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Energy Security, Economic Development and Global Warming Addressing short and long term challenges

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Abstract

Energy security, economic development and averting global warming are conflicting objectives in a fossil fuel economy. In the long run, sustainable development requires a shift to renewable energy sources. In the short run the climate change problem requires swift action[2] and different strategies. There is no “silver bullet” and a combination of technologies and strategies will be required to meet the Intergovernmental Panel on Climate Change (IPCC) requirements.[3] The article develops one example based on ‘negative carbon’ using *air capture of carbon dioxide* for storage into geological sites and solid materials. When driven by energy produced by carbon-neutral sources (such as Concentrated Solar Power or CSP) this approach can co-produce electricity while reducing carbon concentration in the atmosphere (Jones 2008, 2008b, Chichilnisky 2008, Chichilnisky and Eisenberger, 2009, Chichilnisky and Eisenberger et. al., 2009). While providing additional energy the process makes fossil power plants net carbon sinks, however changing entirely the relationship between the three problems: in the short run it advances energy security and economic development while averting climate change. In the long run, the approach accelerates the transition to renewable sources of energy and is compatible with sustainable development. The article addresses short and long run challenges with this capability in the context of the economic incentives provided by the carbon market of the UN Kyoto Protocol, whose functioning is analyzed. We explore the implications for extending Kyoto’s Clean Development Mechanism (CDM) in a way that benefits most the developing nations in Latin America and Africa, and the global transition from a fossil to a renewable economy.

Keywords: United Nations Kyoto Protocol, Energy Security, Economic Development, Climate Change, Global Environment, Clean Energy, United Nations Climate Convention, Sustainable Development, Catastrophic Risks, Risk Management, Global Thermostat, Alternative Energy, Developing Nations, Technology Transfer, Solar Energy, Solar Economy, Concentrated Solar Power, International Energy Agency, World Bank, The Carbon Market

1. Introduction

At a time when China and India are flexing their geopolitical muscles and the developing countries rapidly increase their energy use, the world faces for the first time the environmental consequences of a long and successful period of Western industrialization.[4] The timing could not

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[2] Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES), 2000

[3] Graciela Chichilnisky acted as Lead Author of the IPCC, 1996-2000.

[4] Chichilnisky and K. Sheeran Saving Kyoto, New Holland UK October 2009, and Chichilnisky 2008: Beyond the Global Divide: from Basic Needs to the Knowledge Revolution, Columbia University, www.chichilnisky.com ‘Books and Articles.’

be worse. Two centuries of industrialization based on fossil fuels emitted large amounts of carbon dioxide into the atmosphere and created a serious risk from climate change. For many the results are unfolding in front of our eyes. Entire towns in Alaska are sinking in the melting permafrost and warming seas[5] and Florida is the next most vulnerable US site.[6] It is now widely accepted that catastrophic climate change could happen, and the possibility by itself calls for action. Yet the thirst for fossil fuels continues unabated across the world. China is building a new coal plant each other week, and the US consumer uses more energy than ever and faces the highest oil prices since the OPEC embargoes. An understandable desire for energy independence creates a powerful incentive to use abundant coal resources in China as well as in the US, so as to meet the rapidly growing need for energy. [7]

Today three of every five barrels sold in the petroleum market originate from insecure regions: the Persian Golf, North Africa, Angola, Venezuela, Russia and the Caspian states. Political, military or terrorist events could disrupt oil markets. Reducing vulnerability to such events is a main task for energy security policy. For a nation such as the US that is "oil addicted"[8] curtailing imports from its major trading partners – Mexico and Canada – is unlikely to be beneficial. US vulnerability depends mostly on how closely its energy infrastructure is tied to petroleum use, and the same is true for the world. [9] However energy use is essential to economic development: in fact, there is a direct connection between energy use and Gross Domestic Product, see Figure 1 below.

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[5] NY Times, Sunday May 27th, 2007, "Engulfed by Climate Change, Town seeks Lifeline" by W. Yardley, front page. The permanently frozen subsoil, known as permafrost, upon which the town of Newtok and many other Native Alaskan villages rest is melting, yielding to warming air temperatures and a warming ocean. Erosion has already made Newtok an island, the village is now below sea level and sinking, and studies say that the entire town will be washed away in a decade. The US Army Corps of Engineers has estimated that to move Newtok could cost at least $130 million, which comes to almost $413,000 for each of its 315 residents.

[6] A recent OECD study on the largest cities at risk identified Miami as the largest cit at risk of global warming with projected losses of $3.2 trillion; Shangai is next with $2.2 trillion in losses, cf. OECD Paris France.

[7] Energy use is expected to raise five to ten fold during this century, see US Department of Energy, 2009. The US coal industry presented recently an ambitious plan to secure enormous subsidies for coal production in the name of energy independence.

[8] To paraphrase former US President George W. Bush's terminology.

[9] Hillard Huntington (2008).

Figure 1
GNI per Capita vs. Carbon Emissions per Capita

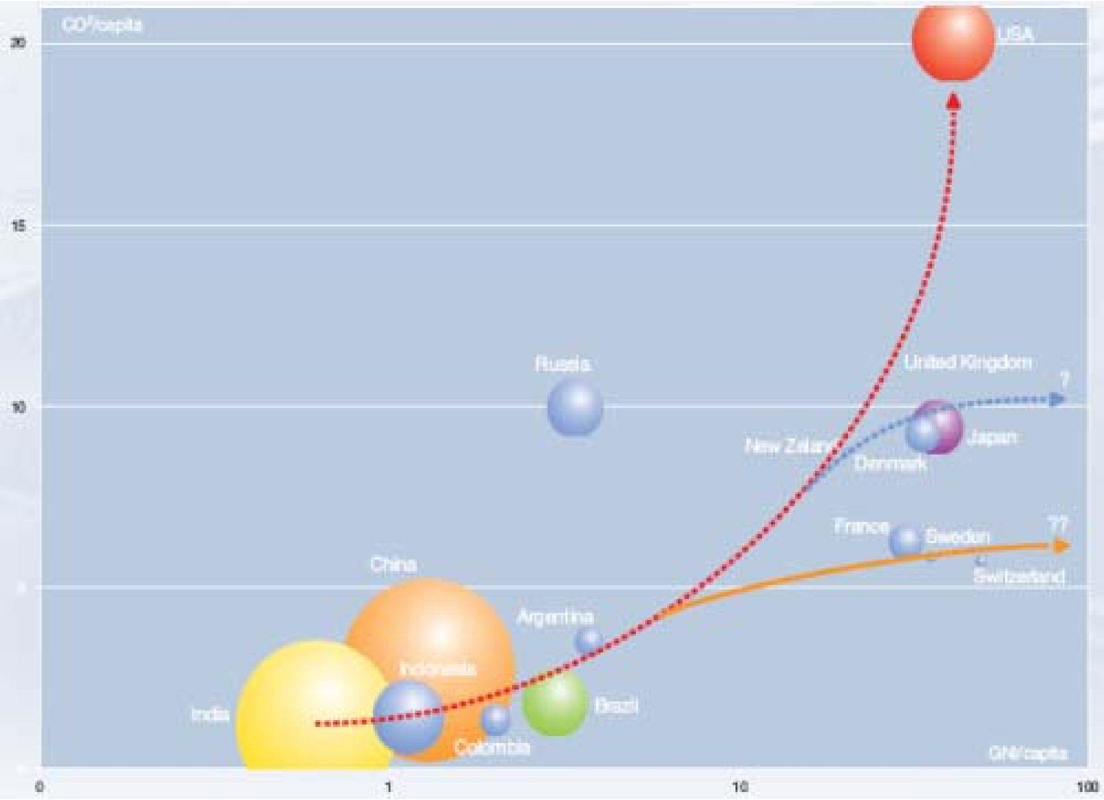

Figure 1. Horizontal axis: GNI per capita. Vertical axis: CO2 per capita. The size of the balls denotes total emissions
<u>Source:</u> UNEP-Building and Climate Change Report-2007

Fossil fuels tie together into a *Gordian knot* three key global issues: energy security, economic development and climate change. The fossil fuel age faces a cruel choice: economic development and energy independence clash against a stable climate. We can't have them all. The attendant geopolitical conflict takes several forms. Fossils generate about 87% of energy used in the world today. Since they are unevenly distributed in the earth's crust, they have led to wars and conflicts, prompting understandable calls for energy security and independence. Economic development in industrial and developing nations still depends crucially on the use of energy, and in today's economy, this means fossil fuels. But burning fossil fuels increases the risk of climate change. In the longer term, the only solution is to disentangle the use of energy from carbon emissions, make available clean and abundant renewable energy sources.[10] This is not feasible in the short term because of the sheer scale of the fossil infrastructure that must be replaced: about $43 – 50 trillion

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[10] Solar energy is considered renewable in this context.

today, and with current trends about $400 trillion by the end of the century (IEA, DOE, 2006 and 2008). The short term and the long term present different problems, and require different solutions.

Time is not on our side. IPCC scientists agree that we need to reduce carbon emissions by 60 – 80% in the next 10-20 years.[11] Avoiding further carbon emissions emphatically does not solve the short-run problem (Chichilnisky, 2008). Even if we *stabilize* at the current level of emissions we still continue to add carbon dioxide to the atmosphere at a rate of about 30-40 billion tons per year, and therefore continue to increase carbon concentration in the atmosphere. New coal plants that clean the carbon they emit (Carbon capture and sequestration or CCS hereafter) are a step forward,[12] but they create burdensome economic costs and in at best they merely stabilize the implacable growth of carbon concentration at current rates. More to the point, such coal plants defeat the long-run objective of making an orderly transition to non-fossil resources (Nature 2009).

The general agreement is that there are no silver bullets and a variety of approaches will be needed. It is shown below that a low-risk level of carbon in the atmosphere requires a significant carbon- negative mitigation component: removing CO2 from the atmosphere (Chichilnisky, 2008, Jones 2008, Eisenberger et al 2009). Studies using integrated assessment models (Nordhaus 2007, 2008) have found that as yet unspecified future carbon-negative measures may be the most economically effective path to climate targets.

To explore the limits of the possible, and how to merge short-run goals with long term strategies, we focus on an *air capture* technology[13] that was introduced recently (Chichilnisky 2008, Jones 2008, 2009, Chichilnisky and Eisenberger, 2009, Eisenberger et. al., 2009) and has the capability to co-produce electricity at the same time that it reduces carbon concentration in the atmosphere. The process is ‘carbon negative’ because it reduces the carbon concentration in the atmosphere. It can be used in conjunction with electricity generation (Chichilnisky 2008, Jones 2008, 2009 and Eisenberger et al, 2009). Somewhat surprisingly the more electricity is produced, the more carbon is reduced. The technology captures carbon most efficiently when used in conjunction with renewable sources of energy such as concentrated solar power (CSP), Eisenberger et al 2009. The carbon thus captured can be converted into fuels, plastics and even cement, stored in geological sites and used for enhancing oil recovery. This provides real protection against human induced climate change since it allows us to become carbon neutral in the short term, and enables an orderly transition to an alternative energy future, thereby enhancing energy security and economic development.

The article shows how such carbon-negative technologies can help resolve current global conflicts between rich and the poor nations in connection with the 1992 UN Agenda 21 and the

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[11] See IPCC Special Report on Emissions Scenarios (SRES) 2000. In some global emissions peak about 2020, and fall again by about 80% of 1990 levels by 2050. For simplicity of exposition we use the term “carbon” to mean “carbon dioxide” – other greenhouse gases could be considered such as methane.

[12] See “Can Coal be Clean?” Editorial p. 299 Nature, May 2009.

[13] The potential role of air extraction in reducing future emissions has been considered by Keith (2005) and by Pielke (2009).

UN Climate Convention goal of "common but differentiated responsibilities." It examines the functioning and implications for the carbon market of the 1997 Kyoto Protocol that succeeded in regulating global carbon emissions limits and was ratified as international law in 2005. At the end of the paper we examine the implications for industrial and developing nations of using such negative carbon technologies as part of Kyoto's CDM. We explore the workings of the Kyoto Protocol carbon market and Kyoto's future, the post 2012 regime to be decided in Copenhagen at the COP 15 ofDecember 2009, as well as the dynamics of a transition from today's fossil fuel economy into the renewable economy of the future.

2. Short-run goals and long-term objectives

Climate change risks are potentially catastrophic, but managing catastrophic risks is not a new activity. As discussed below, we routinely insure against earthquakes and floods, and new building codes mitigate potential losses.[14] However the novelty and magnitude of climate change risks require more sophisticated forms of decision making than the ones used for standard risks (Chichilnisky, 2000, 2002, 2006, 2009). For this purpose we divide the problem into short-run goals and long-term objectives.

A transition away from fossil fuels to alternative sources of energy[15] that are more broadly distributed can provide economic development and security without inducing global warming. This transition seems inevitable in the long run, because fossil fuels are limited in supply. The rapidly growing world demand for energy[16] will require a variety of alternative sources of energy and technologies. Supplies are not the problem. Solar energy on its own, for example CSP can easily meet with current technologies a ten-fold increase of today's fossil energy using less than 1% of the solar energy that hits the planet's surface.[17]

However, as we show below *the short-run and the long-term problems are quite different and require different solutions.* For the long-term a transition we need a non-fossil fuel economy; for the short run we may need to continue using fossil fuel energy use and simultaneous *decrease* the carbon content of the planet's atmosphere. How to achieve this? It is a major challenge, and the topic of the article.

2A. Short-run goals

However optimistic one may be for the long run, it is important to appreciate that a long-run renewable energy solution is *not* realistic in the short run. A transition to renewable energy sources will take a long time because most of the energy used in the planet today is obtained from fossil fuels from such as oil, gas and coal.[18] As discussed further below, the change will require a

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[14] Earthquakes are infrequent risks and the risk for any one location is extremely small.

[15] Such as wind, biomass, hydroelectric, solar, geothermal, nuclear and even possibly fusion.

[16] Which by the end of this century is expected to be five to ten times larger than today's energy use,

[17] DOE 2008

[18] 87% of the energy used today comes from fossil fuels and less than 1% is from renewable sources; 0.01% is solar energy.

new massive and expensive infrastructure costing about $43 – 50 trillion (International Energy Agency IEA)[19] or about two thirds of the world's GDP, and will take time. Yet for as long as we continue to use fossil fuels and emit carbon we make the problem worse, as we increase the concentration of greenhouse gases and the risk of catastrophic climate change.[20] Stabilizing the level of emissions is helpful, but stabilizing at approximately the current level of 30-40 billon tons of carbon dioxide emitted annually is not a solution. This will only continue to build up carbon dioxide in the atmosphere[21] and increase risk. For this reason, the IPCC asserts that we need to decrease emissions of carbon dioxide by about 60-80% within the next fifteen or twenty years.[22] This is a steep challenge. Long-run policies of transitioning to renewable resources do not suffice; immediate action is required to manage the risk of climate change (Eisenberger et al, 2009).

