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

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

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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

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, 1998), 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 discusses several issues related to the use of mathematical models for climate policy design, and Section 6 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 the 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.

4.1.1 An application with the MERGE IA model

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.

MERGE is a world integrated assessment model that distinguishes among 9 geopolitical regions. It is composed of four modules as displayed in Figure 1.

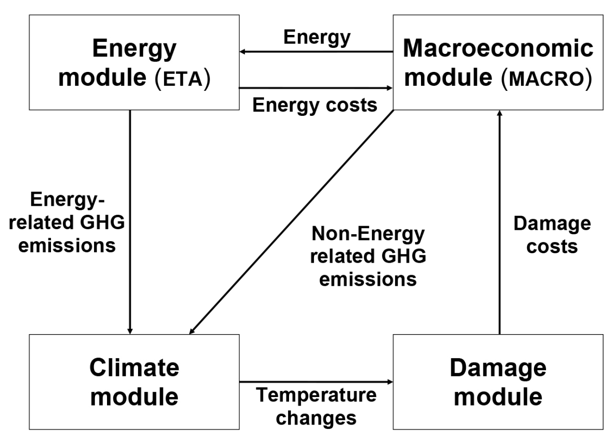

Figure 1: Overview of the MERGE modules

The first module (ETA) follows a bottom-up approach to represent the energy supply sector of each region. It distinguishes between the generation of electricity and the production of non-electric energy (fossil fuels, hydrogen, synthetic fuels and renewables), using close to 40 explicit energy technologies. Besides several explicit energy technologies, ETA also contains several generic technologies. For instance, it models a generic advanced 'high-cost' power plant that relies on biomass, nuclear, solar, and/or wind and corresponds to a 'backstop' technology with unlimited capacity. Energy transition to low-carbon systems is modeled through substitutions between the different energy carriers and energy technologies.

The second module (MACRO) follows a top-down approach to represent the other economic sectors. It uses a nested constant elasticity of substitution (CES) production function that models substitutions between a value-added aggregate (capital and labor) and an energy aggregate (electric and non-electric energy). This allows to capture macroeconomic feedback between the energy supply sector and the rest of the economy. The resulting regional ETA-MACRO models maximize a welfare function corresponding to the net present value of regional consumption. These models fall into the hybrid E3 category. The regional welfare functions are then aggregated into a global welfare function maximized by MERGE cast as a dynamic nonlinear programming model.

ETA-MACRO models compute anthropogenic emissions of CO_2, CH_4, N_2O (nitrous oxide), HFCs (hydrofluorocarbons) and SF_6 (sulfur hexafluoride). The third module (Climate module) describes next how these GHG emissions affect atmospheric temperatures. To do so, it successively computes changes in atmospheric GHG concentrations, in the earth's radiative forcing balance and finally in atmospheric temperatures. Finally, the fourth module (Damage module) quantifies the resulting economic losses. To do so, it considers both market damage (valued by market prices) and nonmarket damage (estimated using a willingness-to-pay approach).

In Bahn et al. (2011), we used the first three modules of MERGE only, following a cost-effectiveness approach, to define the GHG emission trajectories that maximize global welfare, while respecting temperature constraints that would prevent getting too close to a THC tipping point. 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. This is achieved by a transition to 'clean' energy systems (carbon capture and sequestration systems, nuclear, and renewables). The 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.

4.1.2 An application with the bottom-up NATEM model

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)? MERGE used in the previous application provides only generic information as the solution relies on generic backstop technologies and does not allow to distinguish between nuclear and renewable energies for electricity generation. To get more specific insights, one should rather use a detailed bottom-up energy model such as TIMES. As an illustration, one can consider Vaillancourt et al. (2017a) that analyze deep GHG emission reductions using a TIMES model for Canada (NATEM).

NATEM models the Reference Energy System (RES) of each of the 13 Canadian jurisdictions (provinces and territories); see Figure 2. NATEM is driven by 70 end-use demands for energy services in 5 sectors: agriculture (AGR), commercial (COM), industrial (IND), residential (RSD) and transportation (TRA). On the supply side, NATEM distinguishes between two sectors: electricity and heat production; and supply of all other energy forms (in particular, fuels from fossil and biomass sources). As in MERGE, decarbonization is modeled through substitutions between the different energy carriers and energy technologies. But the energy database is here much more detailed: NATEM models more than 4,500 specific technologies and 475 different commodities.

NATEM is cast as a dynamic linear programming model. The objective is to minimize the net total cost of the energy system. The main variables are technology specific investment and activity levels, energy consumed or produced by technology, transfers of energy commodities between jurisdictions, as well as international imports and exports. The constraints deal in particular with the scarcity of energy resources, energy balances within the energy system, and the satisfaction of useful energy demands.

