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. Alternative energy sources are needed for sustainable development in the long run. But in the short run the climate change problem requires immediate action and somewhat different strategies. One solution is to use carbon - neutral sources of thermal energy to co-produce electricity and air capture & storage of carbon dioxide, a process that provides more energy while reducing the carbon concentration in the atmosphere. This process changes entirely the relationship between the three problems: it can advance energy security and economic development while averting climate change in the short run. In the long run, it can accelerate the transition to alternative sources and is compatible with sustainable development. Short and long run challenges are addressed with this capability in the context of the carbon market created by the UN Kyoto Protocol, and the implications for industrial and developing nations of the transition from a fossil to a renewable economy.

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. The timing could not be worse. Two centuries of industrialization based on fossil fuels

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emitted large amounts of carbon dioxide into the atmosphere and created a serious risk of 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[2] and Florida is the next most vulnerable US site. It is now widely accepted that catastrophic 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 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. [3]

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 conflicts take several forms. Fossils generate about 87% of energy used in the world today. Since they are unevenly distributed on the earth's crust, they have led to wars and conflicts, prompting understandable calls for energy security and independence. At the same time economic development still depends

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[2] 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.

[3] Energy use is expected to increase five to ten times during this century, see 1. P. Eisenberger and G. Chichilnisky (2007) "Reducing the Risk of Climate Change while Producing Renewable Energy" Columbia University, May 2007. The US coal industry presented recently an ambitious plan to secure enormous subsidies for coal production in the name of energy independence.

crucially on the use of energy, and in today's economy, this means fossil fuels. In the longer term, the only way out is to disentangle the use of energy from carbon emissions, namely make available clean and abundant renewable energy sources. But this is not feasible in the short term because of the sheer scale of the fossil infrastructure that must be replaced: about $40 trillion today, and with current trends about $400 trillion by the end of the century[4]. The short term and the long term present different problems, and require different solutions.

Time is not on our side. Scientists from the Intergovernmental Panel on Climate Change[5] agree that we need to stabilize or reduce carbon concentration in the atmosphere in the next 20 years[6]. Avoiding further carbon emissions emphatically does not solve the short - term problem. Even if we stabilize at the current level of emissions we still continue to add carbon dioxide to the atmosphere at the current rate of 24 billion tons per year, and therefore increase carbon concentration. New coal plants that clean the carbon they emit are a step forward, but they create burdensome economic costs and in any case they merely stabilize the implacable growth of carbon concentration at current rates. More to the point, such coal plants defeat the long term objective of making an orderly transition to non fossil resources.

A new technology[7] has the capability to co-produce electricity without emitting carbon at the same time that it *decreases* carbon emissions by air - extraction and storage of carbon

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[4] US Department of Energy (DOE), 2006, http://www.eia.doe.gov/oiaf/aeo/index.html, table A1.
[5] Also denoted IPCC. The author of this article acted as lead author of the IPCC.
[6] For simplicity of exposition we will use the term "carbon" to mean "carbon dioxide" – although there are other greenhouse gases to be considered such as methane.
[7] Introduced in Eisenberger and Chichilnisky, 2007, op.cit.

dioxide emitted from other sources. In this process, the carbon concentration in the atmosphere decreases while producing electrical power. 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 from the short term to an alternative energy future, enhancing energy security and economic development. The paper shows how this technology can help resolve current global conflicts, and examines its implications for the carbon market created by the 1997 United Nations Kyoto Protocol. At the end of the paper we examine the implications for industrial and developing nations of using this technology, and the dynamics of moving from the fossil economy into a renewable energy economy.

2. Short term goals and long run objectives

A long run transition away from fossil fuels to alternative sources of energy[8] that are more broadly distributed can provide economic development and security without inducing global warming. The transition away from fossils sources seems inevitable in the long run, because they are limited in supply. Alternative sources of energy are a necessary condition for sustainable development in the long run, and the rapidly growing world demand for energy will require a variety of alternative sources. Supplies are not the problem. Solar, on its own, can easily meet a ten fold increase using only 2% of the energy that hits the planet's surface.

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

However optimistic one may be for the long run it is important to appreciate that this long run solution is *not* appropriate for the short run. A transition to alternative energy sources is expected to take a long time since most of the energy used in the planet today is obtained from fossil fuels from such as oil and coal[9]. As already pointed out the change will take time and require a massive new and expensive infrastructure.[10] Yet as long as we continue to use fossil fuels and emit carbon we increase the concentration of greenhouse gases, and the risk of catastrophic climate change.[11] Stabilizing the level of emissions is certainly helpful, but stabilizing at the current level of 24 billon tons of carbon dioxide emitted per year will continue to build up carbon dioxide in the atmosphere and increase risk. For this reason the IPCC asserts that we need to decrease emissions of carbon dioxide about 60-80% within the next fifteen or twenty years.[12] Clearly long run policies do not suffice. Immediate action is required to manage the risk of climate change.[13]

Managing catastrophic risks is not a new activity. 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

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[9] 87% of the energy used today comes from fossil fuels and less than 1% is from renewable sources, 0.01% is solar energy.

[10] See Table 1 below and Eisenberger and Chichilnisky, 2007, op. cit.

[11] Scientists agree that we need to consider 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. The earth's climate is generally believed to be one of them. In general, one views the risks as having "heavy tails" so that the possibility of rare events turns out to be much larger than expected.

[12] Currently 40% of out emissions are naturally removed from the atmosphere and stored largely in the oceans. In the long term, however, we may not be able to depend on this to happen, because in the past the reverse ha also been true, the oceans and land have stored less and the atmospheric concentration has increased.

[13] As we reach 500 parts of carbon per million, the average temperature is expected to increase by 3 degrees centigrade, which means about three times this amount in the polar caps triggering sea level rise.

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

decision making than the ones used for standard risks. For this purpose we divide the problem into short - run goals and long - term objectives; we show that these are quite different problems, and analyze them both,[15] including the challenging transition from short to long term strategies.

The short run problem is acute and time is not on our side. As already mentioned, a quick and drastic reduction in emissions is not feasible due to the sheer size of the fossil infrastructure to be replaced.[16] Indeed, rich and poor nations could be seriously affected by 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 is 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.

It seems clear that the two problems – managing risks in the short and in the long run – are quite different and require different solutions. For the long run a transition is needed to a non - fossil fuel economy, one that can accommodate the rapidly growing needs of 80% of the world's population who are starting their path to industrialization that will lead to a 10 fold increase in energy demand within this century. But for the short run we need instead a continuation of fossil fuel energy use and a simultaneous *decrease* in the

[15] We use here an approach to decision making in situations that was pioneered in 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, and . G. Chichilnisky "The Topology of Fear" Working Paper, Columbia University, 2006. It calls for the simultaneous consideration of standard and rare events using in each case decision tools that are appropriate for the timing and the scale at stake.

[16] Transitioning away from fossil fuels in a short period of time could increase the risk of social disruption, which could be catastrophic in its own right, since most human life is dependent on energy.

carbon content of the planet's atmosphere. This is a major challenge, and the topic of the article.

It is critical that short run goals be compatible with long term objectives, to avoid the trap of defeating long run aims by focusing solely on short run targets. Capturing carbon dioxide directly from fossil fuel power plants may delay the time of reckoning but it adversely impacts the long term objective of replacing fossil fuels by carbon neutral sources.

The technology strategy should accommodate both the short and long term goals, and the transition of the short term into the long term. This is a tall order because such a technology must simultaneously facilitate the transition to alternative sources providing for massive increases in energy supplies for the long run, while in the short run it allows the continued use of fossil fuels *and* decreases the carbon content in the planet's atmosphere.

We analyze a technology that offers this combination, using renewable energy to co-produce electricity and carbon dioxide capture & storage[17]. Such a combination is unusual and contrasts with the physical realities of the fossil fuels economy, when the more energy is produced the more carbon dioxide is emitted. The technology proposed has the property that the more electricity power it produces, the more it reduces the carbon content in the atmosphere. A summary of this technology and an assessment of its

[17] Eisenberger and Chichilnisky, 2007, op. cit.

costs is provided in the text box below. What remains is to examine its economic and political feasibility.