The short run problem is acute for rich and poor nations alike. They could suffer economic disruptions caused by a drastic decrease in the use of fossil fuels. Rapidly growing nations such as China and India are heavily dependent on coal, and so are the US and Russia. It does not seem feasible to drastically decrease the use of fossil fuels in the short term, which is why there is an increasing call to capture the carbon emitted by fossil fuels plants and store it safely (Nature, 2009).

To explore the realm of the possible, we illustrate the situation in reference to two scenarios studied in Eisenberger et al (2009) emerging from the IPCCC Special Report on Emissions Scenarios, 2008. The two scenarios differ mainly on the degree and speed of future energy transition. They are both optimistic, describing a century of strong economic growth along with rapid development and diffusion of technology. Energy intensity declines at a strong 1.3% per year. The fossil fuel emission profiles are shown in Figure 2 below. Within this domain, CO2 emissions peak around the middle of the century and decline thereafter as the transition from fossil resources compensates for increased economic growth.

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[19] See also Table 1 below.

[20] Scientists agree on the possibility of a 'tipping point' namely a level of heating that triggers catastrophic climate change, which is typical of physical systems that have complex feedback effects.

[21] CO2 remains for a long time in the atmosphere, at least 60 – 100 years or more.

[8] The 60% figure was chosen because currently 40% of our emissions are removed naturally from the atmosphere and stored largely in the oceans. In the long term we cannot depend upon this continuing to happen, because in the past the reverse has been true, the oceans and land have stored less and the atmospheric concentration has increased.[22] As we reach 500 carbon parts per million, the average global temperature is expected to increase by 3 degrees centigrade, which means three times this amount in the polar caps triggering seal level rise.

Figure 2

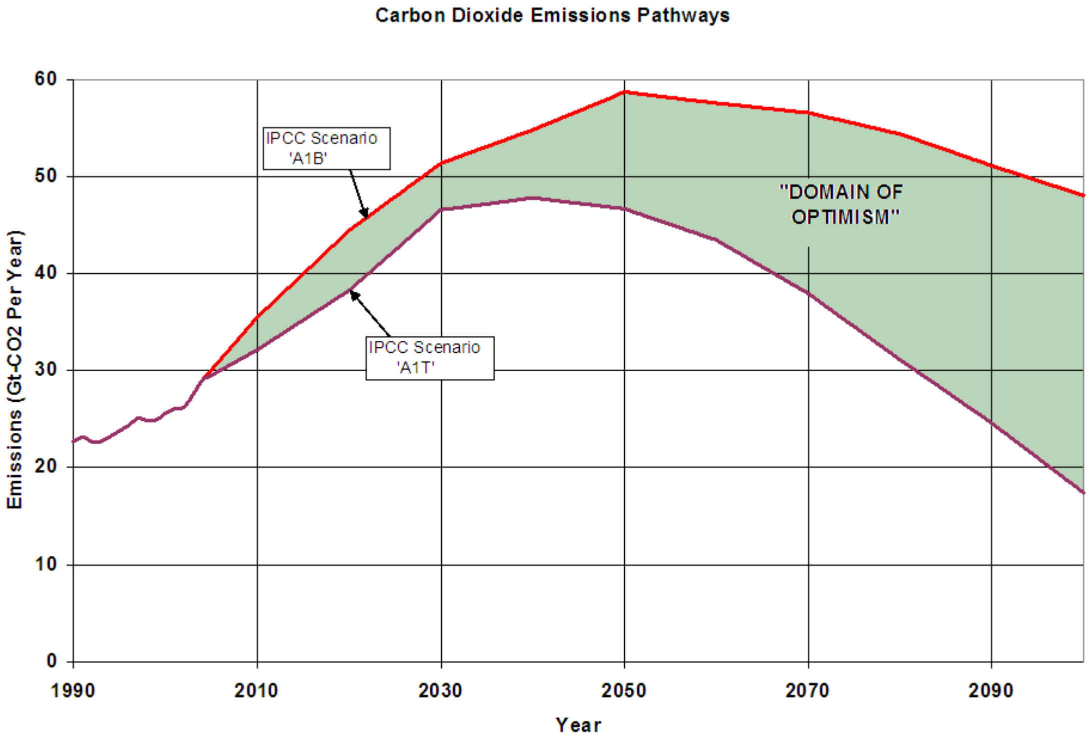

Figure 2. (Eisenberger el at 2009) Carbon dioxide emissions pathways to 2100 for the IPCC A1B and A1T scenarios. The region between the curves is labeled the "Domain of Optimism," because it represents what could be achieved by future technology efficiency gains and a substantial shift to emission- less energy, while maintaining strong worldwide economic growth. Within the domain, emissions peak around the middle of the century and decline thereafter. (The emissions scenarios shown in the figure have been adjusted slightly upward from the Special Report on Emissions scenarios of the IPCC in order to achieve consistency with the actual emissions history since 2000).

The levels of concentration of CO2 in the atmosphere are calculated from a carbon cycle model[23] and are shown in Figure 3 below. Emissions peak in the middle of this century and decrease afterwards, while atmospheric CO2 increases throughout the entire century and continues into the next. Figure 3 demonstrates that even optimistic IPCC scenarios do not prevent atmospheric CO2 from exceeding twice the pre industrial levels. Ultimately CO2 levels exceed 550 parts per million, which is twice the level of 19th century pre industrial Earth (Eisenberger et al, 2009). This is due to the long time remaining before emissions peak, several decades, which is in turn due to the large capital investments required to go from fossil to carbon neutral energy. Hoffley et al (1998) and Wigley et al (1996) estimate that by 2050, 10-30 trillion watts of new emission-less energy is needed to stabilize the atmosphere at 550 ppm. With current renewable technology

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[23] Employed in the IPCC-TAR (2001).

costing \$5-7 per installed watt on the average, the capital requirements would exceed \$50 trillion over 40 years, about two thirds of the world's economic output today.

Figure 3

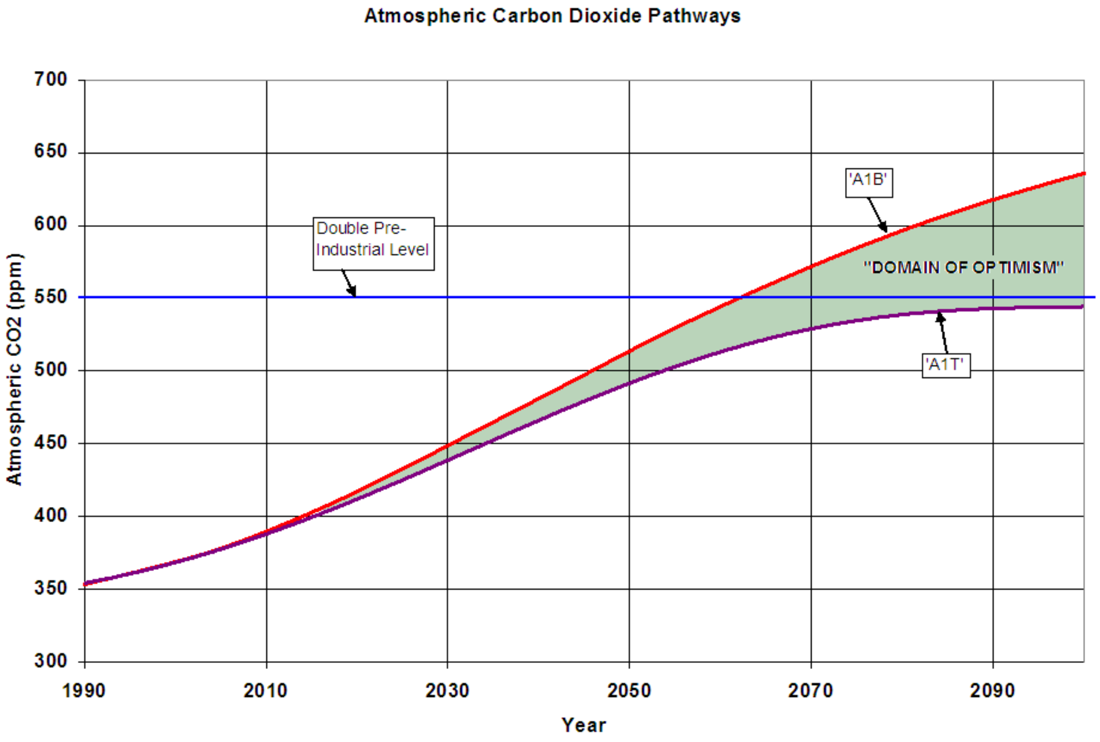

Figure 3. (Eisenberger el at 2009) Atmospheric carbon dioxide levels to 2100 corresponding to the emissions scenarios of Figure 2. Atmospheric carbon dioxide eventually exceeds 550 parts per million, twice the estimated pre-industrial level.

In the short run a low risk level of CO2 in the atmosphere cannot be reached without a significant carbon negative mitigation component. This requires removing carbon from the atmosphere in net terms (Chichilnisky, 2008, Jones, 2008, 2009, Chichilnisky and Eisenberger, 2009, Eisenberger et al 2009).

Several carbon negative technologies are possible, including ocean fertilization, forest sequestration, bio-energy with carbon storage, atmospheric aerosols and space borne reflectors.[24] All proposed measures have costs, issues and uncertainties that must be considered along with their potential to achieve a safer atmosphere (Eisenberger et al 2009). Air extraction, considered here, offers the ability to control CO2 without direct intervention in the biosphere and with relatively modest land - use. A description of the air capture technology and its capabilities can be found in Eisenberger et al (2009). It absorbs CO2 directly from air, and it does so without the

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[24] See Oliver Norton, 2009.

problems that have been normally associated with low concentration air extraction in the past, an issue that was explained earlier in Keith (1995) and Pielke (2005). The particular process illustrated here is unique in that it is driven by *low- temperature heat*. It can therefore use low-cost "process heat" that is a by-product of energy production, thus making the process rather inexpensive and compatible with electricity generation. The amount of heat required for regeneration is greatly reduced, making possible large extraction capacities in sites where process heat is available, such as power plants (nuclear, CSP, fossil), cement smelters, oil refineries and other industrial establishments. Because the only inputs required are heat and air, the location is completely flexible (Eisenberger et al, 2009).

Figure 4 below shows a representative emissions profile that achieves a carbon negative solution based on a new air extraction technology. The scenario of Figures 2 and 3 is used as a reference case. The scenarios in Figures 4 and 5 below assume deployment beginning in 2015, a date that is believed to be achievable given the current state of development.[25] By 2020, worldwide deployment rate achieves half the projected deployment rate of new primary power generation assets, and emissions begin to decline (Eisenberger et al, 2009). From 2020 through 2040, the pace of deployment matches the growth of power assets in the A1T scenario, while maintaining a 50% installation ratio. There is no further net deployment after 2040, and a rate of 34 gigatons of CO2 extraction is maintained for the rest of the century. As shown in the figure, the extraction level eventually offsets not only all power generation emissions (which are currently 41% of the world's fossil fuel emissions) but the transportation and the industrial/commercial sectors as well. Consequently CO2 emissions achieve negative values.

Figure 5 below shows the effect of air extraction on atmospheric CO2, relative to the optimistic A1T scenario of the IPCC. At the end of the century the CO2 level has returned to current values and is still declining, representing a substantially lower risk atmosphere. In terms of costs, the lowermost curve in Figure 5 below shows the cost as percentage of world GDP, assuming a constant undiscounted extraction and storage cost of $25 per ton of CO2 (Eisenberger et al 2009) The total implementation cost to 2100 is about $60 trillion, representing 0.18% of the world's GDP. Adopting a 1.5% discount rate as in Nordhaus et al (2006) reduces this figure by half.

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[25] These scenarios were developed by Roger Cohen, cf. Eisenberger et al 2009

Figure 4

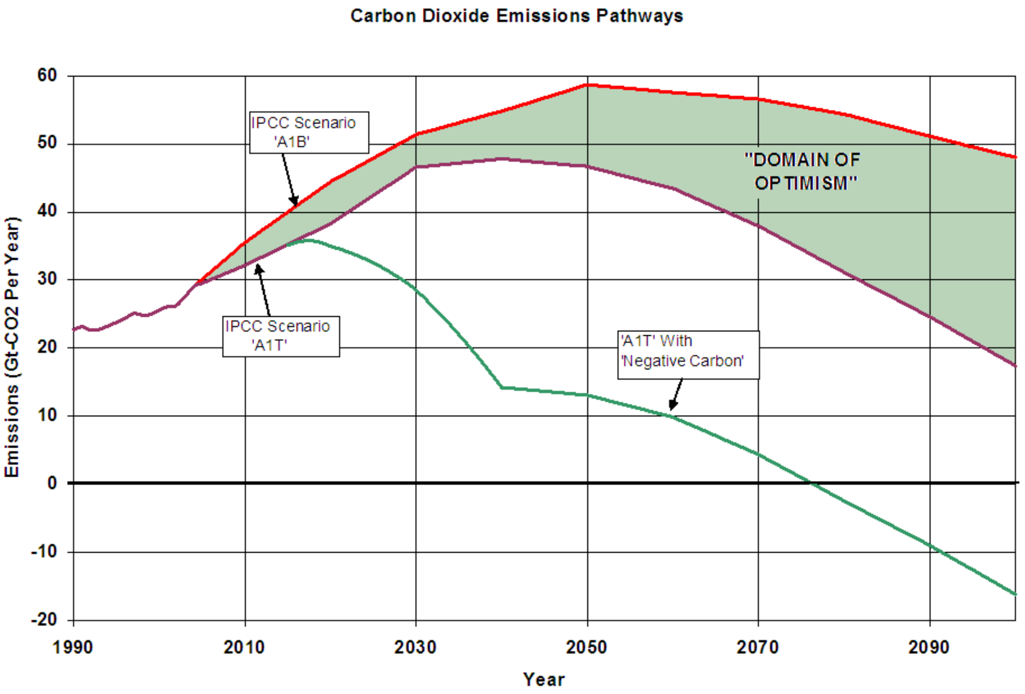

Figure 4 (Eisenberger et al 2009). Carbon dioxide emissions pathways of Figure 2 with the addition of a carbon-negative mitigation scenario to A1T, as discussed in the text. Carbon-negative mitigation via air extraction begins in 2015 and reaches 34 Gtonne-CO_2/yr in 2040. This level is sustained for the remainder of the century. Emissions peak by 2020 and become net negative later in the century as the energy shifts and efficiency gains of scenario A1T take hold.

While air capture can resolve many problems, there are no silver bullets. Extensive deployment of air extraction technology is still to happen, it is new and will take time and costs – however air capture has the potential to substantially lower the risk of greenhouse gas emissions, while maintaining global economic growth but the process will take time and it should be deployed along with other solutions to take a "portfolio" approach to risk. Yet with air capture, the short-run and the long-run objectives can blend together. The reason is that the technology described here can be run by sources of heat without emissions – such as CSP, wind to propel the air in air capture, or even nuclear energy.

