Energy security, economic development and global warming: addressing short and long term challenges

Graciela Chichilnisky* and Peter Eisenberger

Columbia University,
New York, 10027 USA
E-mail: chichilnisky@columbia.edu
E-mail: peter.eisenberger@gmail.com
*Corresponding author

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 it requires swift action (IPCC) and different strategies[1]. The article analyses a negative carbon process to co-produce electricity while reducing carbon concentration in the atmosphere (Jones, 2008, 2009; Chichilnisky, 2008b; Chichilnisky and Eisenberger, 2009; Eisenberger et al., 2009). While providing additional energy the process makes fossil power plants net carbon sinks. 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, created by one of the authors in 1997 (Chichilnisky, 1993, 1996; Chichilnisky and Heal, 1994, 1995; Chichilnisky and Sheeran, 2009; Pagnamenta, 2009). We propose extending Kyoto's clean development mechanism (CDM) in a way that benefits Latin America and Africa (Chichilnisky and Heal, 1999; Chichilnisky, 1996), and analyse the global transition from a fossil to a renewable economy.

Keywords: Kyoto Protocol; carbon market; energy security; economic development; climate change; global environment; clean energy; sustainable development; catastrophic risks; global thermostat.

Reference to this paper should be made as follows: Chichilnisky, G. and Eisenberger, P. (2009) 'Energy security, economic development and global warming: addressing short and long term challenges', *Int. J. Green Economics*, Vol. 3, Nos. 3/4, pp.414–446.

Biographical notes: G. Chichilnisky is the Director of Columbia Consortium for Risk Management, Professor of Economics and Statistics at Columbia University, and the architect of the Carbon Market of the Kyoto Protocol. Website: www.chichilnisky.com.

P. Eisenberger is a Professor of Earth and Environmental Sciences at Columbia University, and a Founder and Director of the Princeton Materials Institute, Director of Lamont Doherty Earth Observatory at Columbia University 1996–2000, Former Vice Provost of Columbia University, and the Founder and Director of The Earth Institute at Columbia University.

1 Introduction

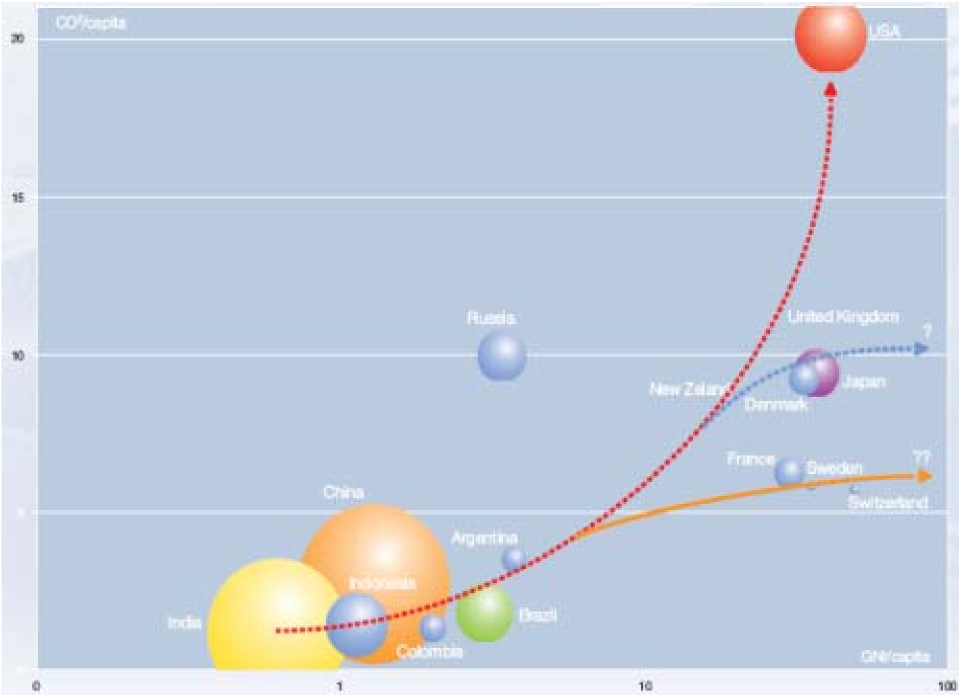
At a time when China and India are flexing their geopolitical muscles and the developing countries rapidly increase their energy use, the world faces the environmental consequences of a long and successful period of Western industrialisation.[2] The timing could not be worse. Two centuries of industrialisation 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[3] and Florida is the next most vulnerable US site.[4] 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.[5]

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'[6] 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 (Huntington, 2008). Energy use is essential to economic development: there is a direct connection between energy use and gross domestic product, see Figure 1 below.

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 not 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 by making available clean and abundant renewable energy sources.[7] 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 by 2050 (IEA, 2008), and with current trends[8] about \$165 trillion by the end of the century. The short term and the long term present different problems, and require different solutions.

Time is not on our side. Intergovernmental Panel on Climate Change (IPCC) scientists agree that we need to reduce carbon emissions by 60–80% in the next 10–20 years.[9] Avoiding further carbon emissions emphatically does not resolve the short-run problem (Chichilnisky, 2008b). Even if we *stabilise* 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 storage denoted CCS hereafter) are a step forward (Nature, 2009a), but they create burdensome economic costs and at best they merely stabilise 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 (Chichilnisky and Eisenberger, 2009).

Figure 1 GNI per capita vs. carbon emissions per capita (see online version for colours)



Notes: Horizontal axis: GNI per capita. Vertical axis: CO_2 per capita. The size of the balls denotes total emissions.

Source: UNEP (2007)

The general agreement is that there are no silver bullets and a variety of approaches are needed. It is shown below that a low-risk level of carbon in the atmosphere requires a significant carbon-negative mitigation component: sucking CO_2 from the atmosphere (Chichilnisky, 2008b; Jones, 2008; Eisenberger et al., 2009; Pagnamenta, 2009). Studies using integrated assessment models (Nordhaus, 2007, 2008) have found that 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[10] that was introduced recently (Chichilnisky, 2008b; 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, 2008b; Jones, 2008, 2009; Eisenberger et al., 2009). Somewhat surprisingly with this capability, 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; Pagnamenta, 2009). The carbon thus captured can be converted into fuels, plastics and even cement, stored in geological sites and used for enhancing oil recovery (Newall, et al., 2000; O'Connor et al., 2001). This provides real protection against human induced climate change since it allows an economy 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 UN Climate Convention goal of 'common but differentiated responsibilities'. It examines the functioning and implications of 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 developing and using negative carbon technologies as part of its clean development mechanism (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 in December 2009, and the transition to 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.[11] 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; Chichilnisky and Heal, 1993). For this purpose we divide the problem into short-run goals and long-term objectives.

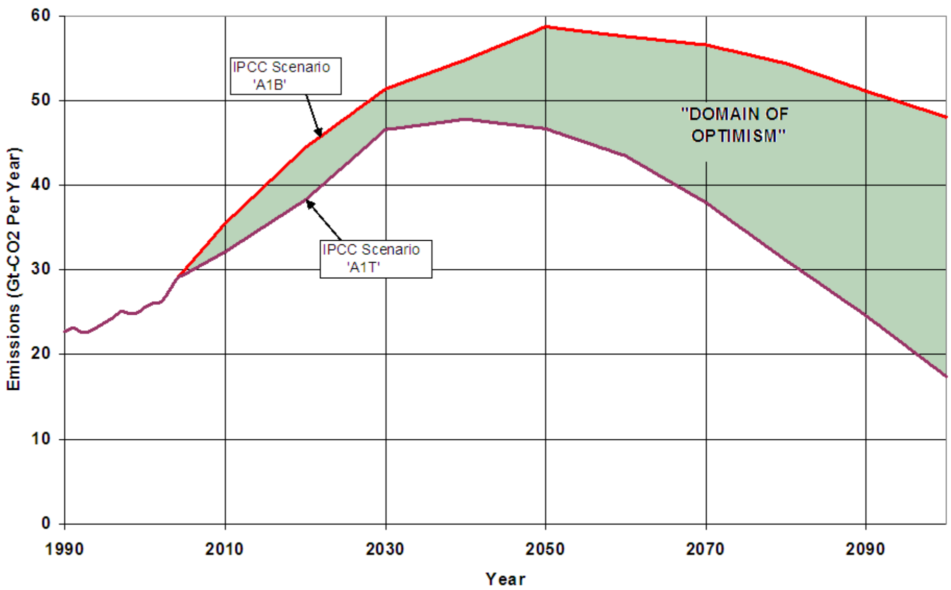
A transition away from fossil fuels to alternative sources of energy[12] that are more broadly distributed can provide economic development and security without inducing global warming. A transition seems inevitable in the long run, because fossil fuels are limited in supply. The rapidly growing world demand for energy[13] 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 the energy provided today by fossil fuels with current technologies. Converting solar energy into electricity can meet the predicted 3.5-fold increase of today's fossil energy use by 2100 (IEA, 2008; DOE 2008) and this would require less than 1% of the solar energy that hits the planet's surface.

