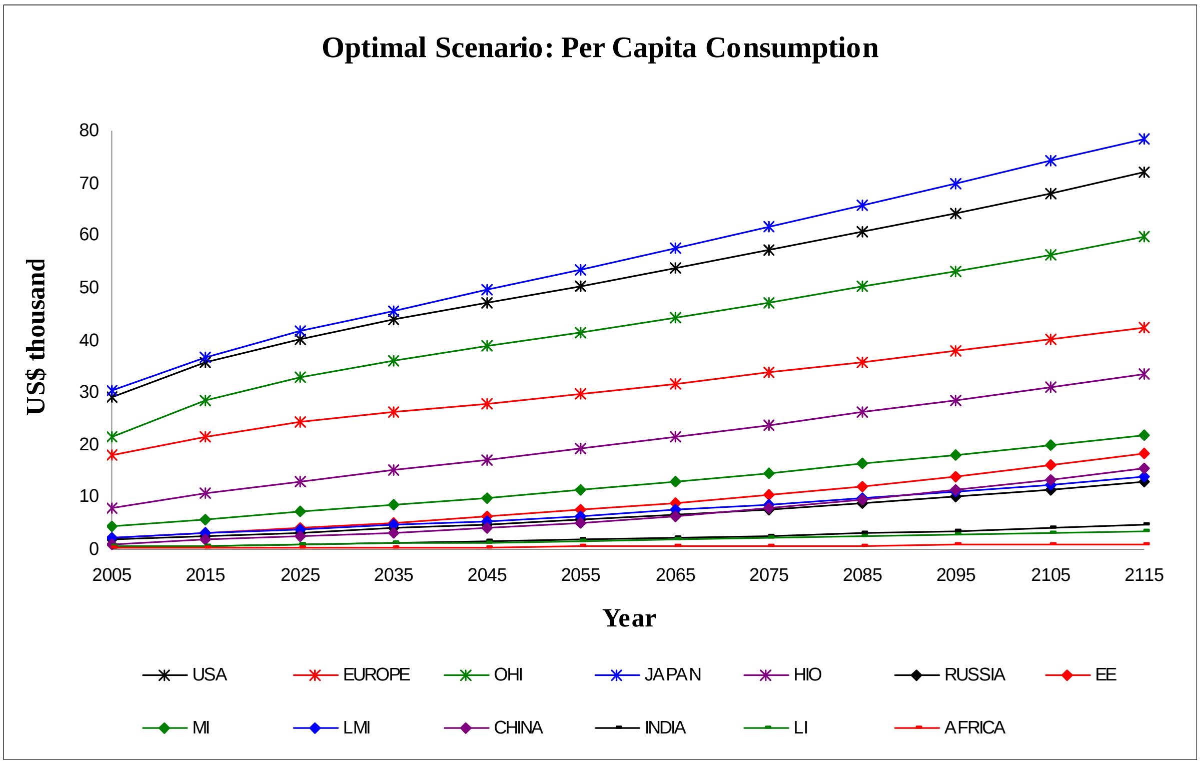
A - Figure 2: Endogenous CCS Scenarios – carbon emissions avoided due to CCS (2005-2115)



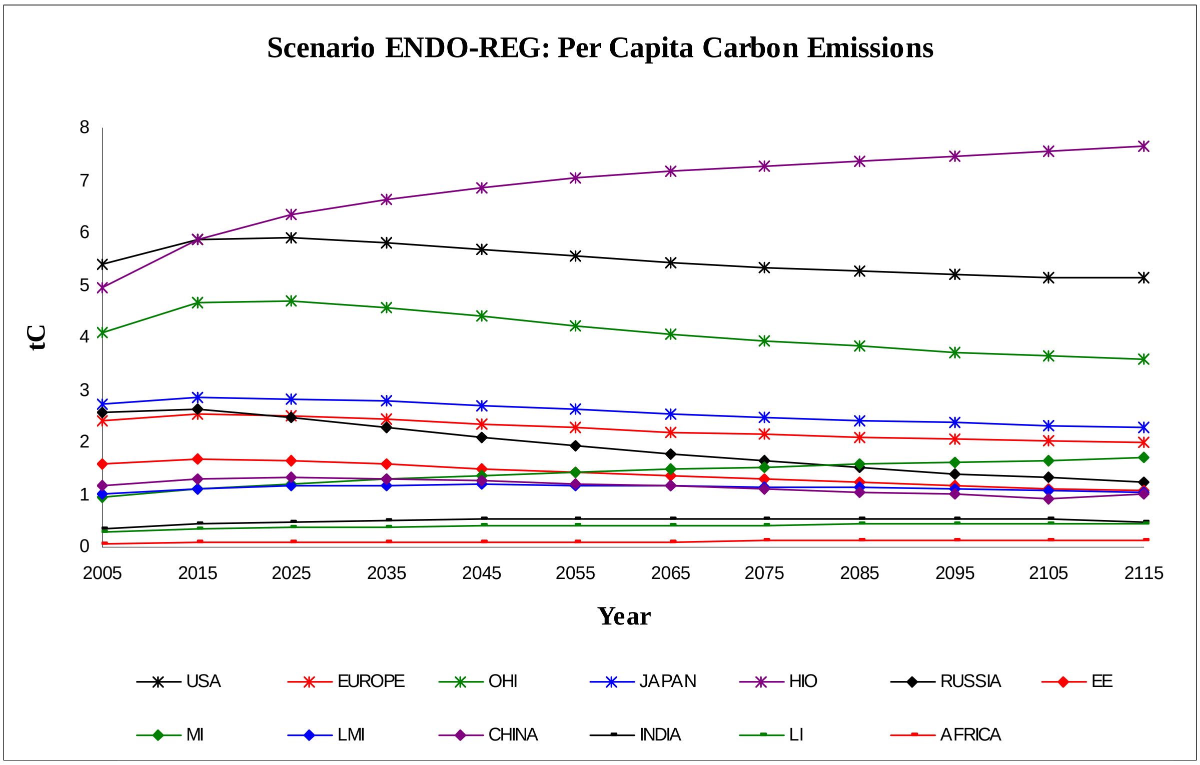
A - Figure 3: Optimal scenario – per capita carbon emissions (2005-2115)



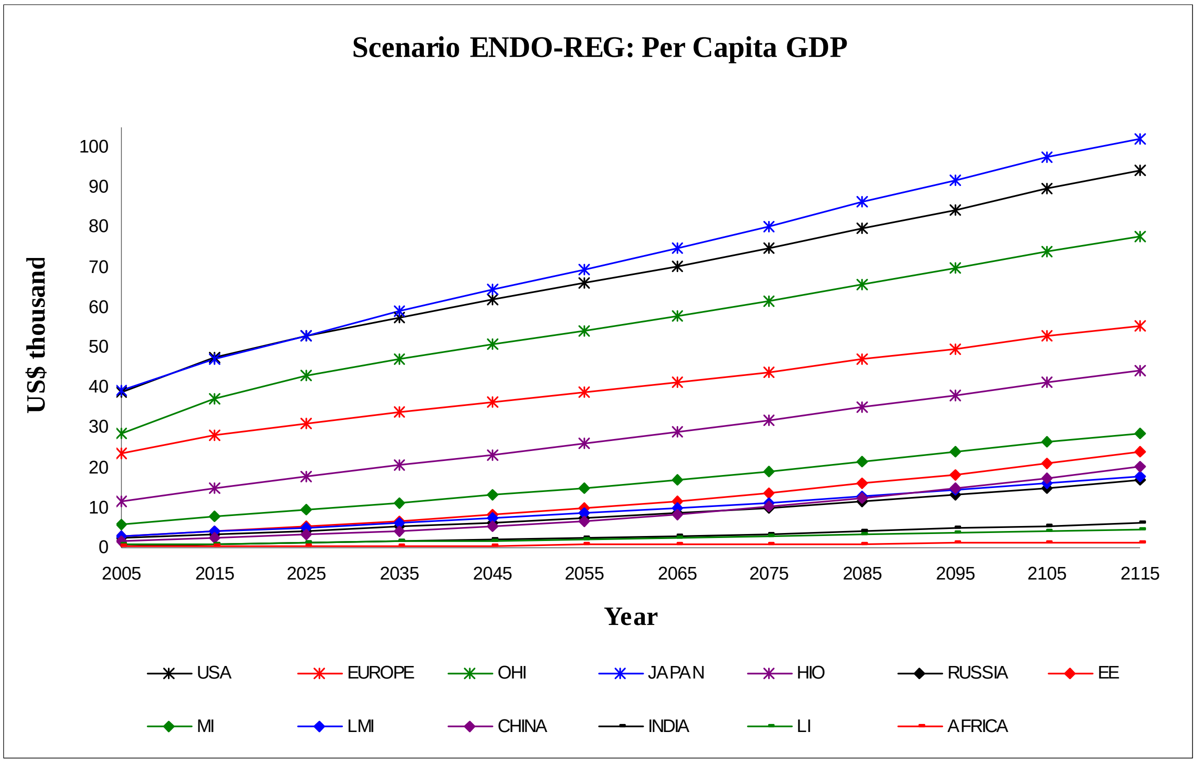
A - Figure 4: Optimal scenario – per capita GDP (2005-2115)



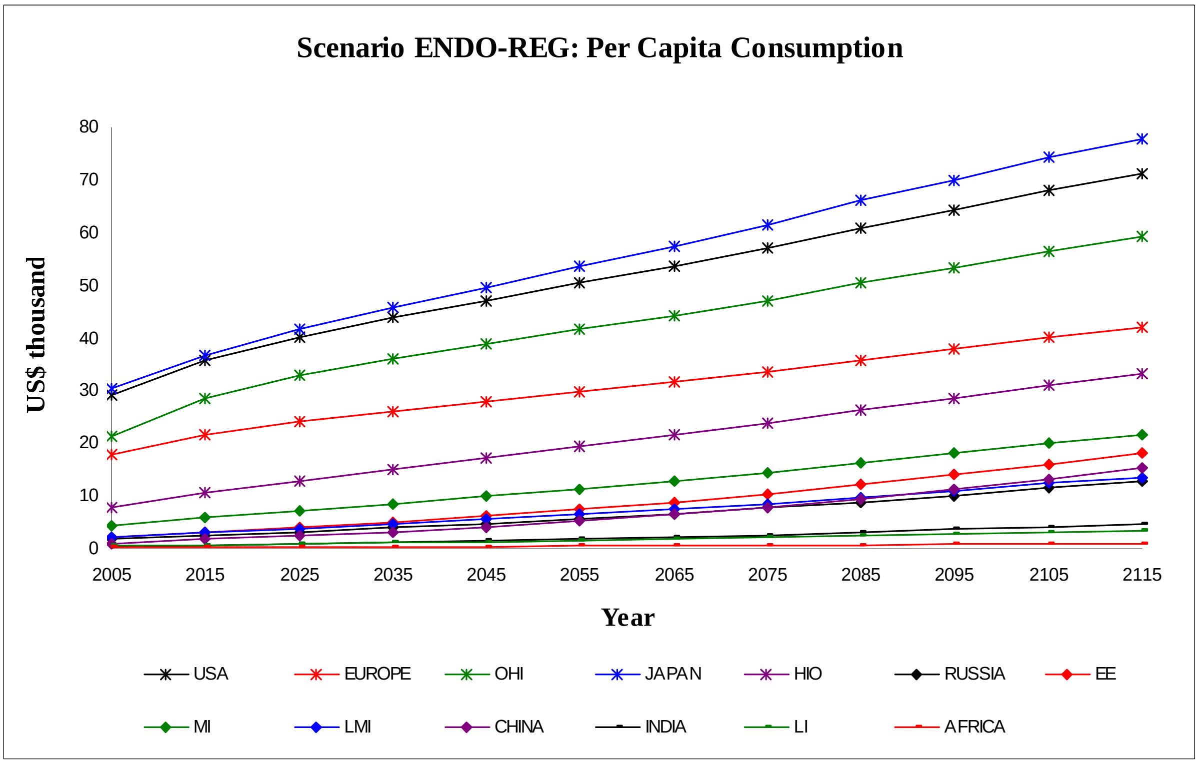
A - Figure 5: Optimal scenario – per capita consumption (2005-2115)



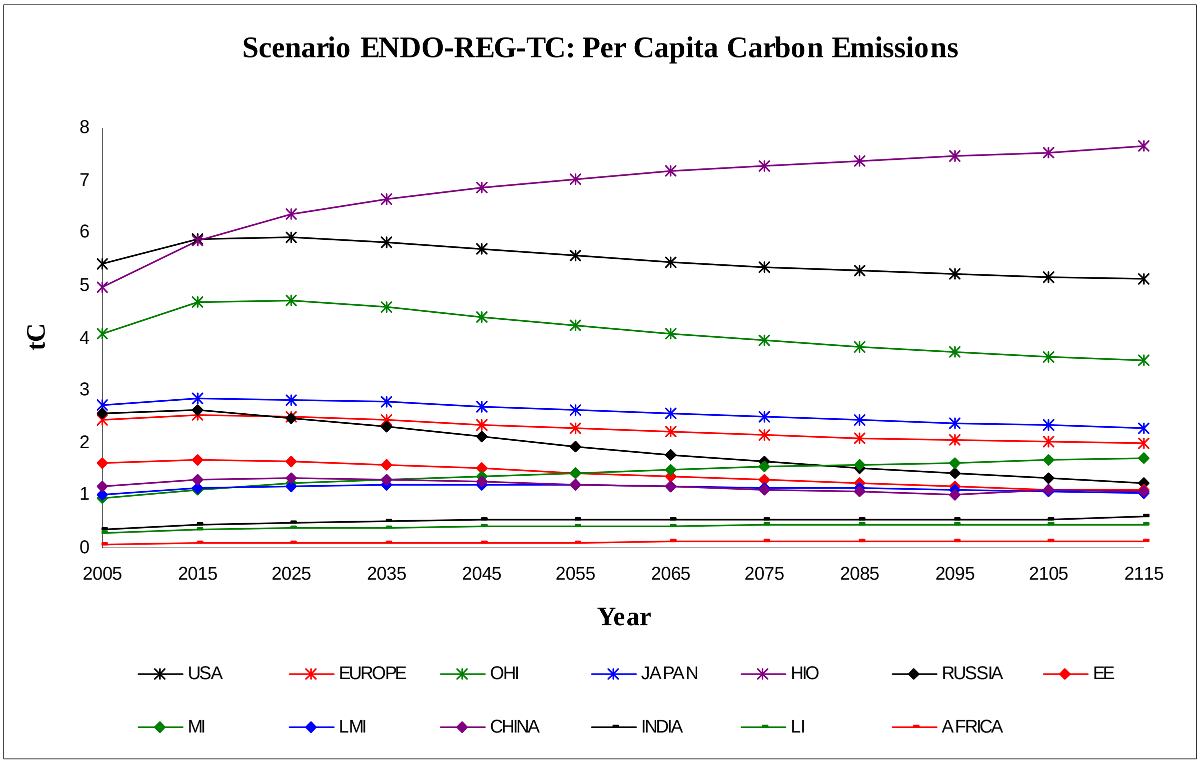
A - Figure 6: Scenario ENDO-REG – per capita carbon emissions (2005-2115)



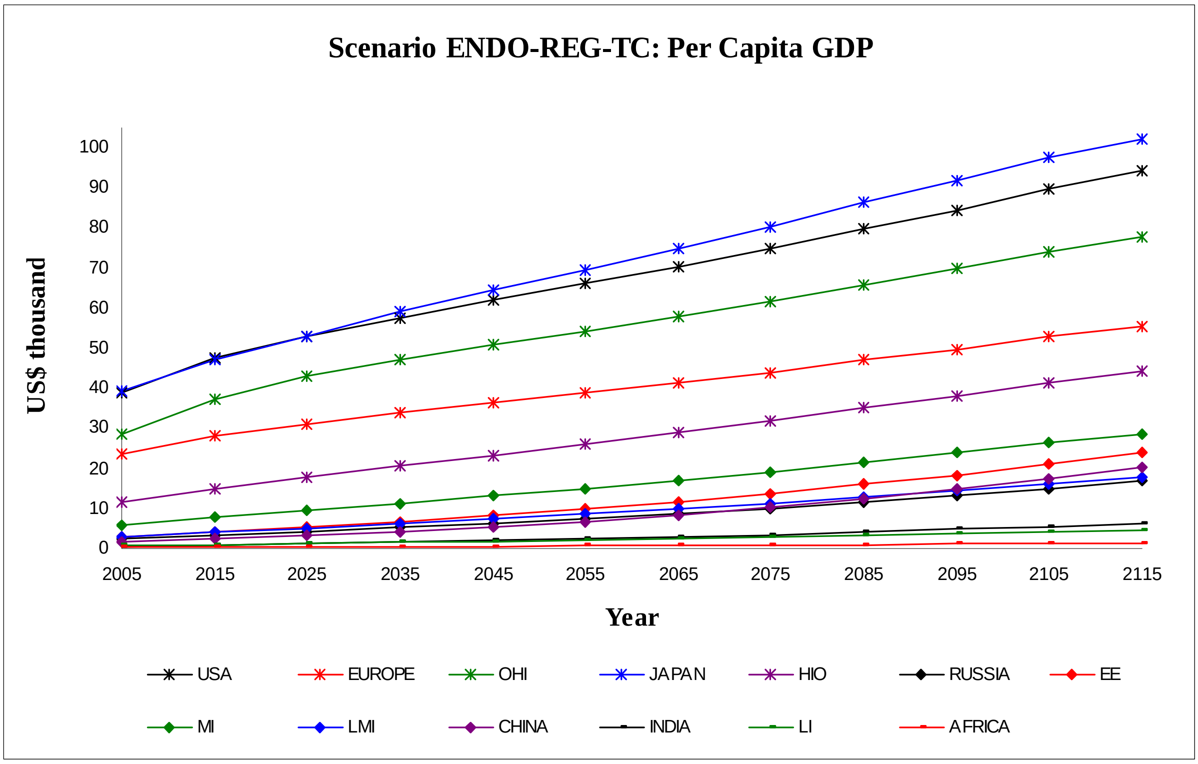
A - Figure 7: Scenario ENDO-REG – per capita GDP (2005-2115)



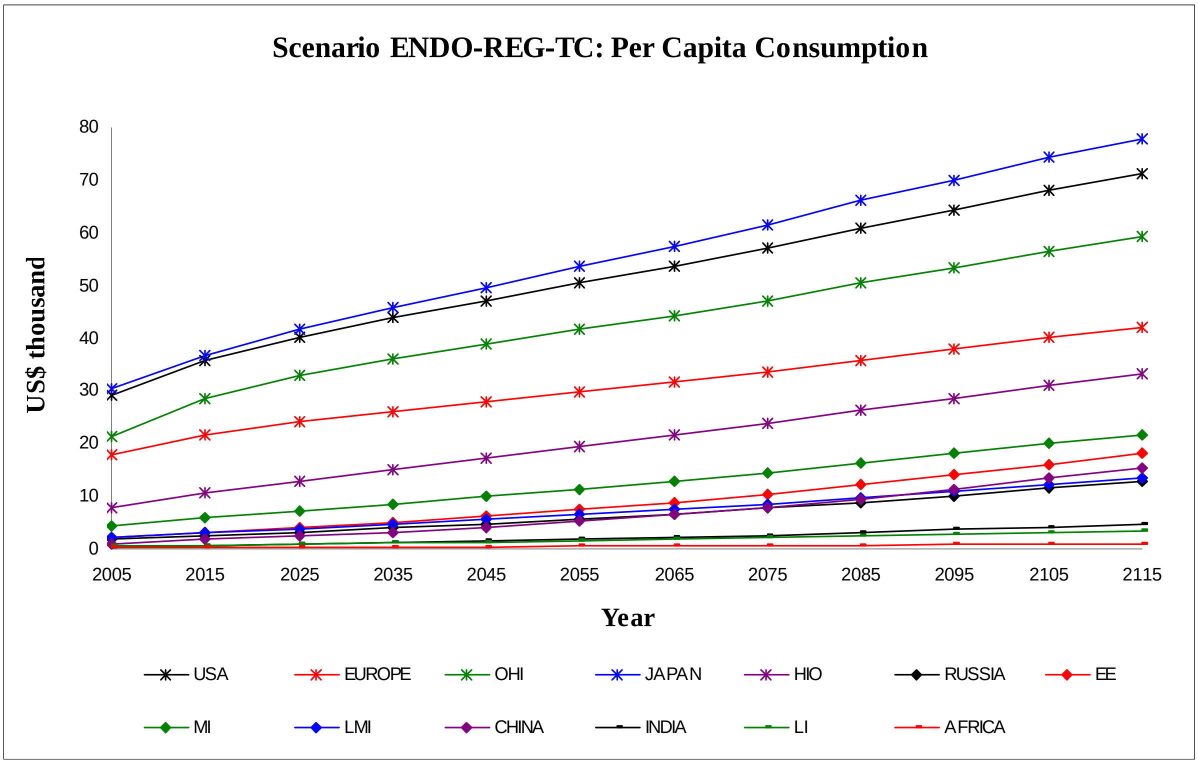
A - Figure 8: Scenario ENDO-REG – per capita consumption (2005-2115)



