Les Cahiers du GERAD ISSN: 0711–2440

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G–2017–78

September 2017

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The contribution of mathematical models to climate policy design: A researcher's perspective

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September 2017

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Abstract: Energy and the environment are closely interconnected. In particular, energy-related carbon dioxide emissions are major contributors to climate change. To analyze options within the energy sector to curb greenhouse gas emissions, or to study alternative climate strategies such as adaptation and geo-engineering measures, policy-makers can rely on mathematical decision support models, in particular E3 (economy/energy/environment) models and integrated assessment models (IAMs). This paper reviews some of my recent contributions to climate policy design using different types of E3 models and IAMs.

Keywords: Climate change, climate policy, energy policy, integrated assessment models, mathematical models in economy/energy/environment

Acknowledgments: The author wishes to acknowledge financial support from the Natural Sciences and Engineering Research Council of Canada (NSERC individual grant).

1 Introduction

Since my doctoral thesis at the University of Geneva, which focused on the coupling of national energy models to study the harmonization of greenhouse gas (GHG) emission reduction efforts among several European countries (Bahn et al., 1994), I have been interested in the relationship between energy and the environment, particularly in the context of climate change.

Energy and the environment are closely interlinked. The energy sector draws its resources from the environment. It is also responsible for releasing various pollutants, and these pollutants threaten the environment at different levels. For example, the release of carbon monoxide (CO), volatile organic compounds (VOC), or particulate matter (PM) from gasoline-fueled vehicles contributes to air pollution in large cities. This is essentially local pollution. The energy sector, especially when using sulfur-rich fossil fuels, can also emit sulfur dioxide (SO_2) and nitrogen oxides (NO_x), which are the main precursors of acid precipitation. These can have an environmental impact on large regions potentially covering several countries. However, neither of these problems affects the entire planet. The situation is different for GHG emissions, such as carbon dioxide (CO_2) and methane (CH_4) emissions due in particular to the combustion of fossil fuels. The accumulation of GHGs in the atmosphere threatens the Earth's global climate balance, leading to an increasingly negative impact on both ecosystems and the environmental services they provide, as well as on society.

However, if the production and consumption of energy can threaten ecosystems and populations, the reverse is also true, since the environmental problems associated with energy production and consumption can threaten the development of particular energy forms. Ensuring the sustainable development of the energy sector, as well as providing economic agents with an energy supply that is economical and environmentally friendly, thus poses major challenges.

The complexity of the links between energy and the environment suggests the use of a systemic approach. In this context, mathematical programming models, and in particular mathematical decision support models, provide a rational framework for analyzing the impact of energy and environmental policies on the energy sector and the environment.

The remainder of this paper focuses on climate change and is organized as follows. In Section 2, I present an overview of different strategies (mitigation, adaptation, and geoengineering) to address climate change. Section 3 surveys different model types (bottom-up, top-down, hybrid, and integrated assessment models) that can be used to design climate policies. In Section 4, I present several applications of such models based on my research in this field. Section 5 provides concluding remarks.

2 Climate change policies

To address the threats posed by climate change, three main strategies may be used: mitigation, adaptation, and geoengineering.

2.1 Mitigation

Mitigation aims to reduce anthropogenic GHG emissions. Many countries have made such commitments. For instance, Canada (my home country) committed itself to reducing its GHG emissions by 6% below 1990 levels by 2008–2012, under the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) adopted in 1997. Unable to achieve this target, it withdrew from the protocol in 2012. Canada has now committed itself to reducing its emissions by 17% below 2005 levels by 2020, within the 2009 UNFCCC Copenhagen Accord. In addition, it plans to reduce its GHG emissions by 30% below 2005 levels by 2030, under the 2015 UNFCCC Paris Agreement.