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

2.1 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 will take a long time because most of the energy used in the planet today is obtained from fossils sources such as oil, gas and coal.[14] As discussed further below, the change will require a new massive and expensive infrastructure costing about \$43–50 trillion (IEA, 2008)[15] or about two thirds of the world's GDP and this 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.[16] Stabilising the level of emissions is helpful, but stabilising 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[17] 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 15 or 20 years.[18] 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).

Figure 2 Carbon dioxide emission pathways (see online version for colours)



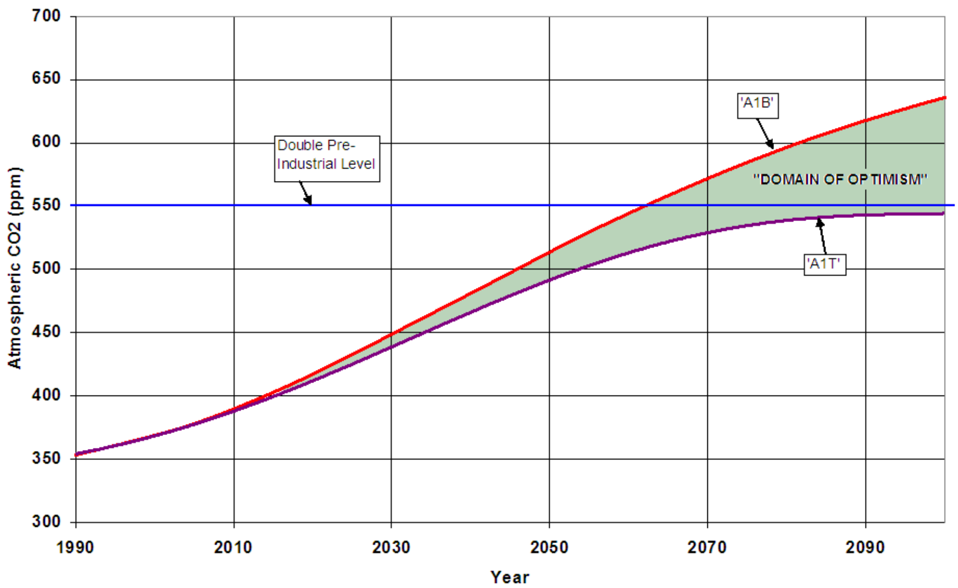
Notes: Carbon dioxide emissions pathways to 2100 for the IPCC A1B and A1T scenarios. The region between the curves is labelled the 'domain of optimism', because it represents what could be achieved by future technology efficiency gains and a substantial shift to emission-less energy, while maintaining 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 (Nakicenovic et al., 2000) in order to achieve consistency with the actual emissions history since 2000).

Source: Eisenberger et al. (2009)

The authors and many economists contend that it is not feasible to drastically decrease the use of fossil fuels in the short term. This is why there is an increasing call to capture the carbon emitted by fossil fuel plants and store it safely (*Nature*, 2009a; Chichilnisky and Eisenberger, 2009; Pagnamenta, 2009). Rapidly growing nations are heavily dependent on coal, and so are the US and Russia at present. Resources are being made available to invest on the assumption that carbon will have to be captured and stored.

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 IPCC Special Report on Emissions Scenarios, 2000. 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 above. Within this domain, CO_2 emissions peak around the middle of the century and decline thereafter as the transition from fossil resources compensates for increased economic growth.

Figure 3 Atmospheric carbon dioxide pathways (see online version for colours)



Notes: 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.

Source: Eisenberger et al. (2009)

The levels of concentration of CO_2 in the atmosphere are calculated from a carbon cycle model[19] and are shown in Figure 3 above. Emissions peak in the middle of this century and decrease afterwards, while atmospheric CO_2 increases throughout the entire century and continues into the next. Figure 3 demonstrates that even optimistic IPCC scenarios do not prevent atmospheric CO_2 from exceeding twice the pre industrial levels. Ultimately CO_2 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. Hoffert et al. (1998) and Wigley et al. (1996) estimate that by 2050, 10–30 trillion watts of new emission-less energy is needed to stabilise the atmosphere at 550 ppm. With current renewable technology 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.

In the short run a low risk level of CO_2 in the atmosphere cannot be reached without a significant carbon negative mitigation component. This requires removing carbon from the atmosphere in net terms (Chichilnisky, 2008b; Jones, 2008, 2009; Chichilnisky and Eisenberger, 2009; Eisenberger et al., 2009; Stolaroff et al. 2006; Pagnamenta, 2009).

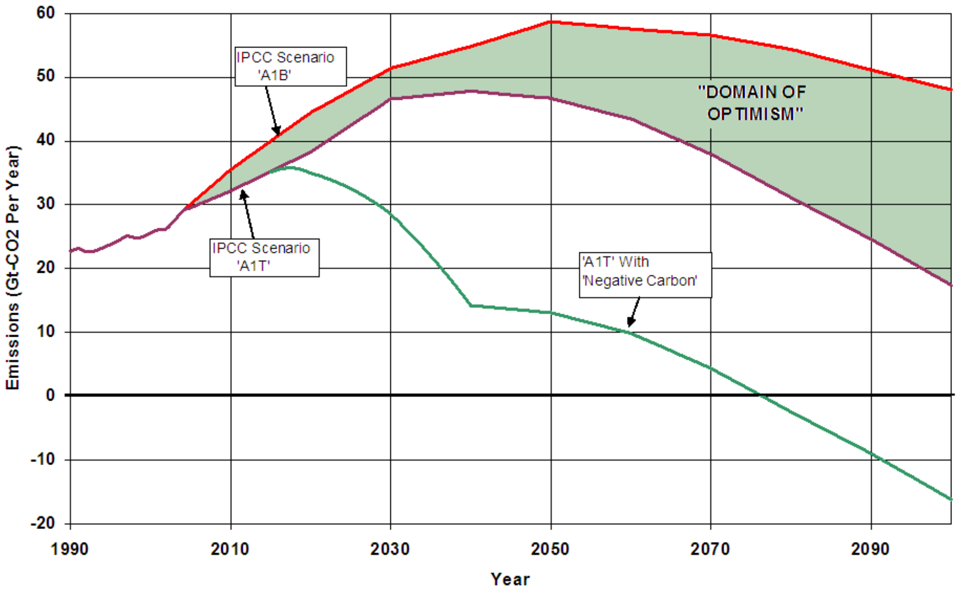
Several carbon negative technologies are possible, including ocean fertilisation, forest sequestration, bio-energy with carbon storage, atmospheric aerosols and space borne reflectors (see Norton, 2009; The Royal Society, 2009). All proposed measures have costs, issues and uncertainties that must be considered along with their potential to achieve a safer atmosphere (Eisenberger et al., 2009). Air extraction, considered here, offers the ability to control CO_2 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 CO_2 directly from air, and it does so without the problems that have been normally associated with low concentration air extraction in the past, an issue that was explained in Keith et al. (2005) and Pielke (2009). 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 scenario 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.[20] 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, while maintaining a 50% installation ratio. There is no further net deployment after 2040, and a rate of 34 gigatons of CO_2 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 CO_2 emissions achieve negative values.