We estimate the short and long run costs of co-processing of electricity and carbon capture & sequestration, using solar thermal energy as an input.[18] The overall costs needed to reduce carbon dioxide in the atmosphere as required by the IPCC are examined, allowing for a ten fold increase in energy use that is predicted for the rest of this century. Finally we discuss the implications that such a technological transition would have on the global economy and for the continuation of the global climate negotiations, including in particular the carbon market created by the United Nations Kyoto Protocol beyond 2012.

3. Risk Management for the Long Run – Learning by Doing

Long term issues are more frequently tackled by the literature and provide the best starting point. This section examines the costs involved in averting the risks of Global Warming in the long term, exploring ways to ensure that expected benefits will exceed expected costs. One way to avoid the long run the risk of climate change is by transitioning away from fossil to alternative fuels and, for this purpose, one has to predict the future costs of power production using alternative energy sources.

[18] Other energy sources that produce thermal energy before producing electricity can also be used in a similar manner, Eisenberger and Chichilnisky, 2006 op. cit.

Hydroelectric power is only 6% of world energy use, about the same as nuclear, and 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 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[19]. It shows how efficiency increases at higher capacity or, equivalently, how the cost of producing energy decreases with installed capacity.

Since we focus on the long run, we take into consideration that 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, as mentioned above. 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), and hydroelectric lacks the capacity and has environmental consequences. But solar could meet the demand with

[19] See Andy S. Kydes, "Modeling Technology Learning in National Energy Modeling Systems", EIADOE-0607(99) The general methodology has been called "learning by doing" and it was introduced in economics by Kenneth Arrow in 1952. The data used in the article comes from the US Department of Energy, see Eisenberger and Chichilnisky, 2007. An illustration of the methodology for solar energy showing Department of Energy 'learning curves' for solar power production is in H. 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

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* are considerable simplified if we observe that, in a competitive market economy, the lowest costs alternative 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 coal - produced 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. For solar the case is quite different. Only 0.01% of the world's power is generated from solar energy generally, and in particular the technology called Concentrated Solar Power Parabolic Trough, also denoted CSP PT, being evaluated has an order of magnitude less installed capacity.[20] 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 1 below shows the evolution of CSP PT efficiency[21] in producing electricity when capacity expands, as predicted by the US Department of Energy.

Specifically, the US Department of Energy (DOE) showed that, as installed capacity of CSP PT solar plants increases, the cost of solar[22] goes down by 15% per each doubling of capacity.[23] This is illustrated in Figure 1, 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, however, 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.[24] 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

[20] See H. Price et al, op cit.
[21] Both for Solar Photovoltaic and for CSPPT namely 'Concentrated Solar Power Parabolic Through'
[22] CSPPT
[23] Cf, DOE op. cit. and Eisenberger and Chichilnisky op cit.
[24] Eisenberger and Chichilnisky 2007. For economic considerations all that is needed for the alternative sources to be competitive with fossil fuel electricity production.

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. Therefore, 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 cost, 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 1 depict 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 1 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.

At the same time, however, 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, we eliminated in the computation made above 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 amortization of fixed costs.[25] However if implemented in the short run one must consider the fixed costs and, as Table 1 below shows, these can be enormous, about between $200 and $400 trillion for the long run solution.

The entries in Table 1 below were computed on the basis of the number of 400MW CSP PT plants that would be needed to meet the long term increase in energy use for the rest of this century, expected to be a five to tenfold growth in energy use, as well as the

[25] This figure applies to the case of solar thermal energy driving electricity output, Eisenberger and Chichilnisky, 2007. 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.

number of plants needed in the short term to extract the current level of carbon dioxide emissions of 24 billion tons annually. The capital cost per plant were based upon a performance of 3 cents a kWh and $8 a tonne of carbon extracted, both achieved after learning; these are largely capital costs and imply approximately $200 million dollars of capital per 400 MW CSP PT plant.

Table 1
Number of Plants and Fixed Costs Needed in the Long and the Short Run[26]

	Long Run CSP PT Plants	**Short Run** Global Thermostat Plants
Plants Needed	1,000,000 - 2,000,000[27]	15,000[28]
Capital Costs[29]	$200 - $400 trillion[30]	$3 trillion[31]

The $200 - 400 trillion figure in Table 1 above represents the capacity needed to provide the 5 to 10 fold long run increase in energy demand and is clearly not realistic for a short term transition, since it is larger than the GDP of the entire planet, even though it is appropriate for the long run.

[26] Table 1 summarizes results in Eisenberger and Chichilnisky, 2007 and the assumptions under which it was created are in the text.
[27] This is based on today's global electricity production of $1.5x10^{14}$ kWh. Each plant is assumed to produce $0.7x10^{9}$ kWh yearly, cf. Eisenberger and Chichilnisky op.cit..
[28] The figure must be increased by the cost of stabilizing total emissions at today's levels, see Pacala and Socolow 2004. It is based on capturing & storing 24 giga tonnes of carbon annually at approximately $8 per tonne.
[29] Capital costs include the cost of building plants. The figures presented here do not include the income that flows from the sale of electricity and/or carbon captured. The Global Thermostat solution could produce profits almost immediately from the co-production of electricity and carbon credits sold in the carbon market.
[30] The range $200 - $400 trillion represents an allowance for the increase in energy that is expected in the long run. For example the $400 trillion capital cost represents the ten fold increase to satisfy the rapidly increasing energy demand of about 2.7%/year for the rest of this century.
[31] This capital cost is predicated on a $200 million per plant, under the assumptions of footnote 18 above, see Eisenberger and Chichilnisky 2007.

There are other ways of illustrating the difference between the long and the short term issues. The costs reported in Table 1 above involve replacing electricity power generated by coal, by electricity power generated by solar thermal, and the comparison can be problematic as long term 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, for example 'transportation', which represents about 28% of total energy use. Transportation is one of the fastest growing uses of energy in the world today, and the electricity produced by solar thermal could not replace fossil fuels in the short term 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.[32] 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 will be the topic of next section.

[32] 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 and Chichilnisky, 2007.

