# Climate Change:
# Combining Mitigation and Adaptation

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Forthcoming in: "Beyond Kyoto: Meeting the Long-Term Challenge of Global Climate Change", edited by David Michel; Washington: Center for Transatlantic Relations, Johns Hopkins University, 2004.

***Executive summary***

*Anthropogenic climate change currently develops as an externality from human energy use. This externality causes far-reaching inefficiencies in the working of the global economy. A rich body of research has shown that the best way to eliminate these inefficiencies is to let the owners of non-tradable resources threatened by climate change sell tradable permits to use some, but not all, of these resources. In the long run, this should lead to a flow of economic resources from highly industrialized countries to less developed countries – a resource flow also desirable for a healthy development of the global economy.*
*To deal with the inevitable uncertainties involved in climate change, the receipts from selling permits should be used to finance insurance pools. These pools can then be administered by insurance businesses, enabling effective insurance schemes in regions of the world where otherwise no viable insurance markets could be established.*
*By establishing a market for emissions permits coupled to an insurance pool to cover adaptation and damage costs, the climate externality can be fixed. In order to do so, negotiations are necessary to define and allocate the relevant property rights. Viable bargaining solutions can be found by building win-win situations on the basis of heterogeneous preferences, and by developing and applying social norms of fair behavior.*
*Climate policy, however, can and must do much more than eliminating an externality. The world economy as a system of interdependent markets differs from an isolated market by offering a variety of possible equilibria. Climate policy means to choose what kind of equilibrium we want the world economy to realize.*
*This task of equilibrium selection raises a serious issue of trans-atlantic co-ordination. Neither the U.S. nor the EU is in a position to select a global economic equilibrium unilaterally, or in fact without involving other regions of the world. So far, the trans-atlantic siblings have not yet found a way to tackle the task of equilibrium selection in a pluralistic mode. Promising first steps, however, are currently being undertaken around the prospect of establishing hydrogen as a main energy carrier. Patiently extending these commitments in a process of social learning seems the most promising way to build on the precious, albeit limited experience of the Kyoto Protocol.*

## 1. The challenge

Each human being forms an eddy in the stream of solar energy running through the biosphere.[1] We are not like crystals, more like flames. The molecules making up any human body get substituted in the course of time; what stays is a unique pattern of energy flow, like an eddy in a mountain creek. For the largest part of history, we humans have shaped our environment mainly via this energy that keeps our bodies going – like an eddy slowly smoothing the stone over which it flows. The pharaohs of ancient Egypt could build pyramids, but only by forcing large numbers of slaves to carry the stones. Of course, humans learnt quite early to use fire for cooking and heating, animals for drawing wagons and pulling ploughs, wind-energy for sailing, the gravitational energy of rivers for driving mills, and, most importantly, solar energy for growing plants. Still, the less than 100 Watt of power flowing through the human body remained the key source of energy until the concept of physical energy was discovered out of new technological practices.

This discovery was the work of specialized communities - of scientists, engineers, craftsmen - already living in a complex market system. The same market system enabled miners to dig coal out of the ground, other workers to produce steam engines, still other ones to produce all kinds of goods – machines, textiles, clothes, etc. - with machines driven by the power gained from coal. Without the market mechanism, it would have been impossible to co-ordinate all these activities, as the failure of centrally planned economies has so dramatically shown. In the industrial revolution, technological and institutional innovation went hand in hand.

Meanwhile, electricity is omnipresent in highly industrialized countries, the car has changed the face of cities and landscapes, oil and natural gas have supplemented coal as major sources of commercial energy. These developments were combined with the amazing sophistication of the human activities dealing with physical energy. New industries - like the car industry - and new forms of professional knowledge - like electrical engineering - have emerged, with older ones deeply transformed by progress in energy technologies. As a result, nowadays the power provided by the human body is dwarfed by the more than 10,000 Watts of fossil-fuel based energy used per head in North America, or by the more than 5,000 Watts used in Europe and Japan.[2] There is no doubt that this increase in commercial energy use has been an important component in the increase of human welfare in many dimensions - life expectancy, levels of schooling, range of medical treatments, opportunities for traveling, material comfort, etc.