Figure 5 below shows the effect of air extraction on atmospheric CO_2, relative to the optimistic A1T scenario of the IPCC. At the end of the century the CO_2 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 CO_2 (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 (2007) reduces this figure by half. It has been shown however that with the carbon market in place, these costs are income to other sectors, resulting in zero net cost to the global economy as a whole (Chichilnisky and Sheeran, 2009).

Figure 4 Carbon dioxide emissions pathways (see online version for colours)



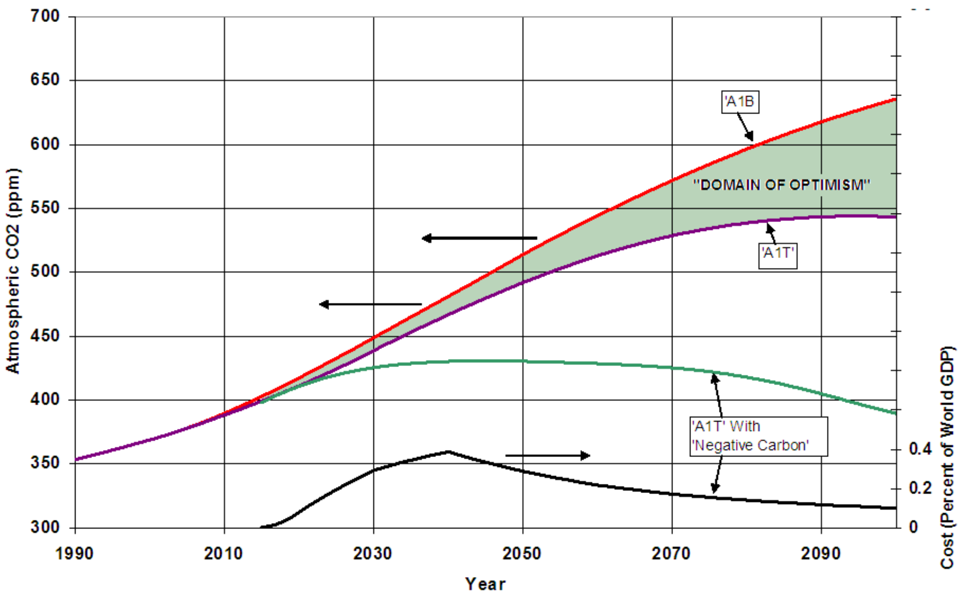
Notes: Carbon dioxide emissions pathways of Figure 2 with the addition of a carbon-negative mitigation scenario to A1T, as discussed in the text. Carbon-negative mitigation via air extraction begins in 2015 and reaches 34 Gtonne-CO_2/yr in 2040. This level is sustained for the remainder of the century.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

Source: Eisenberger et al. (2009)

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 to develop and will take time. Air capture has the potential to substantially lower the risk of greenhouse gas emissions, while maintaining global economic growth. The process should be deployed along with other solutions to take a 'portfolio' approach to risk. 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. 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. Significant incentives exist to accelerate R&D efforts in this direction, and in 2009 the US Department of Energy has already started such efforts.[21]

Figure 5 Atmospheric carbon dioxide pathways (see online version for colours)



Notes: 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 percentage 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 (2007) reduces the total cost over the century by about half.

Source: Eisenberger et al. (2009)

2.2 *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 utilisation of such sources expands considerably beyond today's levels. 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[22] (Kydes, 1999). An illustration of the methodology for solar energy showing Department of Energy learning curves for solar power production is in 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 approximately 3.5 times the energy used in the world today. This is a standard projection of energy demand by the end of this century (IEA, 2008; DOE, 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.

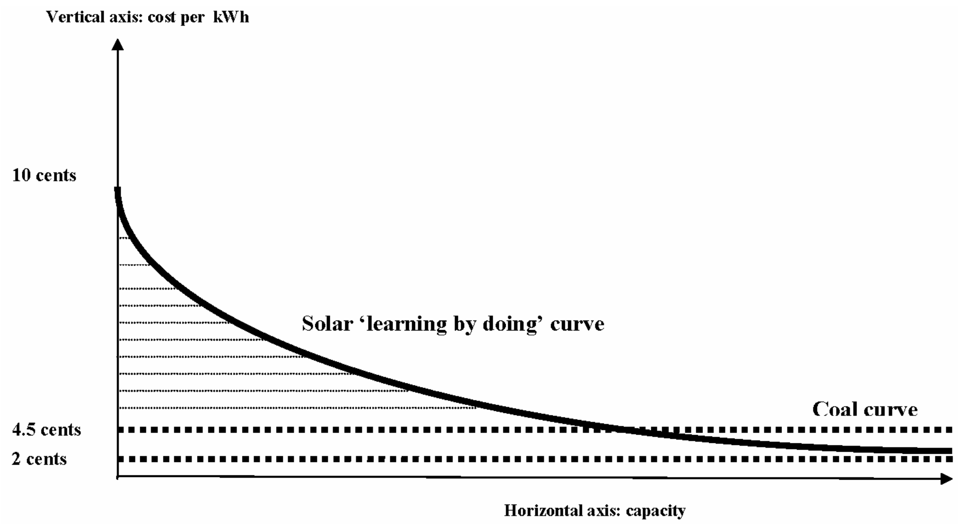
The computation of *long-run transition costs* is considerably simplified when we observe that, in a competitive market economy, the lowest cost alternatives will always prevail. In view of this fact, the cost involved in the transition to renewable sources of energy can be bounded by the cost of transitioning 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 by 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 utilise 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. Coal produces currently 27% of the world's electricity and global fossil fuels generates 3×10^{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 (CSPPT) being evaluated has an order of magnitude less installed capacity (Price et al., 2003)[23]. Correspondingly, the learning curve for CSPPT 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 CSPPT efficiency[24] in producing electricity when capacity expands, as predicted by the US Department of Energy.

Specifically, the DOE showed that, as installed capacity of CSPPT solar plants increases, the cost of solar[25] goes down by 15% per each doubling of capacity (Price and Carpenter, 1999). 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 per 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 per 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.

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[26]



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 visualise 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 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.[27]

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 above for solar produced electricity represents amortisation of fixed costs.[28] 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 US$165 trillion for the long-run solution, almost three times the GDP of the planet.

There are other ways of illustrating the difference between 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 USA and about 15% 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.[29] 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 curves 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 organisational 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 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 capturing carbon from air (Pagnamenta, 2009) and increasing energy supplies in the short run while decreasing carbon in the atmosphere and thus the risk of global warming. In a competitive market and with sufficient information, the realised 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 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 stabilising carbon emissions at current levels is in place (Stern, 2006; Pacala and Socolow, 2004). Currently we are emitting in net terms about 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 fossil fuels that cause troublesome carbon emissions. 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 (Stern, 2006) 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, 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 assets' risks:

Table 1 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
Industrialised 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
G_7	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

Note: *This includes coverage of man-made and natural disasters but not life insurance

Source: Swiss Re, Economic Research & Consulting, Sigma No. 3/2008 and Chichilnisky and Sheeran (2009).