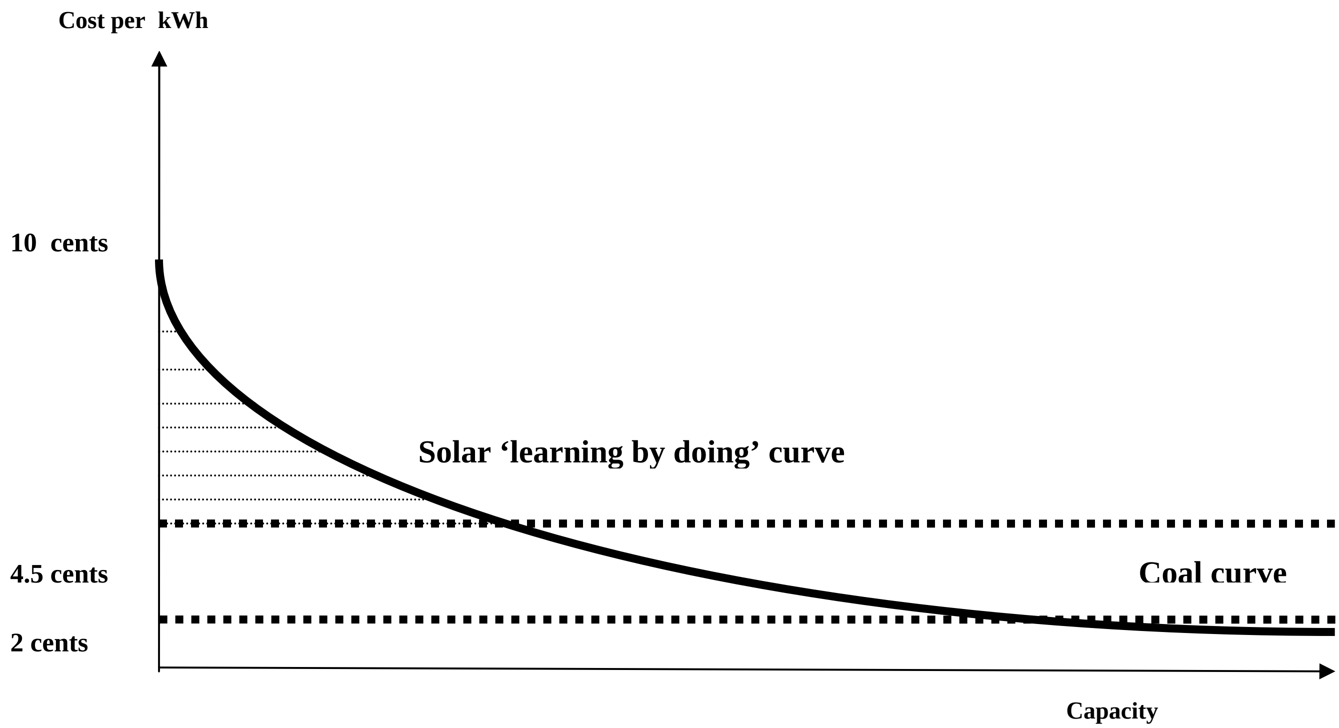

Figure 1
Expected long – run transition costs from coal- produced to solar - produced electricity are given by the shaded area above the 4.5 cents line and below the solar learning curve[33]

3. Managing Short Term Risks

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.

[33] Renewable resources other than solar thermal 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.

In the short term things are 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 till successful experience has occurred.[34]

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 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

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[34] A. Grubler "Long Wave: Technology Diffusion and Substitution" Daedalus, Summer July 1st, 1996.

different capacity levels. In the next section we compare these short term 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.[35] Currently we are emitting in net terms about 24 gigatons of carbon per year. 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 &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 Global Thermostat proceeds by increasing the built capacity of solar thermal plants, and the facilities created can eventually replace fossil fuels as a source of power. 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 fuels sources when they have depreciated their investments, we will by the end of the century reduce the need to extract CO_2 from the atmosphere, 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 fossil fuels, and therefore without further troublesome carbon

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[35] See Nicholas Stern, The Economics of Climate Change Cambridge University Press, 2006, Chapter 6, p. 188-189 and S. Pacala and R. Socolow , "Stabilization Wedges: Solving Climate Problem for The Next Fifty Years with Current Technologies" Science Vol. 305 (August 13, 2004), 268-272.
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emissions. The solution thus satisfies our requirement that short run policies should facilitate rather than defeat long term objectives.

The economic costs involved in the entire Global Thermostat processes are examined below, as are the consequences for the economics of carbon markets that were created by the 1997 United Nations Kyoto Protocol, which are discussed in the last two sections. Following the assumptions made above, the cost of capturing and sequestering 24 gigatons of carbon annually are as provided in Tabled 1 above. [36]

4. Insurance Premium for Catastrophic Risks of Climate Change

A recent widely distributed report[37] 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 term 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.[38] In order to compare the costs with standard insurance approaches, we provide now 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] Detailed computation and assumptions are provided in Eisenberger and Chichilnisky, 2007, op. cit.
[37] Nicholas Stern "The Economics of Climate Change" Cambridge University Press, 2006, Chapter 6, p. 188-189.
[38] A word of warning is in order when comparing the cost of insurance with the cost of carbon abatement: the implementation of the latter may not lead to a dollar for dollar reduction of insurance premiums and, of course, the beneficiaries many not be the same in the two cases.

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

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

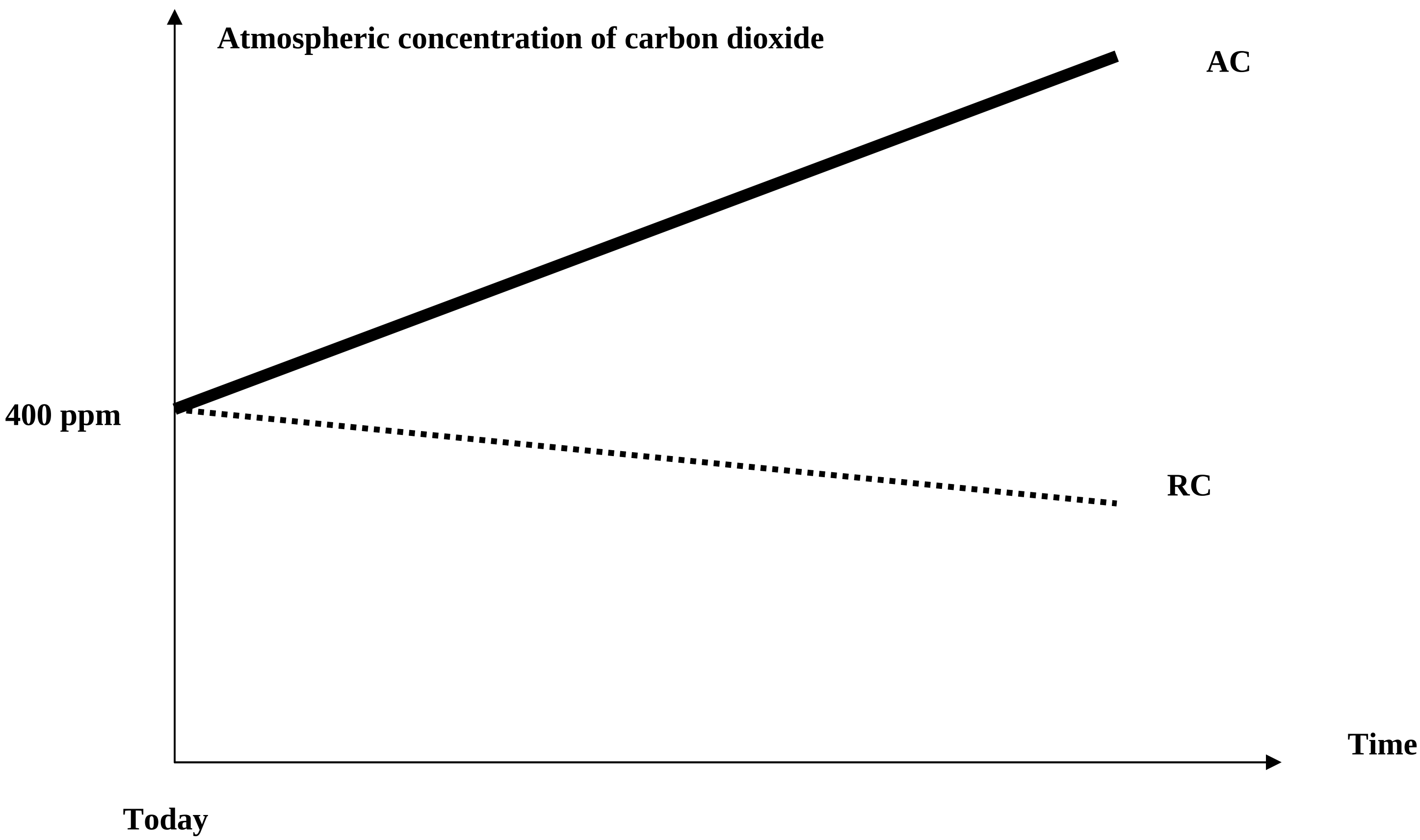
In Table 1 of the previous section we provided an estimate of the costs of using a Global Thermostat approach to avert the short term and the long term risks of Global Warming. Taking into account Sterns' evaluation of the potential costs involved in the catastrophic case[39] which is about 20% of global GDP or about 12 trillion,[40] while the annual premium implicit in the Global Thermostat as reported in Eisenberger and Chichilnisky 2007 is $200 billion, computed as the cost of capture & storage of 24 gigatons per year, at about $8 the ton. This annual cost is 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 the Table above, which 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

[39] Stern, op. cit., 2006, chapter 6.
[40] Current global GDP is about $62 trillion; 20% is about $12 trillion.

current levels, approximately 24 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 Global Thermostat 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 *carbon reduction* that actually reduces the current level of emissions or even *reducing the total concentration of carbon* in the[e] planet's atmosphere, therefore reducing the risk of climate change. Figure 2 below illustrates the three cases – only the third can avert climate change in the short run:

Figure 2
AC = Avoided carbon: reduces emissions but carbon concentration still increases
RC = Reduced carbon: reduces concentration through air capture of CO_2



5. The Carbon Market and its Impact on the Abatement of Global Emissions

A key economic incentive to transition away from fossil fuels and curb carbon emissions was provided by the creation of a so called "price signal" for carbon. These are costs on emitting carbon that are imposed by recent international agreements that resulted in the creation of the *carbon market*, which was proposed and wrote into the Kyoto Protocol by the author and adopted and signed by 196 nations in December 1997. Simply put, a negative incentive to emit is created by charging an emitter a price to emit each ton of carbon, which is determined by supply and demand in the newly created carbon market.[41] 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 Kyoto Protocol into international law in 2006.

