Economic Analysis of Global Warming: FEEM's WITCH Model

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Global warming is a complex phenomenon. Human activities, such as energy consumption, industrial processes, land use, are responsible for emissions of GreenHouse Gases (GHGs) that concentrate in the atmosphere. Complex exchanges with the biosphere contribute to an absorption of GHGs and thus to a natural reduction of concentrations. The rapid increase in GHGs emissions into the atmosphere - especially CO_2 emissions from fossil fuels - has outpaced the natural absorption capacity thus leading to a rapid increase in concentrations. The community of scientists is almost unanimously convinced that this increased stock of GHGs in the atmosphere is responsible for the rise in the average atmospheric temperature, which is in turn cause of deviations of weather events from their historical pattern and of the insurgence of problematic phenomena, such as sea level rise. Climate change effects are not always bad: some areas of the world that could not host human life may turn into productive agricultural lands and growth of forests might be spurred by higher temperatures. However, it is widely agreed that the overall impact of climate change will be negative. Sea level rise, erratic and violent rainfalls, droughts, glaciers retreat, increased diffusion of tropical diseases, health stress for vulnerable people, all contribute to a negative impact on human life. Economists are working closely with scientists to assess the nature, magnitude and frequency of plausible impacts in order to attach an economic value to them. The impact of climate change on the economy can be synthetically captured by a so called "damage function" that represents in a compact form a multitude of relations allowing to translate a given variation of an atmospheric indicators, i.e. temperature, into an economic loss. This complex chain of interactions is schematically represented in Figure 1.

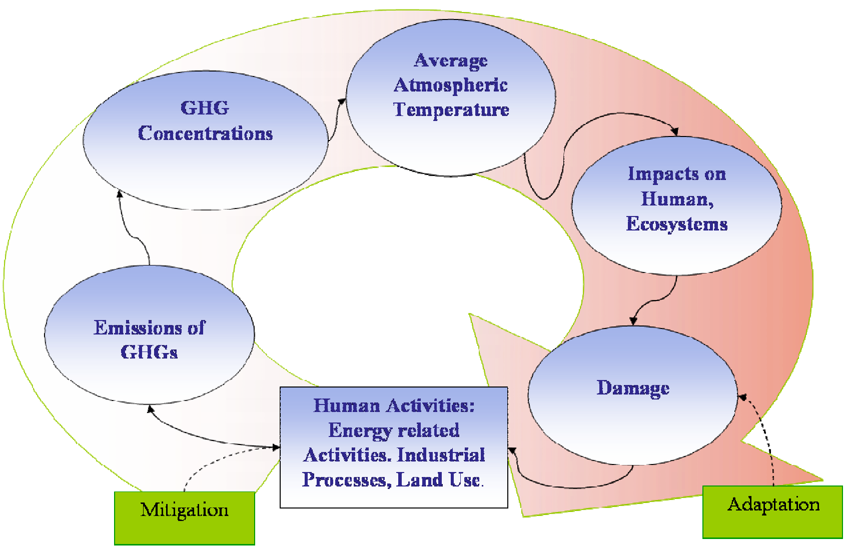

Figure 1: Representation of the economy-climate feedback

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Measures can be undertaken to reduce the negative effects of climate change. In the first place it is possible to eliminate the source of increasing world temperatures by reducing the flow of GHGs emissions so as to stabilize concentrations in the atmosphere. This approach, which foresees a correction at the beginning of the causal chain depicted in Figure 1, is referred to as “mitigation of climate change”. It is also possible to intervene by reducing the economic impacts of climate change to make societies and ecosystems less vulnerable to climate change. This second approach goes under the name of “adaptation to climate change”.