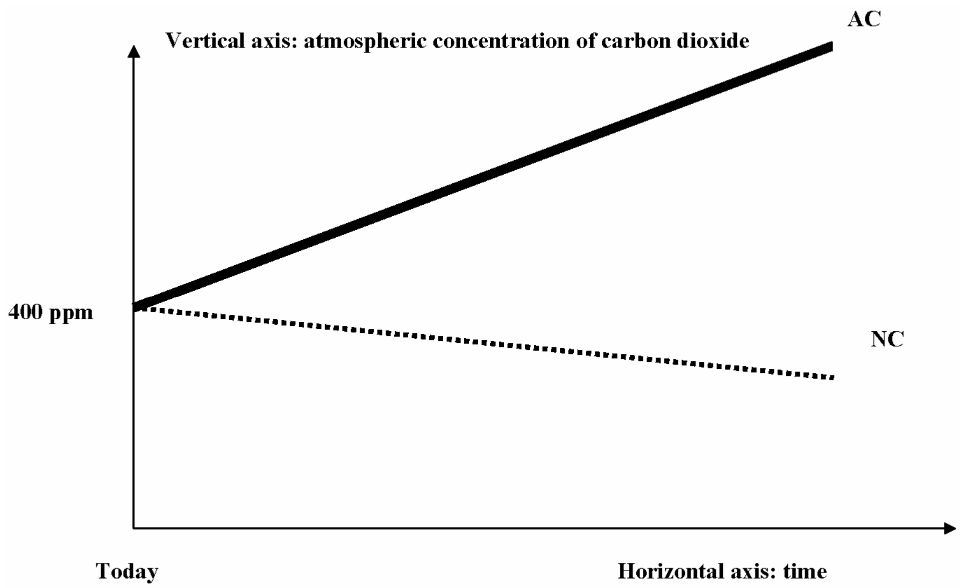
Table 1 provides an estimate of the costs of using an air extraction approach to avert the risks of global warming. In terms of costs, the lowermost curve in Figure 5 showed the cost as percentage of world GDP, assuming a constant undiscounted extraction and storage cost of $25 per ton of CO_2. The total 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 (2007) reduces this figure by half. The annual cost of the air extraction solution is therefore consistent with and in fact lower 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.

Table 2 Property insurance premiums on standard and catastrophic risks

Percentage paid to protect covered amount		*Avg. premium per $1,000 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

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
Chichilnisky and Sheeran (2009)

Figure 7 Technology that *avoids* carbon versus technology that is *carbon negative*



Notes: AC = avoided carbon: reduces emissions but carbon concentration still increases;
NC = negative carbon: reduces concentration through air capture of CO_2.

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 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 *reduces the total concentration of carbon* in the planet's atmosphere, therefore mitigating the risk of climate change. Figure 7 above illustrates two cases – avoided carbon and negative carbon – and only the second can avert climate change in the short run.

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

How does the transition to renewable energy occur in practical economic terms? A key economic incentive to transition is the creation of the carbon market and its so-called 'price signal' for carbon. These are costs on emitting carbon that are imposed by an international agreement, the United Nations Kyoto Protocol, and its carbon market (see Capoor and Ambrosi, World Bank 2007; Chichilnisky, 1993, 1994; Chichilnisky and Sheran, 2009; Chichilnisky and Heal, 1995; Chichilnisky, 1996). Simply put, a negative incentive to emit is created by the price to emit each ton of carbon, that overemitters pay to underemitters in the newly created carbon market. The carbon market was designed and written into the Kyoto Protocol by Chichilnisky (Chichilnisky, 1993, 1996; Chichilnisky and Heal, 1995; Chichilnisky and Sheeran, 2009), and 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). The Protocol became 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 on total emissions. *This means a strict numerical limit on emissions must be agreed by the traders nation by nation.* Otherwise, there is no carbon market.[30] 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, while markets do (see Chichilnisky, 1993; Chichilnisky and Heal, 1995, 1996). The market approach of the Kyoto Protocol was adopted and signed by 196 nations.[31] The Kyoto Protocol carbon market has unique characteristics, which distinguish it from other markets. It provides preferential treatment for poor nations, in a manner that increases market efficiency, although it is expected that as they reach the same level of development as others, they will face similar caps. No other market has these characteristics.

What do carbon traders trade? They either buy rights to emit above their caps, or sell rights to emit by emitting below their caps. The market ensures a total global ceiling on emissions that 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 25% of total global carbon emissions) nor the developing nations (who emit about 40% 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 SO_2 does not distribute uniformly over the atmosphere as CO_2 does. 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 (see Capoor and Ambrosi, World Bank 2007). In June 2009 the US House of representatives passed an energy bill (also called the Waxman-Markey Bill) that authorises the creation of caps on US emissions and a US carbon market following the Kyoto Protocol structure. This bill was passed even though the US currently does not abide by the Kyoto Protocol rules that it signed in 1997. During 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 Kyoto 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 (see Chichilnisky and Sheeran, 2009). The carbon market and its CDM are a key part of the negotiation, and their future is discussed below.

The following provides basic statistics and summarises how the carbon market operates, who are the buyers and sellers, what they trade, and what has been achieved until now. By 2006 the carbon market grew in value to an estimated US $30 billion, three times greater than in the previous year, it reached a US$60 billion level in 2007[32] and US$120 billion was traded by 2008. The market was dominated by the sale and resale of European Union Allowances (EUAs). Project based activities primarily through the CDM and joint implementation (JI) projects of the Kyoto Protocol also grew to a value of about $25 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 NSW market in Australia
6. North American companies with voluntary but legally binding compliance objectives in the 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) 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, 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 2006 emissions cap was not set at an appropriate level relative to actual emissions in that period, so that prices dropped rapidly during 2006.[33] 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, in the period 2002–2007 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 (Capoor and Ambrosi, World Bank 2007; Chichilnisky and Sheeran, 2009), 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 US$120 billion annually and has succeeded to reduce carbon emissions and transferred 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 this section, but it is possible to identify market 'fundamentals' that determine carbon prices. 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

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 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). The body of theory underlying the carbon market was developed by one of the authors who proposed the creation of the Kyoto Protocol 'carbon market' system to the international community starting from 1993, and drafted it into the Protocol in December 1997 (Chichilnisky, 1993, 1996; Chichilnisky and Sheeran, 2009; Chichilnisky and Heal, 1995, 2000). Although carbon markets operate in some ways that are similar to regular markets, in other ways they are quite distinct and behave differently.

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 8 below. We know that about 87% 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:

$$X = F(E)$$

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

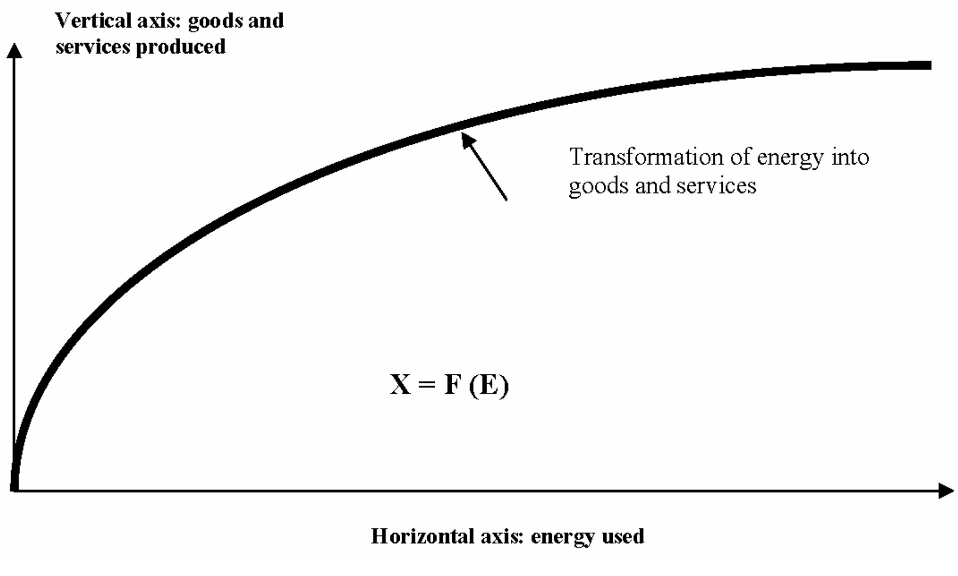
$$X = \psi(A), \qquad d\psi / dA < 0$$

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

$$E = -A$$

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

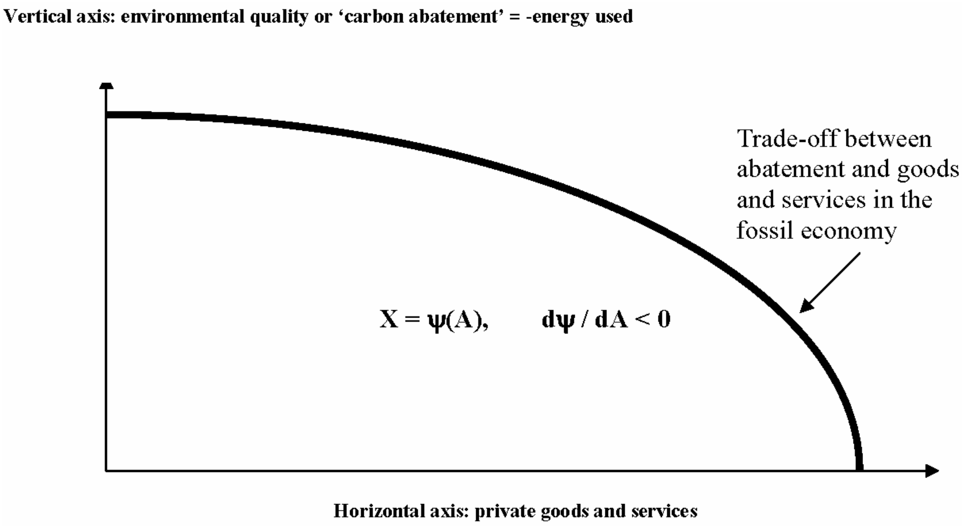


It is important to realise that the quality of the atmosphere – measured for example by the concentration of carbon dioxide in the atmosphere, in parts per million – can be considered a 'good' or a 'bad' depending how it is measured. Indeed, lower concentrations of CO_2 are associated with a more stable 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 stable weather improves 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 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 independent from the choices of others – 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. It is physically impossible for one nation to face 430 ppm of carbon in the atmosphere, while another faces 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 (Chichilnisky, 1993; Chichilnisky and Heal, 1994, 1995; Chichilnisky and Heal, 2000).

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 trade-off 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, industrialisation 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.

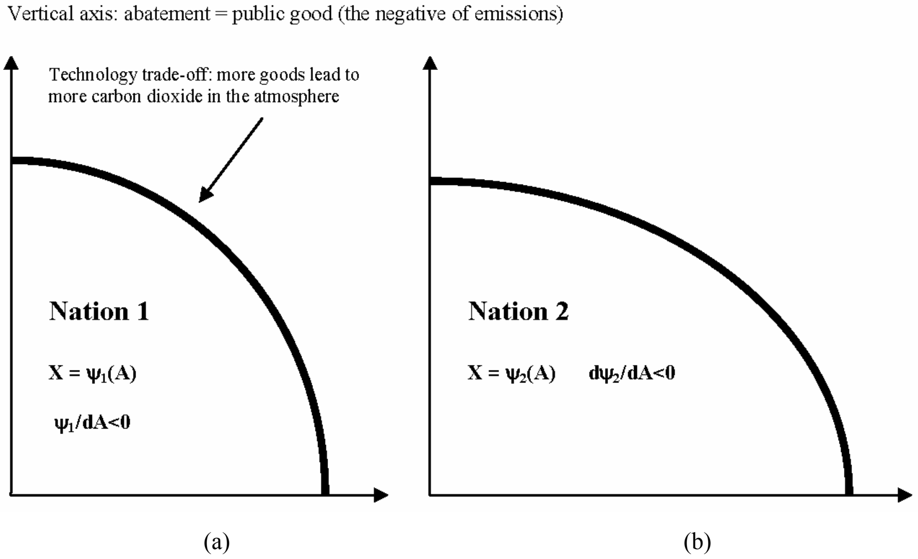
Figure 9 The more fossil energy we use, the more carbon we emit, and the less we abate



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.

Each nation may use a different production technology. Therefore, each nation in Figure 10 may have a different transformation or trade-off curve. 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



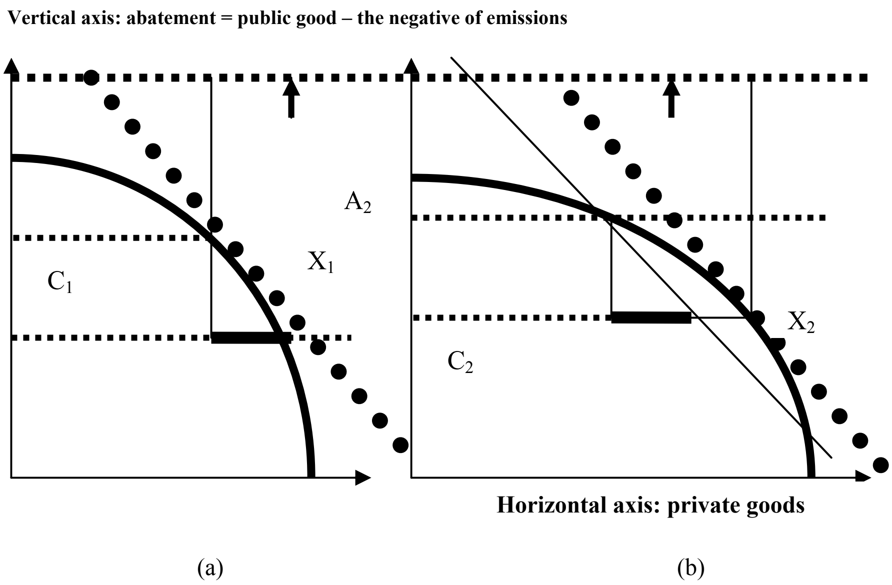
Notes: Each faces a technological trade-off: (a) producing more goods and using more energy (b) emitting less carbon/abating less.

We now introduce the carbon market, as illustrated in Figure 11 below. For this we assume that each of the two nations in Figure 10 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 11 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_1 and A_2 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 a common horizontal heavy 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. The total amount abated is determined not just by the US caps, but also by the emission caps in the rest of the world. This is because, the overall level of carbon dioxide in the planet's atmosphere is the same for all people in the planet, it 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 that affects the USA and vice-versa.

Figure 11 Carbon trading between two nations (a) Nation 1 (b) Nation 2



Notes: 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 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.

The equations that describe the carbon market are as follows:

Each nation i = 1,2 optimises 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:

$$\mathrm{Max}_{A,X} W_i(X_i, A)$$
$$\text{subject to } X_i = \psi(A) + \pi(A - A_i)$$

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 maximise its welfare, it produces X using A, and 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. Each nation maximises 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:

$$C_1 + C_2 = A_1 + A_2$$

and

$$X_1 + X_2 = \psi_1(C_1) + \psi_2(C_2).$$

In Figure 11 above the small upward arrows indicate the market solution after trading takes place. Each nation produces goods and abatement so as to maximise 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). Nation 2, instead, abates *less* than what is required (the requirement is at point A_2, which is higher than C_2). Therefore one nation will buy and the other will sell permits to emit. 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 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, this price depends on two important parameters that we call the *market fundamentals*:

1 the technological transformation between more goods and more abatement

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. This is 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.