An ideal package, recommended here, is the development of CSP energy sources together with low heat air extraction as described above. This would encourage the deployment of solar power plants and increase energy in the world economy in the long run, while simultaneously accelerating the capture of carbon to decrease climate risks in the short term. Therefore, significant incentives exist to accelerate R&D efforts in this direction, and in 2009 the US Department of Energy has already started such efforts.[26]

Figure 5

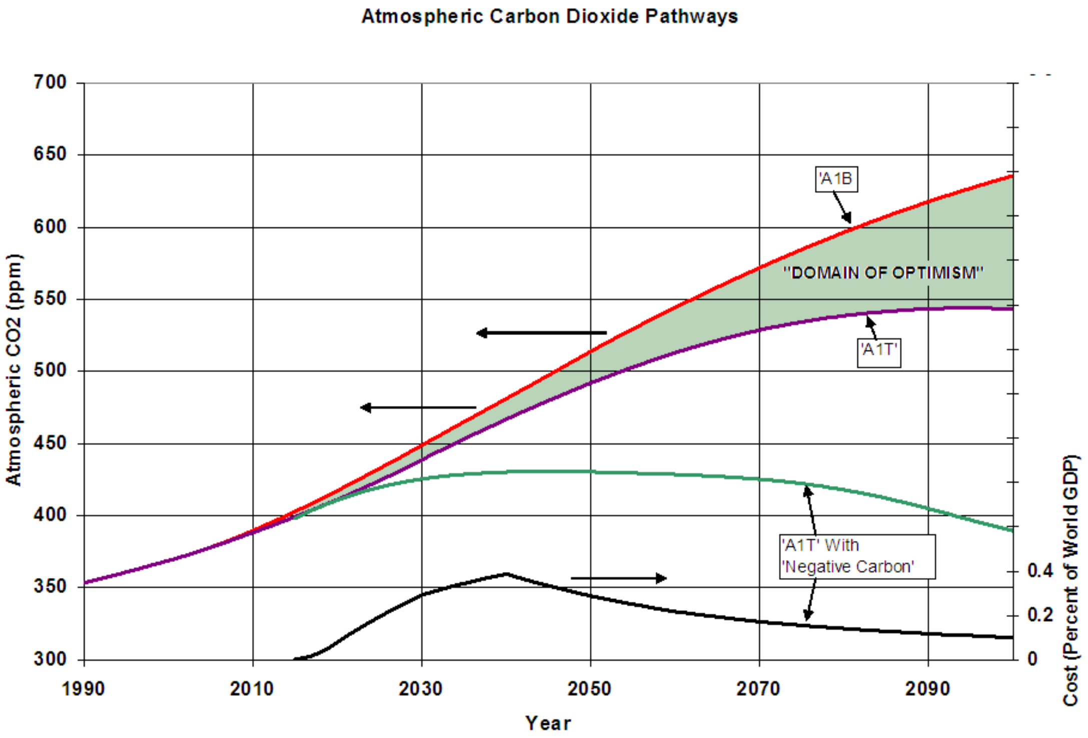

Figure 5 (Eisenberger et al, 2009). Atmospheric carbon dioxide levels to 2100 corresponding to the emissions scenarios of Figure 4. With the carbon-negative scenario of Figure 4, the atmospheric level peaks at only 10% above the current level and returns to current levels by century's end. The annual undiscounted cost of carbon-negative mitigation via air extraction, as a percent of world GDP, is shown in the lowermost curve (right hand vertical axis), for a constant unit cost of $25/tonne-CO$_2$. Adopting the 1.5% time discount rate used by Nordhaus (2006) reduces the total cost over the century by about half.

2B. Long-run Objectives – Learning by doing

To evaluate the transition from fossil to emission-less sources one has to predict the future costs of power production using renewable energy sources.

Hydroelectric power is only 6% of world energy use, about the same as nuclear, and other renewable sources are only 1% of world's energy production today. We need a methodology that can predict future expected costs in power production from alternative sources as the world's utilization of such sources expands considerably beyond today's levels; ten times to meet today's

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[26] In May 2009, the US DOE allocated for the first time US$2.4 billion for research projects that include air capture of CO2, as referred to here.

energy needs but 100 times to meet the needs at the end of the century. A widely accepted methodology used for this purpose is ‘learning curves’, which are standard predictors of the improvement in a technology’s efficiency as the capacity of production expands[27] (A. Kydes, 1999). An illustration of the methodology for solar energy showing Department of Energy learning curves for solar power production is in H. Price et.al., 2003. These publications show how efficiency increases at higher capacity or, equivalently, how the cost of producing energy decreases with installed capacity. Using this methodology, we now estimate the long-run costs of a transition away from fossil fuels and into renewable energy sources.

Since we focus on the long run, the alternative source should be able to provide up to five to 10 times the energy used in the world today. This is a standard projection of energy demand by the end of this century (IEA, IPCC and DOE, 2006, 2008). Neither wind, nor geothermal, biomass, hydroelectric energy or nuclear energy can offer this possibility by themselves -- either because they lack the capacity or because to do so would create additional problems. For example, biomass for energy competes with food production, and is much less efficient per square meter than solar (about 3% of the energy potential provided by solar for the same surface area); hydroelectric lacks the capacity and has environmental consequences, and nuclear fuel is limited in supply and cannot replace fossil fuels today, in addition to the environmental consequences for nuclear waste disposal in the long run. But solar could meet the demand with limited environmental impact. A combination of all of these energy sources that includes solar could therefore offer a reasonable long run solution.

The computation of *long-run transition costs* is considerably simplified when we observe that, in a competitive market economy, the lowest cost alternatives will always prevail. In view of this fact, the cost involved in the transition to renewable sources of energy can be bounded by the cost of transitioning to a single source, such as solar thermal, which can offer a complete solution by itself. In order to offer a conservative estimate, we consider the costs involved in transitioning to a solar thermal source of electricity production for the long-run and compare its costs with the most cost efficient fossil fuel used today, namely coal, which is used as a proxy for fossil fuels. In sum: we provide an estimate of the long run costs by computing the costs of shifting away from coal produced electricity and into solar produced electricity.

It is appropriate to reduce the computation to a standard measure of energy such as electricity, because this is used the world over and offers a universal and flexible measure of energy availability. In the case of fossil fuels we consider the costs of using coal to produce a kWh of electricity.

To estimate the future evolution of costs, from electricity that is produced from coal to solar – produced electricity, we utilize the learning curve approach for both technologies as explained above. It turns out that the learning curve for coal is already pretty flat, since most of the learning has already been achieved by the enormous built capacity in this industry.[28] Coal produces

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[27] The general methodology has been called “learning by doing” and it was introduced in economics by Kenneth Arrow in 1962. The data used in the article comes from the US Department of Energy, see Eisenberger et al, 2009

[28] US DOE 2008.

currently 27% of the world's electricity and global fossil fuels generates 3x10[14] kWh of electricity. For solar the case is quite different. Only 0.01% of the world's power is generated from all types of solar energy, and in particular the technology called Concentrated Solar Power Parabolic Trough, or CSP PT, being evaluated has an order of magnitude less installed capacity (H. Price et al, 2003)[29]. Correspondingly, the learning curve for CSP PT is quite steep. This means that as capacity expands, the costs for electricity are expected to drop rapidly and those for coal will remain at about the same level as today since they have already benefited from learning. Figure 6 below shows the evolution of CSP PT efficiency[30] in producing electricity when capacity expands, as predicted by the US Department of Energy.

Specifically, the DOE showed that, as installed capacity of CSP PT solar plants increases, the cost of solar[31] goes down by 15% per each doubling of capacity (DOE, 2008). This is illustrated in Figure 6, where we compare the learning curves of coal and solar thermal. In the case of coal, the costs are very low today (about 4.5 cents per kWh, but since all the learning has already been achieved in coal's technology the costs are expected to remain constant at about 4.5 cents the kWh. In the case of solar, the costs are more than twice as high today as coal, but in the long run they are expected to be $0.02 to $0.03, which is roughly half the cost of coal per kWh, (Eisenberger et al, 2009). For economic considerations all that is needed is for the alternative sources to be competitive with fossil fuel electricity production. As discussed above, in a competitive market economy one generally assumes that lower cost alternatives will prevail in the long run. Therefore we can assume that once the cost of solar energy equals or becomes lower than that of coal, namely lower than 4.5 cents the kWh, solar production of electricity or other alternative sources will be widely adopted, thus providing a market driven transition to renewable sources in our model. If one is focused solely on the long run, the cost of the transition can be measured by the total additional cost of using, in our example, solar to produce electricity *only during the period when these costs are higher than the cost of producing electricity using coal*. In other words: in the long run one measures the expected total costs of the transition away from fossils to renewable energy, as the difference between what solar costs and what coal costs, integrated over the relevant period. The relevant period is while solar energy's costs of electricity production exceed the costs of coal.

It is important to remember that the *relevant period* is defined not in time but rather in built capacity. The learning curves used in Figure 6 illustrate the evolution of costs (solar, coal) with capacity, and not with time. However both can be related, since there is a limit to the amount of capacity that can be built in each period of time.

One can visualize the problem geometrically, by measuring the cost of the long-run transition from fossil into renewable energy as the area of the shaded triangle in Figure 6 that is bounded below by the kWh price of coal today (4.5 cents) and bounded above by the decreasing cost of kWh that is expected from DOE learning curves, for electricity produced from solar as capacity increases. In taking into consideration the DOE learning curves, both for coal and solar as new

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[29] http://www.nrel.gov/csp/pdfs/35060.pdf

[30] Both for Solar Photovoltaic and for CSPPT namely 'Concentrated Solar Power Parabolic Through'

[31] Hereafter Concentrated Solar Power refers to CSPPT unless otherwise noted.

solar plants are built this area is only US $148 million. This is the expected long - run cost of transitioning from fossil fuels to solar. In many developing countries today alternative sources such as CSP are already competitive because of their lack of fossil fuels and the high costs of acquiring and transporting them. The long - run transition cost just provided is rather small, and therefore sets one's mind at rest about resolving the long-run problem.[32]

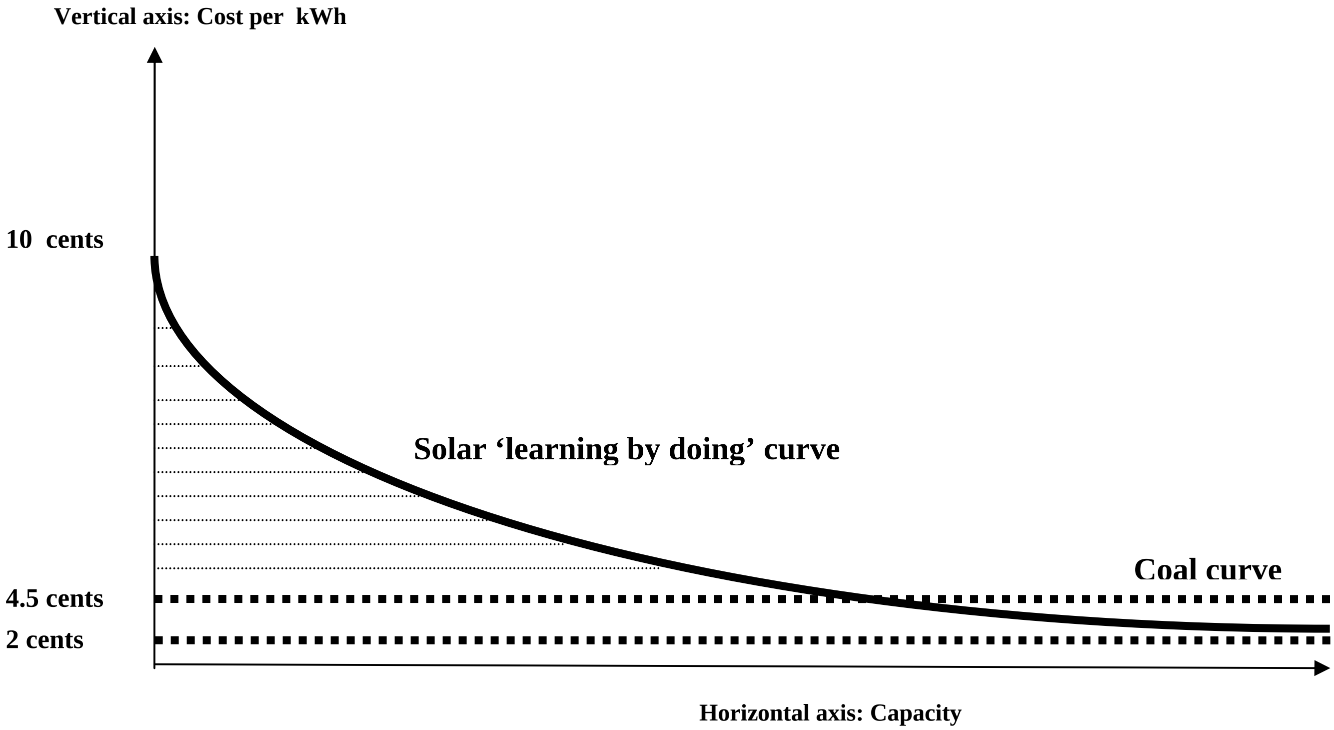

Figure 6
Expected long – run transition costs from coal- produced to solar - produced electricity are given by the shaded area above the 4.5 cents line and below the solar learning curve[33]

This raises an important question: If the long-run transition to alternative sources of energy can be achieved so economically, why not use the same method in the short run? The simple answer is that the solution just proposed does not work for the short run. Specifically, we made assumptions that do not hold in the short run. For example, in the above computation we eliminated the fixed costs involved in building new plants for alternative sources of energy, and we did so on the basis that fixed costs are mostly absorbed in the long run by the variable costs of selling electricity per kWh. This is standard practice, in fact 90% of the 4.5 cent per kWh reported

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[32] In fact, even the first solar plant could be commercial because of local conditions (e.g. nearby low cost fossil fuels) which makes 10 cents per kWh competitive with fossil fuels.

[33] Renewable resources other than solar thermal (or Concentrated Solar Power, denoted CSP) can also drive down the cost of producing electricity as capacity expands. The $148 million additional estimated here is in reality an upper limit, considering that thermal solar alone can achieve this cost efficiency. It is also worth observing that fossil fuels sources such as coal are likely to increase in cost in the near future because the most accessible and easier to process sources are a small proportion of total supplies, and it is estimated that only 17% of the available fossil fuels are high grade resources.

above for solar produced electricity represents amortization of fixed costs.[34] However if implemented in the short run one must consider the fixed costs and these can be enormous, as discussed elsewhere in this article, up to $400 trillion for the long-run solution, almost eight times the GDP of the planet.

There are other ways of illustrating the difference between the long-run and the short-run issues. The costs reported above involve replacing electric power generated by coal, by electricity power generated by solar thermal, and the comparison can be problematic as long-run solutions are not applicable for the short term. For example, in the short run electricity power cannot be used today in certain sectors that run on fossil fuels, such as transportation that represents about 28% of total energy use in the US and about 18% in the entire world. Transportation is one of the fastest growing uses of energy in the world today, and the electricity produced by solar thermal cannot replace fossil fuels in the short-run within the transportation sector. Therefore the methodology used above would only deal with about 70% of the carbon emitted today, although it is realistic to assume that in the long-run it could deal with them all.[35] For these reasons, and others, the long-run problem has a long-run solution that seems economical and reasonably easy to achieve, but a different solution is needed for the short run to avoid the risks of global warming. This is the topic of next section.