Fossil fuels are not the only sources of commercial energy. They have been complemented by hydropower, by other forms of renewable energy, and by nuclear energy. Often, however, discussions on energy issues miss the fact that non-fossil sources provide less than one tenth of today's commercial energy worldwide. What discussions on energy issues don't miss so often anymore are the risks of climate change. The scientific community has succeeded in convincing large parts of public opinion as well as large parts of today's political and business elites that humankind has begun to alter the global climate system in potentially very harmful ways.

When humans learnt to produce commercial energy from fossil fuels, the global atmosphere contained about 600 billion tons of carbon. This amount of carbon was a critical factor in the global climate system, influencing temperature, weather patterns, ocean currents, and the conditions of life all over the planet. By now, we have added some 150 billion tons of additional carbon, bringing the total amount to about 750 billion tons. The analysis of ice-cores, containing traces from pre-historical times, as well as further data, suggests that this amount is much more than has ever be present in the atmosphere for at least three million years.[3] And the analysis of fossil records indicates that our first ancestors started walking upright on the surface of the Earth much later than that.

Our ability to use the energy flowing throuth our bodies to shape much larger extrasomatic energy flows comes with a responsibility. The Earth as a whole has becoming our garden, as it were, and we can make it as wonderful as a Tuscan landscape and as terrible as the ashes of Hiroshima. Learning to manage the additional carbon we are putting into the atmosphere is a step on the way of learning to develop a sense of responsibility for the Earth.

The effects of the additional carbon we have put into the atmosphere so far will take a few decades to become apparent. In the meantime we are increasing it even further. Along with carbon dioxide, we are adding further greenhouse gases to the atmosphere. Roughly speaking, this means that the climate system is being driven away from its past range not only by the 150 billion tons of carbon mentioned above, but by a total amount of greenhouse gases corresponding to more than 200 billion tons of carbon.

Over the past two centuries, we have increased the amount of additional carbon in the atmosphere at a rate of about 1 percent per year. Mainly due to the use of oil besides coal, in recent decades this rate has increased to about 4%. In the coming decades it will be somewhat lower – global population growth is finally slowing down and is unlikely to accelerate again. Fossil fuels use per unit of GDP is decreasing, too, and no technology is in sight that might reverse this trend. Economic growth might accelerate somewhat, but hardly so much as to offset these two effects. A 3 percent annual increase is a reasonable upper bound to what we may do to the atmosphere in the long run.

Are there limits to the growth of greenhouse gas emissions because of limitations in the amount of fossil fuels available? In principle, this is of course the case. In practice, however, the Earth's crust contains enough fossil fuels – especially coal – to enable us to increase the additional carbon in the atmosphere at a rate of 3% for about two centuries, until we would have reached something like seven or more times the pre-industrial level of carbon in the atmosphere.[3a] This is a perfectly realistic scenario, and it would involver huge risks from massive sea-level rise, abrupt climate change, and various kinds of extreme weather events.

The challenge of climate change confronts us with contradictory tendencies in the working of today's global market economy. On the one hand, there is the amazing record of progress in many areas, on the other, the prospect of global risks unknown to earlier ages. Climate change is a major risk of this kind, but certainly not the only one.[4]

To a very large extent, the debate about the contradictions of globalization in general, and about climate change in particular, has been shaped by a key finding of economics: the possible optimality characteristics of market equilibria and their impairment by external effects. The full force of this finding has not yet been appreciated in the debate on climate change, however. By now, the climate debate is at a stage where it will become essential to take advantage of all the knowledge available in this field.[5] Otherwise, the impressive process of international environmental policy that has been triggered by concern about climate change may well end in a stalemate. The mismatch between political rhetoric and actual growth of greenhouse gas emissions would then further increase, and sooner or later large-scale human suffering would result, although it could have been avoided at reasonable monetary costs by starting to move towards effective policies now.

## 2. A few things we know about markets

In many ways, understanding the global economy we live in is as difficult as understanding the brains we think with. We will perhaps never achieve anything close to a comprehensive understanding of these domains of reality, and we certainly have not achieved such understanding so far. Still, in both areas there are robust and important findings, and much suffering can result from ignoring them. In the case of markets, one such finding concerns their efficiency. We do know that markets can be and often are efficient in the following sense. When markets clear – i.e., when demand matches supply for the goods and services traded – they can realize a state of the economy where no economic agent can be made better off without making some other agent worse off. Even when people have very different preferences in many respects, they may well agree that an efficient state is better than an inefficient one.