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.[42] 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.[43] The carbon market has unique characteristics that distinguishes it from other markets, and will be discussed below. In

[41] See G. Chichilnisky "The Greening of the Breton Woods", Financial Times, January 1996, G. Chichilnisky Key Note Speech, Annual Meeting of The World Bank, Washington D.C., December 1996, G. Chichilnisky and G. M. Heal Environmental Markets: Equity and Efficiency, Columbia University Press, New York, 2000, G. Chichilnisky and G. M. Heal "Markets for Tradable 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 Netherlands, 1999, G. Chichilnisky "North - South Trade and the Global Environment" American Economic Review Vol 84, No. 4, September 1994, pp. 851-974, and K. Capoor and P. Ambrosi, "State and Trends of the Carbon Market 2007, The World Bank, Washington D.C., May 2007.
[42] This was provided for the first time by the United Nations Kyoto Protocol in 1997.
[43] See G. Chichilnisky and G. M. Heal, OECD, Paris, Economic Division Report "Markets for Tradable CO2 Emission Quotas, Principles and Practice" OECD Economics Department Working Paper No 153, 1999, 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: 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.

particular 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. For this reason, 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. The Kyoto Protocol actually comprises less than 40% of global carbon emissions.

Nevertheless, the carbon market has been quite active and has already shown great promise in reducing carbon emissions. 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,[44] although it currently does not abide by the Kyoto Protocol rules that it signed in 1997. The Protocol itself is in a period of flux, since its

[44] See World Bank "State and Trends of the Carbon Market 2007"

governmental obligations to restrict emissions expire in 2012, and new follow - up rules are being negotiated at present.

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. In 2006 the carbon market grew in value to an estimated US $30 billion, three times greater than in the previous year.[45] 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 Clean Development Mechanism (CDM) of the Kyoto Protocol, and Joint Implementation (JI) projects also grew sharply to a value of about $15 billion in transactions during 2006. The principles behind the CDM and JI projects are explained in a brief text box below. The voluntary market for reductions by corporations and individuals is much smaller, but it also grew by an estimated US$ 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.

Another frequently asked question is ‘who are the buyers in the carbon markets’. The main compliance buyers in the carbon market are:

1. European private buyers interested in EU ETS.
2. Government buyers interested in Kyoto compliance

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

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 US States 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)

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

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,[46] 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 contrast with the highly volatile 2006 EUA market, project based assets showed great price stability, while transacted volumes also grew steadily, and developing countries supplied nearly 450 MtCO_2e of primary CDM credits for a total market value of $5 billion. Average prices for certified Emissions Reductions (CERs) from developing countries were up marginally in 2006 at $US 10.90 with the vast majority of transactions in the range US$8-14. China continued to have a dominant market-share of the CDM with 61% and set a relatively stable price floor for global supply of CERs.

In sum, since 2002 a cumulative 920 MtCO_2e - equivalent to 20% of EU emissions in 2004 - have been transacted through primary CDM transactions for a value of US$8 billion.

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

[46] 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".

The previous section showed how, starting from a unique theoretical construct in the 1997 Kyoto Protocol, a functioning market was achieved in 2006, a carbon market that trades over $30 billion and has succeeded to reduce carbon emission and transfer about $9 billion to developing nations for CDM carbon reduction projects.

Despite the success of the market strategy, the stability of the carbon market discussed in the previous section 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 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, 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 Global Thermostat 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.

The ‘fundamentals’ of the carbon market, and how the market itself works, are explained in Annex 1 to this paper. Technology 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.

6. The transition from the short to the long run: from the fossil economy to the solar economy

It is possible to illustrate geometrically how a new technology impacts the so - called ‘transformation frontier’ between goods and abatement, and the changes that are introduced in the carbon market when the Global Thermostat technology is adopted.

The introduction of the Global Thermostat leads to Figure 7 below, which replaces the previous Figure 5 that was valid for a fossil fuel economy. Each installation of the Global Thermostat leads to a new curve, as illustrated in Figure 7. Since the Global Thermostat 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 Global Thermostat plant. Each carbon plant increases power and therefore output, but it decreases abatement, see Figure 8. 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 9, 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 Global thermostat 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 Global Thermostat strategy could have on carbon markets. Figure 10 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, eventually, as more of the infrastructure is based on renewable energy fewer caps are needed on emissions and therefore the carbon price will decrease and eventually in the renewable economy the carbon price is of course zero.

In Figure 10 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 4, 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.

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 quite 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 democratically 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 Global Thermostat, in the short and in the long run.

Figure 7
Each new GT plant changes the transformation curve between goods and abatement providing more power and increasing carbon abatement