Crucial features of the climate change phenomenon that need to be pointed out are:

- *Its long run dimension*: atmospheric mean temperature depends on the level of concentrations of GHGs in the atmosphere, which have a strong inertia. The effect on temperature that we are experiencing now is due to the emissions of GHGs happened centuries ago. Thus, responses in the variation of emissions today, are going to be felt centuries from now;

- *Its asymmetry across countries*: benefits of avoided changes in the global temperature and costs of mitigating emissions as well as of adapting to changed climatic conditions vary widely across regions of the world;

- *Its uncertainty*: the climate cycle itself, future technology scenarios, potential unexpected reactions to changes of climatic conditions, these are all issues strongly affected by uncertainty.

Reducing GHGs emissions is a challenging task, as it involves substantial modifications to the economic system at a cost. For example, the energy sector would evolve differently if climate change were completely neglected; the increasing needs of a population that keeps growing 1% a year -a quarter of which is currently without electricity- would call for an extensive deployment of fossil fuels (coal before other fuels) leading to a massive increase of GHGs emissions. Because no one really believes or is ready to accept that the solution to the climate change problem is to reduce the pace of economic growth, designing paths of emissions balancing costs and benefits, and proposing policies meant to achieve at a minimum costs such scenarios is now one of the most fertile area of investigation of a community of interdisciplinary scientists, among whom are economists. The development of mathematical models of the interactions between economic and climate systems are a necessary support for a complete understanding of the problem and for the ability to analyze as many issues as possible among those relevant to climate change.

Different models mimicking some of these complex and interdisciplinary relationships have been designed and used by experts to analyze various issues in climate change economics. An especially difficult task is to contemporaneously account for the economic intercourses of different environmental policies as well as portraying the energy sector related activities, the change in technology and the effects on the climate. In this respect the specialized literature has traditionally distinguished between two broad categories of models: top-down and bottom-up models. Top-down models -generally designed by economists- are suited to analyze all the interaction mechanisms and dynamics within the economy, but usually feature a poor technological representation. On the other hand, Bottom-up engineering models include a wide array of energy technologies, but do not satisfactorily incorporate feedback dynamics on the economy. Recently, models able to combine both aspects (thus termed "hybrid"), and especially to represent the technological change so much advocated to decouple economic growth from climate change prevention, are started to be developed. In addition, models do not often take into to account the dual and conflicting nature of climate change: a global phenomena, on one side, but strongly characterized by regional asymmetries both in damages and mitigation costs, on the other side. Thus, a model designed to study the climate change issue should ideally be regionally disaggregated and include game-theoretical features to simulate regions interactions in the face of such a global concern.

In order to account for these different facets of the climate change issue, FEEM Climate Change Modeling and Policy program (CCMP) has developed a novel modeling tool named WITCH (World Induced Technical Change Hybrid model).[1] WITCH is a hybrid model that brings together an economic module, an energy sector description and a climate module. It is fully intertemporal thus providing projections well far in the distant future that are required to perceive reactions in the climatic components and feedbacks on human activity. It is regional, thus providing a framework to mirror interactions between countries. It is very flexible and can be modified to account for different sources of uncertainty affecting the systems within it described.

As such, WITCH is an innovative tool to analyze the diverse features that characterize the climate change issue. It is meant to be used by academics to analyze methodological issues, by policymakers to assist in the design of optimal policies and by energy analysts to perform normative analysis on investment needs in the energy sector.

Brief Model Description

WITCH – a World Induced Technical Change Hybrid model – is a that combines features of both top-down and bottom-up modelling: the top-down component consists of an inter-temporal economic growth model in which the energy input of the aggregate production function has been expanded to give a bottom-up like description of the energy sector. Hence the term "hybrid". World countries are grouped in twelve regions that strategically interact following a game theoretic structure. It incorporates an endogenous description of how technologies change due to both knowledge or experience. Part of this change may be induced by economic or climate policies. A climate module and a damage function provide the feedback on the economy of carbon dioxide emissions into the atmosphere.