While economic models are often based on rather questionable assumptions, markets can be shown to be efficient under a whole range of quite realistic assumptions. In the 20th century the provision of households with goods and services as well as the productivity of firms under a market regime have shown an amazing superiority in comparison with centrally planned regimes. The comparison with pre-capitalist institutional settings, be they European feudalism or the arrangements of various non-European kingdoms and empires, has shown the same kind of superiority. Moreover, examples abound of inefficient markets due to various forms of political restrictions, with agricultural policy perhaps offering the most striking examples. This is not to say that markets are the best form of life humankind can possibly experience, but it is to say that when it comes to provision of goods and services, markets have a capability to meet the needs and desires of people in a way that is hard to match with other institutional arrangements.

A second finding concerns inefficient markets. It points to the root of the climate change problem. Markets are bound to be inefficient if some economic agents can erode non-tradable resources in possession of other agents. And they are bound to be inefficient if investment decisions depend on inadequate expectations for the future. As we will see, both conditions are combined in the present trend towards anthropogenic climate change.

To investigate efficient and inefficient markets, economists have developed models of interdependent markets with and without externalities.[6] For our purposes, a good start is to imagine an island in the sun, surrounded by a nice white beach somewhere in the Pacific. Its inhabitants enjoy the beach; moreover it enables them to run tourist resorts from which they get their income. The tourists come from a place called moneyland, and they travel to the island once a year to recover from the stress they endure during the rest of the year. By enduring that stress they manage to produce TV sets, computers, and the like, and to earn the money with which they can buy these things as well as fly to the white beaches in the Pacific. However, as soon as the inhabitants of moneyland emit more than some limited quantity of greenhouse gases on their flights to the island, they gradually alter the climate system. As a result, they drive the sea level in the Pacific up. The white beach disappears, making life on our island less pleasant for everybody and less rewarding for the islanders. (One may wish to expand our metaphor by introducing additional sources of greenhouse gases, ranging from heating systems to car traffic – the key point would remain the same.)

If the white beach of our Pacific island is jeopardized by climate change caused by highly industrialized countries, then non-tradable resources of the islanders are relevant for the well-being of all parties involved. Now compare an inefficient equilibrium with serious damage to our island with a conceivable state where less extreme energy use helps preserve its beauty. Clearly, the inhabitants of the island will prefer the latter to the former. One might suspect that the inhabitants of moneyland will see things the other way round, but this need not be the case. After all, tourists enjoy the white beach, too, and they are willing to forego some other consumption in order to fly to the Pacific island. Therefore, if the beach is in better shape thanks to reduced fossil fuel use, the inhabitants of moneyland may actually be better off, too.

Now imagine for a moment that moneylanders would have to buy the right to emit greenhouse gases each time they want to fly to the island. They would have to buy it from the islanders in the form of tradable permits. The non-tradable resource – the white sand beach – would still not be traded. But the right to engage in activities that may degrade the beach can and must be sold and bought. With such an arrangement, the inefficiency caused by the external effect of anthropogenic climate change would disappear, and markets could display their efficiency in this domain, too. Incidentally, this is not so different from what is happening when visitors pay a fee to enter a camp in a national park.

Summing up: If some part of humankind has an entitlement to some non-tradeable resources while another part of humankind is able to take advantage from eroding these resources without paying for them, the resulting global economic equilibrium is inefficient. This inefficiency can be overcome by letting those entitled to the resources in question sell rights to use these resources to those taking advantage from such use.

## 3. Negotiating risks and opportunities

### *3.1 Insuring risks*

In order to apply this insight in actual climate policies, it must be embedded in an understanding of three key features of the climate problem. The first such feature is uncertainty. Politicians have known about the inevitability of uncertainty at least since Machiavelli, who emphasized how successful policies could only result from an interplay between necessary virtues of decision-makers and surprising opportunities brought about by destiny. Science took a bit longer to start recognizing that uncertainty is not a preliminary state of ignorance, but a key feature of the human condition. Advances in the study of non-linear dynamics have fostered greater realism here, and slowly the logic of quantum mechanics is changing the fabric of human knowledge: We have gradually gotten used to the fact that increased certainty about some aspects of reality sometimes generates increased uncertainty about other aspects.[7] As anthropogenic climate change will develop, for instance, we will become more certain about some aspects of this change. At the same time, we will become more uncertain about frequencies and intensities of at least some kinds of extreme events.