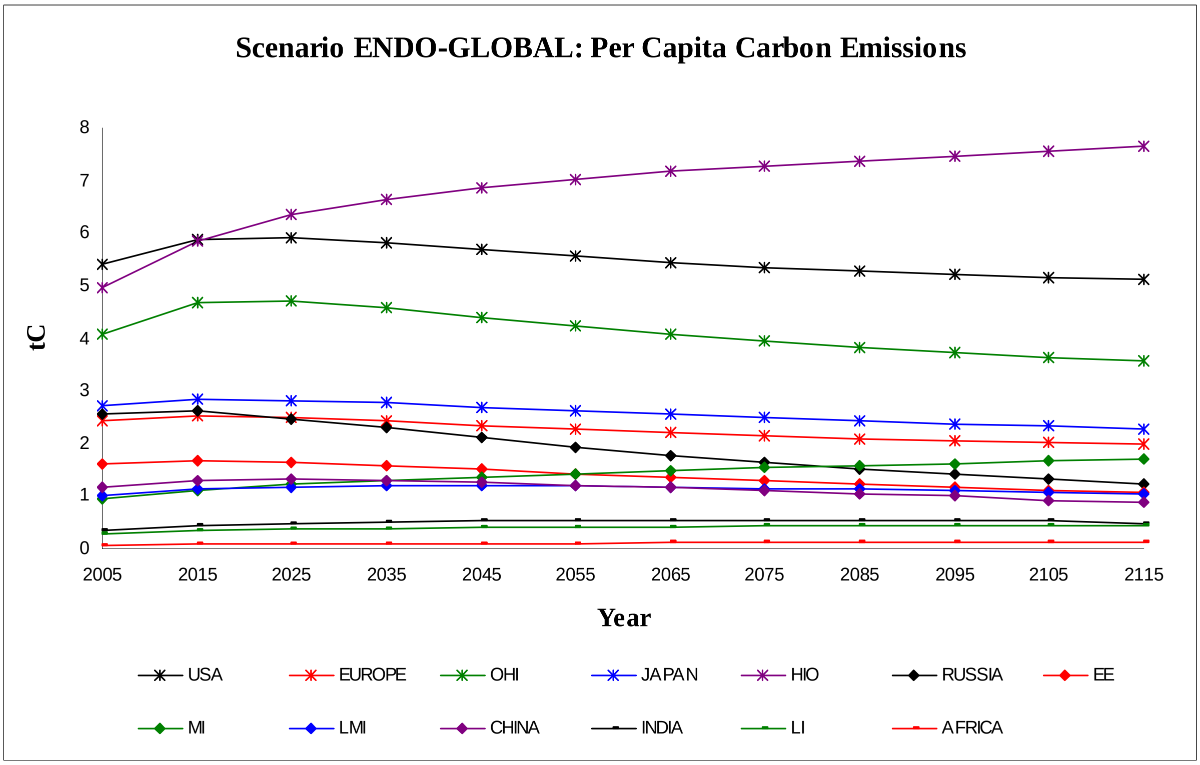
A - Figure 9: Scenario ENDO-REG-TC – per capita carbon emissions (2005-2115)



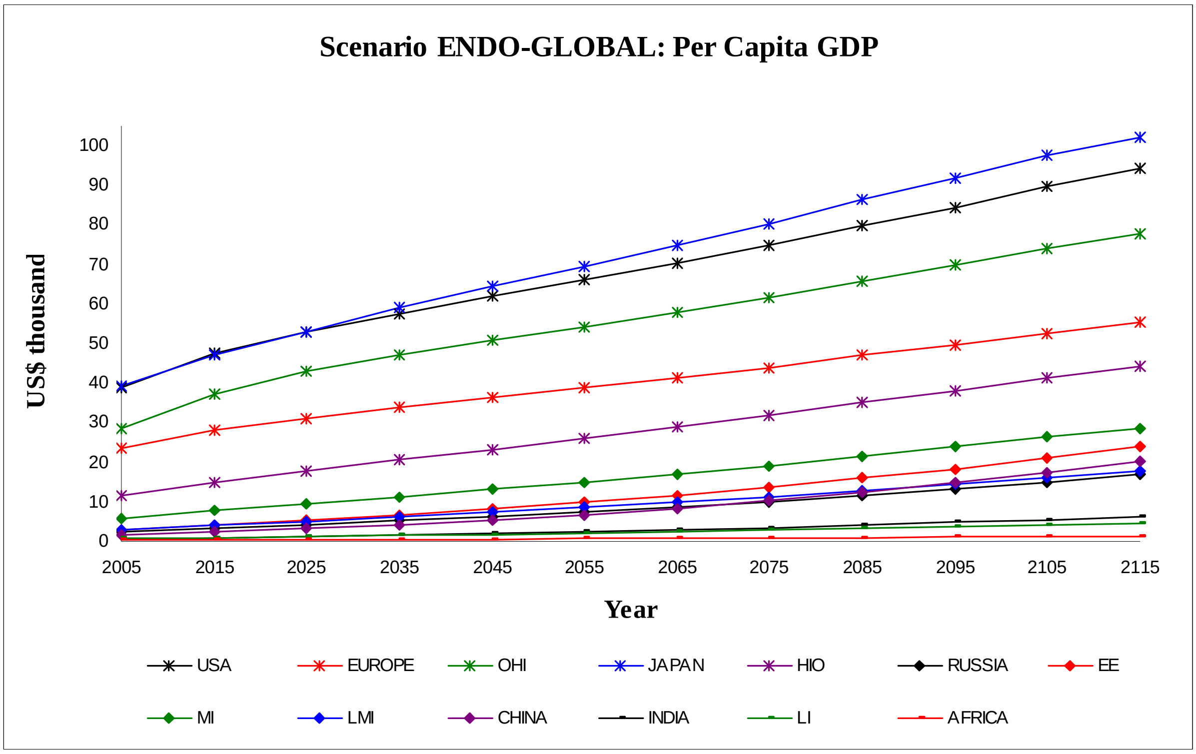
A - Figure 10: Scenario ENDO-REG-TC – per capita GDP (2005-2115)



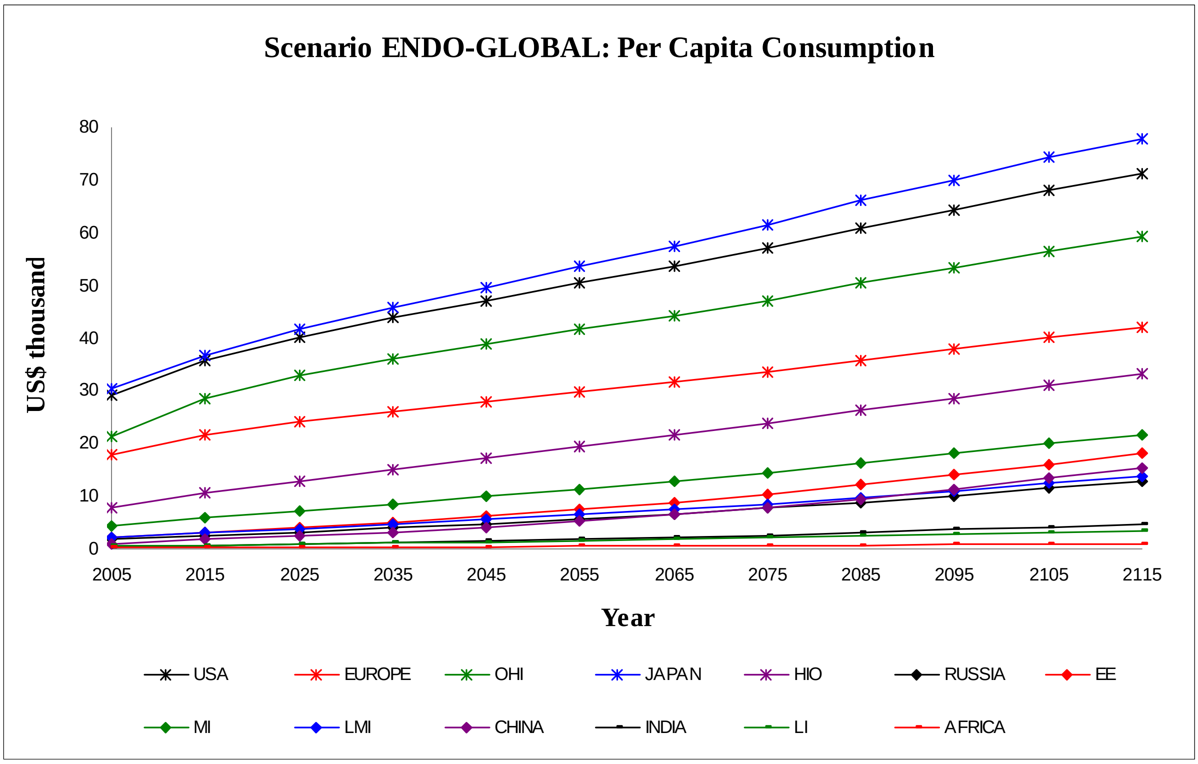
A - Figure 11: Scenario ENDO-REG-TC – per capita consumption (2005-2115)



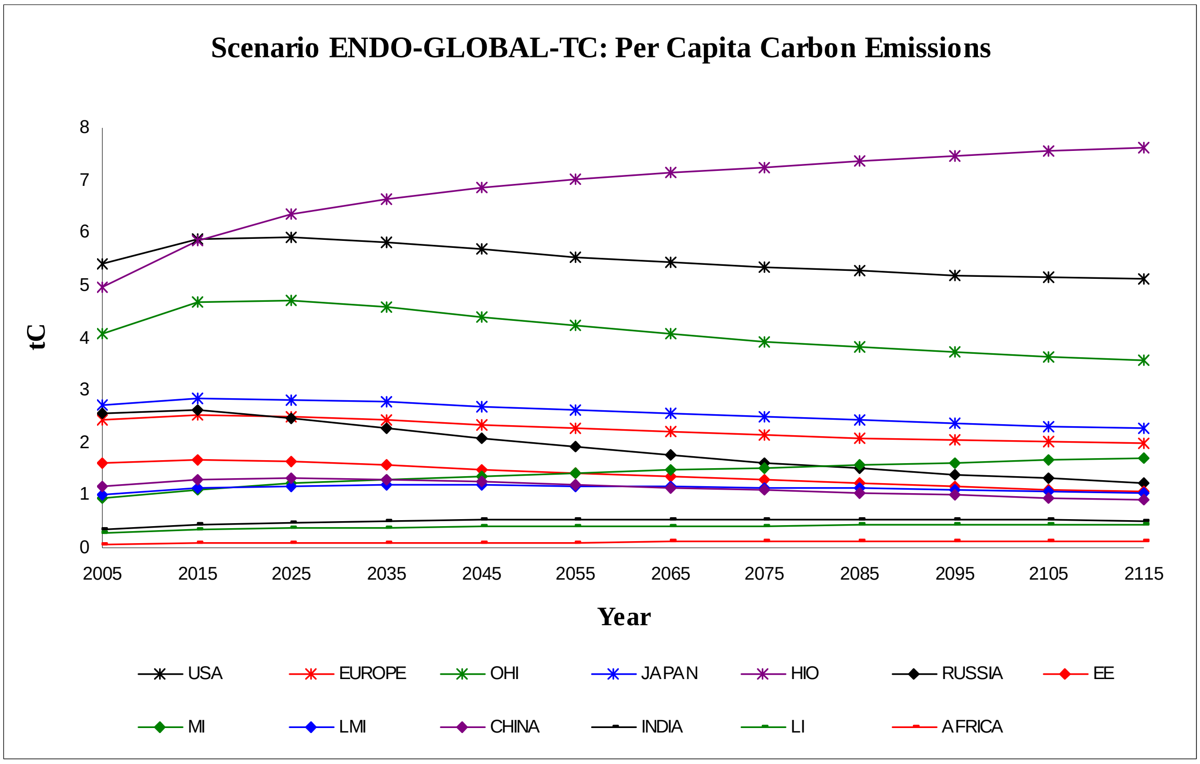
A - Figure 12: Scenario ENDO-GLOBAL – per capita carbon emissions (2005-2115)



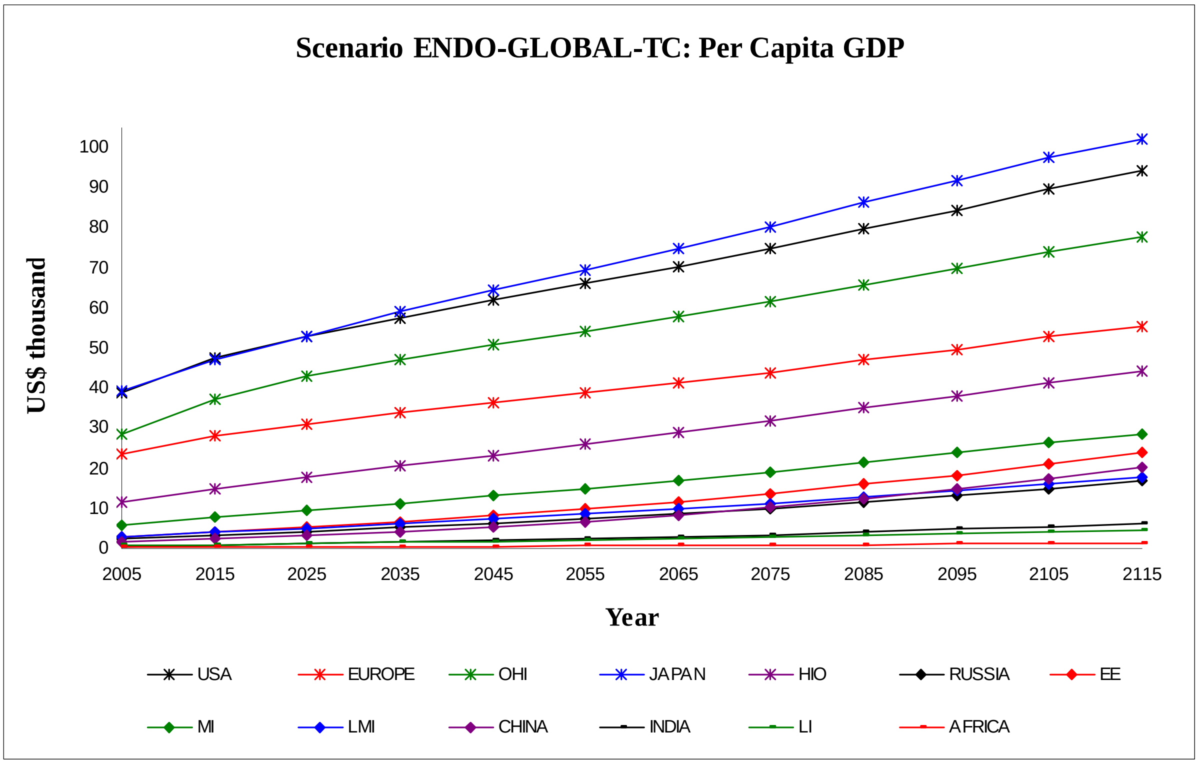
A - Figure 13: Scenario ENDO-GLOBAL – per capita GDP (2005-2115)



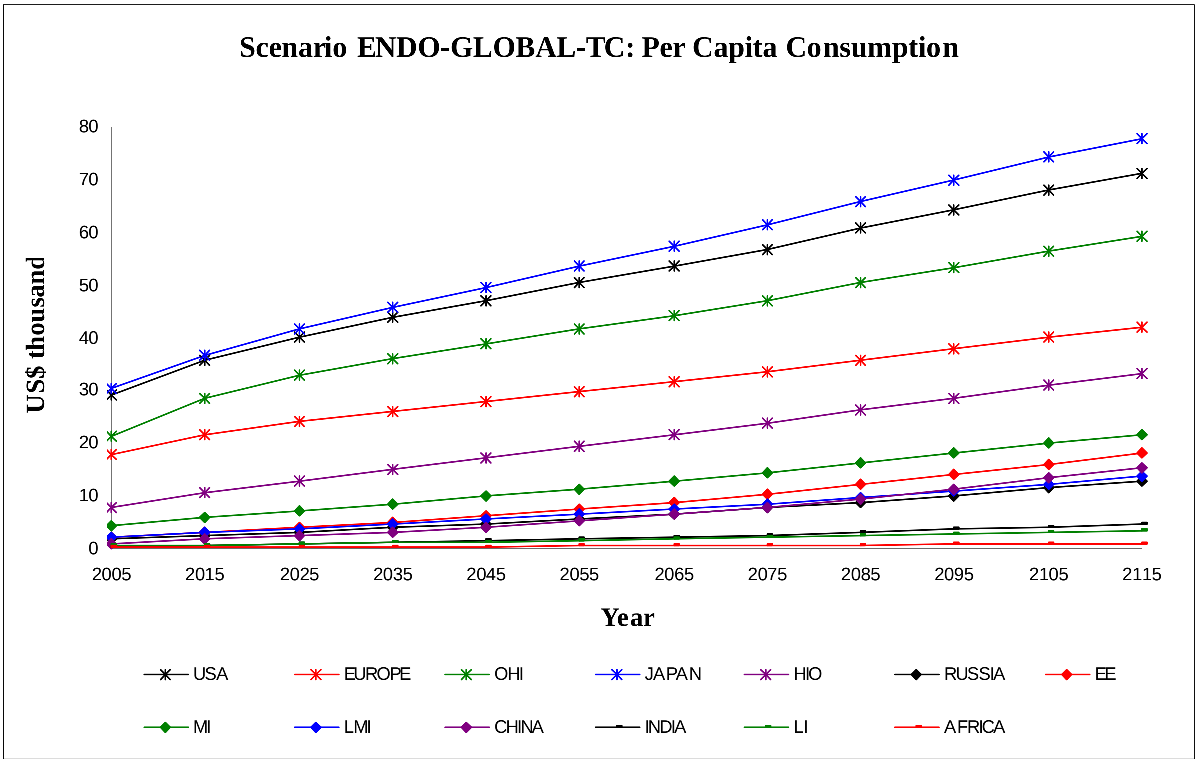
A - Figure 14: Scenario ENDO-GLOBAL – per capita consumption (2005-2115)