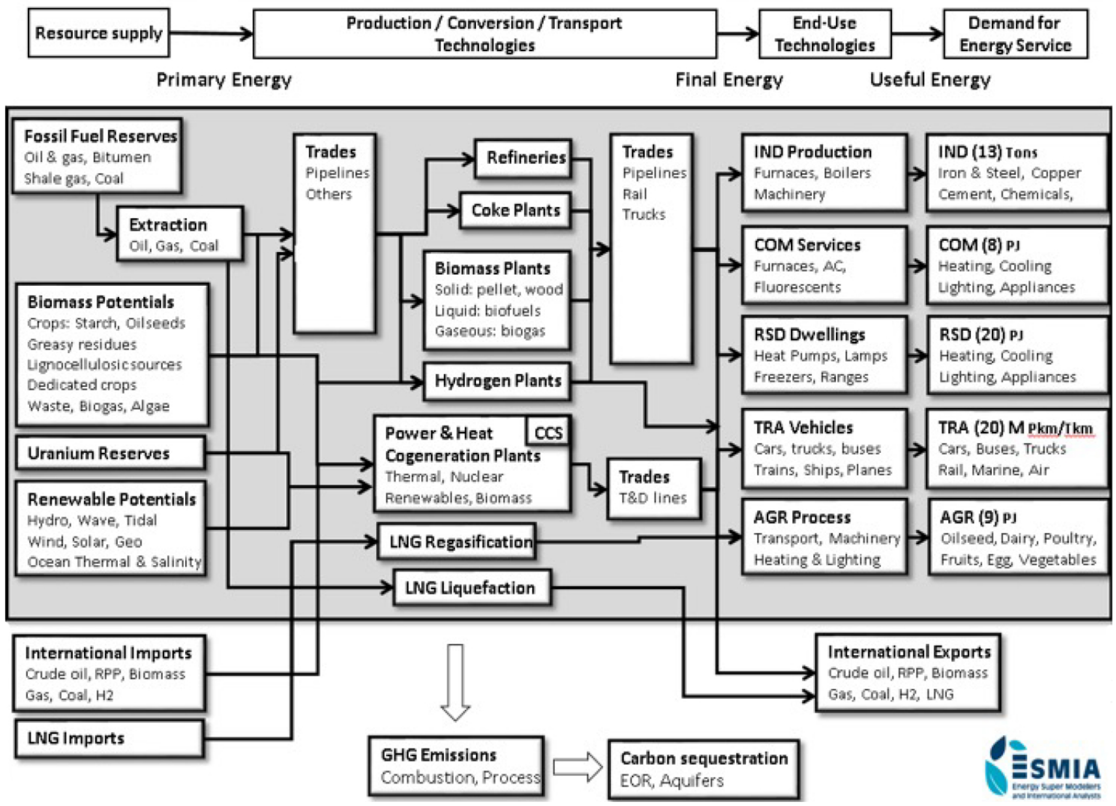

Figure 2: Regional RES in NATEM

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

Despite several international agreements to curb global GHG emissions, the latter are not yet decreasing. Future climate changes become thus unavoidable to some extent. Because of this, adaptation measures have gained a new momentum to become an important element of climate policies. I have started to consider such options in my research since the early 2010s. In this section, I report on two specific studies relying on integrated assessment models of increasing complexity.

4.2.1 An application with the Ada-BaHaMa IA model

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-based economy' (or 'dirty sector'), where economic production requires a high level of fossil fuels, and a 'low-carbon economy' (or 'clean sector'), 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. The resulting model, Ada-BaHaMa, is schematically described in Figure 3. Whereas the original BaHaMa model computes only GHG concentration dynamics, Ada-BaHaMa computes also how changes in GHG concentration affect global temperature. These changes yield economic impacts. The model then distinguishes between 'gross' damage related to temperature increase, and 'net' (reduced) damage that takes into account adaptation efforts through investments in an adaptation capital ('proactive' form of adaptation). Adaptation possibilities are, however, limited through a maximal adaptation effectiveness (exogenously assumed). Ada-BaHAMa is cast as a dynamic nonlinear programming model, where a world planner maximizes social welfare corresponding to the net present value of world consumption.

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 one third 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 Ada-BaHaMa is to combine (at different levels, as mentioned) adaptation and mitigation.