To achieve such reduction targets, policy-makers use different instruments, which are of two main types: mandatory measures, and economic instruments that use an incentive approach. The first type takes the form of regulations, such as environmental emission standards. As an illustration, consider the European standard that will apply from 2020 of 95 g CO_2/km for new vehicles. Such mandatory measures must be enforced by a system of control and sanctions. Alternatively, one may encourage polluters to control their emissions, and this can be achieved via taxes or emissions trading. For instance, in the Canadian context, British Columbia's carbon tax (\$30/t CO_2) increases the cost of fossil fuels in proportion to their carbon content. Another example is the Quebec cap-and-trade system (*Système québécois de plafonnement et d'échange de droits d'émission*, SPEDE) that is part of the North American carbon market of the Western Climate Initiative (WCI).

According to the Intergovernmental Panel on Climate Change (IPCC, 2014), CO_2 emissions from the combustion of fossil fuels (and industrial processes) currently account for about two thirds of anthropogenic GHG emissions. It is thus important to consider which technological options can reduce energy-related carbon emissions. Such options can be grouped for simplicity into three main categories: energy savings, the use of cleaner energy, and carbon capture. The first category corresponds in particular to measures aimed at energy efficiency, for instance the use of more energy-efficient technologies such as LED lighting, or the improvement of thermal insulation in buildings. The second category takes the form of less polluting energy sources, such as natural gas rather than coal, or better still, renewable energy (such as hydro, wind, or solar) that does not (directly) yield carbon emissions. Finally, the third category mainly relates to carbon capture from large sources (such as thermal power plants) and its storage (for instance in geological formations).

2.2 Adaptation

Rather than reducing GHG emissions, adaptation measures aim to adjust economic or social structures in order to limit the impact of climate change without limiting climate change itself. Adaptation strategies cover a wide range of sectors and options. Let us give some examples. An adaptation strategy could involve planting new crops to adapt to changing weather conditions or constructing sea dykes to protect coastal plains from rising sea levels. One could also launch vaccination campaigns in response to the spread of tropical diseases (due to changing climate patterns). Adaptation measures can be implemented in a preventive or reactive manner. For example, a vaccination campaign can be launched as a precaution or in reaction to the urgency of a pandemic.

Adaptation has a number of advantages over mitigation. First, many adaptation measures generate immediate benefits, while most of the expected benefits of GHG emission reductions appear decades later. Second, mitigation requires global cooperation to be fully effective, while adaptation can generally be implemented at the regional level. However, adaptation also has several disadvantages. As the magnitude of climate change increases, the range of uncertainty about the expected damage is greater. Mitigation limits climate change and hence uncertainty about damage, whereas adaptation shields us from some of the impact of climate change without limiting its magnitude. In addition, adaptation probably becomes less effective as the magnitude and pace of climate change increase.

2.3 Geoengineering

Given the current risk of a catastrophic temperature increase, one could consider the use of geoengineering measures. These would deliberately alter the climate system to reduce the impact of climate change and could act as a quick temperature backstop. These measures can be classified into two main categories: carbon dioxide removal (CDR) to reduce atmospheric carbon concentration levels, and solar radiation management (SRM) to reduce incoming solar radiation.

In the second category, the injection of sulfur into the stratosphere has attracted some attention in the scientific literature. Such a measure should be effective in reducing the overall temperature (similarly to a major volcanic eruption), and this at a relatively low cost compared to GHG reduction measures. It could also be deployed quickly to serve as an emergency response to the imminence of rapid and catastrophic climate change.

However, such a measure would entail significant risk: it could have unexpected consequences and adverse side effects. In particular, it could counteract the recovery of the stratospheric ozone layer, cause acid deposition at the poles, trigger regional climatic imbalances (e.g., in the Asian and African summer monsoons), and modify ecosystems (in particular by impacting terrestrial and marine photosynthesis). Moreover, this measure would achieve only an artificial reduction in temperature levels. With a continuous increase in GHG concentrations, sulfur injection should increase proportionally, and any interruption would lead to a significant increase in temperatures, likely with disastrous consequences. Finally, this measure would not counteract other negative consequences associated with high GHG concentrations, such as ocean acidification.