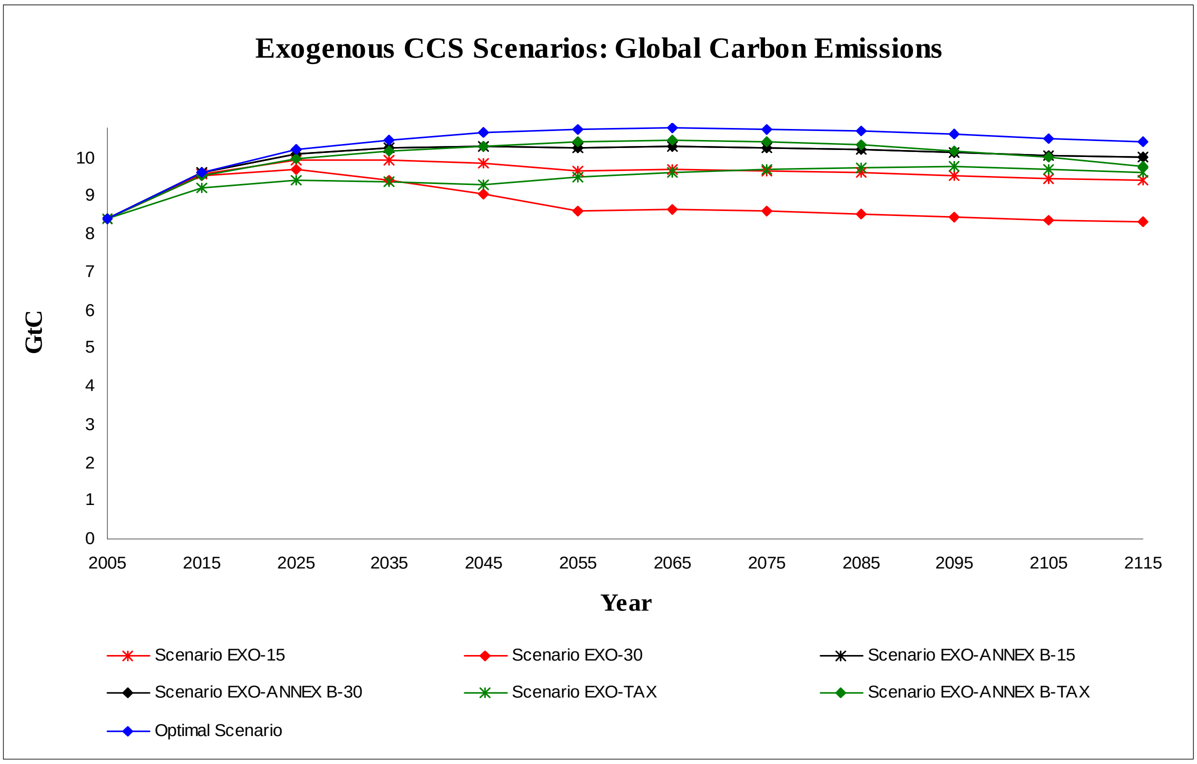
A - Figure 15: Scenario ENDO-GLOBAL-TC – per capita carbon emissions (2005-2115)



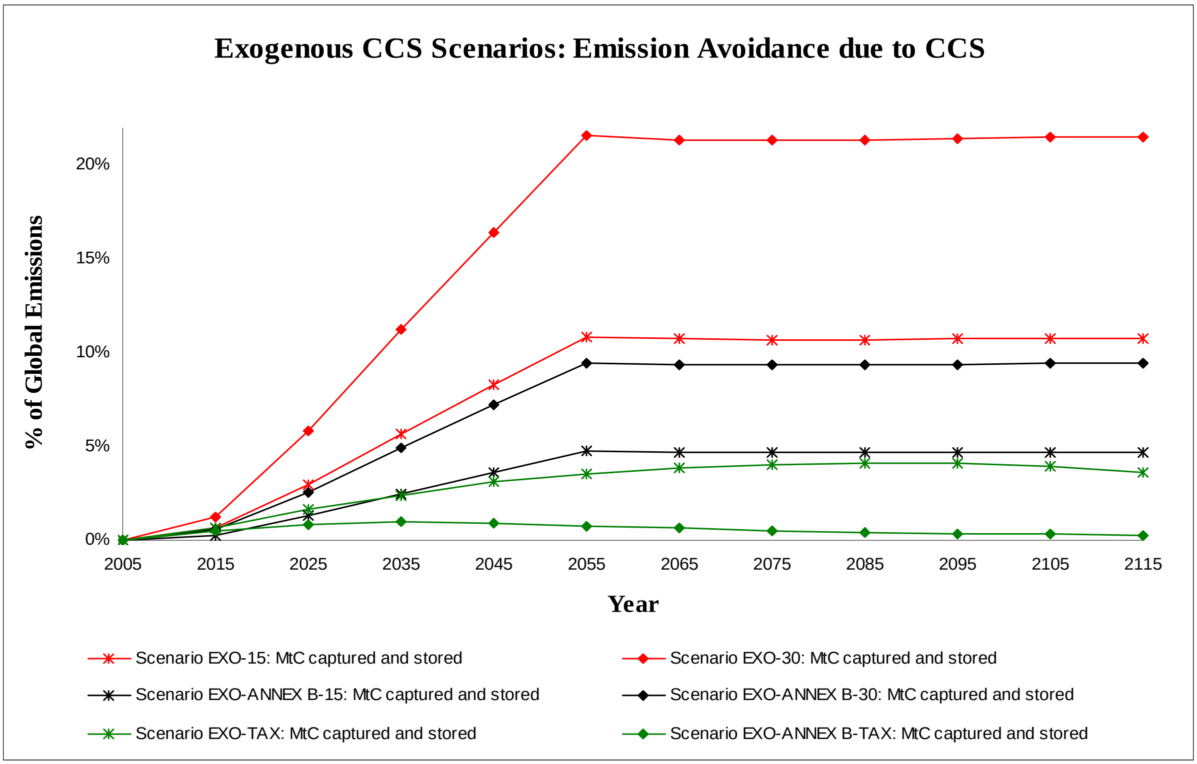
A - Figure 16: Scenario ENDO-GLOBAL-TC – per capita GDP (2005-2115)



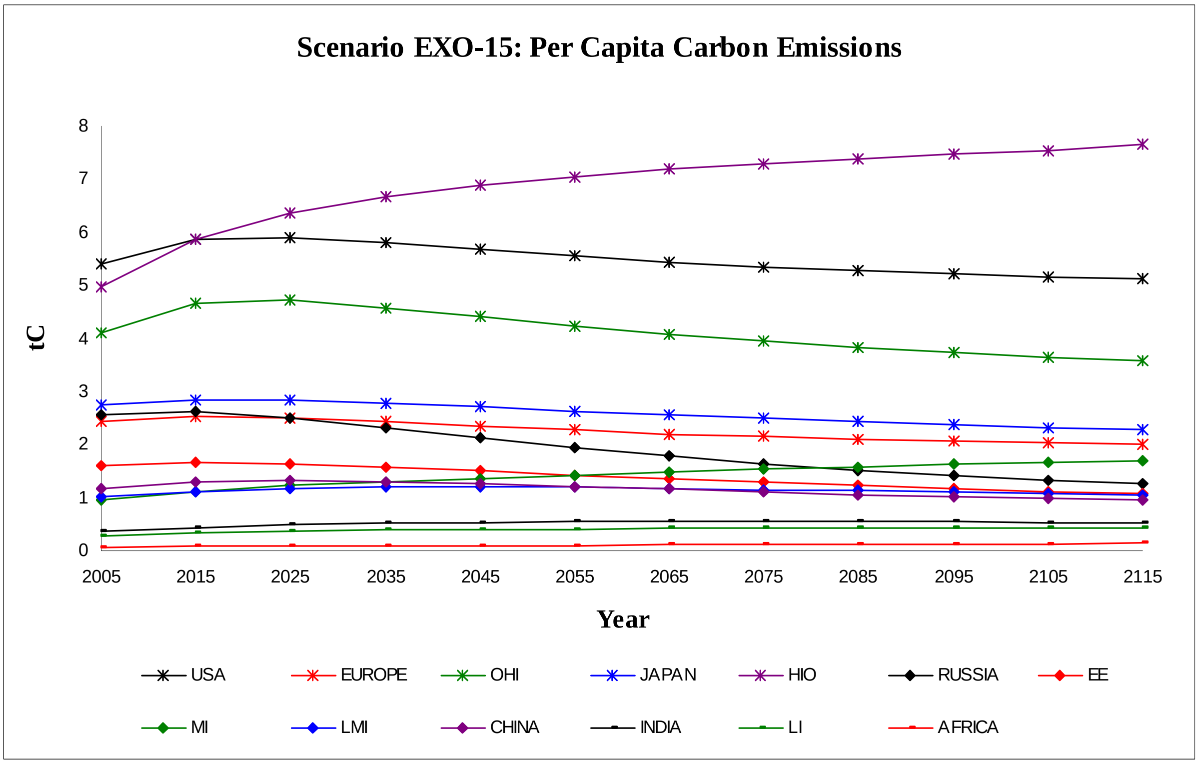
A - Figure 17: Scenario ENDO-GLOBAL-TC – per capita consumption (2005-2115)



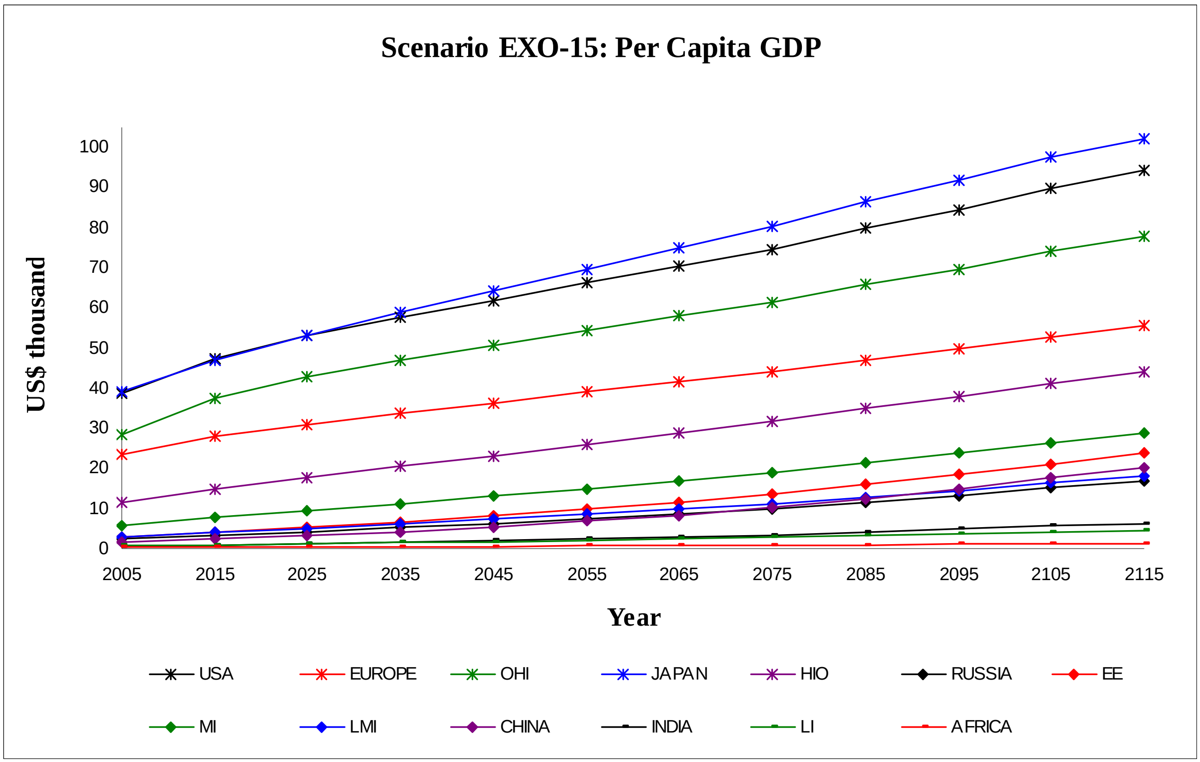
A - Figure 18: Exogenous CCS Scenarios – global carbon emissions (2005-2115)



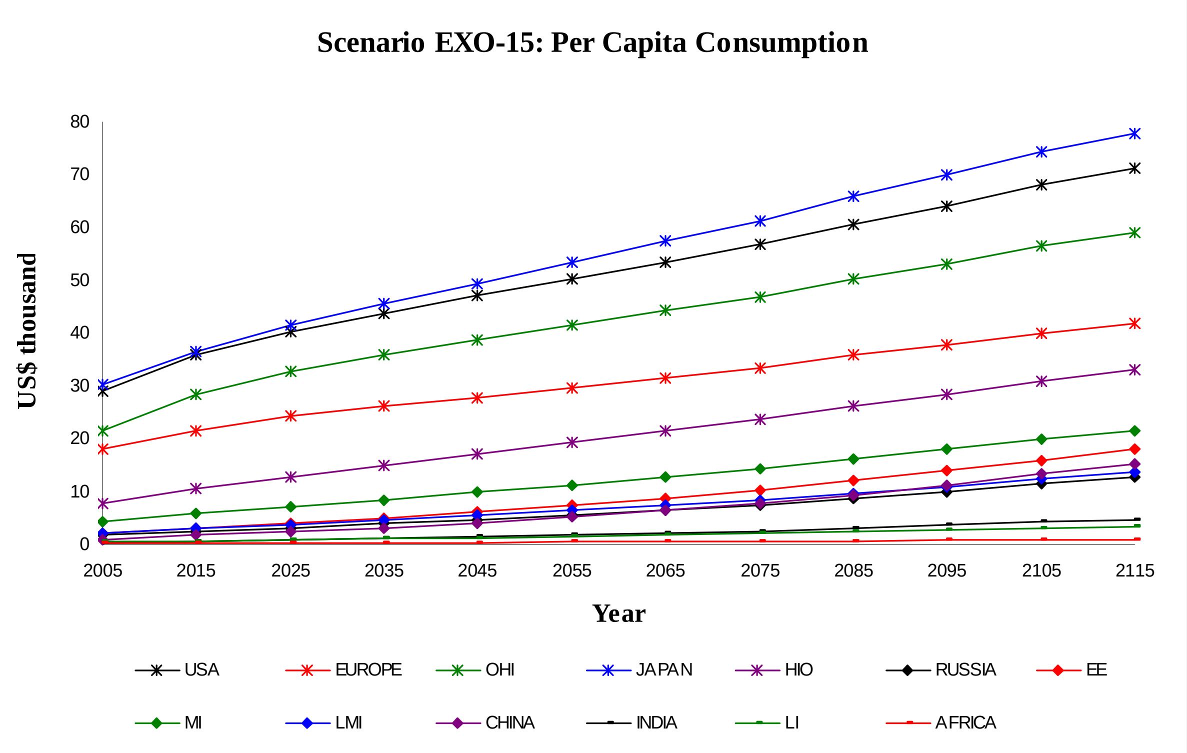
A - Figure 19: Exogenous CCS Scenarios – carbon emissions avoided due to CCS (2005-2115)



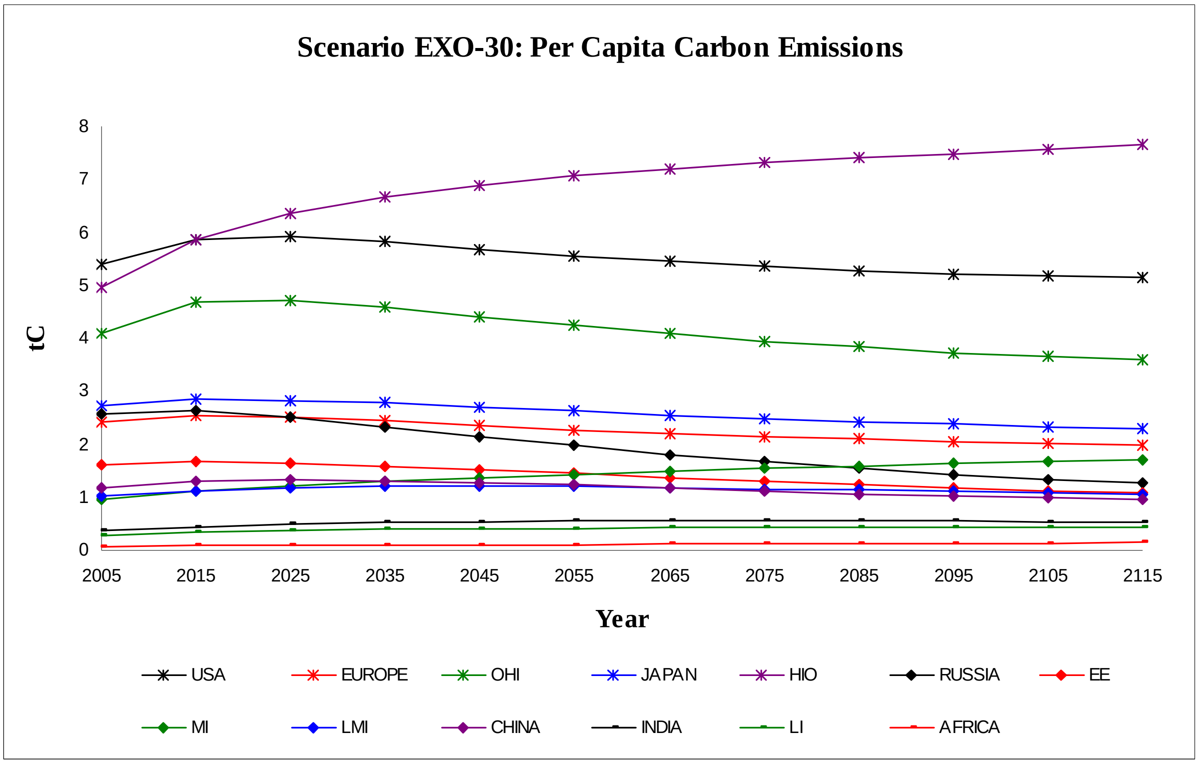
A - Figure 20: Scenario EXO-15 – per capita carbon emissions (2005-2115)



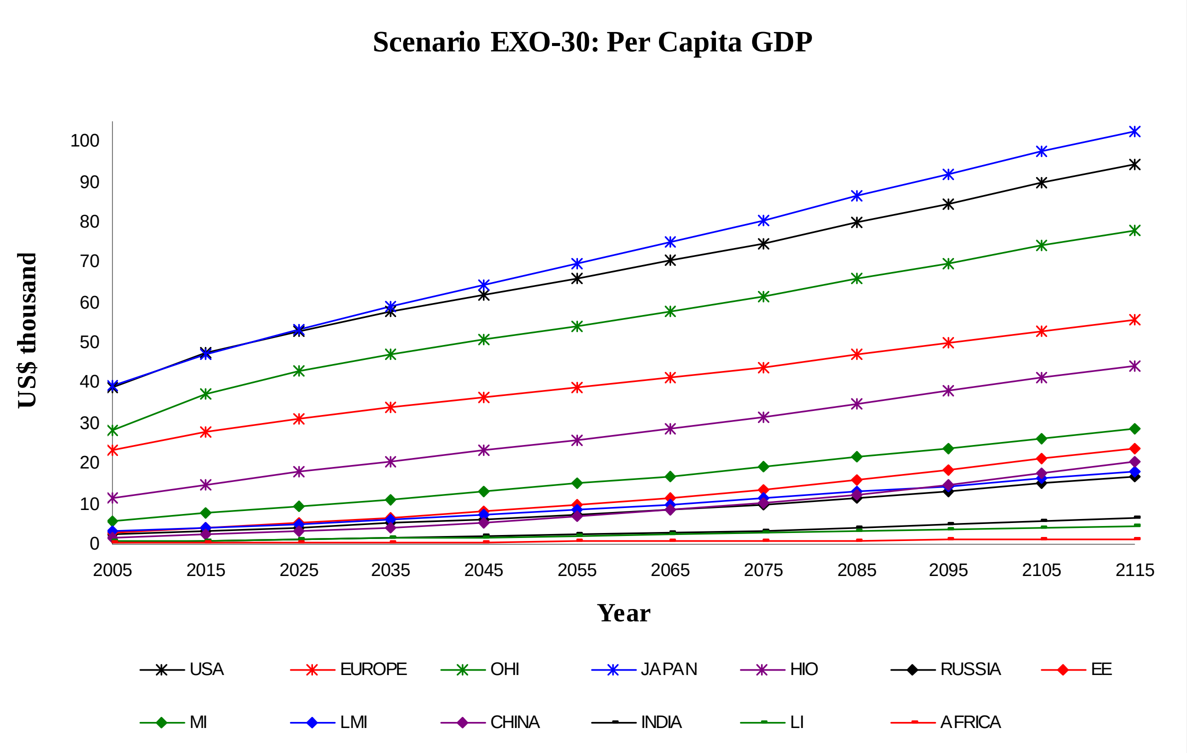
A - Figure 21: Scenario EXO-15 – per capita GDP (2005-2115)