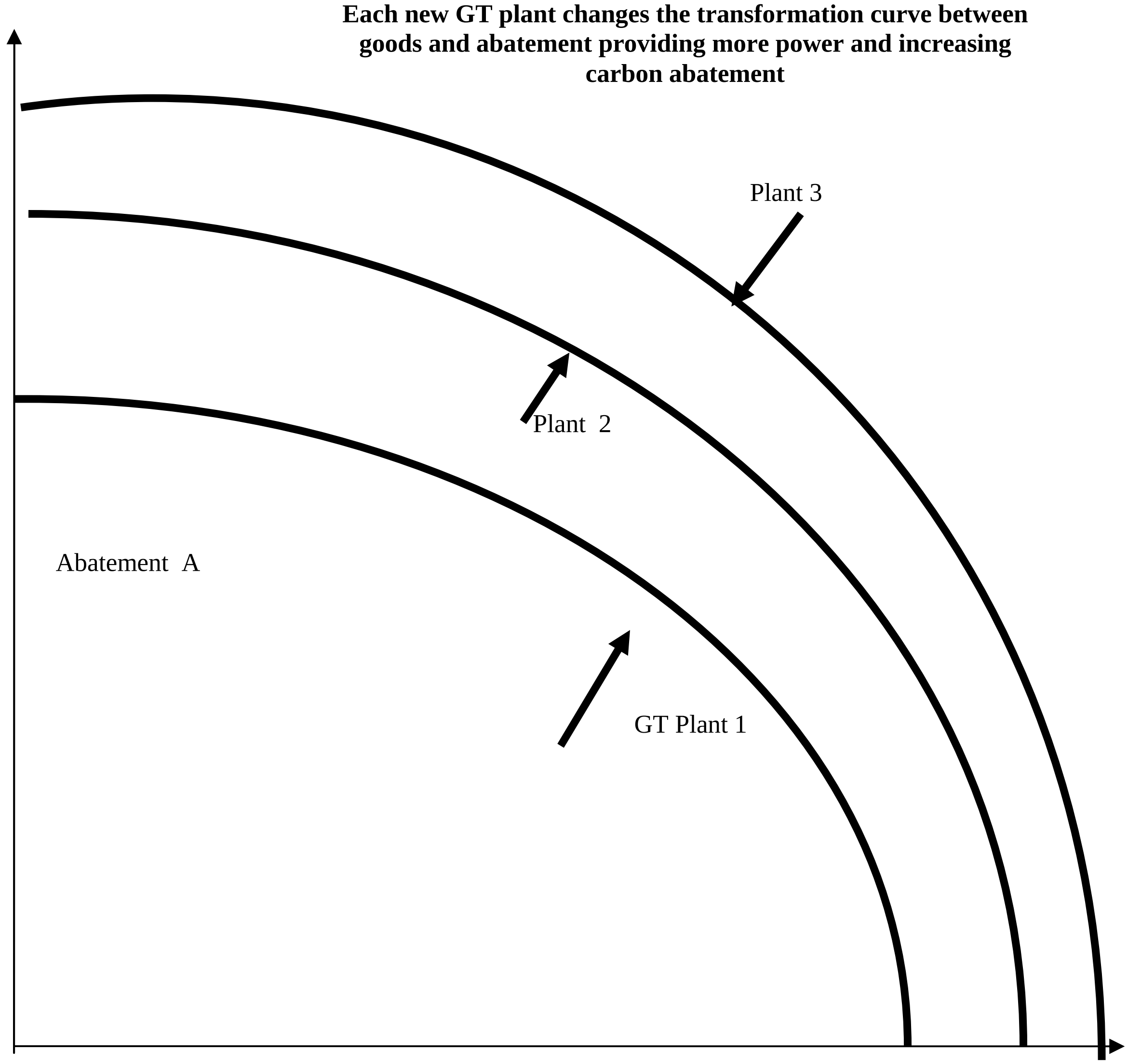


Figure 9
A new "clean coal" plant
Increases power - somewhat less - but maintains abatement

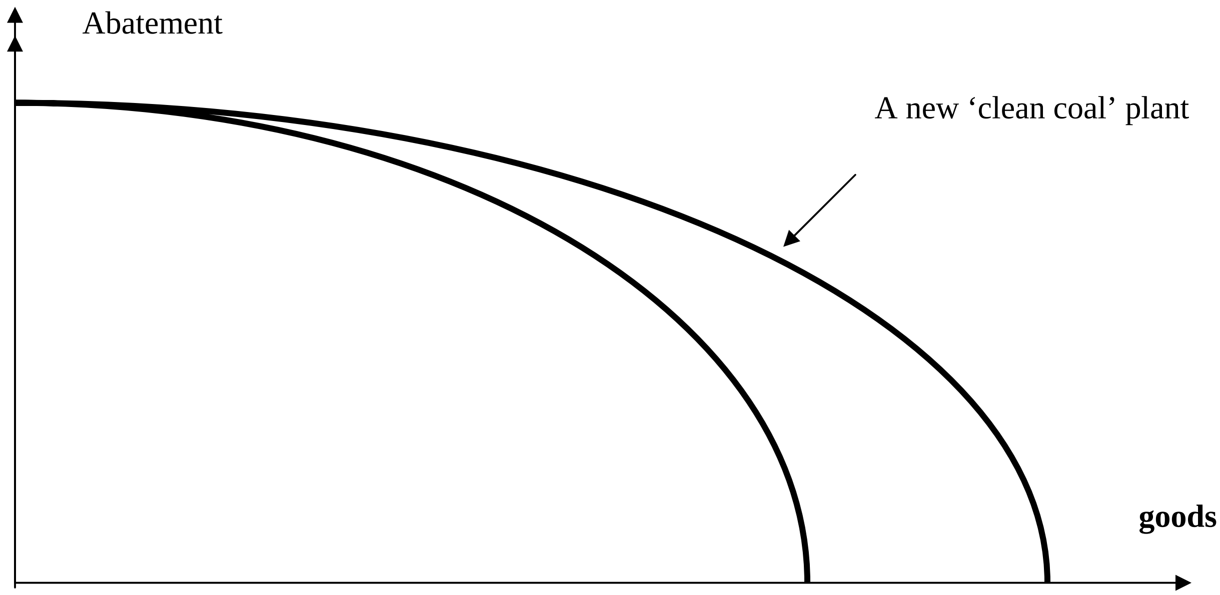

Abatement
A new ‘clean coal’ plant
goods

Figure 8
A new (standard) coal plant is built
It increases power and goods produced, but reduces abatement

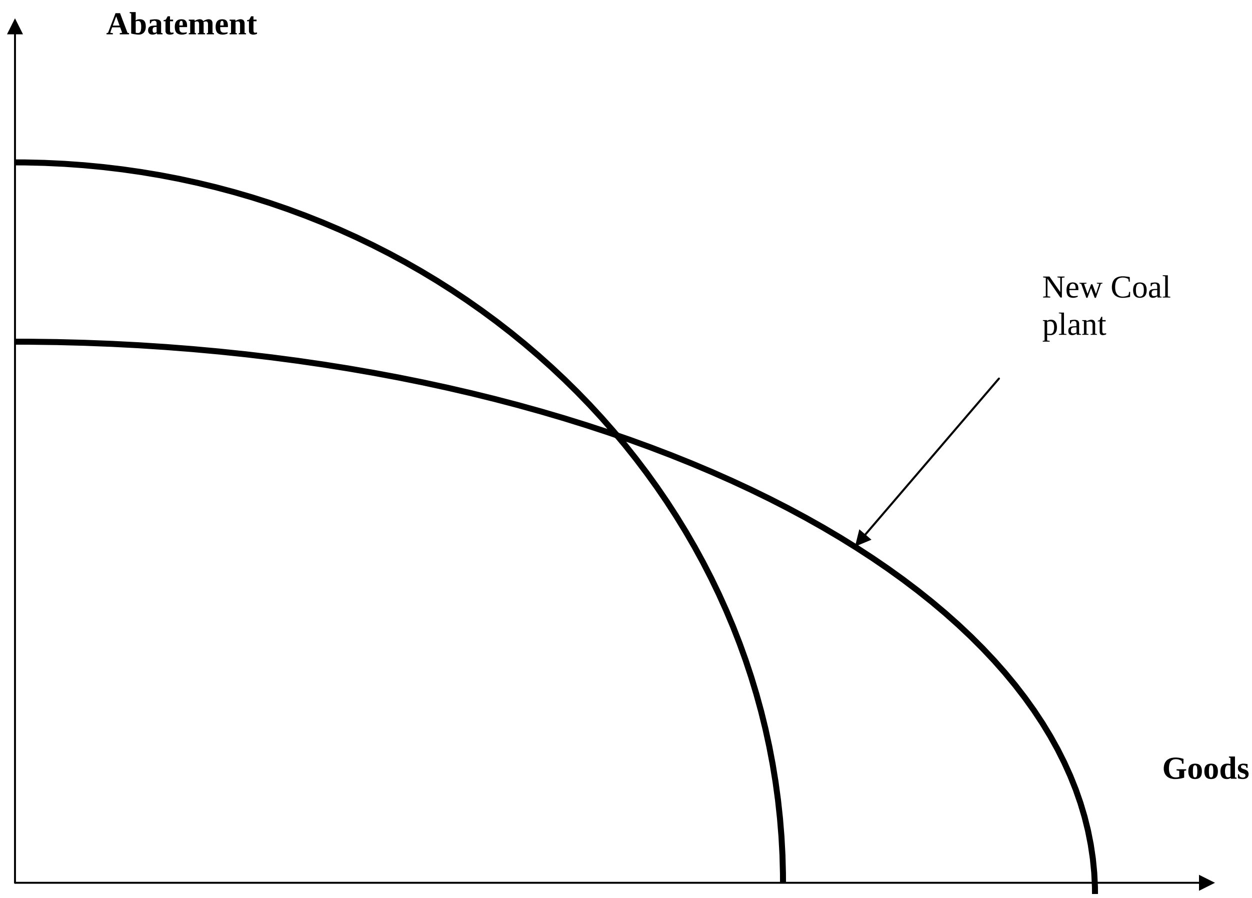


Figure 10
Carbon prices decrease as the fossil fuels are gradually replaced by a renewable sources