3 Decision support models

To design climate policies and select relevant climate-change strategies, policy-makers can use mathematical decision support models. In my research, I use models covering the economy, energy, and the environment (so-called E3 models). These models are mainly divided between two approaches (see for example Bahn et al., 2005): top-down, which uses a macroeconomic approach to modeling the relationship between energy and the economy; and bottom-up, which uses a disaggregated approach to modeling energy production and consumption, considering many alternatives and associated costs.

3.1 Bottom-up E3 models

MARKAL (Fishbone and Abilock, 1981) and TIMES (Loulou et al., 2005) are typical examples of bottom-up models developed within the ETSAP program of the International Energy Agency. They describe in detail the energy sector with a complete list of the various forms of energy, as well as different energy technologies. In particular, these models distinguish production technologies that transform primary energy into secondary energy (for example, refineries that produce gasoline from crude oil, or power plants that generate electricity from hydro energy). They also distinguish demand technologies that transform final energy into energy services (for example, gasoline cars that serve demand for mobility, or light bulbs that serve demand for lighting). In addition to current technologies, they model a variety of alternative technologies that can provide the same services more efficiently (using less energy) and/or in a cleaner way (by emitting fewer pollutants). Technologies are explicitly represented by their economic characteristics (e.g., investment and operating costs) and technical characteristics (e.g., efficiency, lifetime).

Bottom-up models account for all energy flows within the energy sector. They compute total primary and secondary energy production as well as total final energy consumption. Demand for energy services is usually given exogenously. Bottom-up models then determine an optimal configuration of the energy sector to satisfy useful energy demand at a minimal cost, while respecting emission reduction constraints. In particular, these models typically account for CO_2 and CH_4 emissions from the combustion of fossil fuels and industrial processes. Emission reduction is achieved by switching between technologies and/or energy forms, by carbon capture and sequestration, or by reductions in useful energy demand. The time horizon is typically between 2050 and 2100, which enables the model to account for structural changes in the energy sector.

The main weakness of the bottom-up approach is that it does not provide a complete picture of the economy. Indeed, it does not capture all possible interactions between the energy sector and the rest of the economy. The optimal solution of bottom-up models corresponds to a partial economic equilibrium that would be achieved in energy markets under perfect competition.

3.2 Top-down E3 models

In top-down models, a broader equilibrium framework is considered where one computes supply and demand for goods and services in the main economic sectors (energy, but also agriculture, industry, and services). These models capture more interactions between the energy sector and the other economic sectors, but usually without explicitly representing energy technologies. Energy consumption is instead defined as the result of an economic equilibrium. For example, energy consumed by firms is generally determined from the price of energy relative to that of other production factors (such as capital, labor, and materials).

Top-down models are designed to estimate market responses to price changes. They identify relationships between energy prices and energy demand. In the context of climate change, top-down models aim in particular to determine the increase in energy prices, for example through a carbon tax, that would yield the desired reaction from economic agents in terms of reduction of their GHG emissions. Since they describe the whole economy, these models can also determine the expected effect of such a tax on other economic sectors (beyond the energy sector) and on the gross domestic product. When they explicitly contain a governmental sector, top-down models can also consider different ways to use the revenue generated by a carbon tax.

The main weakness of top-down models stems from the fact that they assume the interactions between energy and the economy will be the same in the future as in the past, as described in particular by substitution elasticities between energy and the other production factors considered. Moreover, because the energy sector is typically represented in an aggregated form, top-down models are less suitable for studies where new elements may emerge, such as new energy sources (selected biofuels, for instance) or more efficient energy technologies. As a result, they may not be able to determine which specific alternative energies and technologies should be used to effectively reduce GHG emissions.