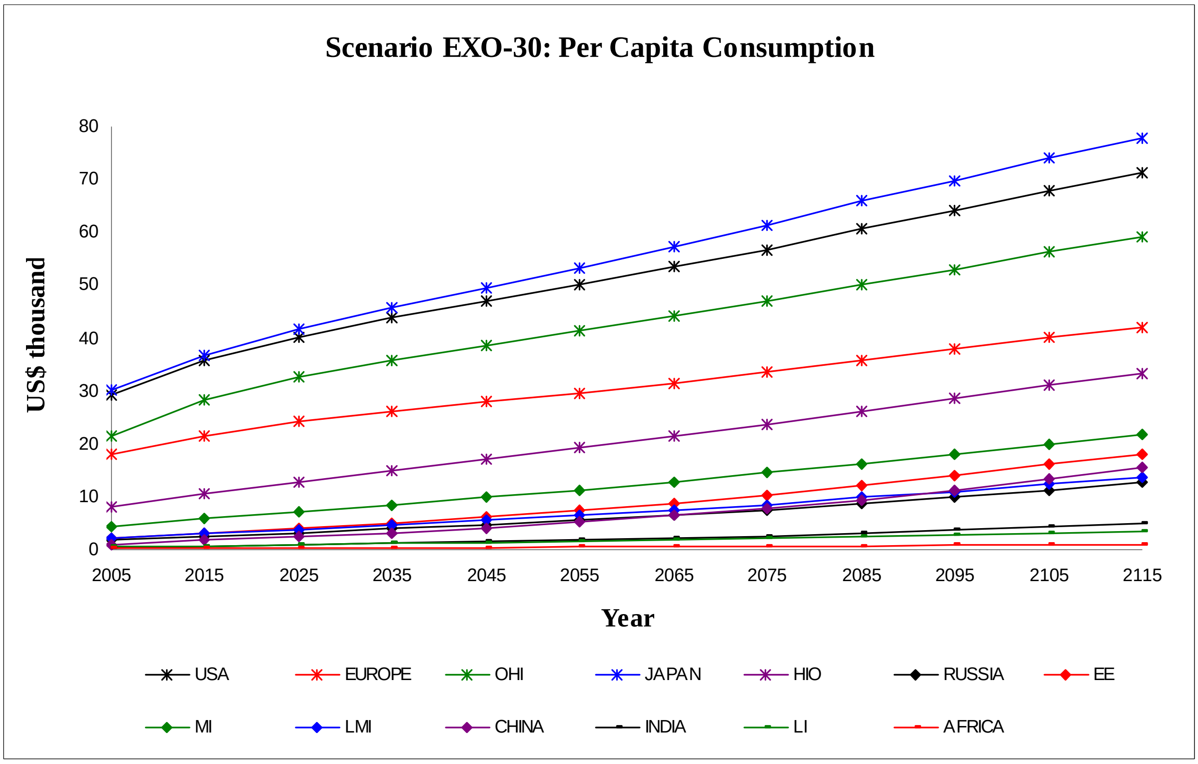
A - Figure 22: Scenario EXO-15 – per capita consumption (2005-2115)



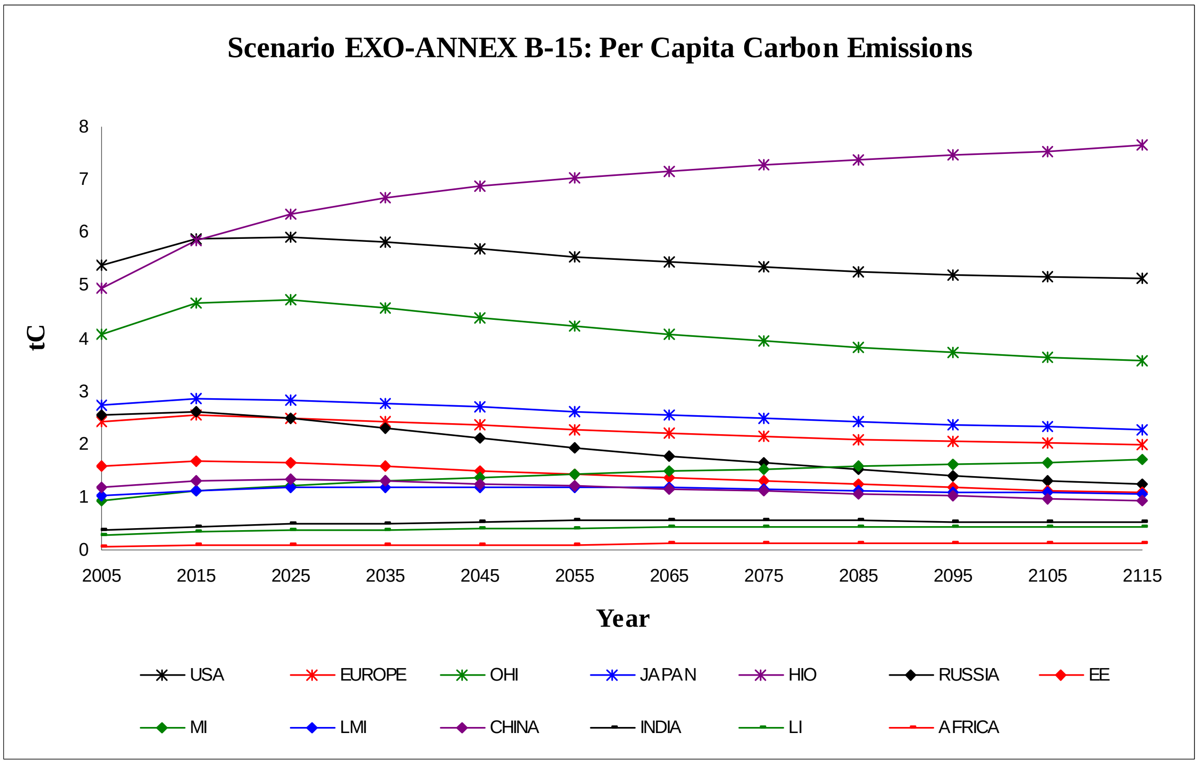
A - Figure 23: Scenario EXO-30 – per capita carbon emissions (2005-2115)



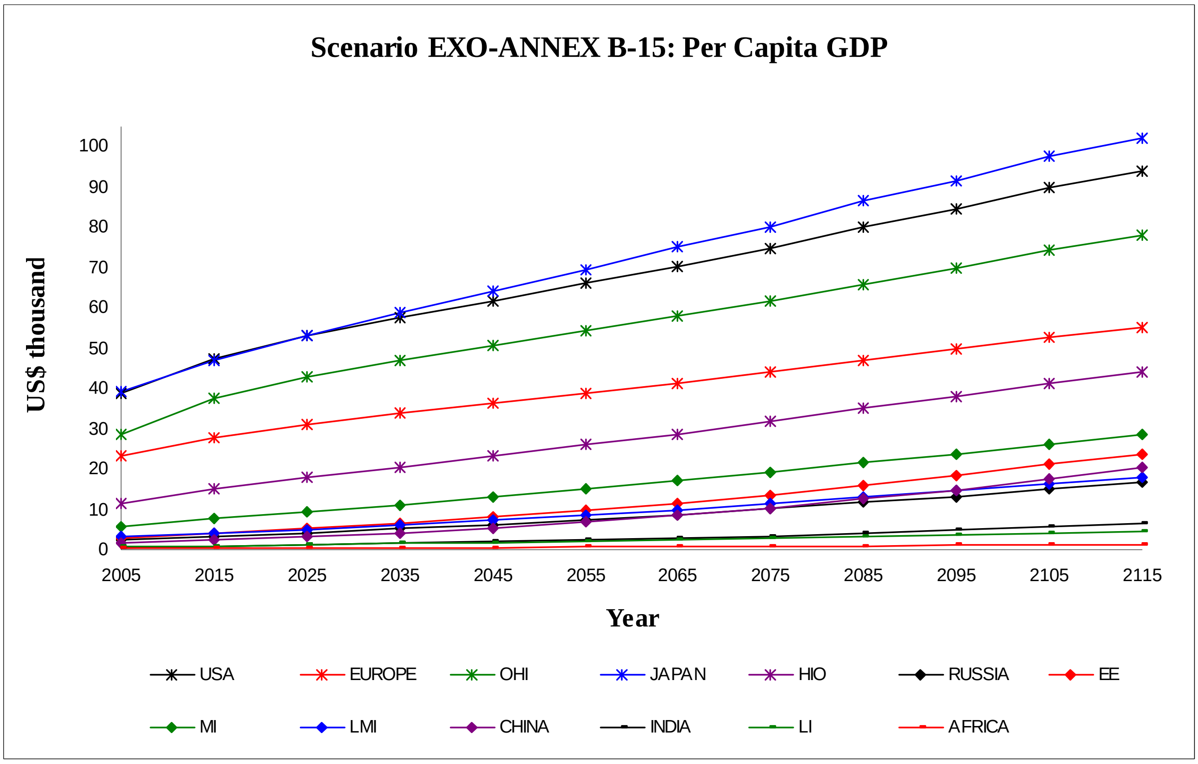
A - Figure 24: Scenario EXO-30 – per capita GDP (2005-2115)



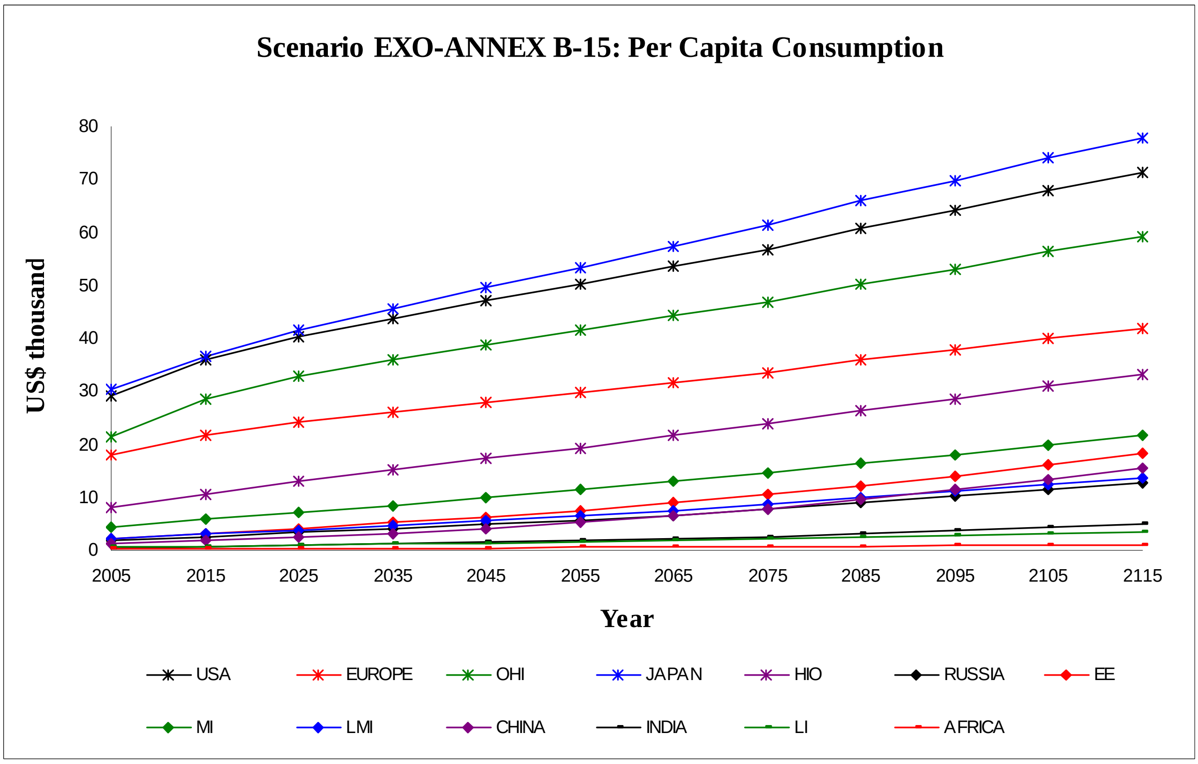
A - Figure 25: Scenario EXO-30 – per capita consumption (2005-2115)



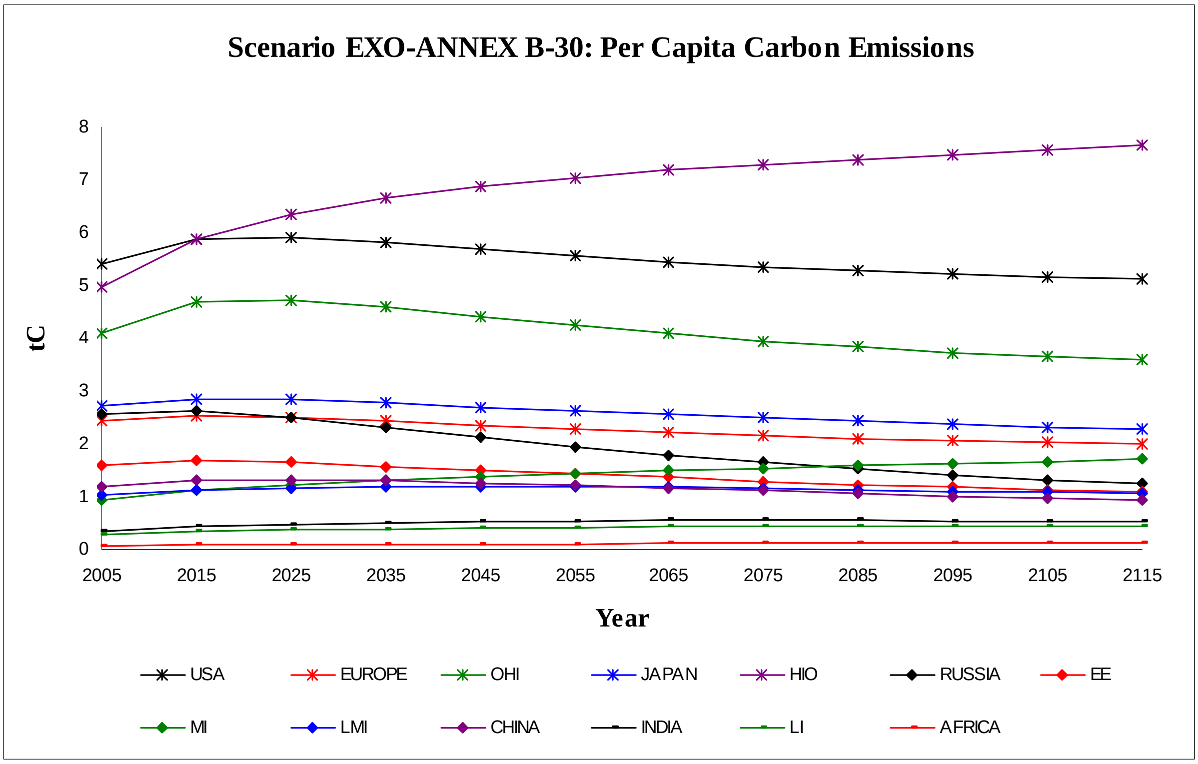
A - Figure 26: Scenario EXO-ANNEX B-15 – per capita carbon emissions (2005-2115)



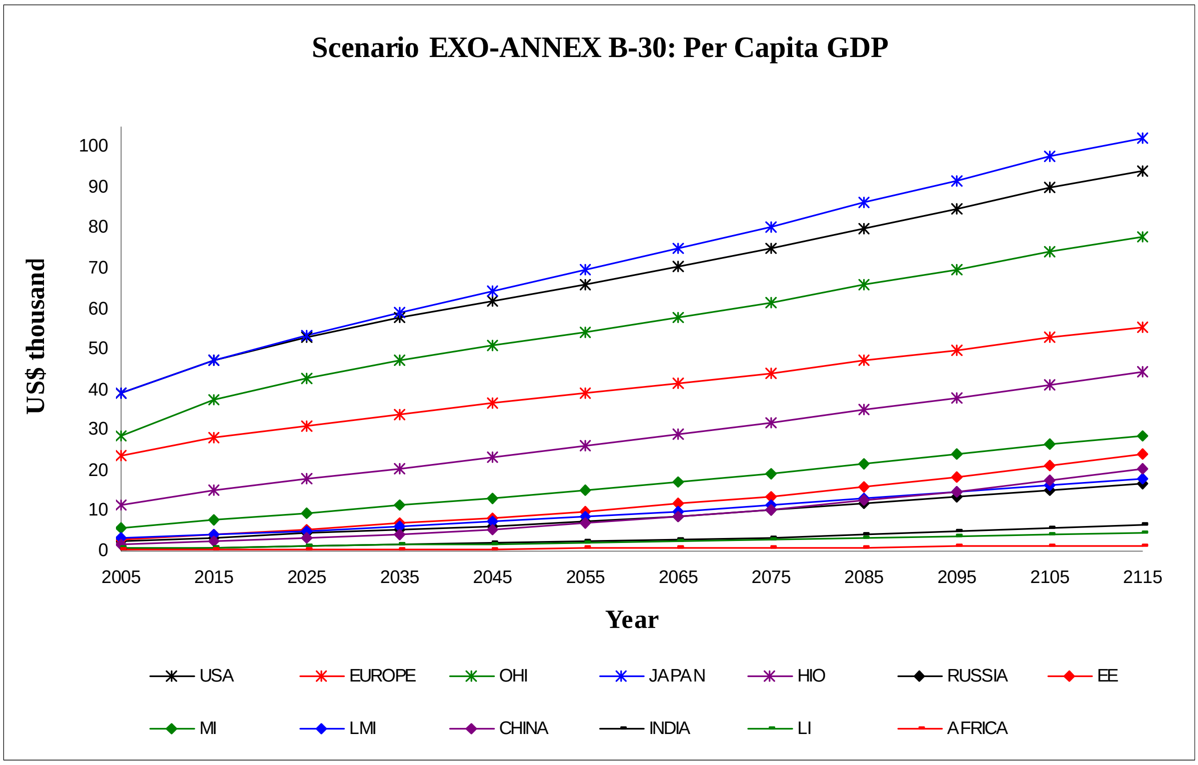
A - Figure 27: Scenario EXO-ANNEX B-15 – per capita GDP (2005-2115)



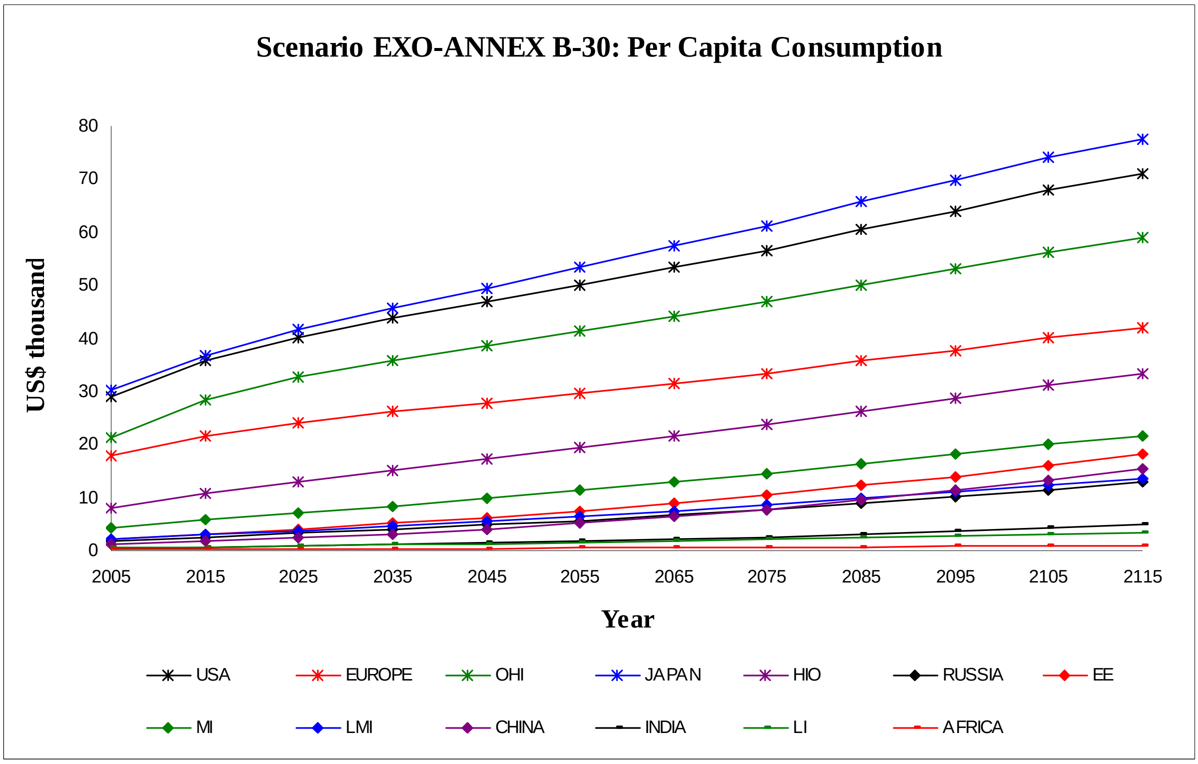
A - Figure 28: Scenario EXO-ANNEX B-15 – per capita consumption (2005-2115)