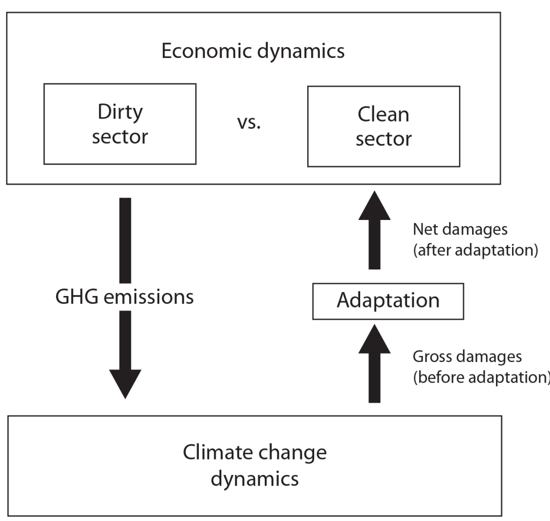

Figure 3: Overview of Ada-BaHaMa

4.2.2 An application with the AD-MERGE IA model

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 relies on the original formulation for nonmarket climate change damage, but replaces the market damage formulation to include the option of adaptation. AD-MERGE distinguishes between reactive and proactive adaptation, the former is modeled through a spending ('flow' adaptation), the latter through a capital build-up 'stock' adaptation). These two forms of adaptation are then aggregated using a CES function, used to compute total adaptation and to reflect the assumption that reactive and proactive adaptation are imperfect substitutes. AD-MERGE then distinguishes between gross damage due to temperature increase, and net damage after adaptation.

AD-MERGE is more detailed than Ada-BaHaMa. In particular, it distinguishes among 9 geopolitical regions (whereas Ada-BaHaMa does not detail the regional level) and among nearly 40 energy technologies (while Ada-BaHaMa uses a macroeconomic approach to represent two carbon-based and low-carbon economies). Besides, it takes into account both forms of adaptation (reactive and proactive), whereas Ada-BaHaMa considers only proactive adaptation.

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 An application to a geoengineering strategy

In Bahn, Chesney, et al. (2015), my co-authors and I modified the Ada-BaHaMa model; see Figure 4. In terms of adaptation, we upgraded the model to include also reactive (flow) adaptation, to complement proactive (stock) adaptation. We also extended the model to consider an SRM geoengineering strategy that would inject sulfur particles into the stratosphere to increase the albedo effect, reducing the radiative forcing (and thus the temperature increase) from an increase in GHG concentrations. We assumed a linear relation to approximate the impact of sulfur injection on radiative forcing. In addition, we carefully explored the potential side effects. In particular, we modeled the potential adverse impacts of the SRM measure as a time-varying and persistent process, function of a (time-varying) intensity factor and the radiative forcing created by sulfur injection. We then used the revised Ada-BaHaMA model to study how uncertainty about the side effects could influence the decision about whether or not to deploy SRM measures.

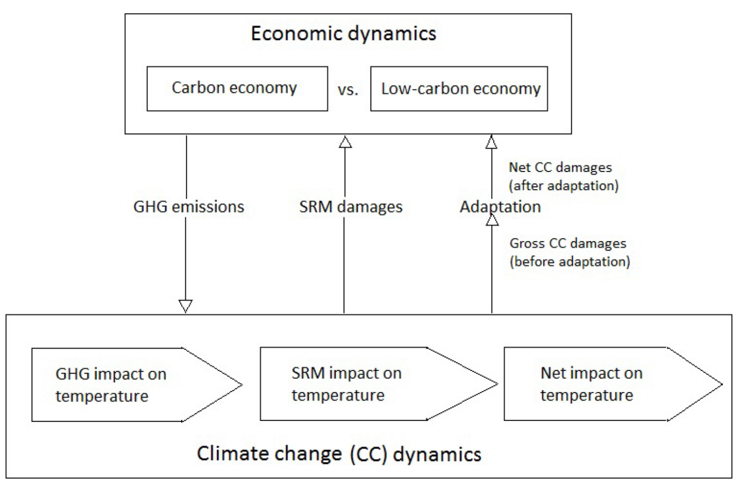

Figure 4: Overview of Ada-BaHaMa with geoengineering (SRM)

First, we considered three illustrative scenarios, where the side effects are known to be ‘weak’ (with an intensity factor 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’ (with an intensity factor 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 (intensity factor) 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 Discussion

Several issues arise with the use of mathematical models for climate policy design, such as the modeling of technological change (see, for instance, Bahn and Kypreos, 2003; Kypreos and Bahn, 2003) or the selection of an 'appropriate' discount factor to account of future costs and benefits of climate strategies. In this section, I briefly discuss two additional issues for which I have made some contributions: the negotiation of climate agreements and the accounting of uncertainty.

5.1 International environmental negotiations

The design and implementation of international environmental agreement (IEA) to curb GHG emissions are difficult tasks, as illustrated by the current negotiations taking place within the UNFCCC Conference of the Parties. In particular, countries may be tempted to free ride, letting the others bear the cost of abating emissions while enjoying a reduced level of climate change at no cost. Mathematical models can contribute to the design of IEA.