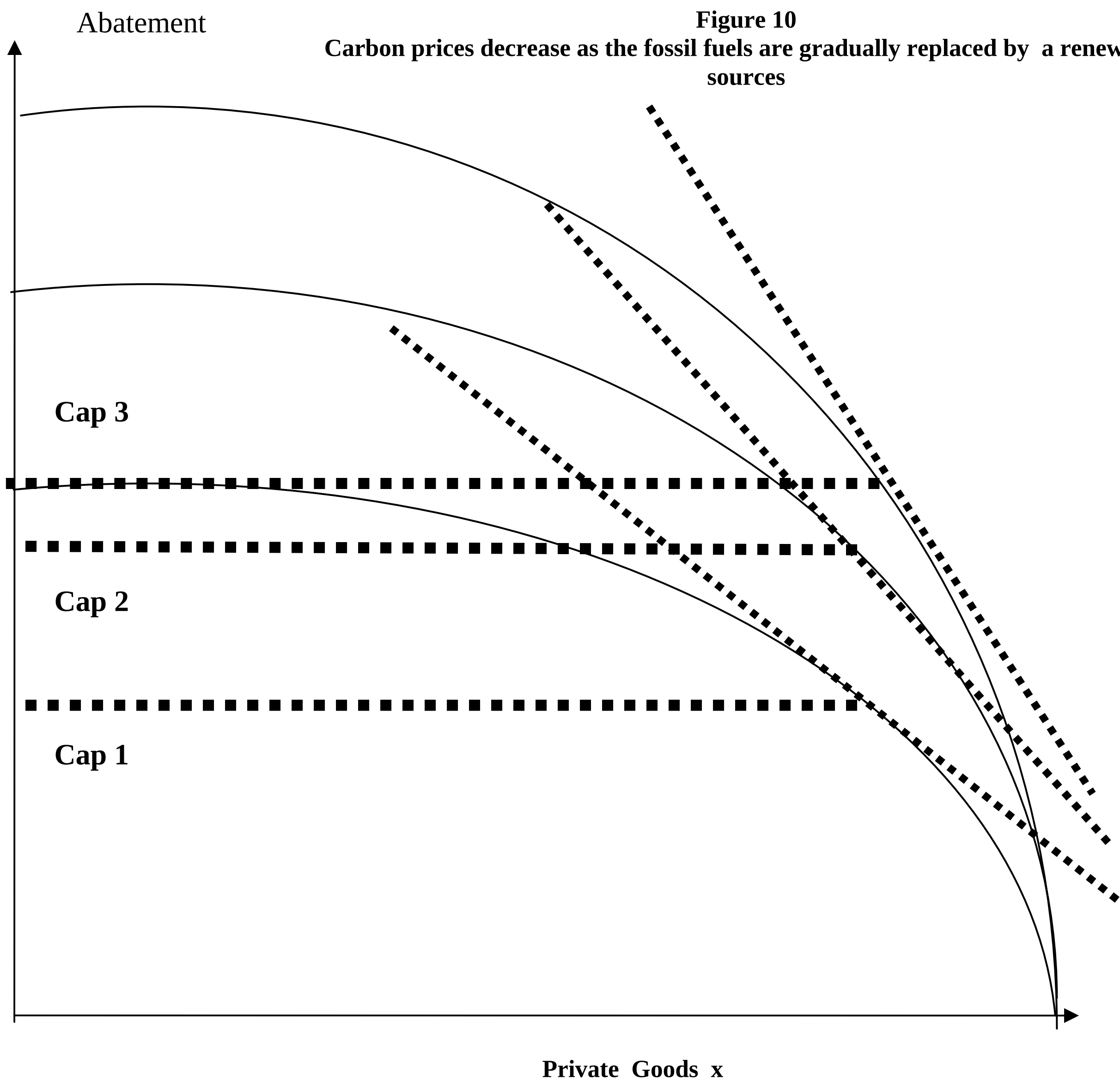


Figure 11:
Transition from the fossil fuel to the solar economy

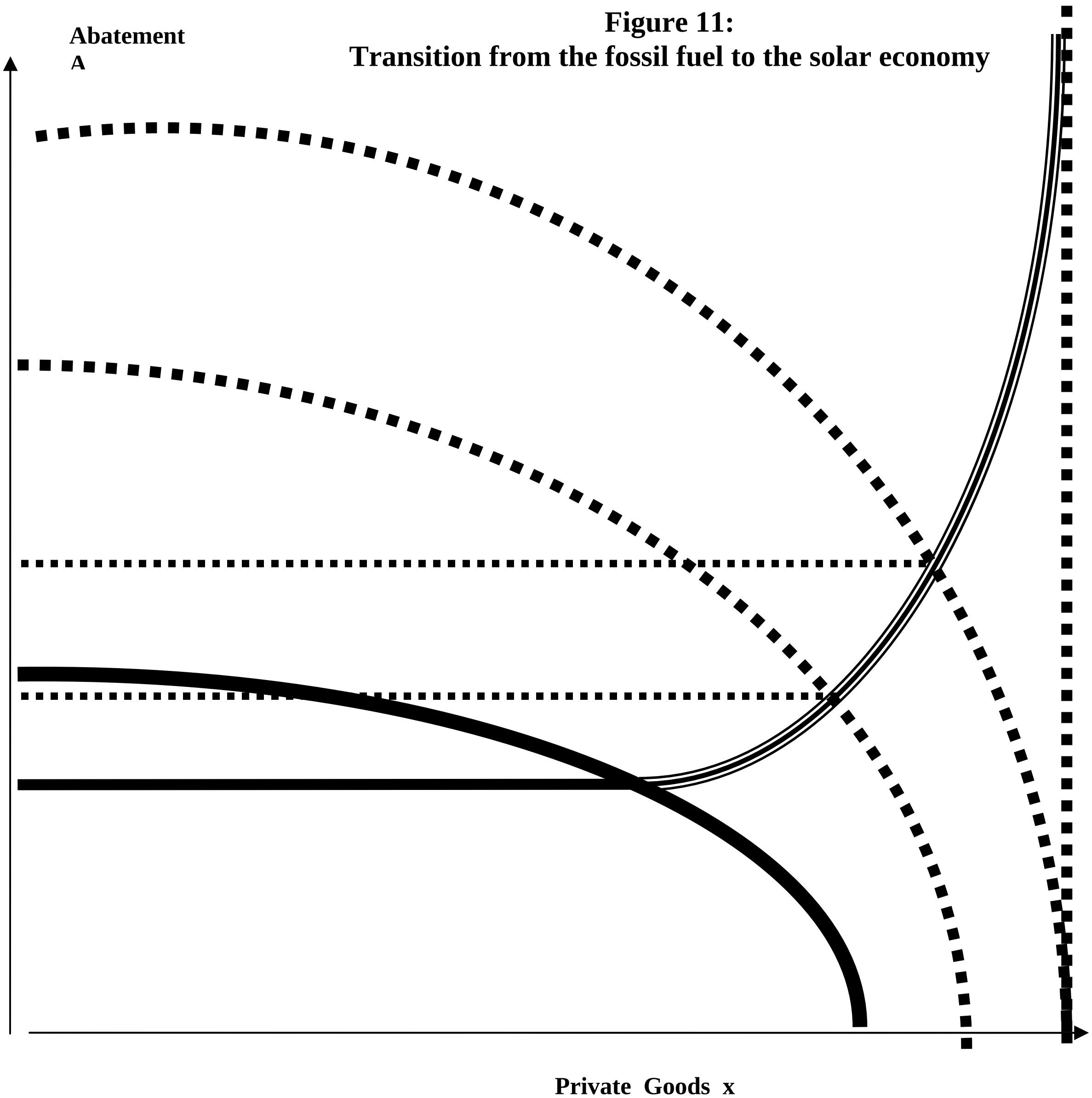


Figure 11 shows how the initial trade - off between more goods and a better environment decreases and finally disappears in the solar age. As Global Thermostat plants are installed and the caps on emissions decrease, the *short run* negatively sloped "transformation" curve indicated with a heavy line 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.

7. Developing Nations: Carbon Avoided and Carbon Reduced

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 plant per week. No policy can reduce the risk of global warming in the long run without finding a way to control and reduce their emissions.

Most of the power produced in this century will come from newly built power plants, because energy used 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 Global thermostat plants.