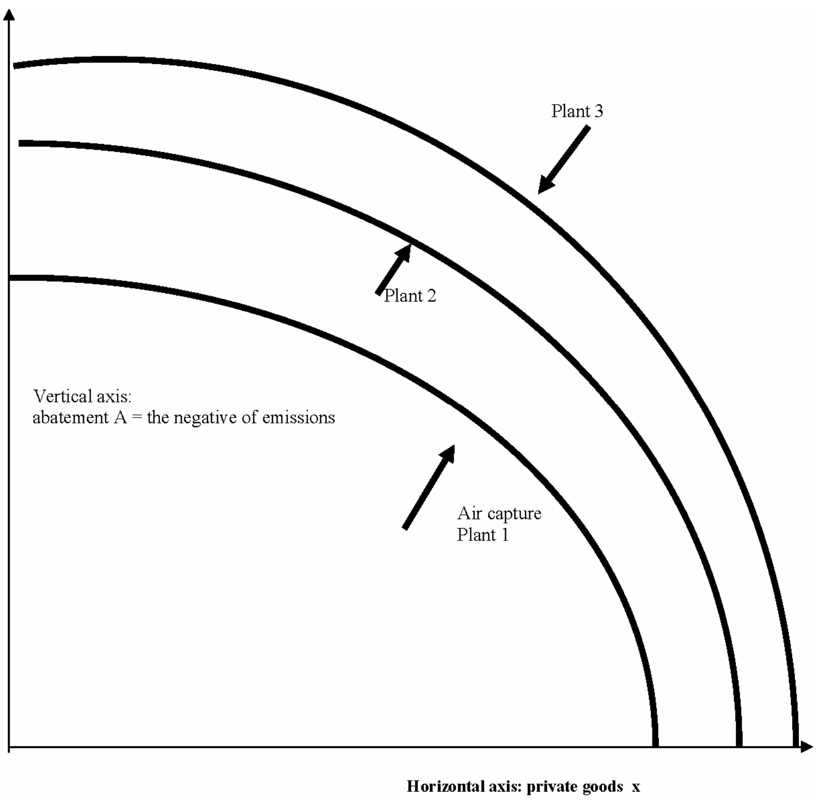
Additionally it is important to appreciate that the technology, or *transformation frontier*, plays a key role. A fundamental result in the theory of competitive markets ensures that the price that equates supply and demand for goods should be equal to the rate of technological transformation between 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 that are properly regulated. 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 – plays 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

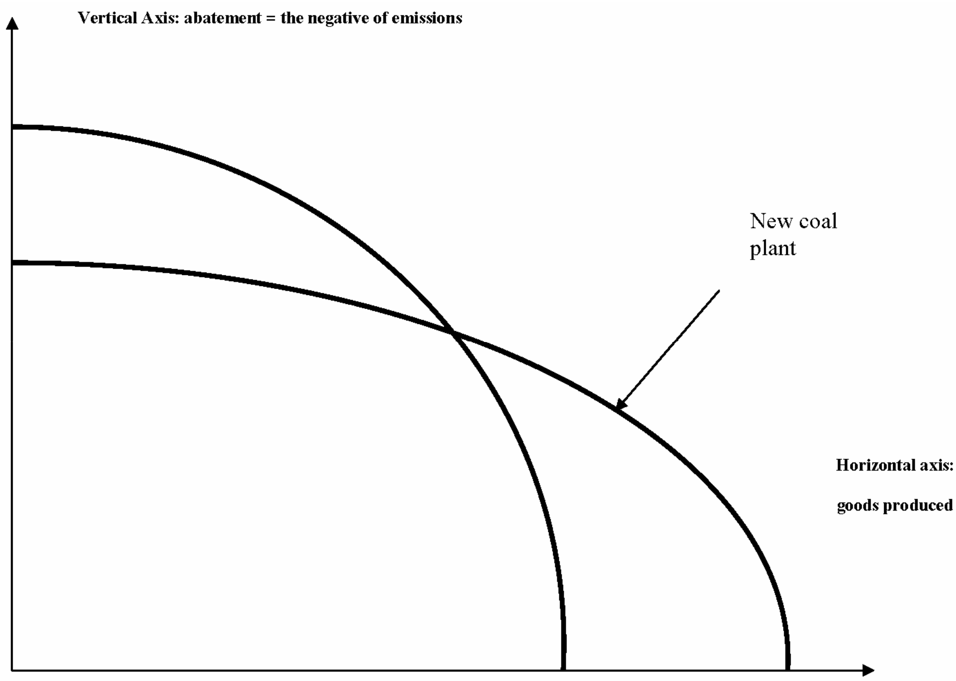
It is possible to illustrate geometrically how a new technology impacts the transformation frontier between goods and abatement, and the changes that are introduced in the carbon market when the air capture technology is adopted.

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



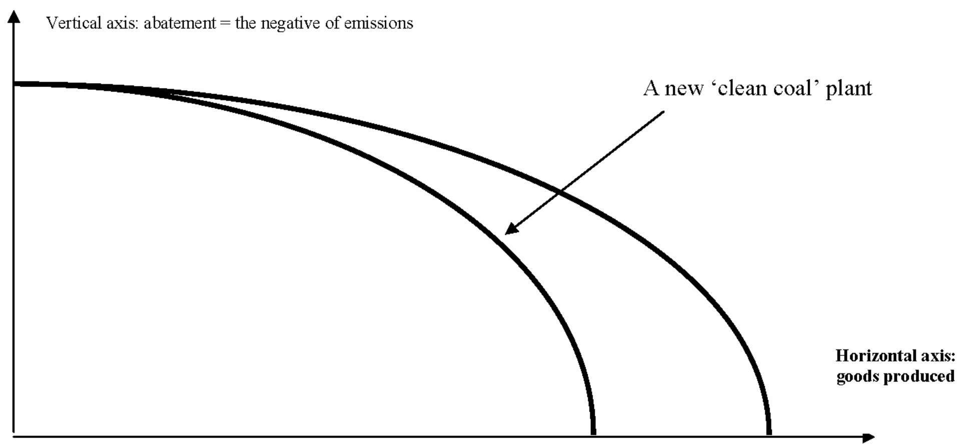
The introduction of the air capture of the type described here and Chichilnisky and Eisenberger (2009) and Pagnamenta (2009) lead to Figure 12, which replaces Figure 10 that is valid for a fossil fuel economy. In Figure 12 we analyse the impact that each newly installed air capture plant has on the 'transformation frontier' between energy and abatement. Each installation of the air capture leads to a new curve. 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.

Figure 13 A new (standard) coal plant is built



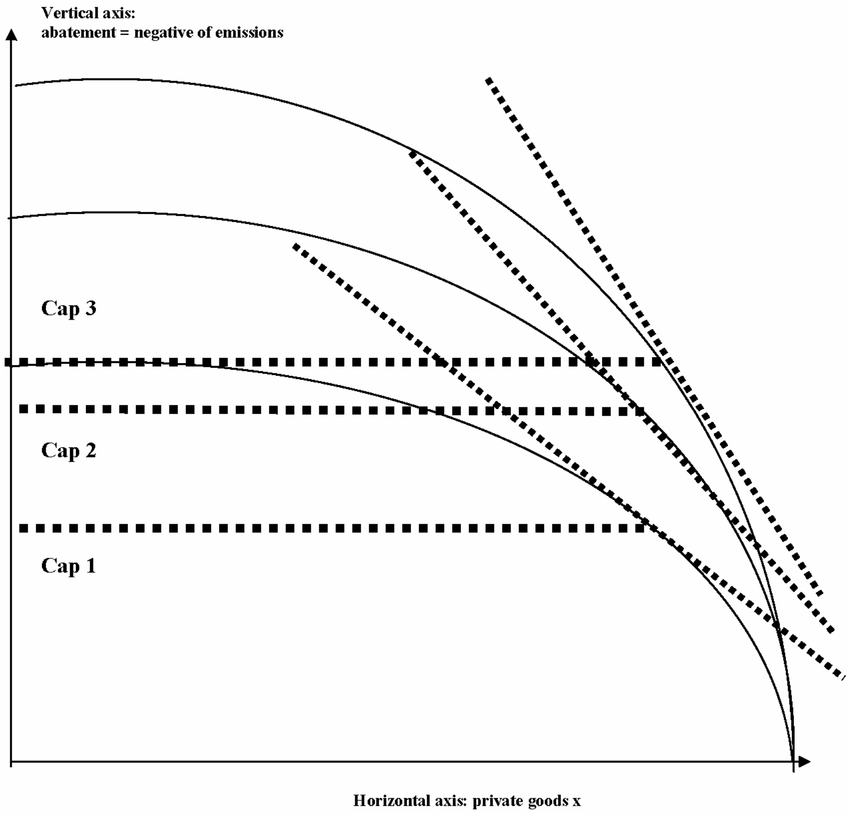
Note: It increases power and goods produced, but reduces abatement.