3. The economics of transition

The assumptions made so far are valid for the long run. For example, we assumed that the lowest cost technology will prevail in a competitive market, which is a long term assumption. We used learning curve as if learning by doing was diffused uniformly across the world, something that can only happen in the long term.

In the short-run the transition is likely to be more uneven and disorderly. There will be trial and error, and a fierce competition among various sources of energy, both fossil fuels and renewable sources, with many start - up efforts emerging, failing and disappearing along the way. No matter how reliable the DOE learning curves, it does not seem possible to compute the actual costs of averting risks as if the economy would automatically follow the most efficient path in the short run. Nor is it realistic to think that the world is uniform in terms of resources or organizational capability. So this technology, like others, will diffuse through the various nations of the world at different rates with some being called early adopters and others waiting until successful experience has occurred (Grubler, 1996).

Therefore, for the short term an estimate of the risk management costs will be achieved in a different way. The rationale behind our approach is that for the short term we can provide *a*

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[34] This figure applies to the case of solar thermal energy driving electricity output, Eisenberger et al, 2009. It does not apply to coal driven electricity, for which the variable costs are about 33% of the variable costs for the coal itself, or for petroleum produced electricity where there is an even higher % is for the raw material.

[35] The alternative energy sources can use the carbon dioxide that is extracted from the atmosphere and hydrogen created by the electrolysis of water to make a renewable fossil fuel in a Fischer-Propisch process, cf. Eisenberger et al 2009.

realistic lower bound for managing the risk of global warming by indicating a possible solution and ways to implement it. The co-production technology uses a specific process that is practical and well matched to the dual problem at hand, namely increasing energy supplies in the short run while decreasing carbon in the atmosphere and thus the risk of global warming immediately. In a competitive market and with sufficient information, the realized costs should not exceed by much a feasible lower bound.

To provide an estimate of the costs involved we use current knowledge about learning by doing, which as already mentioned predicts expected costs of power production at different capacity levels. In the next section we compare these short-run risk management costs with a standard insurance premium rates that are commercially competitive and acceptable all over the world for hedging property risks, catastrophic or not. Furthermore we will assume that a policy for stabilizing carbon emissions at current levels is in place (Stern, 2006, Pacala and Socolow, 2004). Currently we are emitting in net terms about 24 – 30 gigatons of carbon per year. As in Eisenberger et al (2009) it is assumed from now on we will have to capture and sequester this amount of emissions annually.

It is important to observe that the need to co-produce electricity and air capture and storage of carbon using this approach, is limited and has a natural termination when we reach carbon neutrality, namely when we no longer add net CO_2 to the atmosphere. The air extraction technology described above proceeds by increasing the built capacity of solar thermal plants. Once the capacity built has achieved an appropriate size, no more fossil fuels are needed for producing power. If we just meet our increasing needs for energy with alternatives and renewable sources, and phase out fossil fuel sources when they have depreciated their investments, we will reduce the need to extract CO_2 from the atmosphere by the end of the century (although we may still need climate change protection for other reasons). In other words, the solution turns itself naturally into a way to provide renewable energy globally, without using further troublesome carbon emissions from fossil fuels. The solution thus satisfies our requirement that short-run policies should facilitate rather than defeat long-run objectives.

4. Insurance premium for catastrophic risks of climate change

A widely distributed British report[36] has provided new estimates of the potential costs of global warming. Although its framework is quite different from the one adopted here, we could approximate the short-run risks of climate change by the value of the property loss that is at stake in a case of a catastrophic risk case, which has been computed to be approximately 20% of the world GDP now and for the foreseeable future. This number allows us to evaluate the extent to which the short- run solution proposed here fits standard models of risk management, such as those provided by property insurance in the case of catastrophic risks. In order to compare the costs with standard insurance approaches, we provide below percentages that represent the annual premium divided by the coverage amount, or insured value in a variety of real estate risks:

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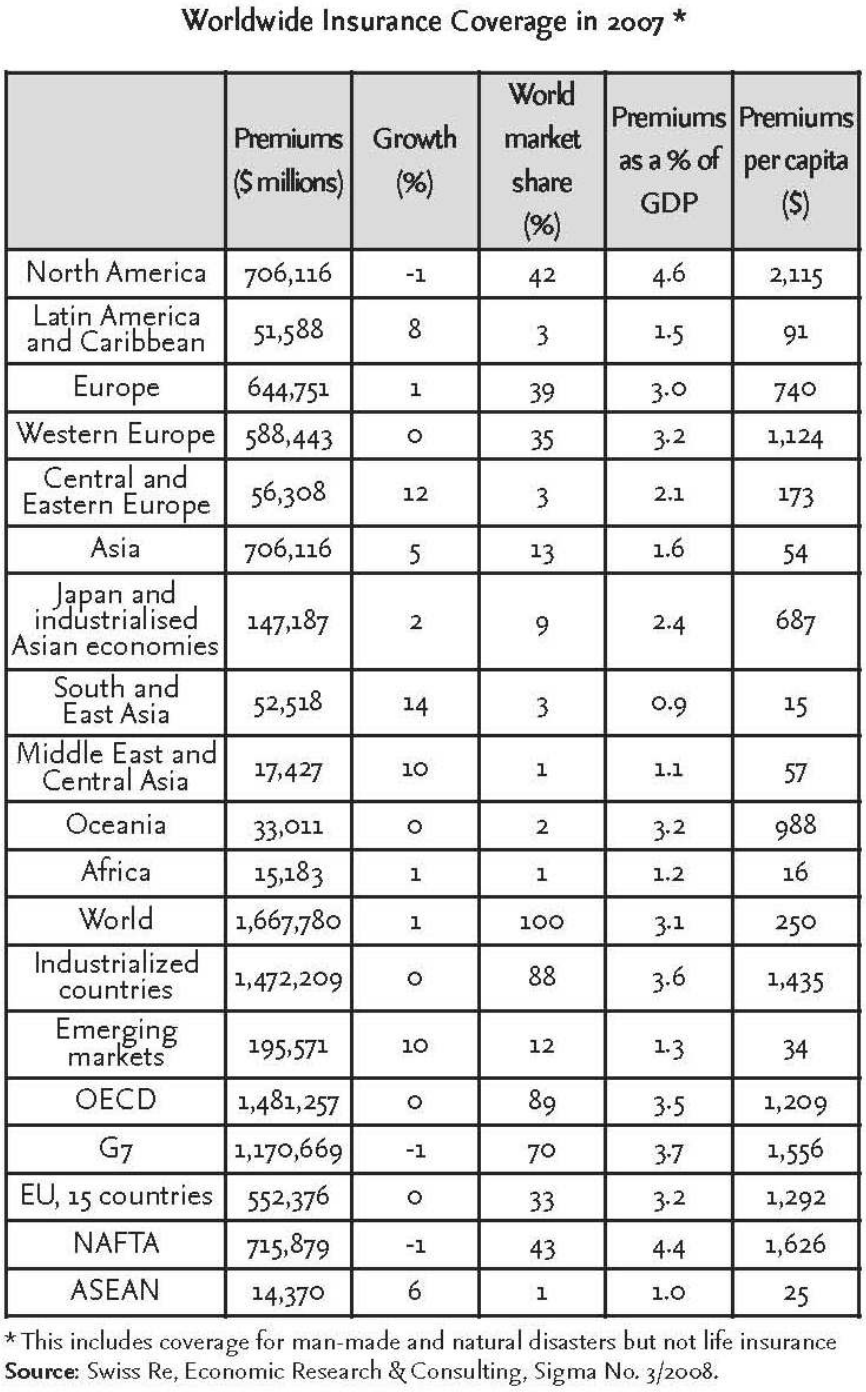
[36] Nicholas Stern The Economics of Climate Change Cambridge University Press, 2006, Chapter 6, p. 188-189.

Table 2
Property Insurance Premiums on Standard and Catastrophic Risks

Percentage Paid to Protect Covered Amount		Avg. Premium per $1000 Protected
Flood[1]	2.2% to 2.8%	$22 to $28
Earthquakes[2]	1.0% to 2.2%	$10 to $22
Basic Homeowner's[3]	0.2% to 0.7%	$2 to $7

Table 3



Worldwide Insurance Coverage in 2007 *

	Premiums ($ millions)	Growth (%)	World market share (%)	Premiums as a % of GDP	Premiums per capita ($)
North America	706,116	-1	42	4.6	2,115
Latin America and Caribbean	51,588	8	3	1.5	91
Europe	644,751	1	39	3.0	740
Western Europe	588,443	0	35	3.2	1,124
Central and Eastern Europe	56,308	12	3	2.1	173
Asia	706,116	5	13	1.6	54
Japan and industrialised Asian economies	147,187	2	9	2.4	687
South and East Asia	52,518	14	3	0.9	15
Middle East and Central Asia	17,427	10	1	1.1	57
Oceania	33,011	0	2	3.2	988
Africa	15,183	1	1	1.2	16
World	1,667,780	1	100	3.1	250
Industrialized countries	1,472,209	0	88	3.6	1,435
Emerging markets	195,571	10	12	1.3	34
OECD	1,481,257	0	89	3.5	1,209
G7	1,170,669	-1	70	3.7	1,556
EU, 15 countries	552,376	0	33	3.2	1,292
NAFTA	715,879	-1	43	4.4	1,626
ASEAN	14,370	6	1	1.0	25

* This includes coverage for man-made and natural disasters but not life insurance

Source: Swiss Re, Economic Research & Consulting, Sigma No. 3/2008.

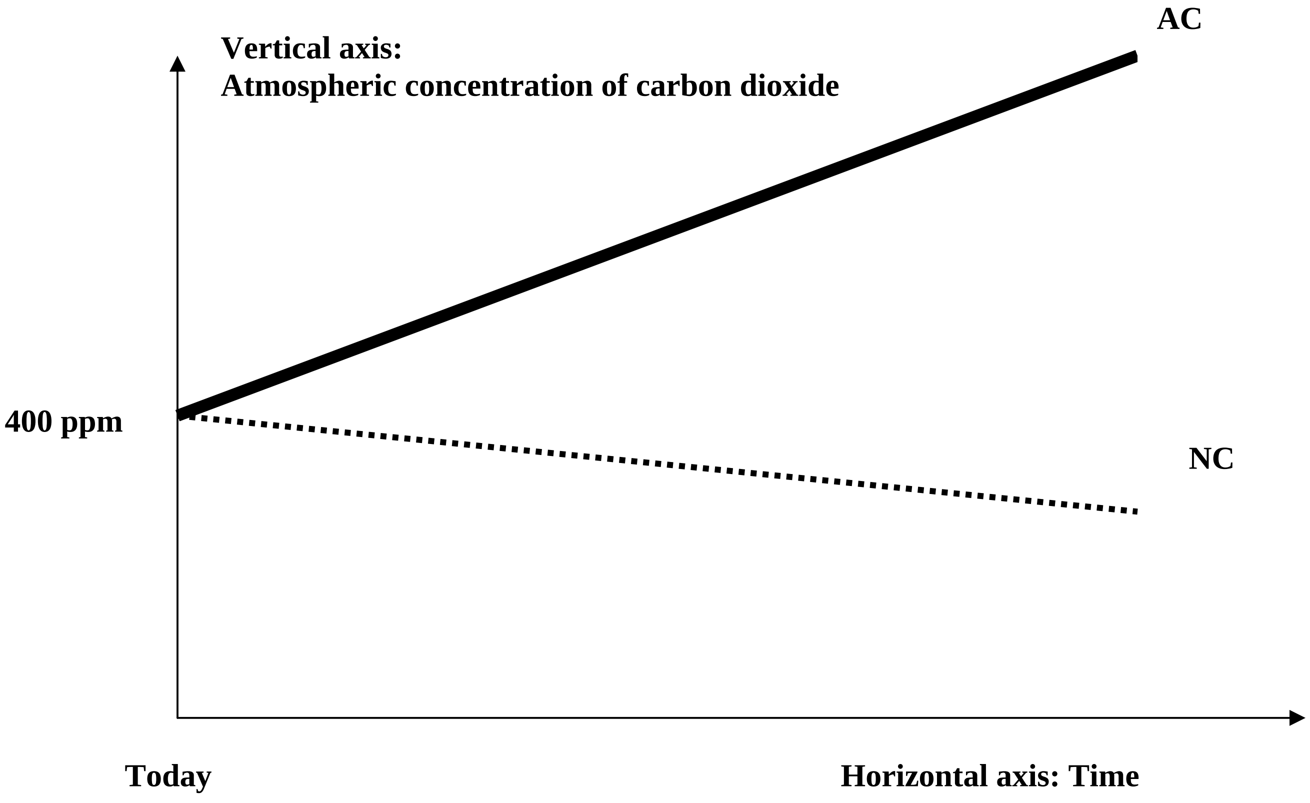
Sources:

1. FloodSmart.gov
2. California Department of Insurance
3. California Department of Insurance and National Association of Insurance Commissioners (the two sources differ by $.1) http://www. aic.org/Releases/2007_docs/NAIC_Releases_Homeowners_Ins_Report.htm, and http://www.naic.org/documents/research_stats_homeowners_sample.pdf
4. G. Chichilnisky and K. Sheeran Saving Kyoto New Holland, UK, October 2009.

In Table 1 we provided an estimate of the costs of using an air extraction approach to avert the risks of global warming. In terms of costs, the lowermost curve in Figure 5 showed the cost as percentage of world GDP, assuming a constant undiscounted extraction and storage cost of $25 per ton of CO2. The total implementation cost to 2100 is about $60 trillion, representing 0.18% of the world's GDP; adapting a 1.5% discount rate as in Nordhaus et al (2006) reduces this figure by half. The annual cost of the air extraction solution is therefore consistent with and in fact over than the market premium charged today for the risk management of a number of real assets within the current insurance markets which, as seen in Table 2, would be about 2.5% of $12 trillion, or about a $288 billion annual premium. It is worth mentioning that this short-run computation may not be valid in the long run, because in computing costs we assumed carbon emissions at current levels, approximately 24 – 30 gigatonnes of carbon annually, an assumption that is realistic in the short run but may not be realistic in the long run.