In the image of our Pacific island, erosion of the white beach will not be a steady process that can be predicted in a detailed manner. Rather, we need to enrich the picture by including storms that initially follow a reasonably well-known probability distribution. Due to anthropogenic climate change, intense storms become more frequent, thereby eroding the beach. But it may take a long time until a new probability distribution can be identified. Another aspect of this uncertainty is that the effect is not only non-linear but lagging: beach erosion may follow much lander than the moneylanders' air travel – and may in fact continue after the moneylanders no longer voyage by air or even vacation on this beach. The problem, however, must and can be addressed before all its effects have played out.

As a consequence, the sale of tradable permits envisaged in the preceding section must be combined with an insurance scheme. To illustrate, let us imagine that different islanders own different parts of the white beach. They would then form an insurance pool to be financed not out of insurance premia paid by beach owners, but rather out of the receipts from selling permits to burn kerosene to the moneylanders. When a particular piece of beach is eroded by a storm, the insurance pool will compensate the owner of that piece.

Such arrangements lend themselves to interesting forms of public-private partnerships. The islanders may well buy the services of regular insurance businesses to run their insurance pool. After all, from the point of view of the insurer, it doesn't matter very much whether the insurance scheme is financed out of standard insurance premia, out of the sale of tradable permits for burning kerosene, or out of some other source of revenue. Given the low purchasing power available, no attempt to finance insurance for flood risks in Bangladesh from standard insurance premia would lead to a viable market. The sort of public-private partnership sketched here, on the other hand, would create such a market. From the point of view of our islanders, the best way to deal with the inevitable uncertainties of climate change may well be to let different insurance businesses make competing offers for running the insurance pool for a given period of time and then select the offer they like best.

*3.2 Bargaining*

Besides uncertainty, a second feature of the climate problem needs to be addressed: the necessity of negotiation. So far, we have seen how market inefficiencies can be overcome by introducing additional markets. Besides the markets for commercial energy, especially the ones for fossil fuels, one needs to establish markets for tradable permits to burn such fuels. And on this basis one needs to establish markets for insurance services provided in a frame of public-private partnerships. But these new markets can only be established on the basis of negotiations.

In the case of the white sand beach, it may be necessary to go through a difficult negotiation process to define who will own what part of the beach. And it will certainly take difficult negotiations to define who is entitled to offer a tradable permit to burn a given amount of kerosene.

If we think about climate policy in the coming decades, we must address the thorny question of who should be compensated with what amount if people die in a flood event of a kind whose frequency may be increasing because of climate change. There is no way of settling such issues without one kind or another of negotiation process involving a whole array of interested parties. And difficult negotiations will be needed if the U.S. is to engage in effective policies to reduce greenhouse gas emissions. The American way of life has developed on the basis of abundant and cheap oil. For many strong reasons, simply scrapping this way of life is not an option. But modifying it so as to free it from the addiction to cheap energy will not be easy.[8] And it will certainly take complex negotiations in which the U.S. is offered strong incentives to perform such a quantum jump in the development of the American way of life. A symmetrical problem arises with countries like China. They have missed the experience of a situation where the availability of cheap energy from fossil fuels could be taken for granted. They will certainly not simply forget this and accept major increases in the cost of using commercial energy without further ado.

Findings about efficient markets are of little use when it comes to negotiations. Even the applicability of game theory is in doubt. There are good reasons to rely on game theory in the analysis of stable organizational settings where certain interactions are repeated time and again.[9] But there are also good reasons not to rely on game theory in the analysis of singular interaction chains like those of negotiations about the second committment period under the Framework Convention on Climate Change. Instead, one may build on historical analogies and anecdotal evidence. While this is certainly appropriate to some extent, there is by now a remarkable body of literature on bargaining and negotiation that provides several important insights. Based on the work of mathematicians like Knaster, Banach, and Nash, scholars working on fair division problems and related questions have elaborated robust procedures to support difficult negotiation processes.[10]

In particular, it is often possible to create win-win situations (i.e. to escape from a social dilemma via a Pareto improvement) by exploiting the fact that different parties usually have different preferences with regard to the same objects. Rather than first reducing all the items relevant for the negotiation to a common metric like GDP, money, transferable utility and the like, it may be much better to deliberately enlarge the issues to be negotiated in such a way as to obtain a range of non-transferable and diverging utility indices.