Examples of top-down models are EPPA (Paltsev et al., 2005), a computable general equilibrium model developed at MIT; GEM-E3 (Capros et al., 1997), a computable general equilibrium model developed for the European Commission; and MACRO (Manne and Wene, 1992), an optimal growth model.

3.3 Hybrid E3 models

The two categories of models (bottom-up and top-down) are complementary, since they address different questions posed by the rationalization of energy production and consumption. Bottom-up models are more appropriate for the evaluation of new energy technologies and energy forms; top-down models are more appropriate for analyzing the macroeconomic impact of energy and climate policies.

Like every taxonomy, this classification of E3 models is limited. So-called hybrid E3 models integrate bottom-up and top-down approaches into the same modeling framework. For example, a bottom-up model (e.g., MARKAL) can be coupled with a top-down model (e.g., MACRO). The resulting model, MARKAL-MACRO (Manne and Wene, 1992), uses a production function that covers all economic sectors. The production factors are capital, labor, and electric and nonelectric energy. These factors can be substituted for each other. The optimization of the energy sector is carried out by the MARKAL part of the model, with the goal of meeting energy demands at a minimal cost. In another example, some recent versions of GEM-E3 (Capros et al., 2013) use a hybrid approach, incorporating a bottom-up description of electricity supply and explicitly considering specific power-generation technologies.

3.4 Integrated assessment models

E3 models represent the energy sector in varying levels of detail. They may also explicitly represent other economic sectors. In terms of the environment, E3 models essentially calculate emissions, such as GHG emissions. This can be done on different geographical scales: city, province, country, region, or even world.

At the world level, one may add to an E3 model a climate module (to assess climate change due to the accumulation of GHGs in the atmosphere) and possibly a damage module to assess the associated economic damage, in order to construct a so-called integrated assessment model (IAM). Examples include DICE (Nordhaus, 1994) and its variants, based on an optimal economic growth model that uses a top-down approach; TIAM (Loulou and Labriet, 2008), based on the TIMES framework that uses a bottom-up approach; and MERGE (Manne et al., 1995) and its variants, a model that uses a hybrid approach to modeling energy and economy.

4 Applications to climate policy design

After my Ph.D. at the University of Geneva, I worked as a researcher at the Paul Scherrer Institute, a Swiss research center that is part of the ETH Domain. In particular, I looked at several options for implementing the UNFCCC Kyoto Protocol using different types of E3 models. For example, I studied the Clean Development Mechanism via MARKAL models that use a bottom-up approach; see Bahn et al. (1999). I analyzed possible consequences of establishing a market of emission reduction units between European countries (Bahn et al., 2001), via MARKAL-MACRO models that use a hybrid approach. I also assessed potential macroeconomic impacts of a carbon tax in Switzerland under different regimes (Bahn, 2001, 2002), via a GEM-E3 model that uses a top-down approach. I will now review several studies that illustrate my research in the field of climate policy design since my arrival at HEC Montréal in 2003.

4.1 Applications to mitigation strategies

In the early 2000s, it appeared that the Kyoto Protocol would not be sufficient to reduce global GHG emissions and that GHG concentrations would continue to rise in the atmosphere. This continued increase could yield a sudden change in the climate. Specifically, climate scientists believe that some elements of the climate system may have tipping points beyond which potentially irreversible changes will occur. These thresholds may depend on both the magnitude and the speed of climate change. One element of the climate system that could present a tipping point is the Atlantic thermohaline circulation (THC).

The THC corresponds to a global ocean circulation pattern. In the Atlantic, it acts as both a large "conveyor belt" and a "heat pump," transporting huge amounts of water and energy (heat) toward the North Atlantic. The THC is driven by differences in seawater density resulting from differences in temperature and salinity. An increase in temperature and precipitation in the North Atlantic, due to anthropogenic climate change, should yield a slowdown in the THC. However, beyond a certain threshold, it may not be possible to avoid a THC collapse. This could be irreversible over planning horizons many orders of magnitude longer than those relevant to current decision-making. A THC shutdown could lead to cooling in the North Atlantic regions as well as, among other factors, changes in hydrological cycles with potentially serious consequences for socio-economic systems.