At the same time, it seems fair to observe that the air extraction approach provides more than insurance. It actually provides a solution of the global warming problem in the short run, which may be much more valuable than the insurance approach that merely compensates after the loss. This distinction is also important when considering the market price for *avoided carbon* that leaves current emissions and the continuous accumulation in the atmosphere unchanged – versus *negative carbon* that actually reduces the current level of emissions and potentially *reducing the total concentration of carbon* in the planet's atmosphere, therefore mitigating the risk of climate change. Figure 7 below illustrates two cases – avoided carbon and negative carbon – and only the second can avert climate change in the short run:

Figure 7
AC = Avoided carbon: reduces emissions but carbon concentration still increases
NC = Negative carbon: reduces concentration through air capture of CO2



5. The economics of transition: The Kyoto Protocol and its incentives

How does the transition occur in practical economic terms? A key economic incentive to transition away from fossil fuels and to curb carbon emissions is the creation of a so-called "price signal" for carbon. These are costs on emitting carbon that are imposed by a recent international agreement, the United Nations Kyoto Protocol, which resulted in the creation of the carbon market.[37] Simply put, a negative incentive to emit is created by charging an emitter a price to

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[37] See World Bank May 2007 Reports: "State and Trends in the Carbon Market, 2007, 2008".

emit each ton of carbon, which is determined by supply and demand in the newly created carbon market. The carbon market is the subject of this section.

The carbon market was born from the commitments of governments to reduce total carbon emissions. The commitments emerged from the 1992 UN Framework Convention on Climate Change and its 1997 Kyoto Protocol, and from Europe's carbon constraints for electricity generators and industry under the European Union Emissions trading Scheme (EU ETS) and the ratification of the Protocol into international law in 2005.

It is important to acknowledge that before any market can exist and operate, there has to be a firm agreement among the parties to reduce total emissions. *This means a strict numerical limit on overall emissions must be agreed by the traders.* Otherwise, there is no carbon market.[38] This feature makes the market approach more attractive than taxes when overall limits on emissions are urgently needed, as they are now. Taxes do not ensure caps on emissions of any sort, while markets do.[39] One of the authors of the article proposed the market approach for the Kyoto Protocol and wrote it in the Protocol itself, a proposal that was adopted and signed by 196 nations.[40] The Kyoto Protocol carbon market has unique characteristics, which distinguishes it from other markets. It provides preferential treatment for poor nations, in a manner that increases the market efficiency, although it is expected that as they reach the same level of development as others, they will face similar caps. No other markets have these characteristics.

What do carbon traders trade? The traders either buy rights to emit above their caps, or sell rights to emit by emitting below their cap. The market ensures a total global ceiling on emissions that trade does not change. In other words: the market approach secures a total ceiling for the global emissions of those who participate. At present neither the US (who emits about 31% of total global carbon emissions) nor the developing nations (who emit a similar amount in total) have committed to such "caps," even though they are both signatories of the 1997 Protocol. Accordingly, the Kyoto Protocol actually comprises less than 40% of global carbon emissions.

In any case the carbon market has been quite active and has already shown great promise in reducing carbon emissions as discussed below. The rest of this section will provide information to evaluate the carbon market's performance to date. A similar market was established in the US for SO_2 and it is widely known that it has been successful in controlling SO_2 emissions within the US, although it does not have the same characteristics of the carbon market in that it treats all traders equally. All signals indicate that soon the US may adopt a cap and trade approach for carbon emissions within the US territory as several proposals have been advanced to date.[41] In June 2009 the US House of representatives passed an energy bill (also called the Waxman – Markey Bill) that authorizes the creation of a US carbon market. This bill was passed even though the US currently does not abide by the Kyoto Protocol rules that it signed in 1997. During

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[38] This was provided for the first time by the United Nations Kyoto Protocol in 1997.

[39] See Chichilnisky and Heal, OECD, Economic Division Report No 153, "Markets for Tradable Emission Rights: Principles and Practice" OECD Paris, 1996.

[40] For a history of the creation of the Kyoto Protocol's carbon market see G. Chichilnisky and K. Sheeran, Saving Kyoto, op.cit. 2009.

[41] See The World Bank "State and Trends of the Carbon Market 2007, 2008" op.cit.

the UN COP13 in Bali, the US agreed to reach an agreement on its participation in the Kyoto Protocol during the Copenhagen UN COP15 of December 2009. The Protocol itself is in a period of flux, since its governmental obligations to restrict emissions expire in 2012, and new follow - up rules are being negotiated at present.[42] The US agreed to participate in the Kyoto Process at the UN COP13 in Bali, with the terms to be negotiated by the COP 15 Copenhagen of December 2009. The carbon market and its CDM are a key part of the negotiation, and their future is discussed below.

It is important to understand how the carbon market operates. The following provides basic statistics and summarizes how the carbon market operates, who are the buyers and sellers, what they trade, and what has been achieved until now in terms of reductions in emissions and investment in clean technologies in developing nations. In 2006 the carbon market grew in value to an estimated US $30 billion, three times greater than in the previous year, and it reached a $50 billion level in 2007.[43] The market was dominated by the sale and resale of European Union Allowances (EUAs) at a value of nearly $25 billion under the EU ETS (European Union Emission Trading Scheme). Project based activities primarily through the CDM and Joint Implementation (JI) projects of the Kyoto Protocol also grew sharply to a value of about $15 billion in transactions during 2006. The voluntary market for reductions by corporations and individuals is much smaller, but it also grew by an estimated US$ 100 million in 2006. Both the Chicago Climate Exchange (CCX) and the New South Wales Market (NSW) saw record volumes and values traded in 2006.

The main buyers in the carbon market are:

1. European private buyers interested in EU ETS.
2. Government buyers interested in Kyoto compliance
3. Japanese companies with voluntary commitments under the Keidanren Voluntary Action Plan
4. US multinationals operating in Japan and Europe and preparing in advance for the regional Greenhouse Gas Initiative (RGGI) in the Northeast states of the US or the California Assembly Bill 32 establishing a state wide cap on emissions
5. Power retailers and large consumers regulated by the New South Wales (NSW) market in Australia
6. North American companies with voluntary but legally binding compliance objectives in the Chicago Climate Exchange (CCX)

A frequently asked question is ‘who dominates the carbon markets?’. In 2006 European buyers dominated the primary CDM and JI markets with 86% of market share (compared with. 50% in 2005) and Japanese purchases were only 7% of the primary market. The UK led the market with about 50% of project - based volumes, followed by Italy with 10%. Private sector buyers,

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[42] See Chichilnisky and Sheeran (2009) Saving Kyoto, op.cit.

[43] Further statistics on the carbon market can be found in “State and Trends of the Carbon Market 2007, 2008”, The World Bank, Washington D.C., May 2007, op. cit.

predominantly banks and carbon funds, continued to buy large numbers of CDM assets, while public sector buyers continued to dominate JI purchases.

To evaluate the performance of the carbon market we now discuss the impact of its creation. The EU ETS (Phase I) demonstrated that a *carbon price signal* in Europe succeeded in stimulating emissions abatements both within Europe and especially in developing countries. Following the release of verified 2005 emissions data, it became clear that the 2005-6 emissions cap was not set at an appropriate level relative to actual emissions in that period, so that prices dropped rapidly during 2006.[44] But in the second part of 2006 the market shifted its attention to Phase II based on expectations that those caps would be much more stringent, thus assuring higher and more stable prices. In the following section we explain this phenomenon from a theoretical viewpoint.

From the physical view point, it is important to keep track of the carbon reductions that the carbon market achieved. In sum, since 2002 a cumulative 920 $MtCO_2$ - equivalent to 20% of EU emissions in 2004 - have been transacted through primary CDM transactions for a value of US$8 billion in 2006, $15 billion in 2007,[45] for a total of $23 billion. Starting from a unique theoretical construct in the 1997 Kyoto Protocol, a functioning market was achieved in 2006, a carbon market that trades over $50 billion annually and has succeeded to reduce carbon emission and transfer about $23 billion to developing nations for investment in CDM emission reduction projects.

6. How the market sets carbon prices, and what controls stability

Despite the success of the market strategy, the stability of the carbon market remains a source of concern for private industry, which seeks firm targets to plan for costs and opportunities in the years ahead. Non-experts are understandably confused about how prices are set in the carbon market, and often believe that they are set by free floating supply and demand forces of the traders. In reality, prices do fluctuate in the short term with supply and demand forces, as shown in the previous section for 2006 and 2007, but it is possible to identify market "fundamentals" that determine carbon prices – and these have nothing to do with short term supply and demand forces on the part of the traders. As discussed in the previous section, the drop in prices during 2006 was due to low emission caps, as was recognized in a statement by the European Union Commission. This section will explain how carbon markets function to determine carbon prices, and how these prices fluctuate over time. We show that in a fossil fuel-dominated economy, there are two fundamentals that determine prices in the carbon market: (1) emission caps, which are a measure of scarcity and the extent of demand for permits' to emit, and (2) the efficiency of technology in transforming fossil fuels into goods and services, which is equivalent to the cost of abatement. The section ends with an explanation of how the carbon market will evolve if the air

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[44] In 2006 the EU Commission stated that Phase I was a 'learning phase' and promised to asses the second period (Phase II) plans in a manner that "ensures the correct and consistent application of the criteria and sufficient scarcity of allowances of EU ETS".

[45] World Bank Reports "State and trends of the Carbon Market 2007, 2008, op.cit.

capture technology is adopted, and a general vision into the market transformation that takes place starting from the fossil fuel economy and ending in the solar age.

To explain how the carbon market fundamentals work, we provide a brief overview of the theory underlying the global carbon market, illustrating this with a number of diagrams (Figures below). Some of these results are already in print since, as already mentioned, the body of theory underlying the carbon market was developed by one of the authors who proposed the creation of the Kyoto Protocol 'cap and trade' system to the international community in 1995 and 1996, and in the actual writing of the Protocol in Kyoto in December 1997 (Chichilnisky 1996, 1997, Chichilnisky and Kristen 2009, Chichilnisky and Heal, 1995 and 2000), and show that although carbon markets operate in some ways that are similar to standard markets, in other ways they are quite distinct and behave differently than other markets.

The background is as follows. In today's economy, fossil fuel energy is used to produce most goods and services according to the representation in Figure 7 above. We know that about 90% of all the energy used in the world today comes from fossil sources, so to simplify the exposition assume that all energy comes from fossils. Due to the physical characteristics of fossil fuels, using more fossil fuels emits more carbon dioxide. We can write these relations simply as follows:

$$\mathbf{X = F\ (E)}$$

denotes the transformation of energy **E** into goods, **X**, and is illustrated in Figure 8 below, and

$$\mathbf{X = \psi(A), \qquad d\psi\ /\ dA < 0}$$

denotes the transformation between goods and carbon abatement A, whose slope is negative, as illustrated in Figure 9 below. By measuring energy and abatement appropriately, we can write

$$\mathbf{E = -\ A}$$

meaning that the more energy is used, the more carbon one emits and the less carbon abatement A is obtained, a fact that is specific of the fossil fuel economy.

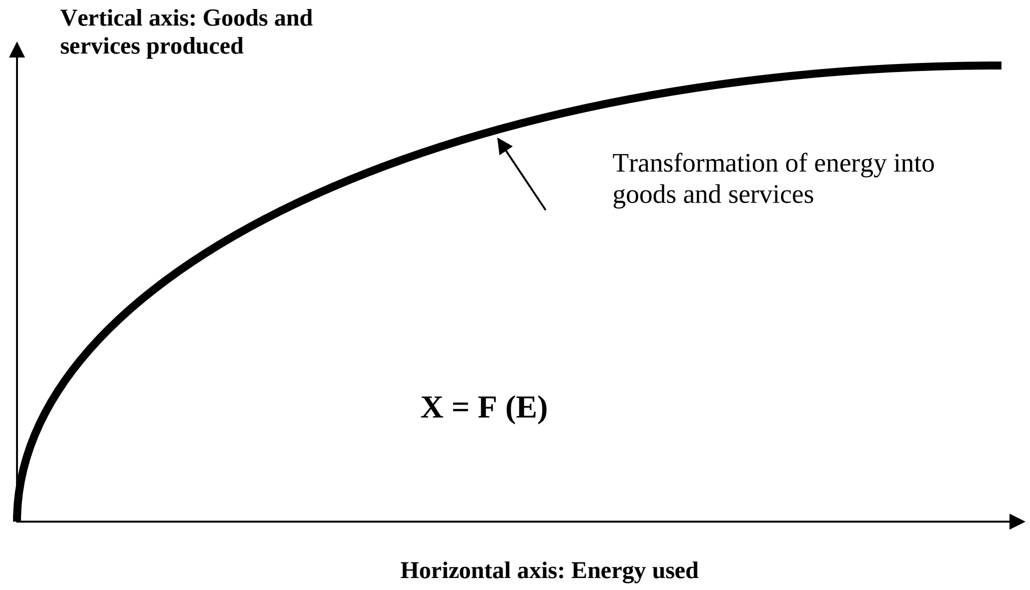


Figure 8
The transformation of energy into goods and services

It is important to realize that the quality of the atmosphere – measured for example by the concentration of carbon dioxide in the atmosphere, in parts per million - can also be considered a ‘good’, or a ‘bad’ depending how it is measured. Indeed, lower concentrations of CO_2 are associated with a more stable climate regime, while higher concentrations of CO_2 increase average temperatures that cause turbulent weather, sea level rise and the risks of catastrophic climate change. The good in question can also be described as the abatement of carbon dioxide, namely a decrease in carbon emissions measured from today’s baseline of about 400 ppm. The abatement of carbon can be considered a good because it can improve our welfare.

Abatement is actually a ‘public good’ due to the physical characteristics of carbon dioxide, which causes it to diffuse uniformly and stably throughout the planet’s atmosphere. This is called a ‘global public good’ because everyone in the planet is faced with the same concentration of CO_2 – there is no choice. Private goods are those where we have a choice about consumption that is independently from what others choose – for example we can choose to consume a certain amount of bananas, bread and cars independently from each other. That the quality of the atmosphere is a public good is neither an economic nor a political statement – it is a physical reality. I can theoretically consume one banana while you choose to consume two or none. But it is physically impossible for me to face 430 ppm of carbon in the atmosphere, while you face 280 ppm. The entire atmosphere has a single carbon concentration, which is the same across all nations. This turns out to be an important feature for the global climate negotiations.

The next step is in Figure 9 below, which illustrates how, in the fossil fuel economy, the more energy we use the less carbon abatement we produce. This translates into a cruel tradeoff that identifies in a nutshell our environmental dilemma: the choice between more goods and a better climate. This is why in the fossil fuel economy, industrialization and consumerism are viewed as the culprits for climate change. Indeed, in the fossil economy the more goods we produce, the lower is our atmospheric quality.