As an instructive example, consider the case of China. Its huge coal reserves offer an opportunity to support economic growth with cheap energy, while Europeans may be rather concerned about the greenhouse gas emissions so generated. On the other hand, China is rightly concerned about the difficulty of producing enough food to feed an increasingly affluent population, given the scarcity of water in large parts of the country. From a Chinese point of view, turning primarily to American food exports is not very attractive for geopolitical reasons. On the other hand, Europe has a serious problem of agricultural overproduction, with well-known consequences for the Common Agricultural Policy. This situation opens up the possibility to create a negotiation space with feasible win-win solutions to a negotiation problem that might be insoluble as a pure climate policy issue.

The second insight from negotiation research concerns the importance of social norms. By combining Edgeworth's analysis of bargaining with Walras' analysis of markets, one can show how the set of possible outcomes of bargaining processes converges to the set of market equilibria as the number of the parties involved increases indefinitely.[11] In this kind of analysis, the outcome of a negotiation about dividing a cake between a few parties can lead to any outcome whatsoever. In practice, however, historical contingencies and social norms greatly reduce the set of possible outcomes.[12] Absent historically given asymmetries, with two bargaining parties, a fifty-fifty sharing is by far the most likely outcome.

A key finding on the importance of social norms comes from research on the so-called ultimatum game.[12a] Here, agent A is allowed to make a single take-it-or-leave-it offer to agent B regarding the division of some sum of money. If B agrees to the split, each receives the amount proposed by A. If B declines, then neither player receives any money. In theory, B should rationally agree to accept any share of the money offered by A, since the alternative is to receive nothing at all. Yet experiments in various settings find that, quite independently from the sum involved and from the wealth of A and B, it is very rare for this deal to work unless B gets a share between one third and one half of the sum. Equally tellingly, though under no obligation to do so, A very often makes an offer significantly greater than the minimum possible. Generally speaking, norms of fairness enable negotiating parties to find acceptable solutions in situations that would otherwise be unmanageable.

While these norms are part of the same historical circumstances involving power relations and other asymmetries, they are not simply given. Even well established social norms usually require the exercise of judgment in their application, and often the relevant norms are not conclusive without further reasoning.[13] Such judgment and reasoning, however, are often feasible in a structured social discourse.[14] It is at this level that the role of public opinion and of agents capable of shaping it becomes so essential for the long-term dynamics of negotiations about climate change. Such agents include scientific institutions as well as religious congregations, some business companies as well as some governments, key media as well as individuals in a position to shape opinions in a given social setting.

### *3.3 Choosing equilibria*

Of course, the force of arguments will rarely overcome the thrust of well-defined self-interest. But often self-interest is much less well-defined than one may think at first sight. This is relevant first of all because even very powerful and knowledgeable people may entertain seriously flawed beliefs about what would lie in their self-interest.[15] But it is also relevant for a key feature of the global economy in which we live. The familiar picture of economic equilibrium in terms of two intersecting curves representing demand and supply for a single good has led to a misleading superstition, according to which a system of interdependent markets has one and only one equilibrium. If such were the case, then the task of climate policy would indeed consist solely in eliminating the inefficiencies of that equilibrium resulting from non-tradable resources. However, over the past decades, rigorous research has led to the unambiguous, if still often ignored, insight that systems of interdependent markets differ fundamentally from an isolated market for a single good. In a system of interdependent market, multiple equilibria are the rule, with the case of a single equilibrium an extremely unlikely exception.[16]

The key point is the fact that an economic equilibrium is a solution to a co-ordination problem. The word equilibrium is used in many ways, in economics as in other fields. For our present purposes, the key fact is that sales on some markets are controlled by queues – as at the box offices for a concert by some mega-star -, but on many markets they are not. In economics, to say that a market is in equilibrium is not to say that it will not change, but that its dynamics is not controlled by queues. Western capitalism has prevailed over soviet communism to a large extent because in the latter queues were the rule, while in the former they are the exception.