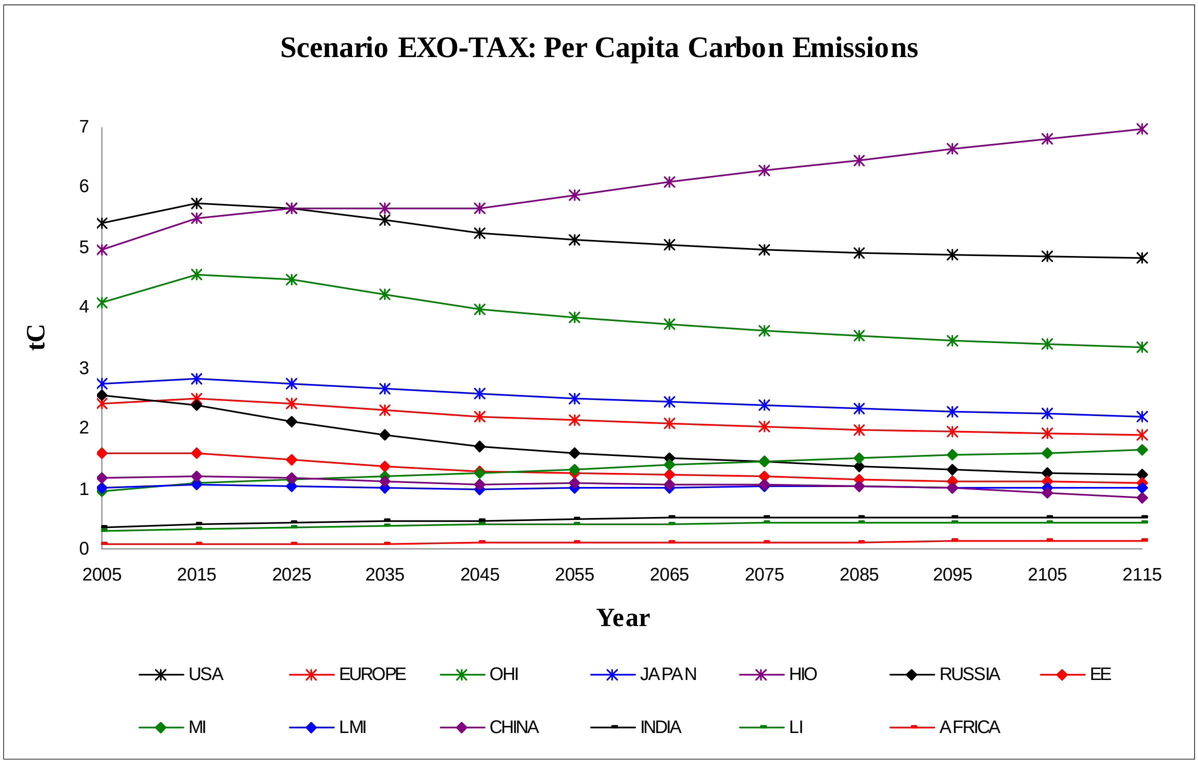
A - Figure 29: Scenario EXO-ANNEX B-30 – per capita carbon emissions (2005-2115)



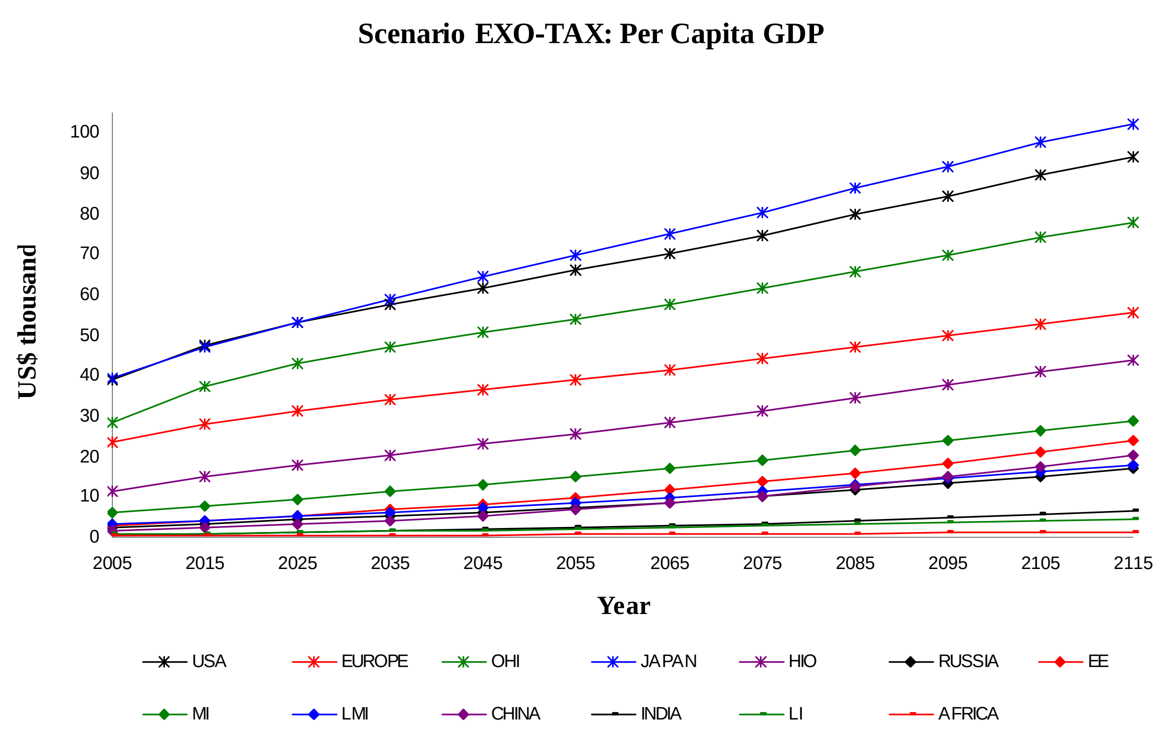
A - Figure 30: Scenario EXO-ANNEX B-30 – per capita GDP (2005-2115)



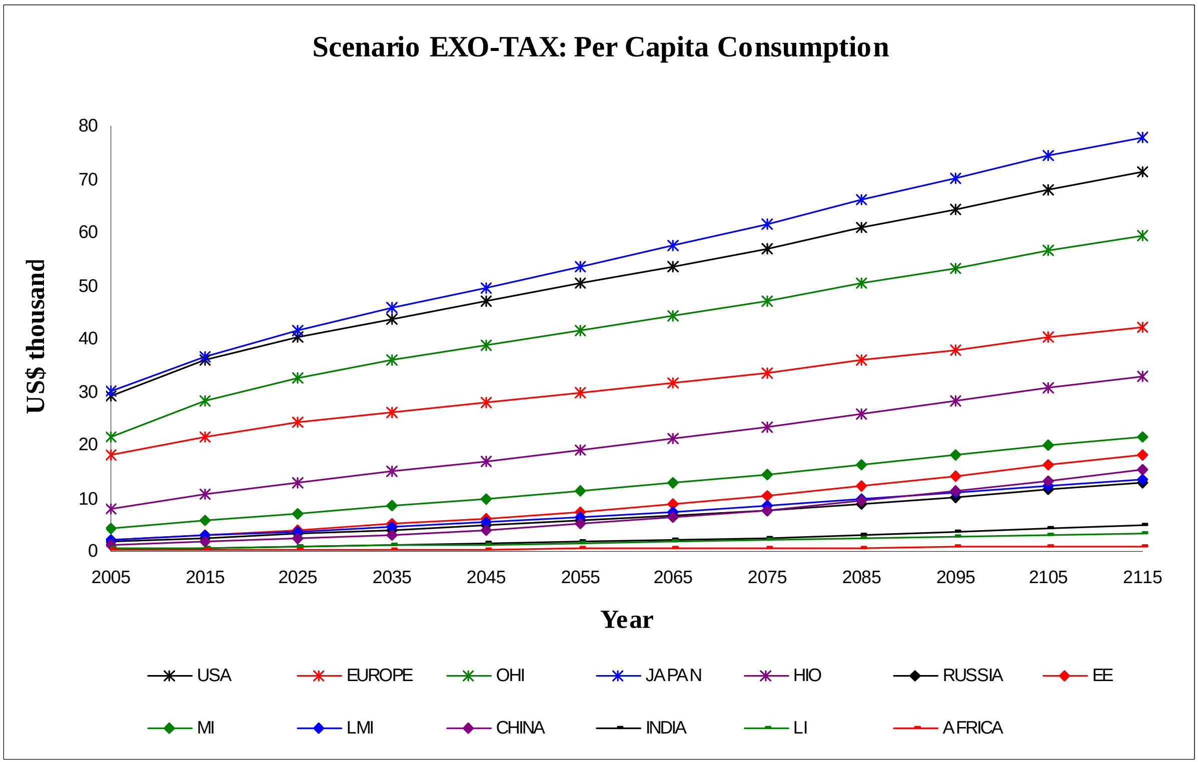
A - Figure 31: Scenario EXO-ANNEX B-30 – per capita consumption (2005-2115)



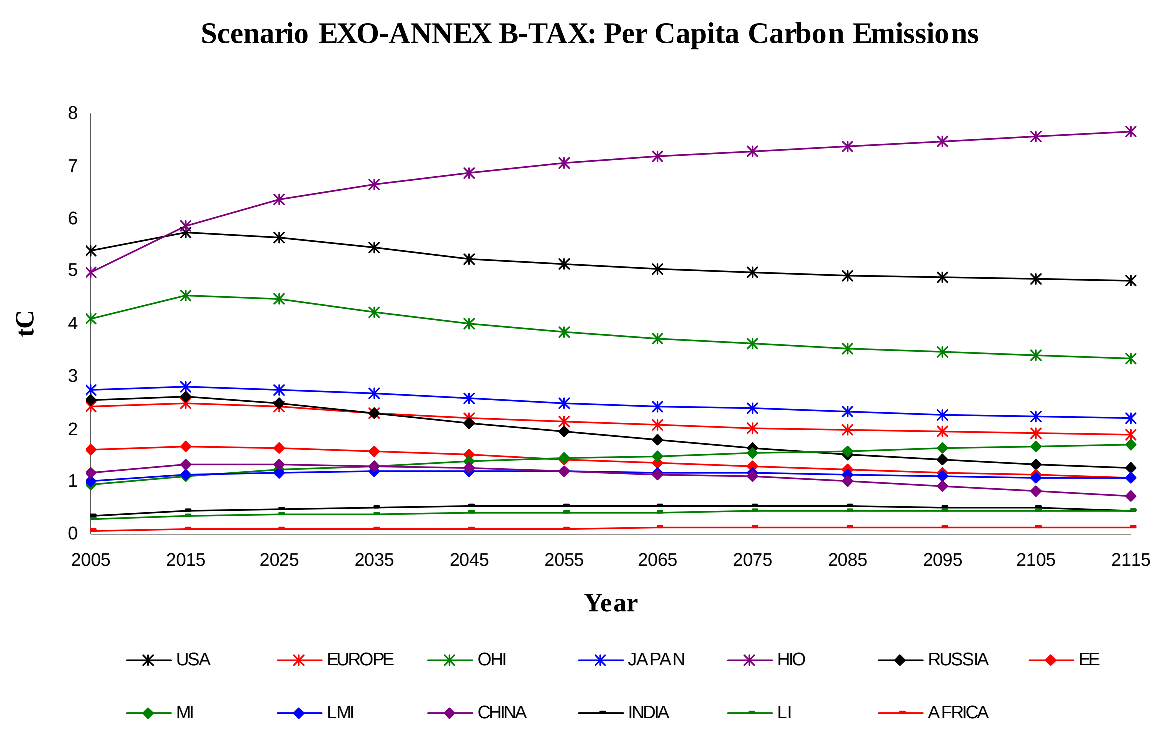
A - Figure 32: Scenario EXO-TAX – per capita carbon emissions (2005-2115)



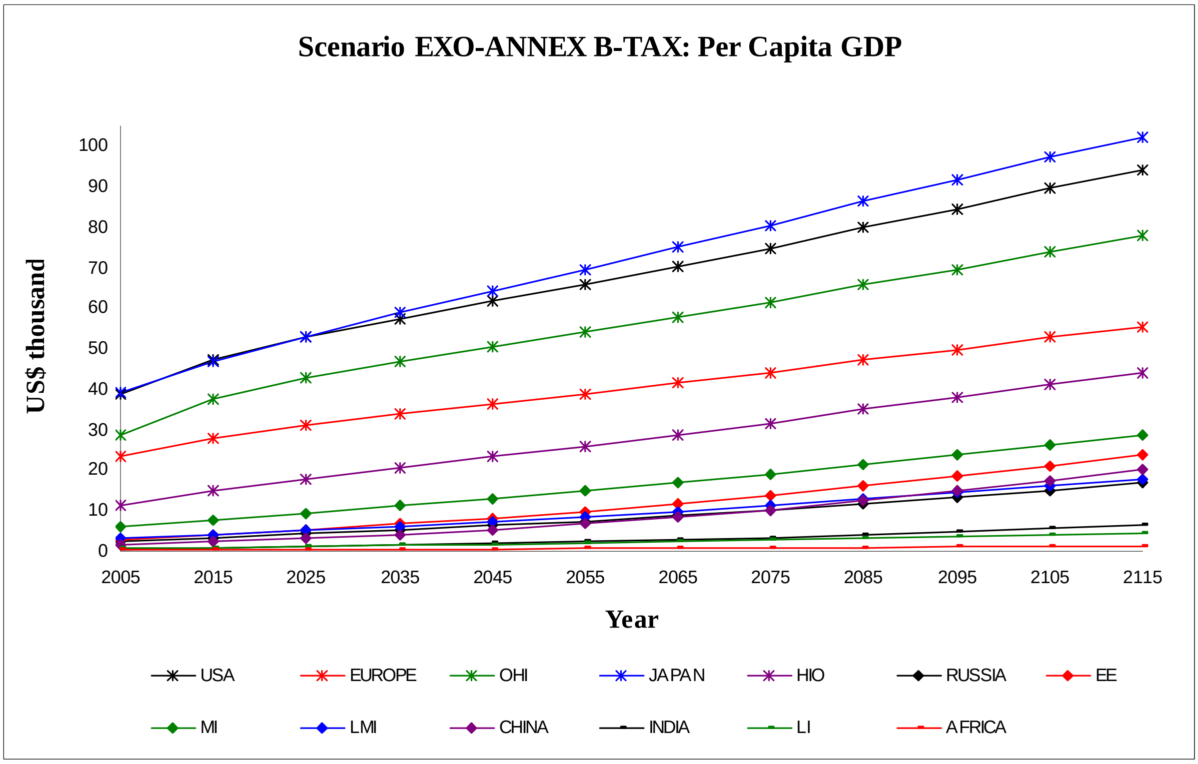
A - Figure 33: Scenario EXO-TAX – per capita GDP (2005-2115)



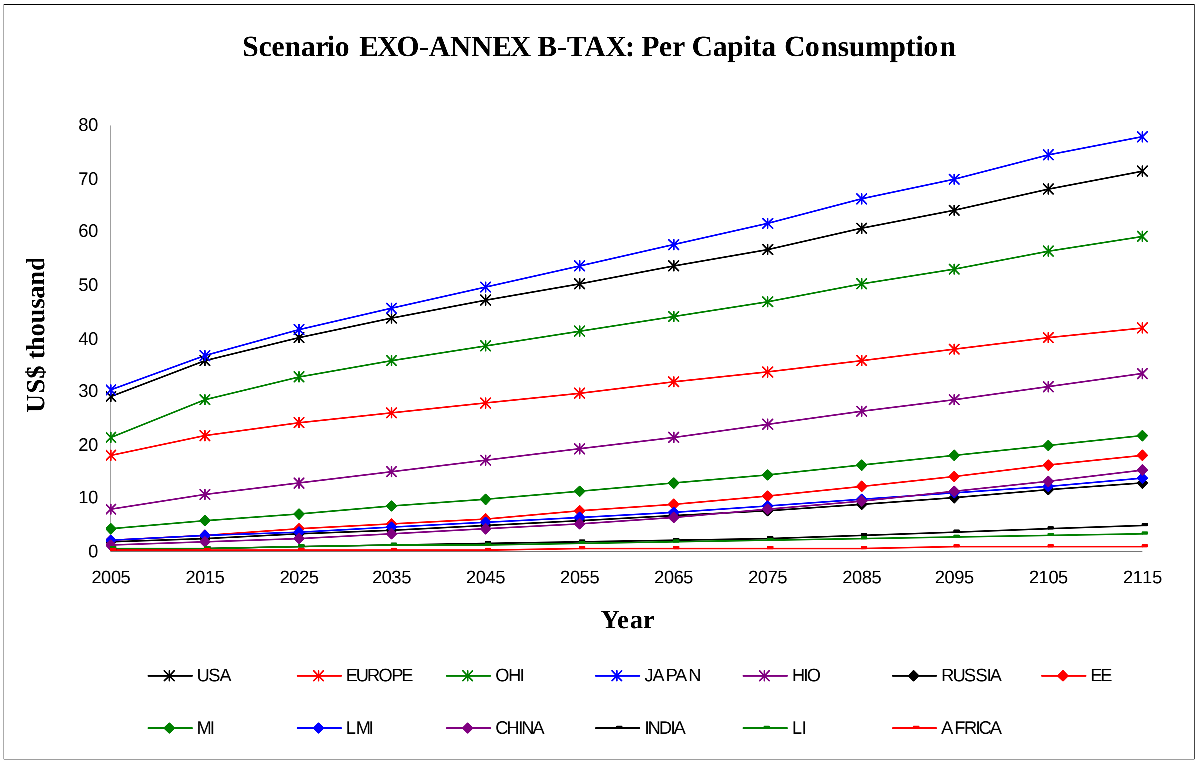
A - Figure 34: : Scenario EXO-TAX – per capita consumption (2005-2115)



A - Figure 35: Scenario EXO-ANNEX B-TAX – per capita carbon emissions (2005-2115)



A - Figure 36: Scenario EXO-ANNEX B-TAX – per capita GDP (2005-2115)



A - Figure 37: Scenario EXO-ANNEX B-TAX – per capita consumption (2005-2115)

Appendix B – Data

A - Table 1: Emission sources (>0.1MtC) located in the region OECD EUROPE

Emission Source	Number of Sources	Emission [kt CO_2]	Emission [kt CO_2 / Source]	Emission [kt C]	Emission [kt C) / Source]
Ammonia Total	42	25'462	606	6'943	165
Ammonia (Pure CO_2)	26	20'559	791	5'607	216
Ammonia (Flue Gas)	16	4'903	306	1'337	84
Cement	227	147'011	648	40'090	177
Hydrogen Total	19	6'088	320	1'660	87
Hydrogen (Pure CO_2))	13	3'750	288	1'023	79
Hydrogen (Flue Gas)	6	2'338	390	638	106
Iron & Steel	232	164'569	709	44'878	193
Power Total	813	1'177'466	1'448	321'098	395
Power Coal	335	799'443	2'386	218'010	651
Power Gas	278	182'375	656	49'734	179
Power Oil	152	180'298	1'186	49'168	323
Power div.	48	15'350	320	4'186	87
Ethanol	55	48'277	878	13'165	239
Ethanol (Pure CO_2)	3	375	125	102	34
Ethanol (Flue Gas)	52	47'901	921	13'063	251
Refineries	101	141'320	1'399	38'538	382
Total	**1'489**	**1'710'192**	**1'149**	**466'374**	**313**

A - Table 2: Emission sources (>0.1MtC) located in the USA

Emission Source	Number of Sources	Emission [kt CO_2]	Emission [kt CO_2 / Source]	Emission [kt C]	Emission [kt C) / Source]
Ammonia Total	19	6'958	366	1'897	100
Ammonia (Pure CO_2)	19	6'958	366	1'897	100
Ammonia (Flue Gas)	N/A	N/A	N/A	N/A	N/A
Cement	106	62'615	591	17'075	161
Hydrogen Total	30	6'839	228	1'865	62
Hydrogen (Pure CO_2))	25	5'701	228	1'555	62
Hydrogen (Flue Gas)	5	1'138	228	310	62
Iron & Steel	44	81'200	1'845	22'144	503
Power Total	1'073	2'377'247	2'216	648'281	604
Power Coal	514	1'998'065	3'887	544'877	1'060
Power Gas	466	296'955	637	80'980	174
Power Oil	73	78'569	1'076	21'426	294
Power div.	20	3'657	183	997	50
Ethanol	90	69'999	778	19'089	212
Ethanol (Pure CO_2)	7	1'155	165	315	45
Ethanol (Flue Gas)	83	68'845	829	18'774	226
Refineries	135	158'563	1'175	43'241	320
Total	**1'497**	**2'763'421**	**1'846**	**753'592**	**503**