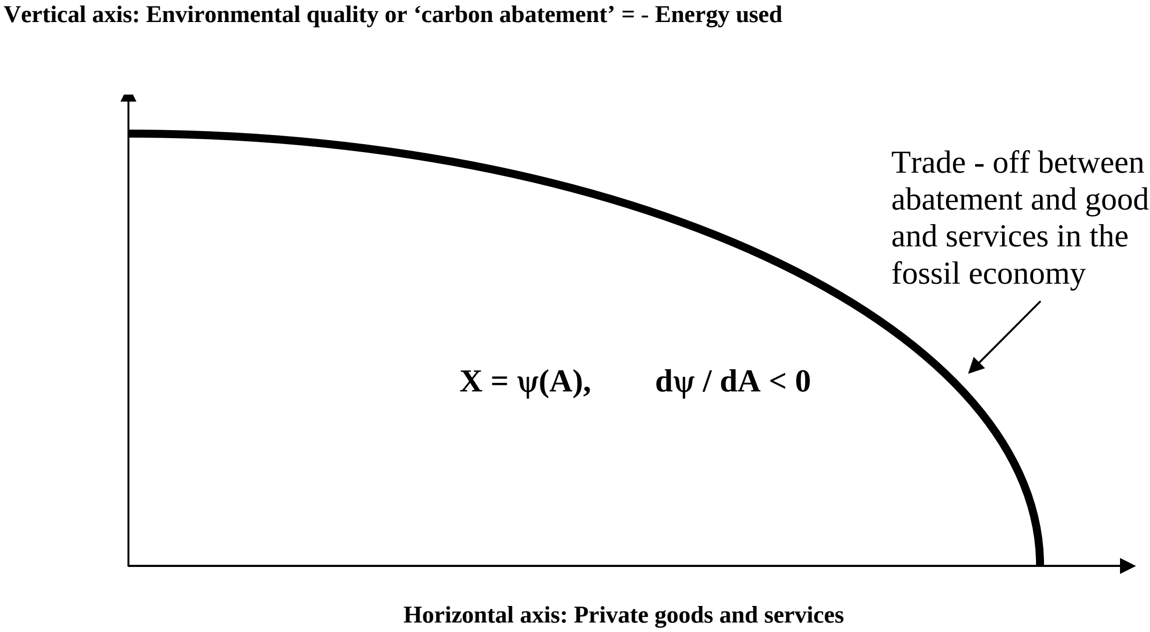


Figure 9
The more fossil energy we use, the more carbon we emit, and the less we abate

One can illustrate geometrically how the carbon market works. Figure 10 below illustrates a world economy with two nations. Each of them is represented by a frame - the left frame corresponds to nation 1 and the right frame to nation 2. The horizontal axis represents consumption levels of goods and services, and the vertical axis represents levels of abatement, the public good. The transformation frontier that is illustrated for each nation in Figure 10 is the same trade-off that is depicted in Figure 9 above.

Observe that each nation may use a different production technology, which is represented in Figure 9 above by a convex transformation curve. Therefore, each nation in Figure 10 may have a different transformation or trade-off curve, because each may have a different production technology. However since both nations use fossil fuels, as shown in Figure 9 above, the more fossil fuel energy the nation uses, the more carbon it emits and the less abatement it produces. For this reason in each of the frames in Figure 10, the convex curve slopes downward, illustrating a negative connection between goods produced and abatement produced that is typical of the fossil fuel economy. In sum: The more goods are produced, the more energy is used and the more carbon is emitted in the fossil economy.

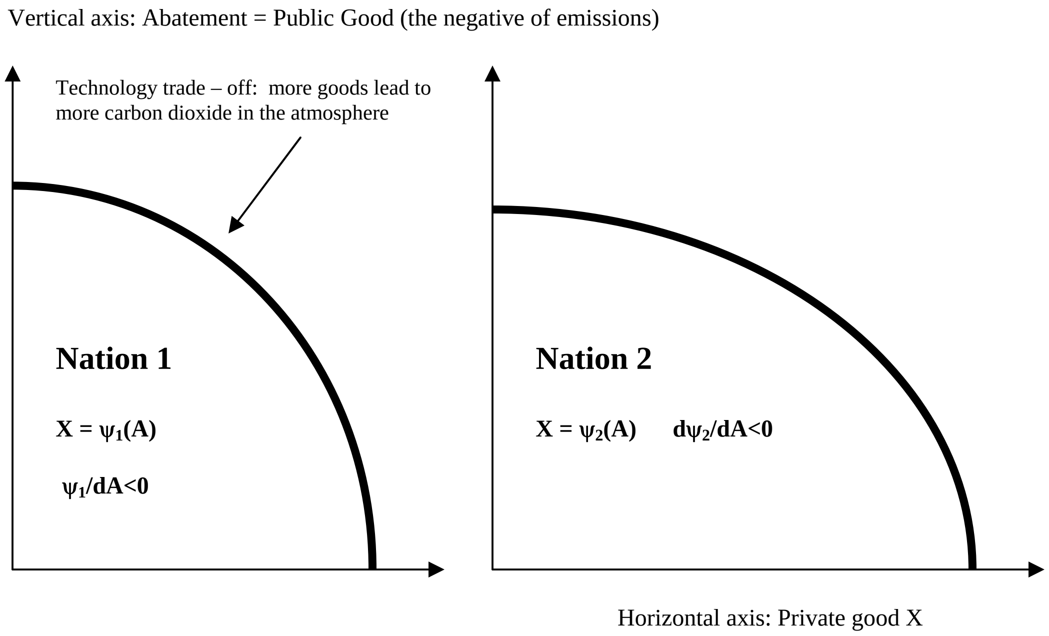


Figure 10

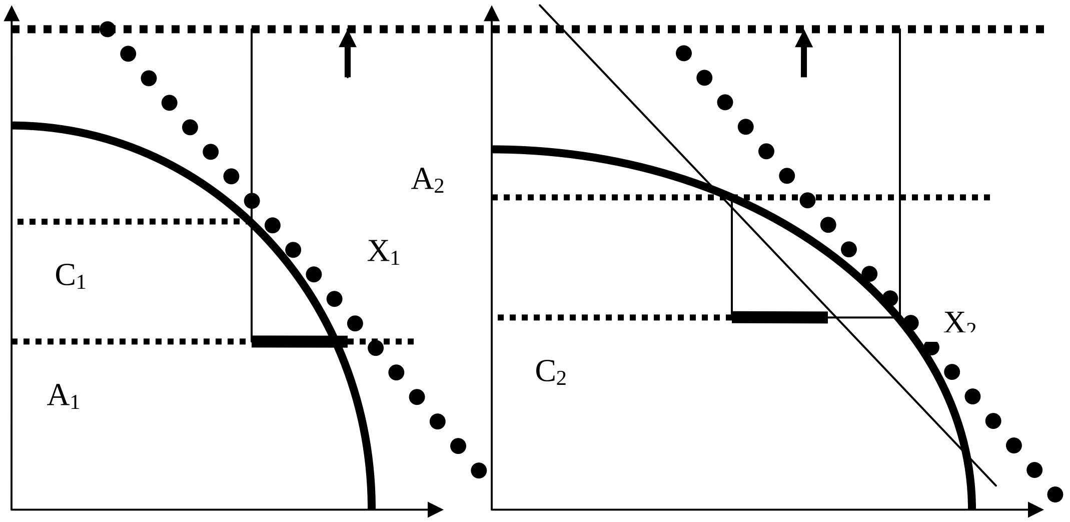
Two nations in the fossil fuel economy. Each faces a technological trade-off: (i) producing more goods and using more energy, or (ii) emitting less carbon/ abating less

We now introduce the carbon market, which is illustrated in Figure 10 below. For this we assume that each of the two nations in Figure 9 has become a signatory of the Kyoto Protocol or has otherwise assumed an abatement obligation – which we called above a commitment or a cap – to limit or reduce its carbon emissions. This is indicated by a horizontal dotted line in Figure 10 that is different in each nation, since each nation may have a different cap. One can interpret the height of this vertical line as the quantity of abatement that the nation has committed to do, and therefore the height is called its commitment or cap. The levels A and B in Figure 11 below denote the caps in nations 1 and 2 respectively.

The total amount of abatement in the world is of course the sum of what is abated by both nations. The total carbon abated is the same for both nations because of the physical properties of CO_2. Therefore there is common horizontal dotted line in Figure 11 that is valid for both nations, denoting the total decrease in emissions in the world economy, or “world abatement.”

Using Figure 11, we can now illustrate the working of a cap and trade system and how prices are set by the market fundamentals. The cap and trade system represented here could be either a trading system for the world economy, or just for the US, and in the latter case the traders may be states, cities, or utilities depending on how the system is structured. However, in the former case, the total amount abated will be determined not just by the US caps, but also by the emission caps in the rest of the world. This is because, as already mentioned, the overall level of carbon dioxide in the planet’s atmosphere is the same for all people in the planet, which is equal to the sum of the emissions originating from every nation in the world. This property is what ties together the welfare of every nation in the global warming dilemma, and what makes possible that developing nations and industrial nations share the same goal in limiting emissions: carbon emissions in India cause the rise in the level of the sea in the US and vice-versa.

Vertical axis: Abatement = Public Good – the negative of emissions



Horizontal axis: Private goods

Figure 11

The *carbon price* is represented by a sloped line with black spheres. It is the same for both nations, due to competitive markets. The slope of this line indicates the exchange rate between carbon and goods. This price depends solely on technology and on the chosen caps The solid horizontal segment in nation 2 represents the value that nation 2 pays for importing permits to emit from nation 1, in terms of the goods it exports to nation 2 in exchange for those permits.

The equations that describe the carbon market equilibrium are as follows:
Each nation i = 1,2 optimizes welfare in terms of its consumption of good X and environmental quality A, within their technology possibilities and subject to a constraint in its national income Y:

$$\mathbf{Max_{A,X}\ W_i\ (X_i,A)}$$
$$\textbf{subject to}\ \ \mathbf{X_i = \psi(A) + \pi(A - A_i)}$$

where π is the relative price of carbon permits with respect to goods X, A_i is the given cap on emissions or rights to emit of nation i, and the price of goods X is assumed to be \$1. This equation means that each nation will consume a certain amount of goods X and environmental quality A that maximize its welfare, given that it produces X using A, and that it trades X and its rights to emit with the other nation. Market equilibrium means a price for permits, production and consumption levels for which supply equal demand so that both markets clear, for goods and for permits, and each nation maximizes its welfare within its income.

Market clearing means that total amount abated equals the sum of what is abated by both nations, and that the amount of goods consumed equals what is produced:

$$\mathbf{C_1 + C_2 = A_1 + A_2}$$

and

$$\mathbf{X_1 + X_2 = \psi_1(C_1) + \psi_2(C_2)}$$

In Figure 11 above the small upward arrows indicate the market solution once trading takes place. Each nation produces goods and abatement so as to maximize its welfare within their income, where national income is measured taking into account the prices of goods and services and of carbon permits. The price in Figure 11 is given by the slope of the line with black spheres. Market equilibrium occurs when *supply equals demand*. Here supply includes not just goods and services but also permits to emit, which are traded across nations. Optimality conditions require that each nation produces at the tangency point between the price line and the transformation frontier, so that nation 1 produces at X_1 and nation 2 produces at X_2 – where the points X_1 and X_2 are as indicated in Figure 11. Nation 1 in Figure 11 abates *more* at its production level X_1 than what is required (the requirement is point A_1, while nation 1 produces at X_1, and the height of point X_1 that indicates its abatement level, namely C_1, is higher than A_1). Nation 2, instead, abates *less* than what it is required to abate (the requirement is at point A_2, which is higher than C_2, which is the height of point X_2). Therefore one nation will buy and the other will sell permits to emit. In fact nation 1 will be a net seller of carbon permits, while nation 2 will be a net buyer of permits, as shown in Figure 11. The two nations produce goods, and there is international trade of carbon permits among them as well as of goods. Nation 1 ends up using the extra income from the export of permits to import more goods, and its final consumption in market equilibrium is at the point indicated with an arrow. This nation exports permits, and imports goods with the income obtained, so it ends up consuming more goods than what it produces. The opposite happens with nation 2, which must buy permits from nation 1, and has to export goods to nation 1 in order to pay for its permits. Nation 2 ends up consuming fewer goods than it produces at market equilibrium, at the point indicated with an arrow. Supply for permits must equal demand for permits, and this occurs when the amount of permits that nation 1 sells is the same as the amount of permits that nation 2 wants to buy. The carbon market price adjusts until supply equals demand both in the goods market and the market for permits. In a competitive market, however, this price depends on two important parameters that we call the market fundamentals: (1) the technological transformation between more goods and more abatement, and (2) the level of abatement or caps that are externally provided by governments. The lower the caps, the higher is the obligation to abate and therefore the higher is the price of carbon. This is how the market operates. Observe that this is exactly as was indicated by the EU Commission in 2006, when they discovered that carbon prices were dropping because the caps on carbon emissions were set too low and promised to adjust these caps correspondingly (see previous section). By setting the caps, the governments determine the demand of permits and influence the price of carbon up and down.

Additionally it is important to appreciate that the technology, or *transformation frontier*, plays a key role. A fundamental result in the theory of competitive markets ensures that the price that equates supply and demand for goods should be equal to the rate of technological transformation between those goods – namely the slope of the transformation curve in Figure 11. This is a standard result and there is no need to discuss it further. However, it is worth pointing out that these fundamental results hold only in well-behaved competitive markets. This means that all traders share the same information, and no trader dominates the market as in monopolistic situations. Under these conditions, the technology that transforms energy into goods and abatement – depicted in Figures 9, 10, and 11 - play a key role in determining the price of carbon, as do the overall market caps that are determined by governments.

The technology as we saw is crucial in determining carbon prices, therefore a change in technology - as proposed here - is bound to have major effects on the price of carbon. This will be examined in the next, and last, section of this article.

7. Economic transition: From the fossil economy to a solar economy

It is possible to illustrate geometrically how a new technology impacts the transformation frontier between goods and abatement, and the changes that are introduced in the carbon market when the air capture technology is adopted.

The introduction of the air capture of the type described here leads to Figure 12 below, which replaces the previous Figure 10 that was valid for a fossil fuel economy. In Figure 12 we analyze the impact that each newly installed air capture plant has on the ‘transformation frontier’ between energy and abatement. Each installation of the air capture leads to a new curve, as illustrated in Figure 12. Since the air capture technology discussed here is able to produce power while at the same time *decreasing* carbon dioxide in the atmosphere, the shifted curve shows *increasingly larger levels of abatement* corresponding to the same level of production of goods. Moreover, since each plant increases the electricity power available, it shifts to the right the feasible production of goods X as well.

It is possible to illustrate and compare the effect of building one standard carbon plant with one air capture plus power plant. Each carbon plant increases power and therefore output, but it decreases abatement, see Figure 13. If the new coal plant has “clean coal” capabilities, namely it captures and stores the carbon it emits, then the situation is as presented in Figure 14, namely after the new plant is built the abatement level remains *the same,* but the total output decreases somewhat from what would be otherwise possible because of the extra cost of the carbon dioxide captured and stored (CCS or Carbon Capture and Storage). In sum: Clean carbon plants are an improvement over standard coal plants because they allow more power and output without increasing carbon emissions. However, both are inferior to the air capture solution because the latter can simultaneously increase output and reduce carbon concentration from the atmosphere, from other sources and over and above what is emitted from the new plant itself.