Several features of the model allow us to investigate a number of issues in a greater detail than is usually done in the existing literature. First, although rather rich in energy detail and close in spirit to Bottom-up energy models, WITCH is based on a Top-down framework that guarantees a coherent, fully intertemporal allocation of investments under the assumption of perfect foresight. Second, the model can track

[1] For a more detailed description of WITCH, its structure, baseline calibration and potential applications see:
Bosetti, V., C. Carraro, M. Galeotti, E. Massetti and M. Tavoni (2006). "WITCH: A World Induced Technical Change Hybrid Model." *The Energy Journal*, Special Issue on Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down, 13-38.
Bosetti, V., E, Massetti and M. Tavoni (2007). "The WITCH Model. Structure, Baseline, Solutions." FEEM Working Papers, 10/2007.

all actions that have an impact on the level of mitigation – R&D expenditures, investment in carbon-free technologies, purchases of emissions permits or expenditure for carbon taxes – and we can thus assess optimal responses stimulated by different policy tools. This leads to a transparent evaluation of abatement costs and to a clearer quantification of the uncertainties affecting them. Also, the regional specification of the model and the presence of strategic interaction among allows to account for the incentives to free-ride in the choice of optimal investments, a crucial issue in global environmental goods protection. Finally, the technological detail as well as the internal specification of technological innovation enable to consistently design energetic scenarios and to assess the evolution of technology that will be central for the economical control of global warming.

A Glimpse at WITCH Results and Insights

One of the possible applications of a model as WITCH is Cost-Benefit analysis. Costs of reducing emissions are weighted against benefits accruing from lower temperatures in order to derive the optimal level of effort that policy makers should undertake so as to tackle the climate change problem. Consider, as an extreme example, the case in which CO_2 emissions were not supposed to cause any global warming effect or any other environmental damage. In this case the model would not prescribe any effort aiming at reducing emissions because the cost of whichever action would be compensated by no gain. It would then be optimal to cover the whole demand for electricity using coal, the least expensive generating technology even though the one producing highest emissions. A more realistic assumption -which is at the basis of the WITCH model- is that CO_2 emissions resulting in higher global temperature causes some economic loss. As a consequence, the optimal solution prescribed by the model will be that of reducing emissions up to the point at which gains -in terms of lower damages- are exactly equal to the mitigation costs. Going back to our previous example, it is optimal to switch, at least partially, from coal-based electricity generation to, say, gas-based electricity generation, which produces much less emissions. Yet, gas-based electricity generation is more expensive than coal. Thus, the model is designed to switch to gas at the point where the higher industrial costs exactly compensate the reduced environmental damage. It is thus neither optimal to reduce emissions all together nor to continue to emit without any bound: from the cost-benefit analysis it emerges the so-called optimal emissions time path and, symmetrically, the optimal abatement trajectories with respect to a world that does not perceive any climate damage.

Cooperation versus Non Cooperation

The WITCH model can be solved using two different approaches describing two different benchmark cases. In the first we assume that the world is alike one single country, or more precisely, it is governed by a central planner taking all decisions with the unique goal of increasing the welfare of each single person on the planet. However, countries are still assumed to be separate entities, they use the same pool of fossil fuels resources, they have technological exchanges in the form of international spillovers, CO_2 emissions produced by any country cumulate in the atmosphere and influence the climate of all other countries. All these effects of domestic behaviour on to other world countries are an example of what economists call externalities, i.e. effects of one’s actions (individuals as well as countries) on other actors in the surrounding which are not regulated by a market price. In this first approach, called cooperative case, the central world government has the power to control all countries' behaviour so that these externalities are internalized.

The second possible approach, the non cooperative case, is based on the assumption that each country runs on its own, maximizing its own welfare only, without considering the effect of its choices on its neighbours. For example, countries will not consider their neighbours' economic losses due to accumulation of CO_2 emissions in the atmosphere. This is equivalent to saying that, in the internal cost-benefit analysis, countries balance mitigation costs with their own reduced damage only and do not consider the beneficial effect that their action might have on other countries' welfare. Thus, the private cost is equalized to the private benefit and not to the social one and the effort spent on cutting emissions is lower than what would otherwise be in the cooperative case. Since all countries behave in this way, the overall effect is to have higher CO_2 concentrations in the atmosphere, resulting in higher temperatures and economic damages. In addition, each country perceives that its effort could be substituted by that of its neighbours. Why investing in cutting emissions, if somebody else might do it for us? The cost-benefit framework is respected in full, but part of the domestic cost is reversed to the neighbouring countries. Economists call this "free riding" incentive, i.e. the incentive to let other people do the effort and only take its benefits. However, it should be well clear that in this fragmented world, this egoistic behaviour in which countries do not internalize social costs and free ride on other countries efforts, is perfectly rationale. The only way to overcome this problem is to create a legal framework that forces countries to cooperate and punishes them in case they do not.