A - Table 3: Emission sources (>0.1MtC) located in Japan

Emission Source	Number of Sources	Emission [kt CO_2]	Emission [kt CO_2 / Source]	Emission [kt C]	Emission [kt C) / Source]
Ammonia Total	5	1'484	297	405	81
Ammonia (Pure CO_2)	5	1'484	297	405	81
Ammonia (Flue Gas)	N/A	N/A	N/A	N/A	N/A
Cement	42	77'091	1'835	21'023	501
Hydrogen Total	16	2'793	175	762	48
Hydrogen (Pure CO_2))	15	2'572	171	701	47
Hydrogen (Flue Gas)	1	222	222	60	60
Iron & Steel	12	70'642	5'887	19'264	1'605
Power Total	259	656'629	2'535	179'064	691
Power Coal	77	387'480	5'032	105'667	1'372
Power Gas	50	124'359	2'487	33'913	678
Power Oil	132	144'791	1'097	39'485	299
Power div.	N/A	N/A	N/A	N/A	N/A
Ethanol	13	11'242	865	3'066	236
Ethanol (Pure CO_2)	N/A	N/A	N/A	N/A	N/A
Ethanol (Flue Gas)	13	11'242	865	3'066	236
Refineries	35	48'143	1'376	13'129	375
Total	**382**	**868'023**	**2'272**	**236'712**	**620**

A - Table 4: Emission sources (>0.1MtC) located in the region OHI

Emission Source	Number of Sources	Emission [kt CO_2]	Emission [kt CO_2 / Source]	Emission [kt C]	Emission [kt C) / Source]
Ammonia Total	9	2'500	278	682	76
Ammonia (Pure CO_2)	9	2'500	278	682	76
Ammonia (Flue Gas)	N/A	N/A	N/A	N/A	N/A
Cement	37	23'860	645	6'507	176
Hydrogen Total	14	2'928	209	799	57
Hydrogen (Pure CO_2))	11	1'608	146	439	40
Hydrogen (Flue Gas)	3	1'320	440	360	120
Iron & Steel	15	27'383	1'826	7'467	498
Power Total	237	493'537	2'082	134'589	568
Power Coal	74	389'871	5'269	106'319	1'437
Power Gas	103	59'768	580	16'299	158
Power Oil	60	43'899	732	11'971	200
Power div.	N/A	N/A	N/A	N/A	N/A
Ethanol	15	16'561	1'104	4'516	301
Ethanol (Pure CO_2)	2	238	119	65	32
Ethanol (Flue Gas)	13	16'324	1'256	4'451	342
Refineries	38	52'474	1'381	14'310	377
Total	**365**	**619'243**	**1'697**	**168'869**	**463**

A - Table 5: Emission sources (>0.1MtC) located in the region HIO

Emission Source	Number of Sources	Emission [kt CO_2]	Emission [kt CO_2 / Source]	Emission [kt C]	Emission [kt C) / Source]
Ammonia Total	1	249	249	68	68
Ammonia (Pure CO_2)	1	249	249	68	68
Ammonia (Flue Gas)	N/A	N/A	N/A	N/A	N/A
Cement	26	23'366	899	6'372	245
Hydrogen Total	7	2'341	334	639	91
Hydrogen (Pure CO_2))	6	2'192	365	598	100
Hydrogen (Flue Gas)	1	149	149	41	41
Iron & Steel	3	1'954	651	533	178
Power Total	184	144'776	787	39'481	215
Power Coal	N/A	N/A	N/A	N/A	N/A
Power Gas	102	75'838	744	20'681	203
Power Oil	82	68'938	841	18'800	229
Power div.	N/A	N/A	N/A	N/A	N/A
Ethanol	11	19'601	1'782	5'345	486
Ethanol (Pure CO_2)	2	344	172	94	47
Ethanol (Flue Gas)	9	19'257	2'140	5'252	584
Refineries	21	36'166	1'722	9'863	470
Total	**253**	**228'453**	**903**	**62'300**	**246**

A - Table 6: Emission sources (>0.1MtC) located in Russia

Emission Source	Number of Sources	Emission [kt CO_2]	Emission [kt CO_2 / Source]	Emission [kt C]	Emission [kt C) / Source]
Ammonia Total	13	8'928.88	686.84	2'434.93	187.30
Ammonia (Pure CO_2)	13	8'928.88	686.84	2'434.93	187.30
Ammonia (Flue Gas)	N/A	N/A	N/A	N/A	N/A
Cement	49	51'911.31	1'059.41	14'156.34	288.90
Hydrogen Total	0	0.00	0.00	0.00	0.00
Hydrogen (Pure CO_2))	N/A	N/A	N/A	N/A	N/A
Hydrogen (Flue Gas)	N/A	N/A	N/A	N/A	N/A
Iron & Steel	9	51'607.77	5'734.20	14'073.57	1'563.73
Power Total	284	490'470.15	1'727.01	133'752.43	470.96
Power Coal	89	220'181.55	2'473.95	60'044.05	674.65
Power Gas	171	228'804.17	1'338.04	62'395.47	364.89
Power Oil	24	41'484.43	1'728.52	11'312.91	471.37
Power div.	N/A	N/A	N/A	N/A	N/A
Ethanol	11	7'291.51	662.86	1'988.41	180.76
Ethanol (Pure CO_2)	N/A	N/A	N/A	N/A	N/A
Ethanol (Flue Gas)	11	7'291.51	662.86	1'988.41	180.76
Refineries	32	65'368.38	2'042.76	17'826.12	557.07
Total	**398**	**675'578.00**	**1'697.43**	**184'231.80**	**462.89**

A - Table 7: Emission sources (>0.1MtC) located in the region EASTERN EUROPE

Emission Source	Number of Sources	Emission [kt CO_2]	Emission [kt CO_2 / Source]	Emission [kt C]	Emission [kt C) / Source]
Ammonia Total	17	5'793	341	1'580	93
Ammonia (Pure CO_2)	17	5'793	341	1'580	93
Ammonia (Flue Gas)	N/A	N/A	N/A	N/A	N/A
Cement	82	62'971	768	17'172	209
Hydrogen Total	1	0	0	0	0
Hydrogen (Pure CO_2))	N/A	N/A	N/A	N/A	N/A
Hydrogen (Flue Gas)	1	0	0	0	0
Iron & Steel	54	38'377	711	10'466	194
Power Total	277	607'135	2'192	165'567	598
Power Coal	161	470'586	2'923	128'330	797
Power Gas	77	85'172	1'106	23'226	302
Power Oil	39	51'377	1'317	14'011	359
Power div.	N/A	N/A	N/A	N/A	N/A
Ethanol	14	8'172	584	2'228	159
Ethanol (Pure CO_2)	N/A	N/A	N/A	N/A	N/A
Ethanol (Flue Gas)	14	8'172	584	2'228	159
Refineries	33	37'109	1'125	10'120	307
Total	**478**	**759'557**	**1'589**	**207'133**	**433**

A - Table 8: Emission sources (>0.1MtC) located in China

Emission Source	Number of Sources	Emission [kt CO_2]	Emission [kt CO_2 / Source]	Emission [kt C]	Emission [kt C) / Source]
Ammonia Total	62	56'277	908	15'347	248
Ammonia (Pure CO_2)	62	56'277	908	15'347	248
Ammonia (Flue Gas)	-	-	-	-	-
Cement	70	21'633	309	5'899	84
Hydrogen Total	N/A	N/A	N/A	N/A	N/A
Hydrogen (Pure CO_2))	N/A	N/A	N/A	N/A	N/A
Hydrogen (Flue Gas)	N/A	N/A	N/A	N/A	N/A
Iron & Steel	23	59'775	2'599	16'301	709
Power Total	462	2'772'485	6'001	756'063	1'637
Power Coal	370	2'698'597	7'294	735'914	1'989
Power Gas	7	3'541	506	966	138
Power Oil	85	70'347	828	19'184	226
Power div.	N/A	N/A	N/A	N/A	N/A
Ethanol	21	17'852	850	4'868	232
Ethanol (Pure CO_2)	N/A	N/A	N/A	N/A	N/A
Ethanol (Flue Gas)	21	17'852	850	4'868	232
Refineries	50	0	0	0	0
Total	**688**	**2'928'021**	**4'256**	**798'479**	**1'161**

A - Table 9: Emission sources (>0.1MtC) located in India

Emission Source	Number of Sources	Emission [kt CO_2]	Emission [kt CO_2 / Source]	Emission [kt C]	Emission [kt C) / Source]
Ammonia Total	25	23'919	957	6'523	261
Ammonia (Pure CO_2)	7	2'092	299	571	82
Ammonia (Flue Gas)	18	21'827	1'213	5'952	331
Cement	157	164'378	1'047	44'826	286
Hydrogen Total	2	380	190	104	52
Hydrogen (Pure CO_2))	1	149	149	41	41
Hydrogen (Flue Gas)	1	231	231	63	63
Iron & Steel	50	88'843	1'777	24'228	485
Power Total	410	1'410'447	3'440	384'632	938
Power Coal	303	1'268'107	4'185	345'816	1'141
Power Gas	88	45'767	520	12'481	142
Power Oil	8	2'858	357	779	97
Power div.	11	93'715	8'520	25'556	2'323
Ethanol	14	10'136	724	2'764	197
Ethanol (Pure CO_2)	1	132	132	36	36
Ethanol (Flue Gas)	13	10'005	770	2'728	210
Refineries	31	44'585	1'438	12'158	392
Total	**689**	**1'742'689**	**2'529**	**475'236**	**690**

A - Table 10: Emission sources (>0.1MtC) located in the region MI

Emission Source	Number of Sources	Emission [kt CO_2]	Emission [kt CO_2 / Source]	Emission [kt C]	Emission [kt C) / Source]
Ammonia Total	4	4'730	1'182	1'290	322
Ammonia (Pure CO_2)	4	4'730	1'182	1'290	322
Ammonia (Flue Gas)	N/A	N/A	N/A	N/A	N/A
Cement	108	121'395	1'124	33'105	307
Hydrogen Total	7	1'590	227	434	62
Hydrogen (Pure CO_2))	5	920	184	251	50
Hydrogen (Flue Gas)	2	670	335	183	91
Iron & Steel	27	57'824	2'142	15'769	584
Power Total	284	616'850	2'172	168'216	592
Power Coal	43	379'301	8'821	103'436	2'405
Power Gas	144	154'504	1'073	42'134	293
Power Oil	97	83'044	856	22'646	233
Power div.	N/A	N/A	N/A	N/A	N/A
Ethanol	44	30'358	690	8'279	188
Ethanol (Pure CO_2)	1	124	124	34	34
Ethanol (Flue Gas)	43	30'234	703	8'245	192
Refineries	37	63'841	1'725	17'410	471
Total	**511**	**896'589**	**1'755**	**244'502**	**478**

A - Table 11: Emission sources (>0.1MtC) located in the region LMI

Emission Source	Number of Sources	Emission [kt CO_2]	Emission [kt CO_2 / Source]	Emission [kt C]	Emission [kt C) / Source]
Ammonia Total	15	5'536	369	1'510	101
Ammonia (Pure CO_2)	15	5'536	369	1'510	101
Ammonia (Flue Gas)	N/A	N/A	N/A	N/A	N/A
Cement	191	146'124	765	39'848	209
Hydrogen Total	9	0	0	0	0
Hydrogen (Pure CO_2))	N/A	N/A	N/A	N/A	N/A
Hydrogen (Flue Gas)	9	0	0	0	0
Iron & Steel	20	41'815	2'091	11'403	570
Power Total	426	570'092	1'338	155'466	365
Power Coal	95	369'369	3'888	100'728	1'060
Power Gas	198	142'528	720	38'868	196
Power Oil	133	58'195	438	15'870	119
Power div.	N/A	N/A	N/A	N/A	N/A
Ethanol	20	20'778	1'039	5'666	283
Ethanol (Pure CO_2)	N/A	N/A	N/A	N/A	N/A
Ethanol (Flue Gas)	20	20'778	1'039	5'666	283
Refineries	66	78'238	1'185	21'336	323
Total	**747**	**862'582**	**1'155**	**235'228**	**315**

A - Table 12: Emission sources (>0.1MtC) located in the region LI

Emission Source	Number of Sources	Emission [kt CO_2]	Emission [kt CO_2 / Source]	Emission [kt C]	Emission [kt C) / Source]
Ammonia Total	15	5'373	358	1'465	98
Ammonia (Pure CO_2)	15	5'373	358	1'465	98
Ammonia (Flue Gas)	N/A	N/A	N/A	N/A	N/A
Cement	147	80'112	545	21'847	149
Hydrogen Total	1	171	171	47	47
Hydrogen (Pure CO_2))	N/A	N/A	N/A	N/A	N/A
Hydrogen (Flue Gas)	1	171	171	47	47
Iron & Steel	7	10'304	1'472	2'810	401
Power Total	301	229'960	764	62'711	208
Power Coal	64	82'593	1'291	22'523	352
Power Gas	108	80'590	746	21'977	203
Power Oil	129	66'778	518	18'211	141
Power div.	N/A	N/A	N/A	N/A	N/A
Ethanol	22	3'610	164	984	45
Ethanol (Pure CO_2)	N/A	N/A	N/A	N/A	N/A
Ethanol (Flue Gas)	22	3'610	164	984	45
Refineries	45	34'897	775	9'516	211
Total	**538**	**364'428**	**677**	**99'380**	**185**

A - Table 13: Emission sources (>0.1MtC) located in the region AFRICA

Emission Source	Number of Sources	Emission [kt CO_2]	Emission [kt CO_2 / Source]	Emission [kt C]	Emission [kt C) / Source]
Ammonia Total	4	1'804	451	492	123
Ammonia (Pure CO_2)	4	1'804	451	492	123
Ammonia (Flue Gas)	N/A	N/A	N/A	N/A	N/A
Cement	36	24'968	694	6'809	189
Hydrogen Total	N/A	N/A	N/A	N/A	N/A
Hydrogen (Pure CO_2))	N/A	N/A	N/A	N/A	N/A
Hydrogen (Flue Gas)	N/A	N/A	N/A	N/A	N/A
Iron & Steel	3	3'404	1'135	928	309
Power Total	79	84'585	1'071	23'067	292
Power Coal	8	15'048	1'881	4'104	513
Power Gas	34	55'085	1'620	15'022	442
Power Oil	37	14'451	391	3'941	107
Ethanol	12	6'985	582	1'905	159
Ethanol (Pure CO_2)	N/A	N/A	N/A	N/A	N/A
Ethanol (Flue Gas)	12	6'985	582	1'905	159
Refineries	24	15'641	652	4'265	178
Total	**158**	**137'386**	**4'584**	**37'466**	**1'250**

A - Table 14: Estimated CCS costs for the region OECD EUROPE

Emission Source	Emission 2005 [GtC]	Emission Ratio	Capture Costs [$ / tCO_2]	Capture Costs [$ / tCO]	Transport & Storage Costs [$ / tCO_2]	Transport & Storage Costs [$ / tCO]	Average CCS Costs [$ / tCO_2]	Average CCS Costs [$ / tCO]
Large Point Sources (all Types)	0.519	100.00%	40.65	149.03	15	55	55.65	204.03
Power Generation	0.283	54.60%	46.44	170.29	15	55	61.44	225.29
Power Coal	0.117	22.50%	41.00	150.33	15	55	56.00	205.33
Power Gas	0.097	18.67%	53.00	194.33	15	55	68.00	249.33
Power Oil	0.053	10.21%	N/A	N/A	N/A	N/A	N/A	N/A
Power Div.	0.017	3.22%	N/A	N/A	N/A	N/A	N/A	N/A
Sum of all other Industry	0.236	45.40%	33.67	123.47	15	55	48.67	178.47
Ammonia Production	0.015	2.82%	9	33	15	55	24	88
Cement Production	0.079	15.25%	45	165	15	55	60	220
Hydrogen Production	0.007	1.28%	9	33	15	55	24	88
Iron & Steel Production	0.081	15.58%	30	110	15	55	45	165
Ethanol Production	0.019	3.69%	9	33	15	55	24	88
Refineries	0.035	6.78%	45	165	15	55	60	220

A - Table 15: Estimated CCS costs for the USA

Emission Source	Emission 2005 [GtC]	Emission Ratio	Capture Costs [$ / tCO$_2$]	Capture Costs [$ / tCO]	Transport & Storage Costs [$ / tCO$_2$]	Transport & Storage Costs [$ / tCO]	Average CCS Costs [$ / tCO$_2$]	Average CCS Costs [$ / tCO]
Large Point Sources (all Types)	0.847	100.00%	42.44	155.61	15	55	57.44	210.61
Power Generation	0.607	71.68%	46.71	171.26	15	55	61.71	226.26
Power Coal	0.291	34.34%	41.00	150.33	15	55	56.00	205.33
Power Gas	0.264	31.13%	53.00	194.33	15	55	68.00	249.33
Power Oil	0.041	4.88%	N/A	N/A	N/A	N/A	N/A	N/A
Power Div.	0.011	1.34%	N/A	N/A	N/A	N/A	N/A	N/A
Sum of all other Industry	0.240	28.32%	31.64	116.02	15	55	46.64	171.02
Ammonia Production	0.011	1.27%	9	33	15	55	24	88
Cement Production	0.060	7.08%	45	165	15	55	60	220
Hydrogen Production	0.017	2.00%	9	33	15	55	24	88
Iron & Steel Production	0.025	2.94%	30	110	15	55	45	165
Ethanol Production	0.051	6.01%	9	33	15	55	24	88
Refineries	0.076	9.02%	45	165	15	55	60	220

A - Table 16: Estimated CCS costs for Japan

Emission Source	Emission 2005 [GtC]	Emission Ratio	Capture Costs [$ / tCO$_2$]	Capture Costs [$ / tCO]	Transport & Storage Costs [$ / tCO$_2$]	Transport & Storage Costs [$ / tCO]	Average CCS Costs [$ / tCO$_2$]	Average CCS Costs [$ / tCO]
Large Point Sources (all Types)	0.190	100.00%	41.82	153.32	15	55	56.82	208.32
Power Generation	0.129	67.80%	45.72	167.66	15	55	60.72	222.66
Power Coal	0.038	20.16%	41.00	150.33	15	55	56.00	205.33
Power Gas	0.025	13.09%	53.00	194.33	15	55	68.00	249.33
Power Oil	0.066	34.55%	N/A	N/A	N/A	N/A	N/A	N/A
Power Div.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Sum of all other Industry	0.061	32.20%	33.59	123.15	15	55	48.59	178.15
Ammonia Production	0.002	1.31%	9	33	15	55	24	88
Cement Production	0.021	10.99%	45	165	15	55	60	220
Hydrogen Production	0.008	4.19%	9	33	15	55	24	88
Iron & Steel Production	0.006	3.14%	30	110	15	55	45	165
Ethanol Production	0.006	3.40%	9	33	15	55	24	88
Refineries	0.017	9.16%	45	165	15	55	60	220

A - Table 17: Estimated CCS costs for the region OHI

Emission Source	Emission 2005 [GtC]	Emission Ratio	Capture Costs [$ / tCO_2]	Capture Costs [$ / tCO]	Transport & Storage Costs [$ / tCO_2]	Transport & Storage Costs [$ / tCO]	Average CCS Costs [$ / tCO_2]	Average CCS Costs [$ / tCO]
Large Point Sources (all Types)	0.165	100.00%	42.57	156.10	15	55	57.57	211.10
Power Generation	0.107	64.93%	47.98	175.94	15	55	62.98	230.94
Power Coal	0.033	20.27%	41.00	150.33	15	55	56.00	205.33
Power Gas	0.046	28.22%	53.00	194.33	15	55	68.00	249.33
Power Oil	0.027	16.44%	N/A	N/A	N/A	N/A	N/A	N/A
Power Div.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Sum of all other Industry	0.058	35.07%	32.55	119.37	15	55	47.55	174.37
Ammonia Production	0.004	2.47%	9	33	15	55	24	88
Cement Production	0.017	10.14%	45	165	15	55	60	220
Hydrogen Production	0.006	3.84%	9	33	15	55	24	88
Iron & Steel Production	0.007	4.11%	30	110	15	55	45	165
Ethanol Production	0.007	4.11%	9	33	15	55	24	88
Refineries	0.017	10.41%	45	165	15	55	60	220