To match supply and demand in a system of interdependent markets so as to avoid control by queues implies co-ordination of a multitude of agents. But even in the simplest co-ordination problems – like deciding whether to drive cars on the right-hand side or the left-hand side of the roads – there is a symmetry between different possible solutions. Whether one wants to call the solutions to the market co-ordination problem an equilibrium is open to debate (choice of terminology is a co-ordination problem, too), but that there are multiple solutions to this problem is a fact.

There are several mutually re-inforcing reasons for this state of affairs. They start with the income effect of price changes: on interdependent markets, changing prices involve changing incomes as well. As a result, changing prices do not simply shift quantities demanded and supplied along given curves. Rather, changing prices shift the very demand and supply curves, with the result that different perfectly efficient equilibria can result with different patterns of relative prices. A second fact of particular relevance for climate policy is the existence of increasing returns and learning by doing.[17] Again, this can lead to multiple equilibria, all of them efficient in the sense that whenever an agent has economic reasons to prefer one equilibrium to another one, there is bound to be some other agent who for economic reasons has the reverse preference. A third important fact is the role of expectations for investment decisions. Airports are not built today as a reaction to consumers buying tickets for flying tomorrow. They are built to meet expected future air travel, and therefore investment decisions depend not on futures markets, but on expectations. Such expectations, of course, can be mistaken. What is more, they can be self-fulfilling or self-defeating.

This sketch of mechanisms bringing about multiple equilibria should be sufficient to show that the economy we live in is bound to involve processes of equilibrium selection that support the more familiar mechanisms of supply and demand. Without such equilibrium selection, supply and demand might as well lead to markets wildly fluctuating between a large number of possible equilibria. While some market fluctuations may indeed be due to an absence of effective equilibrium selection, the historical stability of most, although by no means all, relative prices shows that equilibrium selection is effective in the world we live in. When new markets emerge, however, there is both scope and necessity for suitable processes of equilibrium selection.

Climate policy, then, is not about eliminating inefficiencies so as to let markets find the one and only efficient equilibrium. Climate policy is essentially about choosing the kind of equilibrium we want the global economy to realize.

This, however, points to a further question. In the course of history, human beings have developed many cultural and institutional arrangements to consciously solve those co-ordination problems that don't get settled without requiring particular attention. For problems involving large numbers of people, the nation-state is by far the most influential institution of this kind. However, the single most important insight of economics is that the state should not try to control the working of markets. This insight was developed in the face of monarchic regimes, it was maintained in the face of Nazism and Communism, and it is not irrelevant in the face of democratic governments. It is quite unlikely that nation states will provide the institutional setting needed to solve the co-ordination problems arising in the global economy. As a matter of fact, we simply do not know what kind of institutional arrangement will evolve to tackle these co-ordination problems. We do not yet know by what institutional means we as human beings will gradually assume our responsibility for the Earth as a whole. And it is by no means clear what role nation-states will play in this process. What is reasonably clear, however, is that no single agent – not a single national government, nor a super-government built out of today's nation-states – will be able to solve the problem. The trans-atlantic tensions of our times may well turn out to be part of a long learning process that will ultimately lead to the emergence of institutions that we cannot yet foresee. Developing a successful climate policy may be an important milestone on that road.

## 5. A hydrogen timetable?

For these reasons, trans-atlantic understanding as well as confusion can acquire truly historical momentum. The confusion is as obvious as it is worrying. Fortunately, there are other signs, too. In June 2003, the U.S. and the EU signed an agreement to co-ooperate in a major initiative towards establishing hydrogen as a key energy carrier of the future. This could become an important signal in a global process of equilibrium selection.

Of course, the hydrogen prospect currently is a shaky compromise. The environmental movement has an opportunity to push towards an energy system based on renewables, with fuel cells facilitating the demise of the fossil fuel age and a transition to high levels of energy efficiency. The nuclear industry has an opportunity to make its case by showing that it can provide large quantities of hydrogen in a safe manner, either by developing convincing variants of fission, or by getting fusion to work profitably. The fossil fuel business can try to capture a huge rent by sequestering carbon in a reliable manner and selling hydrogen at a higher price than it could sell fossil fuels. The car industry can develop a new generation of products, reducing possible saturation effects in highly industrialized countries and expanding markets elsewhere. Both the U.S. and the EU have an opportunity to reduce their dependence on huge imports of commercial energy and enhance their energy security. China and other developing countries with their own fossil fuel resources can use these resources with less local air pollution and without playing havoc with the planetary climate system. Developing countries without fossil fuel resources but high levels of solar radiation can take advantage for these.