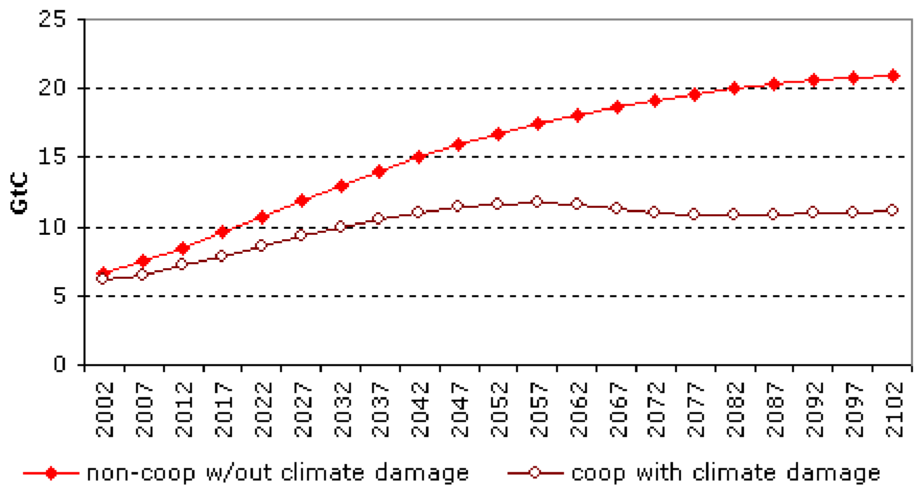

Figure 2: World CO_2 Emissions

For this reason we refer to the "one central government" solution as the "cooperative solution": countries are assumed to be well separated, with different capital endowments, income levels and energy uses, but they are assumed also to cooperate in the management of world externalities. We assume also that there would be a very harsh punishment in case of deviation from cooperation and thus that the coalition so formed is stable. By contrast, the solution in which countries optimize only referring to their domestic benefits and damages is defined as the "non-cooperative" solution.

The optimal path of emissions in the cooperative solution and what is instead the effect of a world in which each country runs on its own on CO_2 emissions is shown in Figure 2, where we report the world emissions path for both cases from now to 2100.

The non-cooperative solution foresees a continued growth in emissions up to 20 GtC in 2100 (a result that falls in the IPCC-SRES B2 range of scenarios). On the contrary, the cooperative solution would entail a significantly less carbon-intensive scenario: the cooperative solution keeps emissions down at about half the level, stabilizing them around 10 GtC, which corresponds to a concentration level of CO_2 in the atmosphere of 600 ppmv (versus the 726 ppmv of the non-cooperative solution) that gives a temperature increase above pre-industrial of 2.4°C (versus 2.9°C of the non cooperative solution). This discrepancy quantifies the magnitude of the under-provision of the global public good due to externalities and to free-riding: the negative feedback from prolonged emissions does not provide enough incentive to moderate pollution once each region is measuring its own costs versus its own benefits, since any effort is dampened by a non-cooperative behaviour of other players. Only a concerted joint effort of all countries has the effect of curbing the level of global emissions. In addition, by carefully exploiting asymmetries in costs and benefits of reducing emissions it is possible to reduce climate change control costs and to create the incentives to override egoistic, even if rational, behaviour, that would push countries to act non-cooperatively.