A - Table 18: Estimated CCS costs for the region HIO

Emission Source	Emission 2005 [GtC]	Emission Ratio	Capture Costs [$ / tCO_2]	Capture Costs [$ / tCO]	Transport & Storage Costs [$ / tCO_2]	Transport & Storage Costs [$ / tCO]	Average CCS Costs [$ / tCO_2]	Average CCS Costs [$ / tCO]
Large Point Sources (all Types)	0.115	100.00%	47.94	175.77	15	55	62.94	230.77
Power Generation	0.083	72.73%	53.00	194.33	15	55	68.00	249.33
Power Coal	N/A	N/A	41.00	150.33	15	55	56.00	205.33
Power Gas	0.046	40.32%	53.00	194.33	15	55	68.00	249.33
Power Oil	0.037	32.41%	N/A	N/A	N/A	N/A	N/A	N/A
Power Div.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Sum of all other Industry	0.031	27.27%	34.43	126.26	15	55	49.43	181.26
Ammonia Production	0.000	0.40%	9	33	15	55	24	88
Cement Production	0.012	10.28%	45	165	15	55	60	220
Hydrogen Production	0.003	2.77%	9	33	15	55	24	88
Iron & Steel Production	0.001	1.19%	30	110	15	55	45	165
Ethanol Production	0.005	4.35%	9	33	15	55	24	88
Refineries	0.010	8.30%	45	165	15	55	60	220

A - Table 19: Estimated CCS costs for Russia

Emission Source	**Emission 2005 [GtC]**	**Emission Ratio**	**Capture Costs [$ / tCO_2]**	**Capture Costs [$ / tCO]**	**Transport & Storage Costs [$ / tCO_2]**	**Transport & Storage Costs [$ / tCO]**	**Average CCS Costs [$ / tCO_2]**	**Average CCS Costs [$ / tCO]**
Large Point Sources (all Types)	0.230	100.00%	45.27	165.98	15	55	60.27	220.98
Power Generation	0.164	71.36%	48.89	179.27	15	55	63.89	234.27
Power Coal	0.052	22.36%	41.00	150.33	15	55	56.00	205.33
Power Gas	0.099	42.96%	53.00	194.33	15	55	68.00	249.33
Power Oil	0.014	6.03%	N/A	N/A	N/A	N/A	N/A	N/A
Power Div.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Sum of all other Industry	0.066	28.64%	36.24	132.87	15	55	51.24	187.87
Ammonia Production	0.008	3.27%	9	33	15	55	24	88
Cement Production	0.028	12.31%	45	165	15	55	60	220
Hydrogen Production	0.000	0.00%	9	33	15	55	24	88
Iron & Steel Production	0.005	2.26%	30	110	15	55	45	165
Ethanol Production	0.006	2.76%	9	33	15	55	24	88
Refineries	0.019	8.04%	45	165	15	55	60	220

A - Table 20: Estimated CCS costs for the region EASTERN EUROPE

Emission Source	**Emission 2005 [GtC]**	**Emission Ratio**	**Capture Costs [$ / tCO_2]**	**Capture Costs [$ / tCO]**	**Transport & Storage Costs [$ / tCO_2]**	**Transport & Storage Costs [$ / tCO]**	**Average CCS Costs [$ / tCO_2]**	**Average CCS Costs [$ / tCO]**
Large Point Sources (all Types)	0.183	100.00%	40.83	149.70	15	55	55.83	204.70
Power Generation	0.106	57.95%	44.88	164.57	15	55	59.88	219.57
Power Coal	0.062	33.68%	41.00	150.33	15	55	56.00	205.33
Power Gas	0.029	16.11%	53.00	194.33	15	55	68.00	249.33
Power Oil	0.015	8.16%	N/A	N/A	N/A	N/A	N/A	N/A
Power Div.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Sum of all other Industry	0.077	42.05%	35.24	129.21	15	55	50.24	184.21
Ammonia Production	0.006	3.56%	9	33	15	55	24	88
Cement Production	0.031	17.15%	45	165	15	55	60	220
Hydrogen Production	0.000	0.21%	9	33	15	55	24	88
Iron & Steel Production	0.021	11.30%	30	110	15	55	45	165
Ethanol Production	0.005	2.93%	9	33	15	55	24	88
Refineries	0.013	6.90%	45	165	15	55	60	220

A - Table 21: Estimated CCS costs for China

Emission Source	Emission 2005 [GtC]	Emission Ratio	Capture Costs [$\$ / \text{tCO}_2$]	Capture Costs [$\$ / \text{tCO}$]	Transport & Storage Costs [$\$ / \text{tCO}^2$]	Transport & Storage Costs [$\$ / \text{tCO}$]	Average CCS Costs [$\$ / \text{tCO}_2$]	Average CCS Costs [$\$ / \text{tCO}$]
Large Point Sources (all Types)	0.899	100.00%	37.62	137.94	15	55	52.62	192.94
Power Generation	0.604	67.15%	41.22	151.15	15	55	56	206.15
Power Coal	0.483	53.78%	41.00	150.33	15	55	56	205.33
Power Gas	0.009	1.02%	53.00	194.33	15	55	68	249.33
Power Oil	0.111	12.35%	N/A	N/A	N/A	N/A	N/A	N/A
Power Div.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Sum of all other Industry	0.295	32.85%	30.25	110.92	15	55	45.25	165.92
Ammonia Production	0.081	9.01%	9	33	15	55	24	88
Cement Production	0.091	10.17%	45	165	15	55	60	220
Hydrogen Production	N/A	N/A	9	33	15	55	24	88
Iron & Steel Production	0.030	3.34%	30	110	15	55	45	165
Ethanol Production	0.027	3.05%	9	33	15	55	24	88
Refineries	0.065	7.27%	45	165	15	55	60	220

A - Table 22: Estimated CCS costs for India

Emission Source	Emission 2005 [GtC]	Emission Ratio	Capture Costs [$\$ / \text{tCO}_2$]	Capture Costs [$\$ / \text{tCO}$]	Transport & Storage Costs [$\$ / \text{tCO}_2$]	Transport & Storage Costs [$\$ / \text{tCO}$]	Average CCS Costs [$\$ / \text{tCO}_2$]	Average CCS Costs [$\$ / \text{tCO}$]
Large Point Sources (all Types)	0.222	100.00%	41.00	150.32	15	55	56.00	205.32
Power Generation	0.132	59.51%	43.70	160.24	15	55	58.70	215.24
Power Coal	0.098	43.98%	41.00	150.33	15	55	56.00	205.33
Power Gas	0.028	12.77%	53.00	194.33	15	55	68.00	249.33
Power Oil	0.003	1.16%	N/A	N/A	N/A	N/A	N/A	N/A
Power Div.	0.004	1.60%	N/A	N/A	N/A	N/A	N/A	N/A
Sum of all other Industry	0.090	40.49%	37.02	135.75	15	55	52.02	190.75
Ammonia Production	0.008	3.63%	9	33	15	55	24	88
Cement Production	0.051	22.79%	45	165	15	55	60	220
Hydrogen Production	0.001	0.29%	9	33	15	55	24	88
Iron & Steel Production	0.016	7.26%	30	110	15	55	45	165
Ethanol Production	0.005	2.03%	9	33	15	55	24	88
Refineries	0.010	4.50%	45	165	15	55	60	220

A - Table 23: Estimated CCS costs for the region MI

Emission Source	Emission 2005 [GtC]	Emission Ratio	Capture Costs [\$ / tCO_2]	Capture Costs [\$ / tCO]	Transport & Storage Costs [\$ / tCO_2]	Transport & Storage Costs [\$ / tCO]	Average CCS Costs [\$ / tCO_2]	Average CCS Costs [\$ / tCO]
Large Point Sources (all Types)	0.168	100.00%	43.25	158.57	15	55	58.25	213.57
Power Generation	0.093	55.58%	50.24	184.22	15	55	65.24	239.22
Power Coal	0.014	8.41%	41.00	150.33	15	55	56.00	205.33
Power Gas	0.047	28.18%	53.00	194.33	15	55	68.00	249.33
Power Oil	0.032	18.98%	N/A	N/A	N/A	N/A	N/A	N/A
Power Div.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Sum of all other Industry	0.074	44.42%	34.49	126.48	15	55	49.49	181.48
Ammonia Production	0.001	0.78%	9	33	15	55	24	88
Cement Production	0.035	21.14%	45	165	15	55	60	220
Hydrogen Production	0.002	1.37%	9	33	15	55	24	88
Iron & Steel Production	0.009	5.28%	30	110	15	55	45	165
Ethanol Production	0.014	8.61%	9	33	15	55	24	88
Refineries	0.012	7.24%	45	165	15	55	60	220

A - Table 24: Estimated CCS costs for the region LMI

Emission Source	Emission 2005 [GtC]	Emission Ratio	Capture Costs [\$ / tCO_2]	Capture Costs [\$ / tCO]	Transport & Storage Costs [\$ / tCO_2]	Transport & Storage Costs [\$ / tCO]	Average CCS Costs [\$ / tCO_2]	Average CCS Costs [\$ / tCO]
Large Point Sources (all Types)	0.399	100.00%	44.82	164.34	15	55	59.82	219.34
Power Generation	0.228	57.03%	49.11	180.07	15	55	64.11	235.07
Power Coal	0.051	12.72%	41.00	150.33	15	55	56.00	205.33
Power Gas	0.106	26.51%	53.00	194.33	15	55	68.00	249.33
Power Oil	0.071	17.80%	N/A	N/A	N/A	N/A	N/A	N/A
Power Div.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Sum of all other Industry	0.172	42.97%	39.13	143.48	15	55	54.13	198.48
Ammonia Production	0.008	2.01%	9	33	15	55	24	88
Cement Production	0.102	25.57%	45	165	15	55	60	220
Hydrogen Production	0.005	1.20%	9	33	15	55	24	88
Iron & Steel Production	0.011	2.68%	30	110	15	55	45	165
Ethanol Production	0.011	2.68%	9	33	15	55	24	88
Refineries	0.035	8.84%	45	165	15	55	60	220

A - Table 25: Estimated CCS costs for the region LI

Emission Source	Emission 2005 [GtC]	Emission Ratio	Capture Costs [$\$ / \mathrm{tCO_2}$]	Capture Costs [$\$ / \mathrm{tCO}$]	Transport & Storage Costs [$\$ / \mathrm{tCO_2}$]	Transport & Storage Costs [$\$ / \mathrm{tCO}$]	Average CCS Costs [$\$ / \mathrm{tCO_2}$]	Average CCS Costs [$\$ / \mathrm{tCO}$]
Large Point Sources (all Types)	0.185	100.00%	44.24	162.21	15	55	59.24	217.21
Power Generation	0.103	55.95%	48.53	177.96	15	55	63.53	232.96
Power Coal	0.022	11.90%	41.00	150.33	15	55	56.00	205.33
Power Gas	0.037	20.07%	53.00	194.33	15	55	68.00	249.33
Power Oil	0.044	23.98%	N/A	N/A	N/A	N/A	N/A	N/A
Power Div.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Sum of all other Industry	0.081	44.05%	38.78	142.21	15	55	53.78	197.21
Ammonia Production	0.005	2.79%	9	33	15	55	24	88
Cement Production	0.051	27.32%	45	165	15	55	60	220
Hydrogen Production	0.000	0.19%	9	33	15	55	24	88
Iron & Steel Production	0.002	1.30%	30	110	15	55	45	165
Ethanol Production	0.008	4.09%	9	33	15	55	24	88
Refineries	0.015	8.36%	45	165	15	55	60	220

A - Table 26: Estimated CCS costs for the region AFRICA

Emission Source	Emission 2005 [GtC]	Emission Ratio	Capture Costs [$\$ / \mathrm{tCO_2}$]	Capture Costs [$\$ / \mathrm{tCO}$]	Transport & Storage Costs [$\$ / \mathrm{tCO_2}$]	Transport & Storage Costs [$\$ / \mathrm{tCO}$]	Average CCS Costs [$\$ / \mathrm{tCO_2}$]	Average CCS Costs [$\$ / \mathrm{tCO}$]
Large Point Sources (all Types)	0.029	100.00%	43.93	161.06	15	55	58.93	216.06
Power Generation	0.015	50.00%	50.71	185.95	15	55	66	240.95
Power Coal	0.001	5.06%	41.00	150.33	15	55	56	205.33
Power Gas	0.006	21.52%	53.00	194.33	15	55	68	249.33
Power Oil	0.007	23.42%	N/A	N/A	N/A	N/A	N/A	N/A
Power Div.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Sum of all other Industry	0.015	50.00%	37.14	136.18	15	55	52.14	191.18
Ammonia Production	0.001	2.53%	9	33	15	55	24	88
Cement Production	0.007	22.78%	45	165	15	55	60	220
Hydrogen Production	N/A	N/A	9	33	15	55	24	88
Iron & Steel Production	0.001	1.90%	30	110	15	55	45	165
Ethanol Production	0.002	7.59%	9	33	15	55	24	88
Refineries	0.004	15.19%	45	165	15	55	60	220

A - Table 27: Macroeconomic and emission data - OECD EUROPE

Country	Industrial CO_2 Emission 2005 [GtC]	Industrial CO_2 Emission 1995 [GtC]	GDP 2005 [trillion US$2000]	GDP 1995 [trillion US$1990]	Capital 2005 [trillion US$2000]	Capital 1995 [trillion US$1990]
Austria	0.01959	0.01618	0.21	0.17	0.35	N/A
Belgium	0.02924	0.02833	0.25	0.19	0.42	N/A
Denmark	0.01471	0.01498	0.17	0.13	0.29	N/A
Finland	0.01820	0.01392	0.13	0.11	0.22	N/A
France	0.10450	0.09282	1.43	1.19	2.42	N/A
Germany	0.21957	0.22792	1.97	1.79	3.42	N/A
Greece	0.02629	0.02082	0.14	0.06	0.22	N/A
Greenland	0.00154	0.00014	N/A	0.00	N/A	N/A
Iceland	0.00604	0.00049	0.01	0.01	0.02	N/A
Ireland	0.01195	0.00880	0.12	0.05	0.16	N/A
Italy	0.12931	0.11893	1.13	1.00	2.01	N/A
Lichtenstein	N/A	N/A	N/A	N/A	N/A	N/A
Luxembourg	0.03085	0.00253	0.02	0.01	0.03	N/A
Netherlands	0.04599	0.03709	0.40	0.30	0.68	N/A
Norway	0.01097	0.01977	0.18	0.13	0.30	N/A
Portugal	0.01636	0.01417	0.12	0.06	0.20	N/A
Spain	0.09606	0.06321	0.68	0.41	1.05	N/A
Sweden	0.01388	0.01217	0.27	0.20	0.44	N/A
Switzerland	0.01141	0.01060	0.26	0.21	0.46	N/A
United Kingdom	0.15505	0.14796	1.62	0.89	2.64	N/A
Total:	**0.961**	**0.851**	**9.130**	**6.892**	**15.324**	**16.079**

A - Table 28: Macroeconomic and emission data for the USA

Country	Industrial CO_2 Emission 2005 [GtC]	Industrial CO_2 Emission 1995 [GtC]	GDP 2005 [trillion US$2000]	GDP 1995 [trillion US$1990]	Capital 2005 [trillion US$2000]	Capital 1995 [trillion US$1990]
USA	1.569	1.407	11046.425	6.176	17.342	13.876

A - Table 29: Macroeconomic and emission data for Japan

Country	Industrial CO_2 Emission 2005 [GtC]	Industrial CO_2 Emission 1995 [GtC]	GDP 2005 [trillion US$2000]	GDP 1995 [trillion US$1990]	Capital 2005 [trillion US$2000]	Capital 1995 [trillion US$1990]
Japan	0.353	0.308	4.993	3.420	8.594	7.872

A - Table 30: Macroeconomic and emission data for Russia

Country	Industrial CO_2 Emission 2005 [GtC]	Industrial CO_2 Emission 1995 [GtC]	GDP 2005 [trillion US$2000]	GDP 1995 [trillion US$1990]	Capital 2005 [trillion US$2000]	Capital 1995 [trillion US$1990]
Russia	0.427	0.496	0.350	0.334	0.483	0.633

A - Table 31: Macroeconomic and emission data for the region OHI

Country	Industrial CO_2 Emission 2005 [GtC]	Industrial CO_2 Emission 1995 [GtC]	GDP 2005 [trillion US$2000]	GDP 1995 [trillion US$1990]	Capital 2005 [trillion US$2000]	Capital 1995 [trillion US$1990]
Andorra	N/A	N/A	N/A	N/A	N/A	N/A
Aruba	0.00063	0.00049	0.00	N/A	0.00	N/A
Australia	0.10146	0.07910	0.72	0.30	0.47	N/A
Bahamas	0.00058	0.00047	0.00	0.00	0.01	N/A
Bermuda	0.00015	0.00012	N/A	0.00	N/A	N/A
B. V. Islands	0.00003	0.00001	N/A	N/A	N/A	N/A
Canada	0.14855	0.11893	0.81	0.54	1.28	N/A
Faeroe Islands	0.00019	N/A	N/A	N/A	N/A	N/A
Guam	N/A	0.00113	N/A	N/A	N/A	N/A
Hong Kong	0.01065	0.00846	0.21	0.08	0.29	N/A
Israel	0.01921	0.01264	0.13	0.07	0.19	N/A
Monaco	N/A	N/A	N/A	N/A	N/A	N/A
New Zealand	0.00832	0.00749	0.06	0.05	0.10	N/A
San Marino	N/A	N/A	0.00	N/A	0.00	N/A
Singapore	0.01533	0.01738	0.11	0.05	0.15	N/A
Virgin Island	N/A	0.00312	N/A	0.00	N/A	N/A
Total:	**0.305**	**0.249**	**2.051**	**1.087**	**2.493**	**2.706**

A - Table 32: Macroeconomic and emission data for the region EASTERN EUROPE

Country	Industrial CO_2 Emission 2005 [GtC]	Industrial CO_2 Emission 1995 [GtC]	GDP 2005 [trillion US$2000]	GDP 1995 [trillion US$1990]	Capital 2005 [trillion US$2000]	Capital 1995 [trillion US$1990]
Belarus	0.01878	0.01619	0.018	0.020	0.022	N/A
Bosnia and Hercegovina	0.00748	0.00464	0.006	0.009	0.007	N/A
Bulgaria	0.01311	0.01038	0.016	0.019	0.026	N/A
Croatia	0.00646	0.00449	0.023	0.004	0.031	N/A
Czech Rep.	0.03133	0.03305	0.068	0.035	0.094	N/A
Estonia	0.00478	0.00404	0.008	0.008	0.011	N/A
Hungary	0.01572	0.01547	0.059	0.025	0.093	N/A
Latvia	0.00204	0.00050	0.012	0.009	0.017	N/A
Lithuania	0.00387	0.00295	0.017	0.002	0.021	N/A
Macedonia	0.00297	0.00293	N/A	0.004	N/A	N/A
Moldova	0.00213	0.00254	0.002	0.006	0.003	N/A
Poland	0.08679	0.09282	0.199	0.074	0.268	N/A
Romania	0.02686	0.03058	0.049	0.037	0.078	N/A
Serbia	0.01453	0.01525	0.011	0.027	0.014	N/A
Slovakia	0.01022	0.00903	0.025	0.060	0.037	N/A
Slovenia	0.00414	0.00320	0.023	0.008	0.031	N/A
Ukraine	0.08704	0.11960	0.045	0.034	0.072	N/A
Total:	**0.338**	**0.368**	**0.582**	**0.381**	**0.828**	**0.749**