It remains to comment on what effect the air capture strategy could have on carbon markets. Figure 15 below illustrates the situation. If the caps on emissions are lowered as appropriate, and as the EU indicates they will continue to do, then the carbon price can remain constant for part of the process. However, as more of the infrastructure is eventually based on renewable energy fewer caps are needed on emissions and therefore the carbon price will decrease and ultimately in the renewable economy the carbon price is of course zero.

In Figure 15 we see that the transformation process continues until all fossil fuel installations have been replaced by alternative energy sources that are carbon neutral. At this point there is no longer a trade-off between more goods and better environment. The total amount of goods will be determined as in Figure 9, by the amount of energy available. In the solar economy this is simply a matter of capital since the raw material is free. There is no longer a trade-off with abatement, and the climate change threat is removed. This is the solar or alternative fuel economy at work, as illustrated in Figure 15.

A last observation that emerges from these diagrams is that the limiting element in production and consumption in the solar economy is capital, for example the ability to build solar plants, which are quite expensive as we know from Table 1. The sun energy is abundant and renewable, it has been said that it provides the equivalent of one foot of petroleum bathing the planet every single day. Although it is not infinite, it is so abundant and its reach is so uniformly distributed on the earth’s surface that solar energy could provide a rapid process of economic expansion without damaging the planet’s atmosphere. Other environmental limits exist, of course. But climate change could be kept in control with the air capture, in the short and long run.

Figure 12
Each new air capture plant changes the transformation curve between goods and abatement providing more power and increasing carbon abatement

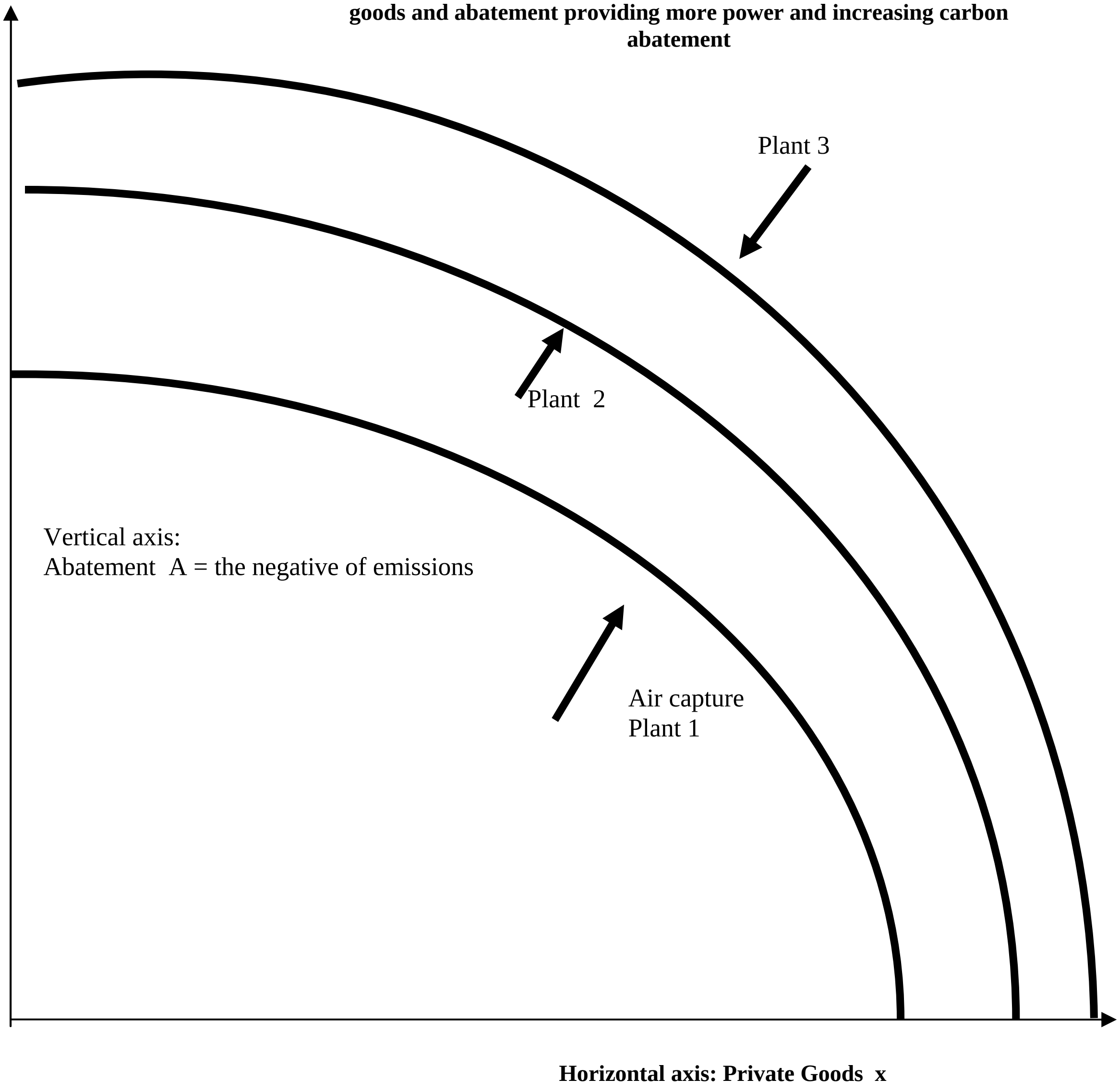


Figure 13
A new (standard) coal plant is built
It increases power and goods produced, but reduces abatement

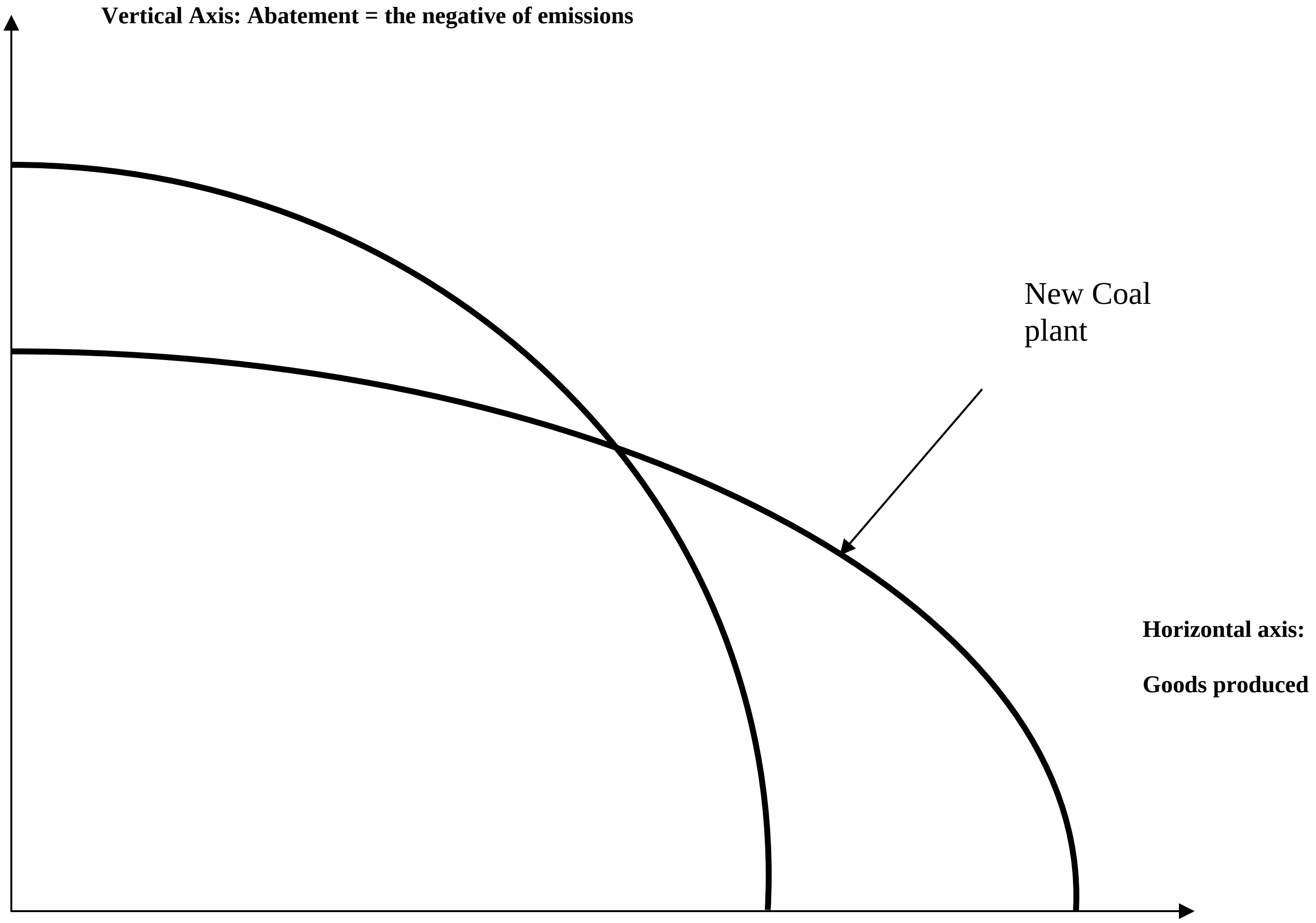


Figure 14
A new "clean coal" plant
Increases power - somewhat less - but maintains abatement

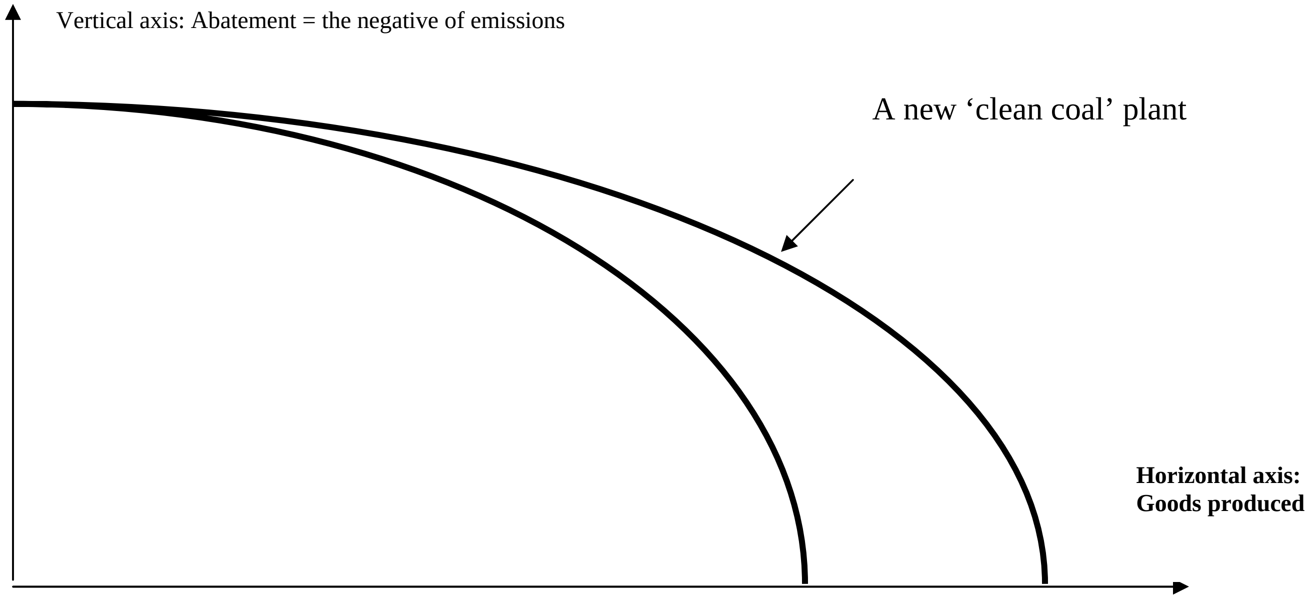
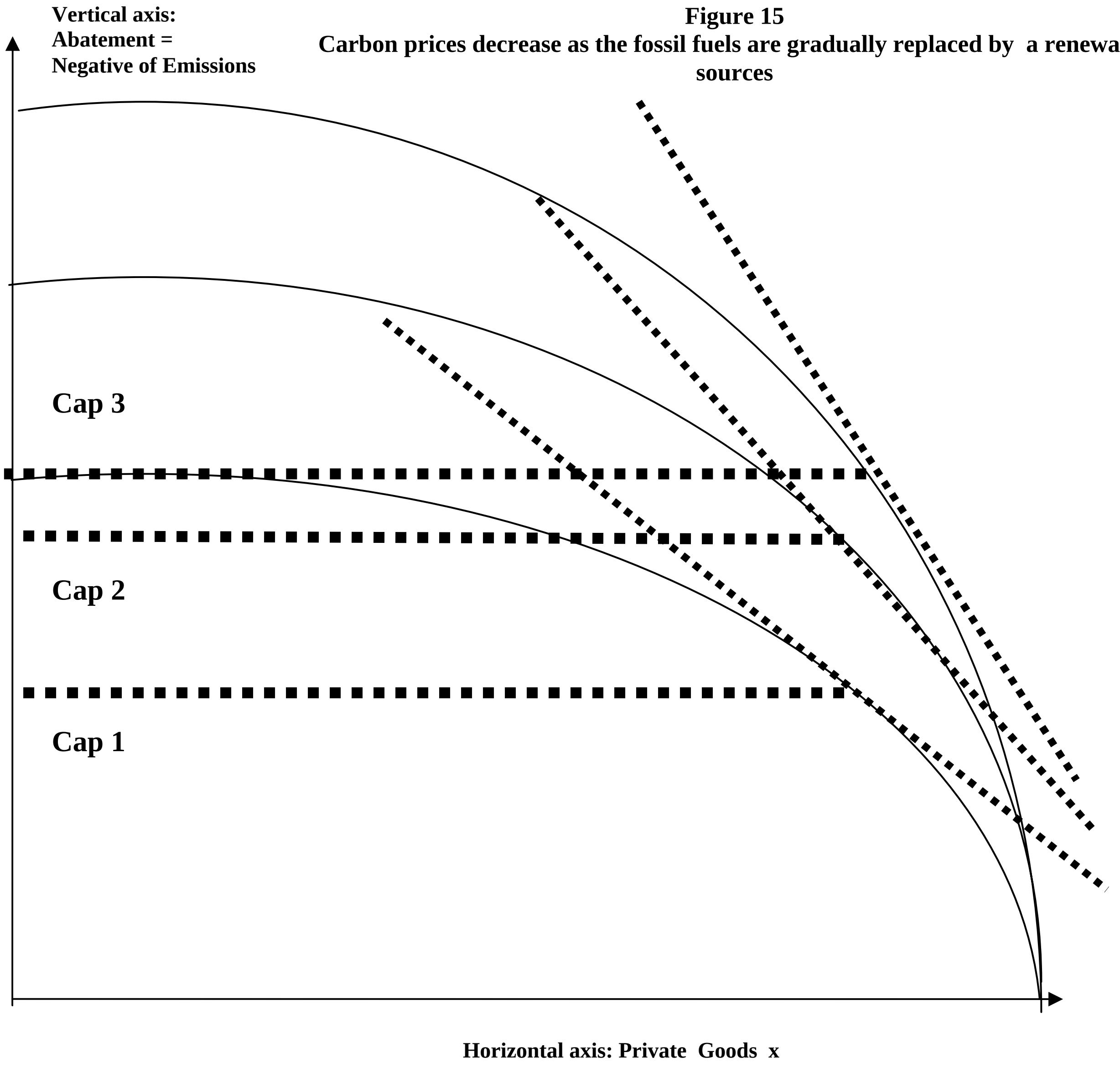