This list shows both the opportunity to bundle initiatives by a wide variety of agents – the hallmark of equilibrium selection – and the danger that the whole idea will fail over bitter fights between the parties involved. Many of these parties have quite attractive possibilities for opting out, and the stakes are high enough to lead to any kind of conflict, including even military conflicts between countries with nuclear capability. Energy resources are so critical to many countries that one should be careful to avoid any illusion of easy solutions for the energy problems of the future. Still, the vague prospect of a global energy system with hydrogen as pivotal energy carrier is a plausible candidate for the process of equilibrium selection required to tackle the challenge of climate change.

We can keep increasing human welfare without emitting further greenhouse gases. More surprisingly, perhaps, we can even take the additional carbon we put in the atmosphere back out again. To get an idea of the technological opportunities involved, consider first the opportunities for smarter uses of energy. They are closely related to the dynamics of cities.[18] All over the world, cities are continuously being modified and rebuilt. While historical settings are preserved over long periods of time for good reasons, the bulk of construction in a city can be renewed in a few decades. In this process, it is possible to switch to buildings that need much less than half the commercial energy for heating and cooling used today. Moreover, it is possible to switch to transport systems that again cut the commercial energy used by more than half. Historically, use of commercial energy has worked as a major status symbol, displayed in dwellings, cars, and overall lifestyles. In an era of mobile phones, laptop computers, and, yes, increased sensitivity for the beauty of the environment, other status symbols may displace commercial energy, nurturing new technologies, markets, and lifestyles.

Second, a major opportunity is provided by the possibility of carbon sequestration in geological formations. One can generate commercial energy by burning fossil fuels while capturing the resulting carbon dioxide. The captured gas can then be pumped into geological formations like saline aquifers and depleted oil reservoirs. There are places that have contained natural gas for millions of years without ever creating problems for humankind, and it should not be too difficult to close the holes used for drilling into such formations with taps of concrete or the like.[19] The carbon-free commercial energy so generated may come in various forms. Electricity is of course an important one, for many purposes chemical energy in the form of hydrogen is another option. It can be burned or processed in fuel cells, leaving water as the end product.

In principle, we can run the global economy without further emissions of greenhouse gases. The ocean would then slowly absorb most, although not all, the additional carbon we have released into the atmosphere. Slowly here means a rate of about 0.2 percent per year.[20] This may not look spectacular in comparison with the 3% at which we may further increase the amount of additional carbon. But if we were able to stop emitting greenhouse gases around 2050, it might keep us away from the scarier kinds of climate risks, as these are to be expected mainly at later stages of greenhouse gas accumulation.[21]

Further carbon can be taken out of the biosphere by using biomass in a sophisticated way. By simply burning biomass to produce commercial energy, no carbon is stored, as the carbon is cycled through the atmosphere. But carbon sequestration is possible with biomass, too. If we were to grow forests and other plants, burn them to produce commercial energy, and store the resulting carbon dioxide along the lines sketched above, we could actually reduce the additional carbon in the atmosphere at a rate of about 2 percent a year.[22]

Clearly, this would be a major operation, and it will not happen in the current decade. But climate change will stay with us for longer, and it is certainly possible that humankind will actually reduce the additional carbon content of the atmosphere at a rate of 2 percent by the middle of our century. The 3 percent increase we are currently engaged in and the 2 percent decrease we might engage in around 2050, then, provide upper and lower bounds to what we can do with the additional carbon in the atmosphere. As similar orders of magnitude apply for other greenhouse gases, it is safe to say that we are able not only to seriously disrupt the global climate system, but also to avoid doing so.

These opportunities may never materialize because of one or both of the following two reasons. First, they may not be seriously explored out of a lack of imagination, creativity, entrepreneurial spirit and political will. Second, they may be mismanaged so as to generate additional risks until they are not viable anymore. These risks can be both technological and economic, and in fact the two are closely linked. All options discussed involve technological and economic risks, and these require sound liability rules like any major industrial operation.