The figures above illustrate the difference between building a new standard coal plant, a “clean” coal plant, and a Global Thermostat 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 introduce instead Global Thermostat plants, which have the capability of increasing power and the production of goods without carbon emissions, and at the same time *decrease* the atmospheric concentration of carbon dioxide from other sources - thus decreasing overall the risk of climate change.

The Kyoto Protocol's carbon market ensures that reducing carbon concentrations provide more financial compensation for the developing nations (through the CDM) than simply stabilizing emissions. In particular the Global Thermostat 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 provides through air capture and storage. Thus the CDM can be a powerful tool in the financing of Global Thermostat Plants 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 transfer of technology and a source of clean and abundant energy to grow their economies.

8. Conclusions

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

Carbon markets have a crucial role to play. The carbon market is key to the adoption of carbon reduction technologies that are suggested here, in commercial terms. Carbon capture and storage adds costs to electricity production plants. Therefore a functioning carbon market with increasingly lower caps on carbon emissions is needed to provide realistic carbon market prices that can provide a revenue for investors in these plants and justify their construction in commercial terms.

Text Box 1: Global Thermostat

The terms Global Thermostat is used to describe a technology that has the unusual capability of increasing energy supplies while at the same time reducing the carbon concentration in the atmosphere. The technology is called Concentrated Solar Power Parabolic Trough, also denoted CSP PT, and deployed in power plants that use *solar thermal energy* as a source of electricity, using equipment called *parabolic troughs* that concentrate the heat produced by the sun and focus it into an absorbent material such as molten salts. The heat is used to run turbines that produce electricity. The residual energy used in this process – also called *process heat* – is then utilized by the Global Thermostat to run a carbon capture facility that extracts carbon from air, and to store the carbon dioxide in the soil within cavities provided for this purpose, or to manufacture solid materials from it such as limestone for housing and for road construction, or lyme as fertilizers. For each kWh of electricity produced, this technology is able to capture and store over 2.2 Kg of carbon. The more electricity the Global Thermostat produces, the more carbon it extracts. The Global Thermostat can use other forms of *process heat* to extract carbon from air, heat that is produced from other sources of renewable energy such as hydroelectric, wind, nuclear or geothermal. It can also use process heat from fossil fuel sources that are used to produce electricity such as coal, oil and gas, although most of the benefits accrues from renewable power plants (in the case of fossil fuel plants, the extraction of carbon has to do 'double duty', reducing the carbon the plant produces as well as the carbon already existing in the atmosphere). The Global Thermostat is able to reduce the carbon concentration in the atmosphere at a desired rate, and therefore in principle control global average temperature, thus explaining its name. While the Global Thermostat technology is new, it is based on proven technologies that provide (i) solar thermal sources of electricity, (ii) air capture of carbon dioxide, and (iii) storage of carbon underground or on solid materials, all of which are known and described in the literature.[47]

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[47] P. Eisenberger and G. Chichilnisky 2007 op. cit, Eisenberger and Chichilnisky own the patent rights for Global Thermostat. Klaus S Lackner et al., "The Case for Carbon Dioxide Extraction from the Air" Source Book 57 (9): p6-10. Klaus S. Lackner et al., "Carbon Disposal in Carbonate Materials", Energy 20,1153-1170(1995). Reference 6 in Kydes Report, 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

Text Box 2: Clean Development Mechanism (CDM)

The United Nations Kyoto Protocol was signed by 166 nations in 1997, including the USA, and was ratified in 2005. It includes a Table that provides limits for each industrialized nation (namely, an OECD nation) a quantity allowed for its emissions of carbon dioxide and other greenhouse gases. Developing nations have no emissions limits. According to the 1992 United Nations Climate Convention, developing nations have no obligation to reduce their emissions unless they are compensated for reducing them. The rationale for this is that, both currently and historically, about 70% of all global emissions originate in the OECD nations, who house about 20% of the world's population. The Kyoto Protocol provided three "flexibility mechanisms" for implementing the global emissions limits. One is the *carbon market*, by which OECD nations may freely trade among themselves their rights to emit, provided that, as a whole, they remain within the global limits. A second "flexibility mechanism" involves industrial and developing nations. It provides that *carbon credits* will be given to investors in industrial nations who invest in projects in developing nations' soil, in 'clean' technologies that can be proven (by the UN Climate Convention) to reduce carbon emissions below agreed

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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. 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.

country's baselines. The *carbon credits* can be used to reduce the obligations of industrial nations to emit, although the actual reductions in emissions occur in developing nations' soil. The credits can be traded in the carbon market at the prices established by the carbon rights trading among OECD nations. In 2006 $30 billion were traded in the carbon market, and a total of $8 billion worth of CDM projects were initiated in developing nations, amounting to about 20% of EU's carbon emissions.[48]

Text Box 3: Joint Implementation (JI)

A third "flexibility" mechanism authorized by the Kyoto Protocol, consists of joint projects initiated by industrial and developing nations with the purpose of reducing global emissions, and is called "Joint Implementation" because it is implemented jointly in industrial nations and in developing nations' soil. This mechanism involves bilateral agreements between countries and is therefore separate from the carbon market, and correspondingly it has been much smaller in scope than the carbon market or the CDM mechanism involving about $100 million in projects as of 2006.[49]

Annex 1

This Annex provides 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 when she proposed

[48] See Chichilnisky and Heal "Environmental Markets: Equity and Efficiency" Columbia University Press, 2000, which contains the Kyoto Protocol and a detailed record of its negotiation and explanation of its provisions including the Clean Development Mechanism.
[49] See World Bank Report "State and Trends of the Carbon Market 2007" op. cit.

the creation of the Kyoto Protocol 'cap and trade' system to the international community in 1995 and 1996, while it was presented in various meetings of the OECD the World Bank and the United Nations Framework Convention of Climate Change, and in the actual writing of the Protocol in Kyoto, December 1997. The results below 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.[50]

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 2 below. 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 3 below, and

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

[50] Some of the results discussed below have been published in G. Chichilnisky and G. M. Heal Environmental Markets: Equity and Efficiency, Columbia University Press, 2002, 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.

denotes the transformation between goods and carbon abatement A, whose slope is negative, as illustrated in Figure 4 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.

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 diffuses uniformly and stably throughout the planet’s atmosphere. This is called a ‘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 each other – 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 4 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.