Figure 15
Carbon prices decrease as the fossil fuels are gradually replaced by a renewable sources



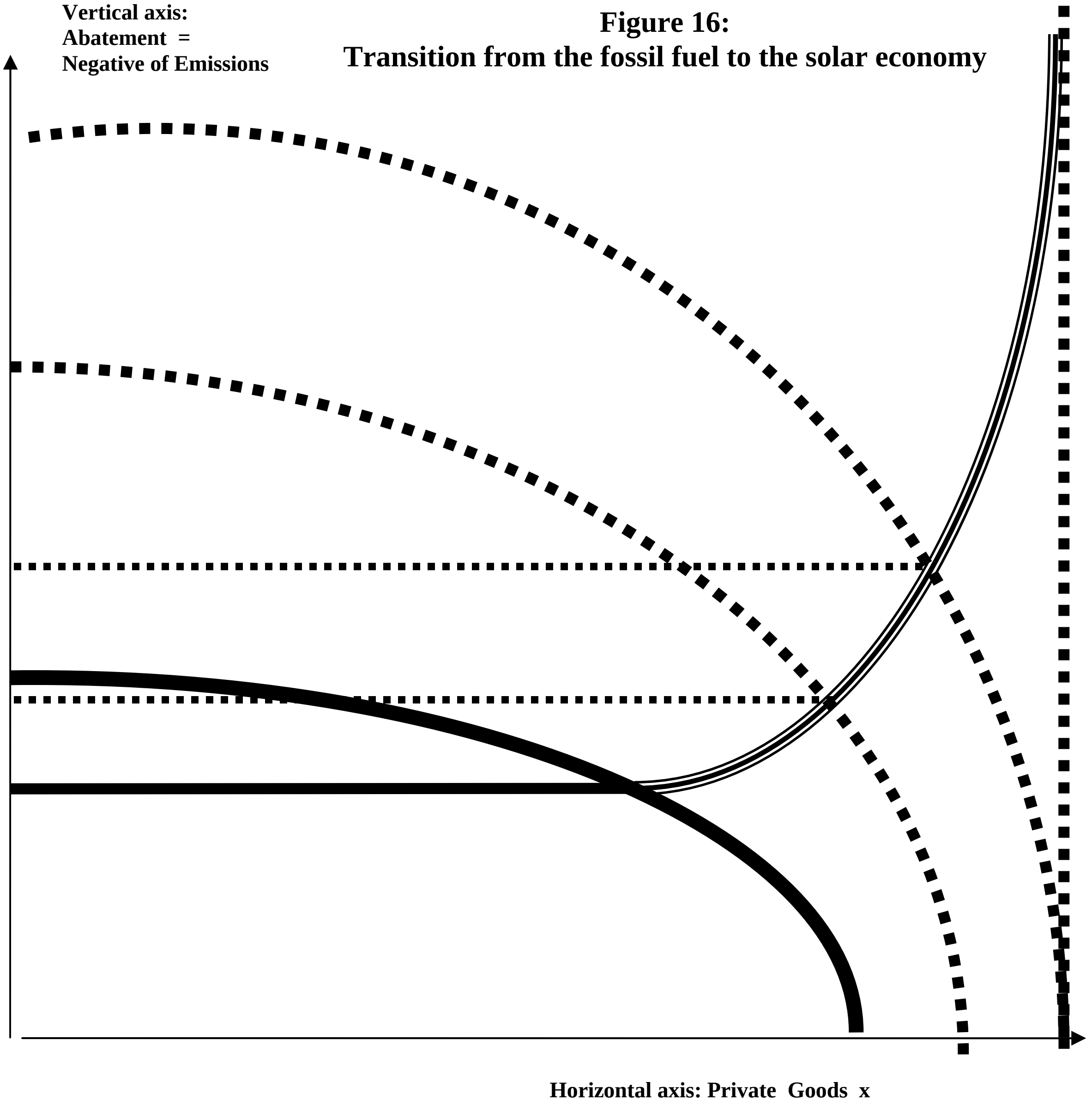


Figure 16:
Transition from the fossil fuel to the solar economy

Figure 16 shows how the initial trade - off between more goods and a better environment decreases and finally disappears in the solar age. As Global Thermostat plants are installed and the caps on emissions decrease, the *short run* negatively sloped “transformation” curve indicated with a heavy line shifts (as indicated by the dotted transformation curves) and the actual curve that is observed in the long run, linking goods produced and abatement achieved, is instead positively sloped: it is the upward sloping curve depicted with a stripped line. In the very long run, this striped line converges smoothly to a vertical dotted line indicating a total amount of goods that are produced by the economy, a quantity that does not depend on, and does not decrease with, the abatement of carbon emissions.

8. Developing nations and negative carbon

Developing nations are massively increasing their use of energy and are expected to become in 20-30 years the largest emitters in the world. Indeed, as already mentioned, China builds one new coal power plant every two weeks. No policy can reduce the risk of global warming in the long run without finding a way to control and reduce China's and all developing nations' emissions.

Currently about 41% of all fossil fuels emissions in the world originate in power plants that generate electricity. In reality, most of the power produced in this century will come from newly built power plants, because energy use is expected to increase 5 - 10 fold in the rest of this century. It is therefore important to appreciate the difference between three different energy strategies, which rely on conventional coal plants, clean coal plants, and air capture plants.

The figures above illustrate the difference between building a new standard coal plant, a "clean" coal plant, and an air capture negative carbon power plant. Standard coal plants increase power and production at the expense of environmental quality, increasing the risks of climate change. Clean coal plants keep similar levels of abatement but increase power and the production of goods (somewhat less). They stabilize emissions since they clean their own emissions, but emissions from other sources keep increasing, thus altering the atmosphere as the carbon concentration increases and leading to increased risks of climate change. The strategy proposed in this article is to instead introduce *negative carbon power plants*, for example plants that co-generate air extraction with electricity generation as described above. These have the capability of increasing power and the production of goods without carbon emissions, and at the same time they can *decrease* the atmospheric concentration of carbon dioxide from other sources - thus decreasing overall the risk of climate change.

Another advantage of the negative carbon strategies recommended here is that they allow regions such as Latin America and Africa to benefit from the Kyoto Protocol's Clean Development Mechanism (CDM) , which has not been possible until now. The CDM has transferred over US23 billion in clean technology investments to developing nations since the Kyoto Protocol became international law in 2005. But until now most of the CDM investments have gone to China and India (between 60 and 80% so far) because the technologies approved under this mechanism are about reducing emissions. Africa and Latin America cannot reduce much in terms of emissions because they emit so little (Africa emits 3% of the global emissions). With negative carbon technologies, however, Latin America and Africa can be recipient of much larger CDM investments because they can achieve carbon reductions that much exceed what they emit. In building air capture plants that co-generate electricity, these regions can increase their energy resources – which are much needed – while benefitting from significant CDM investments that have eluded them so far.

In summary, the Kyoto Protocol's carbon market can provide more financial compensation in the form of clean technology investments for developing nations (through the CDM) than what can be achieved by stabilizing emissions. In particular the air capture power plants would get credit both for the avoided carbon from using a carbon neutral source of energy to produce electricity, *and* for the reduction in carbon dioxide from other sources that they provide through air capture and storage. Thus the CDM can be a powerful tool in the financing of air extraction power in developing nations. This in turn can provide developing nations in the long term with clean energy infrastructure, and in the short term it can provide the transfer of technology and a source of clean and abundant energy to grow their economies.

For industrial nations of the OECD, the new technologies discussed here represent a source of export revenues and of new jobs in an important global industry of massive scale – the global energy industry.

9. Conclusions

Using carbon-neutral sources of thermal energy one can co-produce electricity and air capture and storage of carbon dioxide. This provides more energy while decreasing the carbon concentration in the atmosphere. It advances energy security and economic development while averting climate change. In the long run, the process accelerates the transition to alternative sources and is compatible with sustainable development. We examined strategies that use this capability in the context of the carbon market created by the Kyoto Protocol, and the implications for industrial and developing nations of a transition from fossil fuels to the solar economy. The air capture plus concentrated solar power strategy proposed in this paper is so far the most efficient of the solutions examined, providing a safer and quicker transition to a renewable future.

10. References

Nakicenovic, N. et al Special Report on Emissions Scenarios, Intergovernmental Panel on Climate Change, 2000.
Chichilnisky, G. "Economic development and global warming in the short and the long term", Techint Bulletin, Boletin Informativo del Techint, issue no. 345, April 2008, p. 53-76
P. M. Eisenberger, R.W. Cohen, G. Chichilnisky, N.M. Eisenberger, R. R. Chance and C. Jones "Global Warming and Carbon-Negative Technology: Prospects for a Lower-Cost Route to a Lower-Risk Atmosphere" Energy and the Environment, 2009.
G. Chichilnisky and P. Eisenberger (2007) "How Air Capture could help to Promote a Copenhagen Solution" Nature, June 25, 2009, vol. 459, p. 1053
N. Jones, "Sucking Carbon out of the Air" December 17, 2008, Nature, doi:10.1038/news.2008.1319
http://www.nature.com/news/2008/081217/full/news.2008.1319.html
N. Jones "Sucking it Up" Nature News Feature Climate Crunch, p. 1094-1097.
Nature Editorial, Page 1077, April 30, 2009.
'Can Coal be Clean?' Nature Editorial, Issue 7245, Volume 459, May 21 2009, pp. 299.
Henry Price et al., "The Potential for Low Cost Concentrating Solar Power Systems" National Renewable Energy Laboratory Report NREL/CP-550-26649; also http://www.nrel.gov.csp, 2003, see also http://www.nrel.gov/csp/pdfs/35060.pdf

Hillard Huntington: “The Oil Security Problem” Resources for the Future “The Global Commons”, Spring 2008, Issue No. 168. p. 4

Klaus S Lackner et al., “The Case for Carbon Dioxide Extraction from the Air” Source Book 57 (9): p6-10, 1995

Klaus S. Lackner et al., “Carbon Disposal in Carbonate Materials”, Energy 20,1153-1170(1995)

http://www.grida.no/climate/ipcc/emissions/044.html#fig28

http://www.eia.doe/oiaf/ieo/ieorefcase.html , table A1

Andy S. Kydes, “Modeling Technology Learning in National Energy Modeling Systems”, EIADOE-0607(99)

Franz Trieb et al., “A Renewable Energy and Development Partnership EU-ME-NA for Large Scale Solar Thermal Power & Desalination in the Middle East and North Africa”, http://www.trecumena.org.documents/sanaa paper and annex 2004 04 15.pdf

Joshua Stolaroff et al., “A pilot-scale prototype contactor for CO_2 capture from ambient air : cost and energy requirements”, http://www.ucalgary.ca/~keith/papers/84.Stolaroff.AirCaptureGHGT-8.p.pdf

Mcmahan L. Gray, Amine “Rich Solid Sorbents for Carbon Dioxide Capture”, Patent 6547854, 04/15/ 2003

David W. Keith et al., “Climate Strategy with CO_2 Capture From Air”, Climate Change (2005), DOI:10.1007/s10584-005-9026-x

G. Chichilnisky and G. M. Heal Environmental Markets: Equity and Efficiency, Columbia University Press, 2000.

G. Chichilnisky and G. Heal “Who Should Abate Carbon Emissions: An International Perspective” Economic Letters, Spring 1994, pp. 443-449.

G. Chichilnisky, Development and Global Finance: The Case for an International Bank for Environmental Settlements, UNESCO and UNDP, New York, 1996.

W.K. O’Connor et al., “Carbon Dioxide Sequestration by Direct Mineral Carbonation” First National Conference on Carbon Sequestration, Washington DC, May (2001)

David L. McCollum et al., “Techno-Economic Models for Carbon Dioxide Compression, Transport, and Storage”, Institute of Transportation Studies , University of California Davis, UCD-ITS-RR-06-14

P.S. Newall et al “CO_2 Storage as Carbonate Materials”, IEA Greenhouse Gas Program Report IEA/PH3/17, February (2000)

T..M. L. Wigley, in The Carbon Cycle, T.M.L. Wigley and D.S. Schimel, Eds., Cambridge University Press, 2000) pp 258-276

S. Pacala and R. Socolow , “Stabilization Wedges: Solving Climate Problem for The Next Fifty Years with Current Technologies” Science Vol. 305(August 13, 2004), pp268-272

K. Capoor and P. Ambrosi, “State and Trends of the Carbon Market 2007, The World Bank, Washington D.C., May 2007.

Nicholas Stern, The Economics of Climate Change Cambridge University Press, 2006, Chapter 6, p. 188-189.

G. Chichilnisky and G. M Heal “Global Environmental Risks” Journal of Economic Perspectives, Fall 1993, Special Issue on the Environment, pp. 65-86.

G. Chichilnisky “North - South Trade and the Global Environment” American Economic Review Vol 84, No. 4, September 1994, pp. 851-974.

K. Arrow "The Economic Consequences of Learning by Doing" Review of Economics Studies, 1962.
G. Chichilnisky "An Axiomatic Approach to Choice under Uncertainty with Catastrophic Risks" Energy and Resource Economics, 2000.
G. Chichilnisky, "Catastrophic Risks", Encyclopedia of Environmetrics, 2002.
G. Chichilnisky "The Topology of Fear" Journal of Mathematical Economics, 2009.
33. A. Grubler "Long Wave: Technology Diffusion and Substitution" Daedalus, Summer July 1st, 1996.
G. Chichilnisky: Key Note Presentation at OECD Conference "The Economics of Climate Change", OECD, Paris, June 14-16 1993, published with G. M. Heal in The Economics of Climate Change, (ed. T. Jones) OECD, Paris pp. 159-170.
G. Chichilnisky and G. M. Heal "Markets for Tradeable CO_2 Emission Quotas Principles and Practice", OECD, Paris, Economic Development Working Paper No. 153, and Chapter 10 in Topics in Environment and Resources, (M. Bonnan et al) Kluwer Academic Publishers, The Neatherlands, 1999
Pielke R.A. Jr. "An Idealized Assessment of the Economic Role of Air Capture of Carbon Dioxide in Mitigation Efforts" Environmental Science and Policy, 2009
Hoffert et al "Energy implications of Future Stabilization of Atmospheric CO2" Nature 1998, 395, 881-884
Wigley, M.H. et al, "Economic and Environmental Choices in the Stabilization of Atmospheric CO2 Content" Nature, 1996, 240, p. 240-243.
Oliver Norton, (2009) "Great White Hope: Geoengineering Schemes", Nature April 30, 2009, pp. 1097.