Two basic cases must be distinguished here: risks from regular greenhouse gas emissions and risks from failure of technologies and organizations. Under an emission permits regime, emitting a certain amount of greenhouse gases will be perfectly legal. For at least several decades, however, these regular emissions will generate serious risks and damages in many parts of the world. The insurance scheme proposed in the present paper is designed to manage this kind of risks.

Another issue are risks like those of nuclear waste, of major accidents with carbon storage in geological formation, and the like. Every business will tend to claim that its technologies and management practices are safe, and it will tend to avoid paying for the consequences of malfunction as far as possible. Moreover, a single business may simply be too small to cover the damages, and its owners may escape liability by letting the business go bankrupt. These are serious issues, but not intractable ones. One possibility is to require businesses using risky technologies to be members of a business association and to let that association be liable for damages. The association would then have an obvious incentive to establish safe practices amongst its members, thereby making additional legal regulation superfluous. Further research is warranted to assess to what extent such arrangements should rely on international law and whether synergies can be created with an insurance pool financed from tradable emission permits. Climate risks are an important, but by no means the only example for this kind of problems. They make the design of innovative schemes for managing large scale risks both intellectually challenging and socially useful.[22a]

As for the economic risks involved in a transition towards a hydrogen economy, it is essential to keep in mind the role of multiple equilibria discussed above. Starting from the current situation of the world economy – both in terms of ruling prices and of available equipment and know-how – steps towards solving the climate problem require sizeable investments. If these steps lead to a new equilibrium of the world economy, however, these investments are likely to generate a positive return both in terms of avoided climate risks and in terms of realized business opportunities.

The long term vision of a highly efficient energy system based primarily on solar energy and complemented by a portfolio of further energy sources can capture the collective imagination while offering plausible perspectives for the self-interest of key actors involved. The vision can be fleshed out at the level of the urban regions that will provide the setting for everyday life for the majority of humankind in the foreseeable future. And it can be fleshed out at the level of global markets so as to provide a credible perspective for overcoming the morally unacceptable contrast between amazing wealth and unbearable poverty, a contrast that clearly undermines any possibility of a non-violent social order.

There is no need to formalize such a vision in any binding convention for climate policy. But effective binding agreements are highly unlikely unless some such vision gains sufficient plausibility to operate as a crystallizing point for equilibrium selection. In this sense, formally specifying the ultimate goal of climate policy as a successful transition towards a sustainable world economy without significant greenhouse gas emissions and with widespread human welfare will be a crucial way of extending current commitments in climate policy.

Other commitments are needed to start the transition now. Specific initiatives to develop various variants of fuel cells or to improve various forms of energy storage are as important as incentives for renewable energy and energy efficiency. Incentives should not be unconditional subsidies, as these tend to cripple the creativity of market competition, but rather matching funds and rewards for meeting specific targets. For the same reason, the nuclear industry needs less government subsidies and more clear and fair guidelines for the criteria by which future technologies in this field will be assessed.

As for the tradable permits required to address the basic externality of climate change, two commitments are essential. First, no global authority will be allowed to collect the huge sums of money that would come with a single global permit scheme. Without a system of checks and balances involving competing institutions, skepticism against global solutions will be hard to prove wrong. But schemes of tradable permits can be implemented at the scale of the EU plus other nations that wish to join such a scheme. And if this is doable at a European scale, then the U.S. will certainly be able to come up with a matching scheme, even if probably with some delay. China or a group of South-East Asian countries can do the same, and the same holds in other parts of the world.

The second essential commitment will be to gradually gear the revenues from permit trade to insurance for adaptation cost and damage compensation. This will of course involve resource flows from North to South – and if these flows work as investments creating new markets and greater prosperity worldwide, then they are exactly what is needed for a healthy development of the world economy in the 21th century.

NOTES

[1] I owe this image to a discussion with Murray Gell-Man and Claudia Pahl-Wostl a the Santa Fe Institute. Thanks for helpful discussions also to Dieter Imboden, Rupert Klein, Bert Metz, and the participants of various gatherings of the European Climate Forum, including Jos Delbeke, Bill Hare, Klaus Hasselmann, Stephen Peck, Atiq Rahman, Harlan Watson, and many others. In theses times of trans-atlantic soul-searching, the usual disclaimers apply even more than usual.
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