In Bahn et al. (2011), I analyzed climate policies that would avoid a collapse of the THC. These analyses were carried out with several co-authors, including Prof. Thomas Stocker, a climatologist at the University of Bern who co-chairs the IPCC Working Group I. First, using a climate model, we determined limits, in terms of temperature increase and rate of temperature increase, that should not be exceeded to avoid getting too close to a THC tipping point. These climatic constraints were then included in the MERGE model to determine compatible GHG emission trajectories. We considered several values for climate sensitivity, an important parameter defined as the equilibrium temperature change in response to a doubling of atmospheric carbon concentration compared to pre-industrial levels. For a 3°C climate sensitivity, MERGE determined that global GHG emissions should be reduced by almost 50% by 2050 relative to 2010 levels. Such reduction levels are consistent with the latest IPCC finding (IPCC, 2014) that reductions from 40% to 70% by 2050 will be necessary to "*likely*" keep warming below 2°C. Note that for a higher sensitivity of 4.5°C, global GHG emissions should decrease to close to zero by 2050, a daunting task that requires in the MERGE model the use of CDR geoengineering measures to remove carbon from the atmosphere.

In the absence of geoengineering measures (see below), avoiding abrupt climate change will require a rather rapid transition to energy systems that emit many fewer GHGs. Which energy systems would be consistent with drastic GHG emission reductions (up to 70% by 2050)? Vaillancourt et al. (2017) provide some insight with a TIMES model for Canada (NATEM). Using NATEM, we have identified three major transformations needed to achieve a 60% reduction in Canada by 2050: (i) massive electrification of end-use sectors (for instance, the transport sector), possibly with increasing use of biofuels (if second-generation biofuels become available); (ii) rapid decarbonization of electricity supply, with increased production mainly from hydro, wind, and nuclear power, and also possibly from biomass combined with carbon capture and storage (assuming availability of such CCS technologies); and (iii) implementation of energy-efficiency measures mainly in the transport sector (replacing internal combustion engines by electric ones) and in the residential and commercial sectors (e.g., using more efficient appliances or improving building envelopes). Note that for this level of GHG reduction, the marginal reduction costs quickly exceed $100 per ton of CO_2, eventually reaching several hundred dollars.

4.2 Applications to adaptation strategies

In Bahn et al. (2008, 2010), I proposed with Profs. Alain Haurie and Roland Malhamé the BaHaMa model, an IAM rather similar to the DICE model, since it uses an optimal economic growth approach with economic production being based on three production factors (capital, labor, and energy). However, unlike DICE, BaHaMa distinguishes between two types of economy: a "carbon economy", where economic production requires a high level of fossil fuels, and a "low-carbon economy", where production relies much less on fossil fuels. In BaHaMa, the climate change mitigation strategy consists in a transition from the first economy to the second.

In Bahn et al. (2012), my co-authors and I modified the BaHaMa model to explicitly consider adaptation strategies. We found that the relationships between adaptation and mitigation are complex and largely dependent on their respective attributes. When the adaptation effectiveness is "low" (assuming that only up to 1/3 of climate change damage can be avoided), adaptation serves as a complement to mitigation measures, and it delays the transition to a low-carbon economy by only ten years. The transition is fully achieved by the end of the century. As the adaptation effectiveness increases, adaptation increasingly becomes a substitute for mitigation. Conversely, with a higher climate sensitivity, a faster transition to a low-carbon economy takes place, and adaptation reverts to being only a complement to mitigation. In all cases, the best strategy according to BaHaMa is to combine (at different levels, as mentioned) adaptation and mitigation.