A - Table 33: Macroeconomic and emission data for the region MI

Country	Industrial CO_2 Emission 2005 [GtC]	Industrial CO_2 Emission 1995 [GtC]	GDP 2005 [trillion US$2000]	GDP 1995 [trillion US$1990]	Capital 2005 [trillion US$2000]	Capital 1995 [trillion US$1990]
Anguilla	N/A	N/A	N/A	N/A	N/A	N/A
Antigua and Barbuda	0.00012	0.00009	0.0008	0.0000	0.0012	N/A
Argentina	0.04733	0.03533	0.3136	0.1490	0.5084	N/A
Barbados	0.00037	0.00023	N/A	0.0000	N/A	N/A
Brazil	0.09614	0.06801	0.7378	0.3700	1.1891	N/A
Cyprus	0.00212	0.00141	0.0092	0.0070	0.0137	N/A
French Polynesia	0.00022	0.00015	0.0020	N/A	0.0032	N/A
Gabon	0.00056	0.00097	0.0055	0.0060	0.0097	N/A
Gibraltar	0.00011	0.00006	N/A	N/A	N/A	N/A
Isle of Man	N/A	N/A	N/A	N/A	N/A	N/A
La Reunion	0.00069	0.00042	N/A	N/A	N/A	N/A
Macao	0.00061	0.00034	N/A	0.0040	N/A	N/A
Malaysia	0.05124	0.02910	0.1125	0.0710	0.1532	N/A
Malta	0.00070	0.00047	0.0039	0.0030	0.0063	N/A
Martinique	0.00051	0.00056	N/A	N/A	N/A	N/A
Montserrat	0.00002	0.00001	N/A	N/A	N/A	N/A
Nauru	0.00004	0.00004	N/A	N/A	N/A	N/A
Netherlands Antilles	0.00118	0.00176	N/A	N/A	N/A	N/A
New Caledonia	0.00080	0.00047	0.0016	N/A	0.0026	N/A
N. Mariana Islands	N/A	N/A	N/A	N/A	N/A	N/A
Puerto Rico	N/A	0.00424	0.0423	0.0360	0.0614	N/A
Seychelles	0.00020	0.00004	0.0006	0.0000	0.0010	N/A
South Korea	0.02313	0.10196	0.6394	0.2880	0.8828	N/A
St. Kitts and Nevis	0.00004	0.00003	0.0004	0.0000	0.0006	N/A
St. Lucia	0.00010	0.00005	0.0008	0.0000	0.0011	N/A
St. Pierre and Miquelon	0.00002	0.00002	N/A	N/A	N/A	N/A
Suriname	0.00067	0.00059	0.0011	0.0020	0.0018	N/A
Taiwan	0.07437	0.04672	N/A	0.1950	N/A	N/A
Trinidad and Tobago	0.00916	0.00467	0.0119	0.0060	0.0163	N/A
Turks and Caicos Islands	N/A	N/A	N/A	N/A	N/A	N/A
Total:	**0.310**	**0.298**	**1.883**	**1.137**	**2.852**	**2.465**

A - Table 34: Macroeconomic and emission data for China

Country	Industrial CO_2 Emission 2005 [GtC]	Industrial CO_2 Emission 1995 [GtC]	GDP 2005 [trillion US$2000]	GDP 1995 [trillion US$1990]	Capital 2005 [trillion US$2000]	Capital 1995 [trillion US$1990]
China	1.665	0.871	1.890	0.654	2.118	1.042

A - Table 35: Macroeconomic and emission data for the region LMI

Country	Industrial CO_2 Emission 2005 [GtC]	Industrial CO_2 Emission 1995 [GtC]	GDP 2005 [trillion US$2000]	GDP 1995 [trillion US$1990]	Capital 2005 [trillion US$2000]	Capital 1995 [trillion US$1990]
Algeria	0.03620	0.02491	0.0697	0.0760	0.1053	N/A
Belize	0.00022	0.00011	0.0011	0.0010	0.0015	N/A
Cayman Islands	0.00014	0.00008	N/A	N/A	N/A	N/A
Chile	0.01639	0.01204	0.0925	0.0160	0.1309	N/A
Colombia	0.01730	0.01843	0.0988	0.0570	0.1558	N/A
Cook Islands	0.00002	0.00001	N/A	N/A	N/A	N/A
Costa Rica	0.00214	0.00143	0.0195	0.0070	0.0279	N/A
Cuba	0.00808	0.00793		0.0230		N/A
Dominica	0.00003	0.00002	0.0003	N/A	0.0005	N/A
Dominican Rep.	0.00555	0.00321	0.0234	0.0070	0.0333	N/A
Ecuador	0.00854	0.00618	0.0205	0.0070	0.0315	N/A
El Salvador	0.00176	0.00142	0.0146	0.0070	0.0236	N/A
Fiji	0.00044	0.00020	0.0019	0.0020	0.0030	N/A
French Guiana	0.00024	0.00024	N/A	N/A	N/A	N/A
Grenada	0.00007	0.00005	N/A	N/A	N/A	N/A
Guadeloupe	0.00058	0.00042	N/A	N/A	N/A	N/A
Iran, Islamic Rep	0.12736	0.07199	0.1326	0.2110	0.1926	N/A
Jamaica	0.00331	0.00247	0.0087	0.0040	0.0151	N/A
Kazakhstan	0.05278	0.03709	0.0300	0.0180	0.0358	N/A
Marshall Islands	0.00003	N/A	0.0001	N/A	0.0002	N/A
Mauritius	0.00105	0.00041	0.0055	0.0030	0.0077	N/A
Mexico	0.11895	0.09766	0.6353	0.1790	1.0137	N/A
Morocco	0.01236	0.00800	0.0409	0.0260	0.0633	N/A
Namibia	0.00077	N/A	0.0409	N/A	0.0633	N/A
Niue	0.00000	0.00000	N/A	N/A	N/A	N/A
Pacific Islands	N/A	0.00007	N/A	N/A	N/A	N/A
Panama	0.00175	0.00188	0.0143	0.0080	0.0208	N/A
Papua New Guinea	0.00126	0.00068	0.0037	0.0050	0.0062	N/A
Paraguay	0.00109	0.00104	0.0080	0.0060	0.0134	N/A
Peru	0.01054	0.00834	0.0654	0.0280	0.1003	N/A
Samoa	0.00004	0.00008	0.0003	N/A	0.0004	N/A
South Africa	0.11309	0.08346	0.1608	0.1020	0.2529	N/A
St. Vincent and the Grenadines	0.00005	0.00003	0.0004	N/A	0.0006	N/A
Syrian Arab Rep.	0.01867	0.01256	0.0236	0.0200	0.0353	N/A
Thailand	0.07432	0.04777	0.1571	0.1220	0.2239	N/A
Tonga	0.00004	0.00003	0.0002	N/A	0.0003	N/A
Tunisia	0.00631	0.00418	0.0242	0.0150	0.0345	N/A
Turkey	0.07349	0.04777	0.2462	0.1290	0.3535	N/A
Turkmenistan	0.01203	0.00773	0.0017	0.0010	0.0025	N/A
Uruguay	0.00187	0.00147	0.0216	0.0100	0.0367	N/A
Vanuatu	0.00003	0.00002	0.0003	N/A	0.0004	N/A
Venezuela	0.04680	0.04919	0.1329	0.0650	0.2183	N/A
Wallis and Futuna	0.00001	N/A	N/A	N/A	N/A	N/A
Total:	**0.739**	**0.561**	**2.097**	**1.155**	**3.205**	**2.071**

A - Table 36: Macroeconomic and emission data for the region LI

Country	Industrial CO_2 Emission 2005 [GtC]	Industrial CO_2 Emission 1995 [GtC]	GDP 2005 [trillion US$2000]	GDP 1995 [trillion US$1990]	Capital 2005 [trillion US$2000]	Capital 1995 [trillion US$1990]
Afghanistan	0.00019	0.00034	N/A	0.014	N/A	N/A
Albania	0.00117	0.00050	0.005	0.003	0.007	N/A
Armenia	0.00119	0.00100	0.003	0.001	0.004	N/A
Azerbaijan	0.00956	0.01162	0.010	0.003	0.010	N/A
Bangladesh	0.01135	0.00571	0.061	0.027	0.085	N/A
Bhutan	0.00010	0.00007	0.001	0.000	0.001	N/A
Bolivia	0.00311	0.00286	0.010	0.007	0.015	N/A
Cambodia	0.00111	0.00014	0.006	0.002	0.006	N/A
Egypt	0.04549	0.02502	0.120	0.048	0.174	N/A
Georgia	0.00151	0.00211	0.004	0.003	0.009	N/A
Guatemala	0.00321	0.00196	0.022	0.011	0.034	N/A
Guyana	0.00041	0.00026	0.001	0.001	0.001	N/A
Haiti	0.00049	0.00017	0.004	0.002	0.008	N/A
Honduras	0.00196	0.00105	0.007	0.006	0.011	N/A
Indonesia	0.09095	0.08082	0.208	0.158	0.304	N/A
Iraq	0.02525	0.02702	0.017	0.012	0.021	N/A
Jordan	0.00565	0.00363	0.011	0.009	0.016	N/A
Kiribati	0.00001	0.00001	0.000	0.000	0.000	N/A
Kyrgyzstan	0.00152	0.00149	0.002	0.001	0.003	N/A
Lao, PDR	0.00039	0.00008	0.002	0.002	0.003	N/A
Lebanon	0.00418	0.00364	0.021	0.006	0.028	N/A
Maldives	0.00024	0.00005	0.001	0.000	0.001	N/A
Mongolia	0.00258	0.00231	0.001	0.004	0.001	N/A
Myanmar	0.00273	0.00192	N/A	0.015	N/A	N/A
Nepal	0.00088	0.00042	0.006	0.005	0.010	N/A
Nicaragua	0.00118	0.00074	0.005	0.004	0.007	N/A
North Korea	0.02313	0.07014	N/A	0.015	N/A	N/A
Occupied Palest. Territory	0.00081	N/A	0.004	N/A	0.005	N/A
Pakistan	0.03891	0.02330	0.093	0.056	0.132	N/A
Philippines	0.01864	0.01669	0.094	0.049	0.140	N/A
Samoa	0.00004	0.00004	0.000	0.000	0.000	N/A
Sao Tome and Principe	0.00003	0.00002	N/A	0.000	N/A	N/A
Solomon Islands	0.00005	0.00004	0.000	0.000	0.001	N/A
Sri Lanka	0.00324	0.00161	0.020	0.010	0.028	N/A
Tajikistan	0.00174	0.00102	0.002	0.002	0.002	N/A
Tokelau	N/A	N/A	N/A	N/A	N/A	N/A
Tuvalu	N/A	N/A	N/A	N/A	N/A	N/A
Uzbekistan	0.03155	0.02699	0.018	0.015	0.025	N/A
Viet Nam	0.00232	0.00865	0.045	0.068	0.054	N/A
Western Sahara	0.00007	0.00006	N/A	N/A	N/A	N/A
Yemen	0.00578	0.00393	0.012	0.011	0.015	N/A
Total:	**0.343**	**0.327**	**0.815**	**0.556**	**1.162**	**0.872**

A - Table 37: Macroeconomic and emission data for the region AFRICA

Country	Industrial CO_2 Emission 2005 [GtC]	Industrial CO_2 Emission 1995 [GtC]	GDP 2005 [trillion US$2000]	GDP 1995 [trillion US$1990]	Capital 2005 [trillion US$2000]	Capital 1995 [trillion US$1990]
Angola	0.00289	0.00126	0.015	0.008	0.018	N/A
Benin	0.00085	0.00017	0.003	0.002	0.004	N/A
Botswana	0.00130	0.00061	0.008	0.003	0.010	N/A
Cameroon	0.00099	0.00113	0.012	0.011	0.019	N/A
Congo	0.00040	0.00035	0.004	0.003	0.006	N/A
Cote d'Ivoire	0.00188	0.00283	0.010	0.012	0.019	N/A
Dem Rep. Congo	0.00060	0.00057	0.005	0.005	0.011	N/A
Ethiopia	0.00164	0.00096	0.010	0.010	0.014	N/A
Ghana	0.00252	0.00110	0.006	0.008	0.009	N/A
Guinea	0.00037	0.00030	0.004	0.003	0.005	N/A
Kenya	0.00331	0.00182	0.015	0.011	0.024	N/A
Lesotho	N/A	N/A	0.001	N/A	0.002	N/A
Madagascar	0.00077	0.00031	0.004	0.003	0.006	N/A
Malawi	0.00029	0.00020	0.002	0.002	0.003	N/A
Mali	0.00016	0.00013	0.003	0.003	0.005	N/A
Niger	0.00026	0.00031	0.002	0.003	0.004	N/A
Nigeria	0.02653	0.02476	0.060	0.045	0.087	N/A
Rwanda	0.00022	0.00013	0.002	0.001	0.004	N/A
Senegal	0.00116	0.00084	0.005	0.006	0.008	N/A
Somalia	0.00005	0.00000	N/A	0.001	N/A	N/A
Sudan	0.00295	0.00096	0.017	0.014	0.022	N/A
Swaziland	0.00028	0.00012	0.002	0.001	0.002	N/A
Uganda	0.00074	0.00029	0.008	0.012	0.010	N/A
Zambia	0.00067	0.00066	0.004	0.003	0.007	N/A
Zimbabwe	0.00302	0.00266	0.006	0.008	0.045	N/A
Total:	**0.054**	**0.042**	**0.209**	**0.178**	**0.344**	**0.282**

A - Table 38: Macroeconomic and emission data for the region HIO

Country	Industrial CO_2 Emission 2005 [GtC]	Industrial CO_2 Emission 1995 [GtC]	GDP 2005 [trillion US$2000]	GDP 1995 [trillion US$1990]	Capital 2005 [trillion US$2000]	Capital 1995 [trillion US$1990]
Bahrain	0.00581	0.00405	0.01	0.01	0.01	N/A
Brunei	0.00161	0.00225	0.00	0.00	0.01	N/A
Kuwait	0.02362	0.01330	0.05	0.03	0.07	N/A
Libya	0.01514	0.01075	0.04	0.03	0.04	N/A
Oman	0.01129	0.00312	0.02	0.01	0.03	N/A
Qatar	0.01260	0.00792	n/a	0.01	N/A	N/A
Saudi Arabia	0.10406	0.06939	0.23	0.11	0.35	N/A
U. A. Emirates	0.03806	0.01864	0.10	0.04	0.13	N/A
Total:	**0.212**	**0.129**	**0.461**	**0.234**	**0.649**	**0.755**

A - Table 39: Macroeconomic and emission data for India

Country	Industrial CO_2 Emission 2005 [GtC]	Industrial CO_2 Emission 1995 [GtC]	GDP 2005 [trillion US$2000]	GDP 1995 [trillion US$1990]	Capital 2005 [trillion US$2000]	Capital 1995 [trillion US$1990]
India	0.412	0.248	0.644	0.447	0.827	0.567

Appendix C – Mathematical Framework of the RICE-99

For a verbal description and a detailed discussion of the derivation of the RICE-99 see Nordhaus and Boyer (2000).

Equations of the RICE-99

Welfare function for region J (Objective Function):

(1) $$W_J = \sum_t U[c_J(t),L_J(t)]R(t)$$

Pure time preference discount factor:

(2) $$R(t) = \prod_{v=0}^{t} [1+\rho(v)]^{-10}$$

Pure rate of time preference:

(2b) $$\rho(t) = \rho(0)\exp(-g^{\rho}t)$$

Utility function of consumption:

(3) $$U[c_J(t),L_J(t)] = L_J(t)\{\log[c_J(t)]\}$$

Population at time t:

(4) $$L_J(t) = L_J(0)\exp(\int_0^t g^{pop}{}_J(t))$$

Growth rate of population at time t:

(4b) $$g^{pop}{}_J(t) = g^{pop}{}_J(0)\exp(-\delta^{pop}{}_J t)$$

Production function:

(5) $$Q_J(t) = \Omega_J(t)[A_J(t)K_J(t)^{\gamma}L_J(t)^{(1-\gamma-\beta J)}ES_J(t)^{\beta J}–c^E{}_J(t)ES_J(t)]$$

Relationship between carbon energy input and energy services:

(5b) $$ES_J(t) = \varsigma_J(t)E_J(t)$$

Level of “carbon-augmenting“ technology:

(5b1) $$\varsigma_J(t) = \varsigma_J(0)\exp(\int_0^t g^z{}_J(t))$$

Growth rate of “carbon-augmenting” technology:

(5b2) $$g^z{}_J(t) = g^z{}_J(0)\exp(-\delta^z{}_J t)$$

Level of Hick-neutral technological change:

(5c) $A_J(t) = A_J(0)\exp(\int_0^t g^z{}_J(t))$

Growth rate of Hick-neutral technological change:

(5c1) $g^A{}_J(t) = g^A{}_J(0)\exp(-\delta^A{}_J t)$

Constraint on regional expenditures:

(6) $Q_J(t) = C_J(t)+I_J(t)$

Per capita conumption:

(7) $c_J(t) = C_J(t)/L_J(t)$

Capital stock:

(8) $K_J(t) = K_J(t-1)(1-\delta_K)^{10} + 10 \times I_J(t-1)$,

where $K_J(0) = K_J{}^*$

Cost of carbon energy:

(9) $c^E{}_J(t) = q(t) + \text{markup}^E$

Cumulative use of carbon energy:

(9a) $\text{CumC}(t) = \text{CumC}(t-1) + 10 \times E(t)$,

where $E(t) = \sum_J E_J(t)$

Supply price of carbon energy:

(9b) $q(t) = \xi_1 + \xi_2[\text{CumC}(t)/\text{CumC}^*]^{\xi 3}$

End-of-period mass of carbon in the atmosphere:

(10) $M_{AT}(t) = 10 \times ET(t) + \Phi_{11}M_{AT}(t-1) - \Phi_{12}M_{AT}(t-1) + \Phi_{21}M_{UP}(t-1)$,

where $M_{AT}(0) = M_{AT}{}^*$

CO_2 Emissions from land-use change:

(10a) $LU_J(t) = LU_J(0)(1-\delta_l)^t$

Total CO_2 emissions:

(10c) $ET(t) = \sum_J [E_J(t) + LU_J(t)]$

End-of-period mass of carbon in the upper reservoir (biosphere, and upper oceans):

(11) $M_{UP}(t) = \Phi_{22}M_{UP}(t-1) + \Phi_{12}M_{AT}(t-1) – \Phi_{21}M_{UP}(t-1) + \Phi_{32}M_{LO}(t-1) – \Phi_{23}M_{UP}(t-1)$,

where $M_{UP}(0) = M_{UP}*$

End-of-period mass of carbon in the lower oceans:

(12) $M_{LO}(t) = \Phi_{33}M_{LO}(t-1) - \Phi_{32}M_{LO}(t-1) + \Phi_{23}M_{UP}(t-1)$,

where $M_{LO}(0) = M_{LO}*$

Radiative Forcing:

(13) $F(t) = \eta\{\log[M_{AT}(t)/M_{AT}^{PI}]/\log(2)\} + O(t)$

Forcings of other GHGs (CFCs, CH4, N2O, and ozone) and aerosols

(13b) $O(t) = -0.1965 + 0.13465t \quad t < 11$

$= 1.15 \quad t > 10$

Temperature equation for the atmosphere and the upper ocean:

(14) $T(t) = T(t-1) + \sigma_1\{F(t) – \lambda T(t-1) – \sigma_2[T(t-1) – T_{LO}(t-1)]\}$,

where $T(0) = T*$

Temperature equation for the lower ocean:

(14b) $T_{LO}(t) = T_{LO}(t-1) + \sigma_3[T(t-1) – T_{LO}(t-1)]$,

where $T_{LO}(0) = T_{LO}*$

Damage Function:

(15) $\Omega_J(t) = 1/[1 + D_J(t)]$

Relationship between global-temperature increase and income loss:

(15b) $D_J(t) = \theta_{1,J}T(t) + \theta_{2,J}T(t)^2$

Declaration

under Art. 28 Para. 2 RSL 05

Last, first name: Aerni, Silvan

Matriculation number: 01-116-573

Programme: Master in Climate Sciences

Bachelor ☐ Master ☐ Dissertation ☐

Thesis title: Incorporating Carbon Capture and Geological Storage in an Integrated Assessment Model

Thesis supervisor: Supervisor: Prof. Dr. Gunter Stephan

Advisor: Raphael Bucher

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person, except where due acknowledgement has been made in the text. In accordance with academic rules and ethical conduct, I have fully cited and referenced all material and results that are not original to this work. I am well aware of the fact that, on the basis of Article 36 Paragraph 1 Letter o of the University Law of 5 September 1996, the Senate is entitled to deny the title awarded on the basis of this work if proven otherwise.

....

Place, date

....

Signature