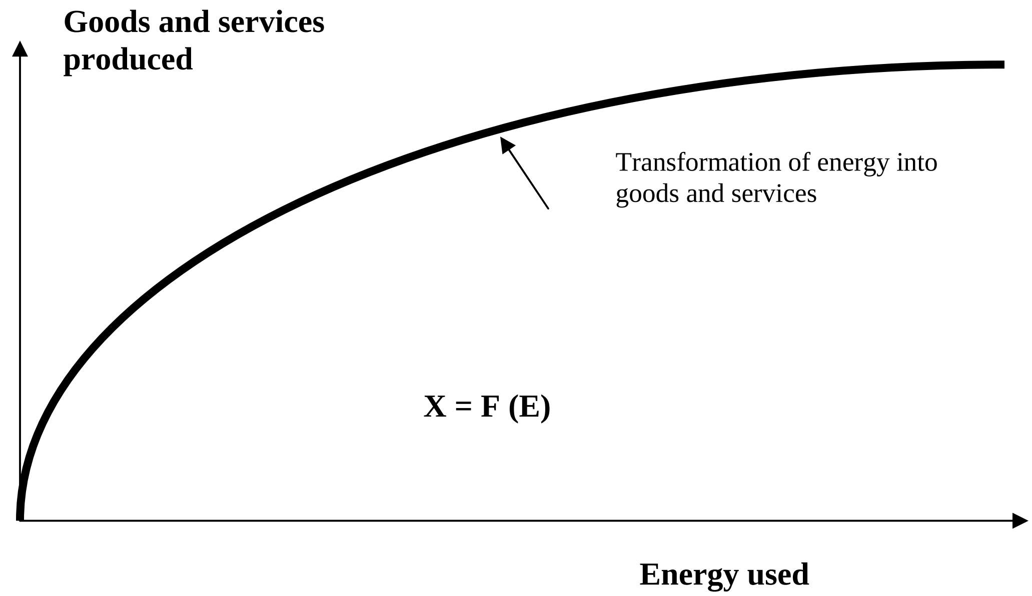

Figure 3
The transformation of energy into goods and services

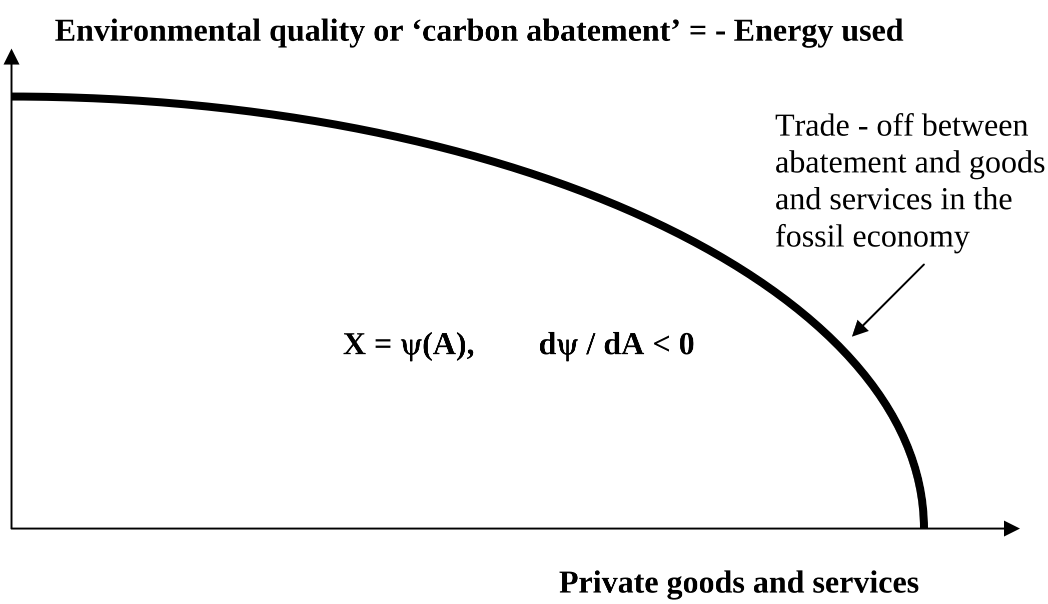

Figure 4
The more fossil energy we use, the more carbon we emit

One can illustrate geometrically how the carbon market works. Figure 5 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 5 is the same trade-off that is depicted in Figure 4 above.

Observe that each nation may use a different production technology, which is represented in Figure 4 above by a convex transformation curve. Therefore each nation in Figure 5 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 4 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 5, 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.

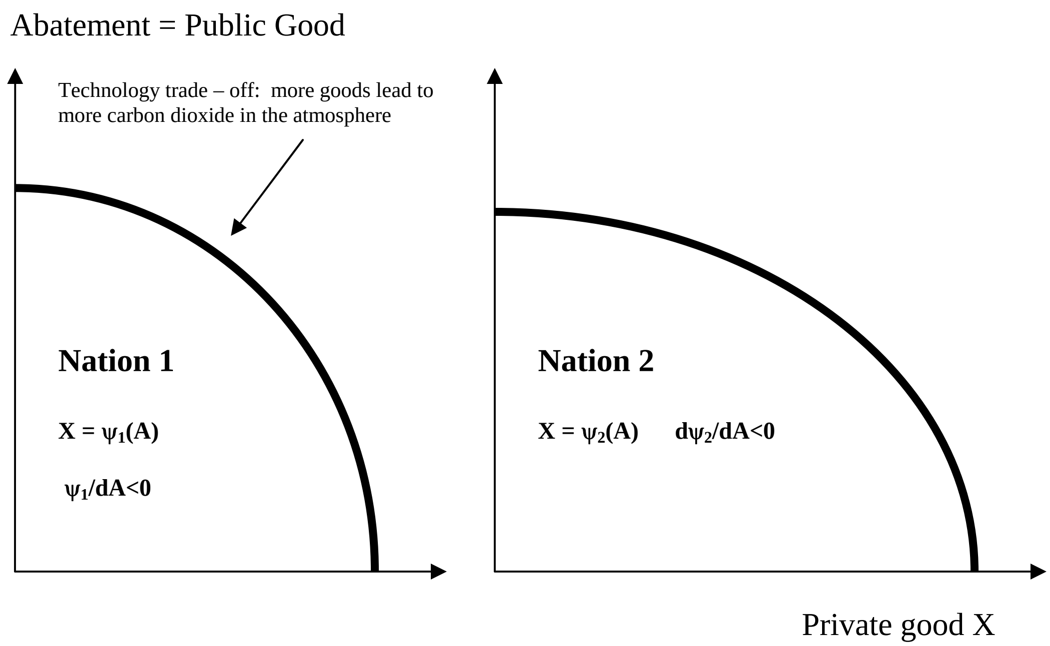

Figure 5

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

We now introduce the carbon market, which is illustrated in Figure 5 below. For this we assume that each of the two nations in Figure 4 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 5 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 6 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 6 that is valid for both nations, denoting the total decrease in emissions in the world economy, or "world abatement."

Using Figure 6, 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 the world economy, or just for the USA, and in the latter case the traders may be states, cities, or utilities depending on how the system is structured. However, in the latter 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. It is in fact 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 America, and vice-versa.

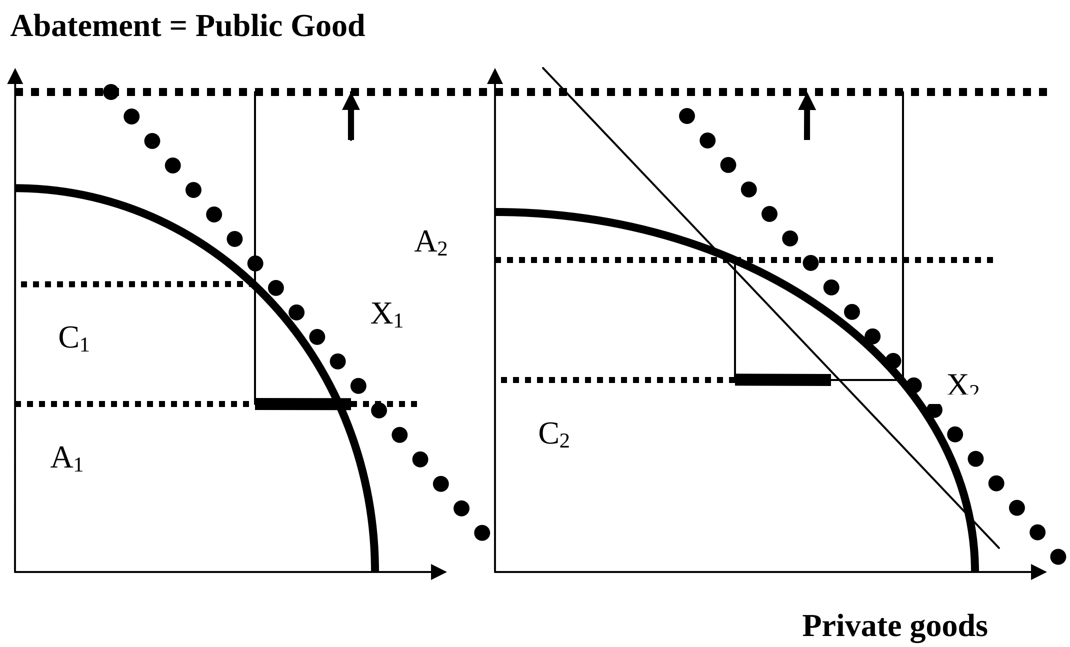

Figure 6

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 6 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 6 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 6. Nation 1 in Figure 1 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 6. 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 nation2 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 6. 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 4, 5, and 6 - play a key role in determining the price of carbon, as do the overall market 'caps' that are determined by governments.