More recently, in Bahn, de Bruin, and Fertel (2015), my co-authors and I included adaptation strategies in the MERGE model. The resulting AD-MERGE model is more detailed than BaHaMa. In particular, it distinguishes among nine geopolitical regions (while BaHaMa does not detail the regional level) and among nearly 40 energy technologies (while BaHaMa uses a macroeconomic approach to represent just two carbon-based and low-carbon economies). However, the results obtained with AD-MERGE again indicate that the best policy is to combine adaptation and mitigation. The use of adaptation now delays by at most 20 years an inevitable transition to energy systems with low GHG emissions (based on renewable, nuclear, and fossil fuels with carbon capture and storage systems). Our results also show that optimal levels of adaptation increase over time, with increasing temperature. By the end of the century, however, mitigation enables one to limit temperature increase and thus the need for adaptation. Our study also illustrates the synergy between adaptation, which reduces damage for a given temperature increase and is effective in the short term, and mitigation, which limits the longer-term increase in temperature. Sensitivity analyses show that energy system configurations depend more on the assumptions about the climate sensitivity than on the adaptation effectiveness.

4.3 Application to a geoengineering strategy

In Bahn, Chesney, et al. (2015), my co-authors and I modified the BaHaMa model to explicitly consider, in addition to mitigation and adaptation measures, an SRM geoengineering strategy that would inject sulfur particles into the stratosphere. In addition to considering the effects of this measure on global temperatures, we carefully explored the potential side effects. In particularly, we studied how uncertainty about the side effects could influence the decision about whether or not to deploy SRM measures.

First, we considered three illustrative scenarios, where the side effects are known to be "weak" (diminishing over time to a negligible damage value), "mild" (corresponding to a constant low GPD loss percentage for a given amount of sulfur injected), or "strong" (increasing over time to a high damage value). The use of geoengineering measures depends on the magnitude of the side effects. With weak side effects, geoengineering substitutes for mitigation, and the transition to a low-carbon economy does not take place. If the side effects are more pronounced, the transition takes place without delay. Specifically, if the side effects are mild, SRM measures are used (for a few periods only) to complement mitigation and adaptation strategies. If the side effects are strong, SRM measures are not used. In contrast, note that adaptation, which shares with SRM the advantages of rapid implementation and immediate reduction of climate change damage, is used in all three scenarios considered.

In a second analysis, we assumed that the magnitude of the side effects randomly increases or decreases over time. Specifically, we considered, following a binomial representation, close to 33,000 evolution scenarios from an initial level of the magnitude of the side effects. As the initial side effects become larger, the frequency with which geoengineering is used drops drastically. The same result is obtained when the side effects are assumed to persist longer. Therefore, taking into account the uncertainty about the magnitude of the side effects and their persistence over time, BaHaMa indicates that this SRM strategy lacks robustness. To further account for uncertainty, we considered that the policy-maker may be mistaken about the seriousness of the side effects. As an illustration, we simulated the case where the policy-maker, believing that the side effects are weak, implements geoengineering at the expense of mitigation. When, after several decades, he realizes that the side effects are actually strong, he stops all SRM measures and initiates a rapid transition to the low-carbon economy. However, given the climate inertia, he cannot prevent a significant rise in temperatures within a few decades, with important economic damage. Similar results are obtained when a technical failure prevents the injection of sulfur into the stratosphere, thus eliminating the ability to artificially reduce global temperatures. Such results again illustrate the risks inherent to this geoengineering strategy and the importance of mitigation and adaptation to deal with climate change.

5 Conclusions

Climate change presents complex challenges. We need to consider not only its economic and technological dimensions but also its political and social aspects. In this context, mathematical programming models, and in particular mathematical decision support models such as E3 models and IAMs, provide a rational framework for the design of relevant climate policies.

According to the different models I have used, and their results as presented in this review paper, adaptation appears essential considering the future climate change we are likely to experience. However, this should not delay the much-needed transition to low-carbon economies. On the other hand, geoengineering, and in particular the injection of sulfur particles into the stratosphere, is unlikely to provide an easy solution, given its inherent risk.

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