Figure 14 A new 'clean coal' plant increases power but maintains abatement



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). 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 in Figure 12 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.

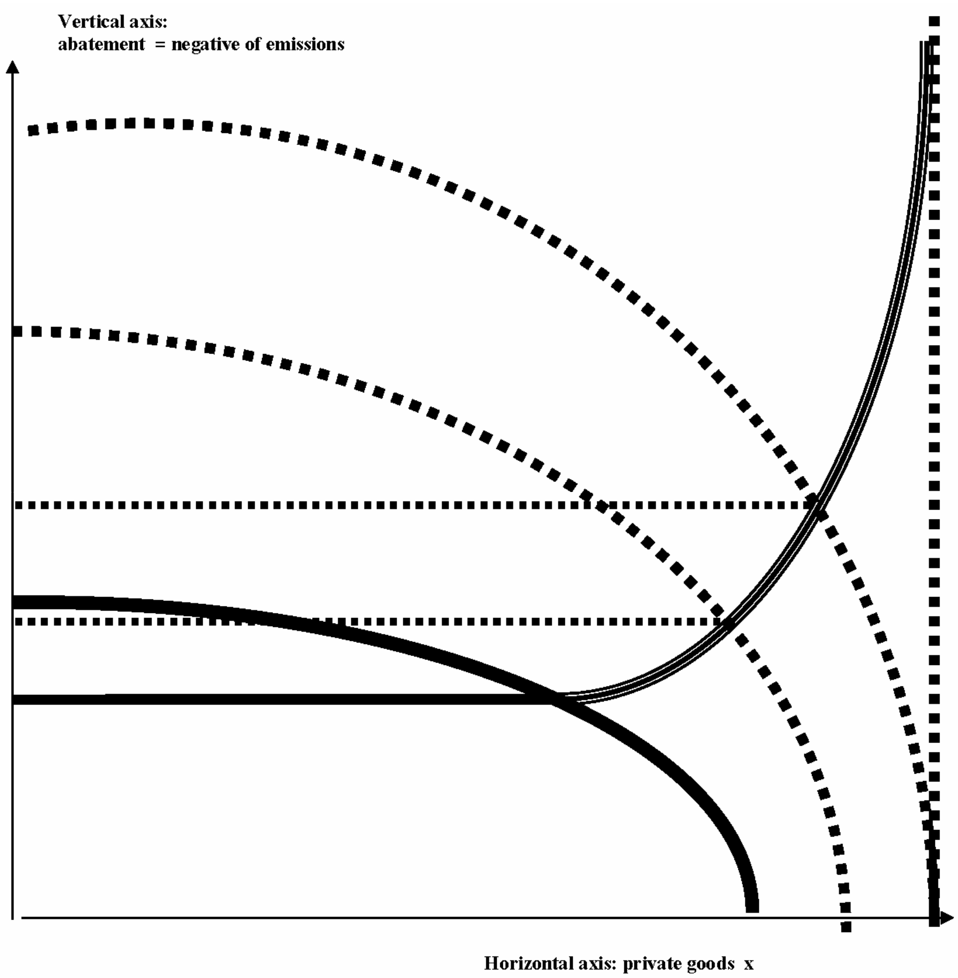
Figure 15 Carbon prices decrease as fossil fuels are gradually replaced by renewable sources



It remains to consider the effect of air capture on carbon markets. Figure 15 above 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 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 16.

Figure 16 Transition from the fossil fuel to the solar economy



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. The sun's 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 16 shows how the initial trade-off between more goods and a better environment decreases and finally disappears in the solar age. As air capture 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 rapidly 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 developing nations' emissions.

Currently about 41% of all fossil fuel 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 at least three folds 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 stabilise 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 is that they allow regions such as Latin America and Africa to benefit from the Kyoto Protocol's CDM, which has not been possible until now. The CDM has transferred over US$23 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 and Latin

America about 5%). With negative carbon technologies, however, Latin America and Africa can obtain much larger CDM investments because they can achieve carbon reductions that 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 benefiting from significant CDM investments that have eluded them so far.

In summary, the Kyoto Protocol's carbon market can provide funding for clean technology investments in developing nations (through the CDM). For example air capture power plants could 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 that they provide through air capture and storage. Thus the Kyoto Protocol CDM can be a powerful tool in the financing of air extraction power in developing nations and the transition to renewable energy in the world. 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. This is a win-win solution for industrialised and developing nations.

9 Conclusions

Using carbon-neutral sources of thermal energy one can co-produce electricity and air capture 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 CSP 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.

References

Arrow, K. (1962) 'The economic consequences of learning by doing', *Review of Economic Studies*, Vol. 29, pp.155–173.

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

Chichilnisky, G. (1993) 'The abatement of carbon emissions in industrialized and developing nations', Key Note Presentation at OECD Conference 'The economics of climate change', OECD, Paris, 14–16 June, published with G.M. Heal in T. Jones (Ed.): *The Economics of Climate Change*, OECD, Paris pp.159–170.

Chichilnisky, G. (1994) 'North-south trade and the global environment', *American Economic Review*, September, Vol. 84, No. 4, pp.851–974.

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

Chichilnisky, G. (2000) 'An axiomatic approach to choice under uncertainty with catastrophic risks', *Energy and Resource Economics*, July, Vol. 22, No. 3, pp.221–231.

Chichilnisky, G. (2002) 'Catastrophic risks', *Encyclopedia of Environmetrics*, Vol. 1, pp.274–279, John Wiley and Sons, Ltd., Chichester, UK.

Chichilnisky, G. (2006) 'Catastrophic risks: the need for new tools, financial instruments and institutions', *Privatization of Risk*, Social Science Research Council, June 2006.

Chichilnisky, G. (2008a) *Beyond the Global Divide: from Basic Needs to the Knowledge Revolution*, Columbia University, available at www.chichilnisky.com, Books and Articles.

Chichilnisky, G. (2008b) 'Economic development and global warming in the short and the long term', *Techint Bulletin*, Boletin Informativo del Techint, April, No. 345, pp.53–76.

Chichilnisky, G. (2009) 'The topology of fear', *Journal of Mathematical Economics*, December, Vol. 45, No. 11–12.

Chichilnisky, G. and Eisenberger, P. (2009) 'How air capture could help to promote a copenhagen solution', *Nature*, 25 June 2009, Vol. 459, p.1053.

Chichilnisky, G. and Heal, G.M. (1993) 'Global environmental risks', *Journal of Economic Perspectives*, Fall, Special Issue on the Environment, pp.65–86.

Chichilnisky, G. and Heal, G.M. (1994) 'Who should abate carbon emissions: an international perspective', *Economic Letters*, Spring, pp.443–449.

Chichilnisky, G. and Heal, G.M. (1995) 'Markets with tradable CO_2 emission quotas: principles and practice', Economics Department Working Paper No. 153, Organization for Economic Cooperation and Development, (OECD), Paris.

Chichilnisky, G. and Heal, G.M. (1996) *Markets for Tradable Emission Rights: Principles and Practice*, Economic Division Report No. 153, OECD, Paris.

Chichilnisky, G. and Heal, G.M. (1999) 'Markets for tradeable CO_2 emission quotas principles and practice', OECD, Paris, Economic Development Working Paper No. 153, and Chapter 10 in M. Bonnan et al. (Eds.): *Topics in Environment and Resources*, Kluwer Academic Publishers, The Neatherlands.

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

Chichilnisky, G. and Sheeran, K. (2009) *Saving Kyoto*, New Holland UK, October.

Department of Energy (DOE) (2008) 'Chapter 6 – industrial sector energy consumption', *International Energy Outlook 2009*. Report #:DOE/EIA-0484(2009), Energy Information Association: Official Energy Statistics from the US Government, available at http://www.eia.doe.gov/oiaf/ieo/industrial.html.