Climate Feedbacks

A few remarks on the role of the assumed climate damage retroaction in shaping these results are in order. In fact, the assessment and economic evaluation of future impacts of climate change is a controversial and extremely difficult task, surrounded by uncertainties that leave ample space to animated discussions among experts. For example the very high estimates of climate damages assumed in the recently published Stern Review have been at the centre of an intense debate.[2] In order to gain some insight and to test effect of our assumptions we have run both the cooperative and non-cooperative solutions considering and subsequently removing the climate feedback, i.e. neglecting global warming. In figure 3 results are compared to those obtained before where damages were accounted for.

Removing the climate feedback from the model has a significant effect on the cooperative solution (from 11 to 18 GtC in 2100) but an almost negligible one in the case of non-cooperation. Externalities and free-riding incentives drastically reduce the degree to which countries react to climate damage: even if central planners in each region were perfectly aware of the severity of global warming consequences, the free-riding incentives arising from the global externalities would still make serious emissions reduction a sub-optimal solution.

Further investigation about the cost of higher temperature levels to society is essential in weighting climate benefits against mitigation costs for the world as a whole and in defining benchmark scenarios of optimal mitigation levels. However, addressing the cooperation issue is an indispensable pre-requisite to making any emission reduction possible. As such, analysis of international and bilateral agreements on emissions caps or technology trade and diffusion are decisive for the

[2] The whole report is available at: www.sternreview.org.uk .

climate policy agenda. Through interplay between game theory, international environmental agreements and integrated assessment modeling, WITCH is a modeling tool especially suited to analyze these issues.

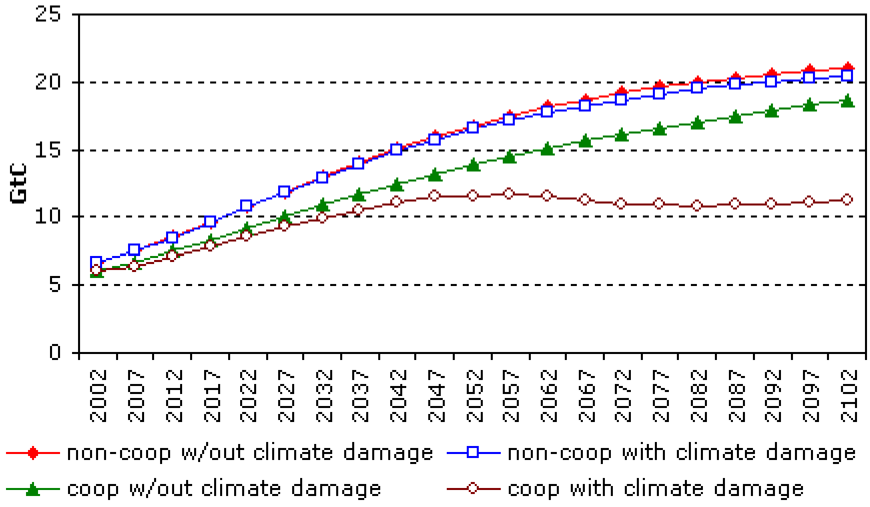

Figure 3: World CO_2 Emissions with and without Climate Feedback

Conclusions

This article has presented a new energy-economy-climate model for the study of climate change issues under development at FEEM's CCMP program. By means of an example of application, we have shown the relevance of the free-riding incentives to prevent the stabilization of the GHGs and avoid potential damages from global warming, as well as the development and adoption of new climate-friendly technologies.

The model lends itself to analyze the impacts of different climate policies, from stabilization targets to technology based ones, as well as evaluate issues such as international knowledge spillovers, uncertainty, adaptation, policy instrument choice. Given the many channels of transmission of climate policy into the economic system, climate policies will likely have an important impact of the dynamics on WITCH's main economic variables. Under what conditions can climate policy achieve the goal of stabilizing GHG concentrations? What are the features of an optimal climate policy? How much would it be technology-based? These are all issues and questions that WITCH can easily address and that will be the subject of future applications of the model.

Further information can be found at the model web site www.feem-web.it/witch or by email at witch@feem.it.