Bahn et al. (2009) explored in particular a punishment mechanism imposed to free riders to enhance country participation in the IEA. It also provided numerical illustrations based on the MERGE model. According to the importance of the punishment, stable agreements of various sizes may be obtained.

Bahn and Haurie (2008, 2016) studied the effect on IEA negotiation of having a supranational body (like the United Nations) imposing to all countries a coupled constraint on the total emissions allowed over the 21st century, or on the concentration of carbon reached at the end of the century. Beyond that, countries would choose non-cooperatively their GHG emission levels. Numerical illustrations were provided using BaHaMa (in Bahn and Haurie, 2008) and Ada-BaHaMa (in Bahn and Haurie, 2016). Both articles were showing that such an approach to IEA negotiations could yield an agreement which could be close to (Pareto) efficiency.

5.2 The uncertainty issue

The climate change issue is clouded with uncertainty, in particular on the true impact of GHG concentrations on global temperature. Likewise, the deployment of specific climate policies depends on uncertain elements. For instance, our capacity to limit GHG emissions in the future depends on (still unknown) future investment levels in green technologies not yet fully deployed on a commercial scale (e.g., carbon capture and storage systems, or systems for the production of second-generation biofuels). The deployment of adaptation shall depend on its effectiveness, not yet fully known. Finally, a possible use of geoengineering options critically depends on the (very uncertain) magnitude of their side effects.

Several approaches may be followed to address such uncertainties. In my research, I typically use (deterministic) sensitivity analysis to assess the impact of key parameters such as the climate sensitivity (for instance, in Bahn et al., 2011) or the effectiveness of adaptation (as in Bahn et al., 2012; and in Bahn, de Bruin, and Fertel, 2015). In Bahn, Chesney, et al. (2015), we assumed that, at each moment of time, the side effects of geoengineering can either increase or decrease (with a given probability) compared to their previous levels, following a binomial representation, so as to generate a large number of scenarios for the possible evolution of the side-effect magnitude. Such approaches are quite useful to deal with uncertainty, but do not yield a clear hedging strategy.

Stochastic programming is another popular approach. In Bahn et al. (2006), where we proposed methods to link optimal economic growth (top-down) models with climate models, we provided a numerical example with the MERGE model, designing a hedging mitigation strategy using a stochastic programming method. The drawbacks of the latter are that probabilities have to be defined over the whole tree and that policy insights are sensitive to the design of the branching scheme.

In Bahn et al. (2008), we proposed a stochastic control IAM (the original BaHAMa model) where the resolution of uncertainty is described as controlled stochastic jump Markov processes. The optimal policy was characterized using the dynamic programming solution to a piecewise deterministic optimal control problem. A numerical illustration provided insights on the timing issue of climate policy. Bahn et al. (2010) extended the previous IAM to a game theoretical framework, assuming non-cooperative behavior of two groups of countries that are affected by climate change-related damages induced by their joint GHG emissions. These two articles proposed thus a more formal and rigorous description of climate policy design under uncertainty, compared to the previous approaches, but at the expense of complex computations. Indeed, a stochastic control approach may considerably increase the size of the problem to be solved, quickly yielding excessive computational times.

Another approach to deal with uncertainty is robust optimization that is currently gaining momentum, although its use for climate policy design remains marginal. Robust optimization allows to solve problems under uncertainty, even if the underlying probabilities are unknown. The idea is to immunize a solution against adverse realizations of uncertain parameters within given uncertainty sets or against 'worst possible' cases. In Andrey et al. (2016), we introduced a concept of α-robust equilibrium for IAMs, where the robustification is achieved through the use of ambiguous probability distributions with a Kullback-Leibler divergence. Numerical illustrations were provided with the BaHaMa model. In Nicolas et al. (2016), we proposed a general robust approach to consider uncertainty in simple climate models typically used in IAMs and provided numerical illustrations with TIAM.

6 Conclusion

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.

I have started my research career working on coupling different types of bottom-up energy models (Bahn et al., 1994, 1998). Today, I am still working on linking different modeling approaches. More precisely, I am currently working on combining information from TIMES models and life-cycle assessment (LCA) to perform consequential LCAs; see Levasseur et al. (2017) for a first effort in that direction. Besides, I will continue working on integrated assessment modeling, paying close attention to the treatment of uncertainty (for instance, using robustification techniques), and on the development of bottom-up energy models to address specific Canadian energy issues, such as the exploitation and transport of Canadian hydrocarbons (see, for instance, Vaillancourt et al., 2015, 2017b).

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