Eisenberger, P.M., Cohen, R.W., Chichilnisky, G., Eisenberger, N.M., Chance, R.R. and Jones, C. (2009) 'Global warming and carbon-negative technology: prospects for a lower-cost route to a lower-risk atmosphere,' *Energy and the Environment*, Vol. 20, No. 6, pp.973–984.

Grubler, A. (1996) 'Long wave: technology diffusion and substitution', *Daedalus*, Summer, 1 July.

Hoffert et al. (1998) 'Energy implications of future stabilization of atmospheric CO_2', *Nature*, Vol. 395, pp.881–884.

Huntington, H. (2008) 'The oil security problem', *Resources for the Future*, 'The global commons', Spring, No. 168, p.4.

Intergovernmental Panel on Climate Change (IPCC) (2000) *Special Report on Emissions Scenarios (SRES)*.

International Energy Agency (IEA) (2008) *Energy Technology Perspectives 2008: Scenarios and Strategies to 2050*, OECD Publishing.

IPCC (2001) *IPCC Third Assessment Report: Climate Change 2001*, available at http://www.ipcc.ch/ipccreports/tar/vol4/english/index.htm.

Jones, N. (2008) 'Sucking carbon out of the air', 17 December, *Nature*, doi:10.1038/news.2008.1319, available at http://www.nature.com/news/2008/081217/full/news.2008.1319.html

Jones, N. (2009) 'Sucking it up', *Nature*, News Feature Climate Crunch, pp.1094–1097.

Keith, D.W. et al. (2005) 'Climate strategy with CO_2 capture from the air', *Climate Change*, Vol. 74, pp.17–74,

Kydes, A.S. (1999) 'Modeling technology learning in national energy modeling systems', EIADOE-0607.

Nakicenovic, N. et al. (2000) *Special Report on Emissions Scenarios*, Intergovernmental Panel on Climate Change.

Nature (2009a) 'Can coal be clean?', Editorial, 21 May 2009, Vol. 459, pp.299–300, doi:10.1038/459299b.

Nature (2009b) 'Time to act', Editorial, 30 April 2009, Vol. 458, pp.1077–1078, doi:10.1038/4581077a.

Newall, P.S. et al. (2000) 'CO_2 storage as carbonate materials', *IEA Greenhouse Gas Program Report IEA/PH3/17*, February.

Nordhaus, W. (2007) 'The challenge of global warming: economic models and environmental policy', Economics discussion paper, July, available at http://nordhaus.econ.yale.edu/dice_mss_072407_all.pdf.

Nordhaus, W. (2008) *A Question of Balance: Weighing the Options on Global Warming Policies*, Yale University Press, New Haven CT.

Norton, O. (2009) 'Great white hope: geoengineering schemes', *Nature*, 30 April, p.1097.

O'Connor, W.K. et al. (2001) 'Carbon dioxide sequestration by direct mineral carbonation', *First National Conference on Carbon Sequestration*, Washington DC, May.

Pacala, S. and Socolow, R. (2004) 'Stabilization wedges: solving climate problem for the next fifty years with current technologies', *Science*, 13 August, Vol. 305, pp.268–272.

Pagnamenta, R. (2009) 'Carbon must be sucked from air, says IPCC chief Rajendra Pachauri', *Times Online*, December 1, available at http://www.timesonline.co.uk/tol/news/environment/article6938298.ece.

Pielke, R.A. (2009) 'An idealized assessment of the economics of air capture of carbon dioxide in mitigation policy', *Environmental Science and Policy*, doi:10.1016/j.envsci.2009.01.002.

Price, H. and Carpenter, S. (1999) 'The potential for low cost concentrating solar power systems', NREL/CP-550-26649, National Renewable Energy Laboratory.

Price, H. et al. (2003) 'The potential for low cost concentrating solar power systems', *National Renewable Energy Laboratory Report NREL/CP-550-26649*, available at http://www.nrel.gov.csp, http://www.nrel.gov/csp/pdfs/35060.pdf.

Stern, N. (2006) *The Economics of Climate Change*, Cambridge University Press, Chapter 6, pp.188–189.

Stolaroff, J. et al. (2006) 'A pilot-scale prototype contactor for CO_2 capture from ambient air: cost and energy requirements', available at http://www.ucalgary.ca/~keith/papers/84.Stolaroff.AirCaptureGHGT-8.p.pdf.

The Royal Society (2009) *Geoengineering Climate Change: Science, Governance and Uncertainty*, September, London UK.

United Nations Environmental Programme (UNEP) (2007) *Buildings and Climate Change – Status, Challenges and Opportunities*.

Wigley, M.H. et al. (1996) 'Economic and environmental choices in the stabilization of atmospheric CO_2 content', *Nature*, Vol. 240, pp.240–243.

Wigley, T.M.L. (2000) 'Stabilization of CO_2 concentration levels', in T.M.L. Wigley and D.S. Schimel (Eds.): *The Carbon Cycle*, Cambridge University Press, pp.258–276.

World Bank (2007) *State and Trends in the Carbon Market, 2007, 2008*, May 2007 Reports.

Yardley, W. (2007) 'Engulfed by climate change, town seeks lifeline', *NY Times*, Sunday, 27 May 2007.

Notes

1 Graciela Chichilnisky acted as Lead Author of the IPCC, 1996–2000.

2 Books and articles available at www.chichilnisky.com (Chichilnisky and Sheeran, 2009; Chichilnisky, 2008a).

3 Front page (Yardley, 2007). 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.

4 A recent OECD study on the largest cities at risk identified Miami as the largest city 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.

5 Energy use is expected to raise about 3.5-fold during this century (IEA, 2008; DOE, 2008). The US coal industry presented recently an ambitious plan to secure enormous subsidies for coal production in the name of energy independence.

6 To paraphrase former US President George W. Bush's terminology.

7 Solar energy is considered renewable in this context.

8 The DOE (2008) estimates average annual growth in worldwide industrial energy consumption will be 1.4% between 2006 and 2030, which, if continued, will amount to about a 3.5-fold increase by the end of the century.

9 See IPCC (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.

10 The potential role of air extraction in reducing future emissions has been considered by Keith et al. (2005) and by Pielke (2009).

11 Earthquakes are infrequent risks and the risk for any one location is extremely small.

12 Such as wind, biomass, hydroelectric, solar, geothermal, nuclear and even possibly fusion.

13 Which by the end of this century is expected to be about 3.5 times larger than today's energy use.

14 87% of the energy used today comes from fossil fuels and less than 1% is from renewable sources; 0.01% is solar energy.

15 See also Table 1.

16 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.

17 CO_2 remains for a long time in the atmosphere, at least 60–100 years or more.

18 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. As we reach 500 carbon parts per million, the average global temperature is expected to increase by three degrees centigrade, which means three times this amount in the polar caps triggering seal level rise.

19 Employed in the IPCC-TAR (2001). See also Wigley (2000).

20 These scenarios were developed by Roger Cohen, cf. Eisenberger et al., 2009

21 In May 2009, the US DOE allocated for the first time US$2.4 billion for research projects that include air capture of CO_2, as referred to here.

22 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

23 http://www.nrel.gov/csp/pdfs/35060.pdf

24 Both for solar photovoltaic and for CSPPT namely ‘Concentrated solar power parabolic through’.

25 Hereafter concentrated solar power refers to CSPPT unless otherwise noted.

26 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.

27 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.

28 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 percent for the raw material.

29 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.

30 This was provided for the first time by the United Nations Kyoto Protocol in 1997.

31 For a history of the creation of the Kyoto Protocol’s carbon market see Chichilnisky and Sheeran (2009).

32 Further statistics on the carbon market can be found in Capoor and Ambrosi (2007).

33 In 2006 the EU Commission stated that Phase I was a ‘learning phase’ and promised to assess 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’.