THE ROLE OF ENERGY SYSTEM MODELING IN SUPPORTING CANADA'S DECARBONIZATION

SUMMARY : Long the domain of operations research and economists, energy system modeling has much to gain from the contributions of physicists.



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Energy systems encompass all the energy sources used by a community, as well as the infrastructure and technologies associated with their production, distribution, conversion, and utilisation in end-use applications, such as: heating a building, transporting people and goods, manufacturing goods, etc. [1]. These systems are complex, interconnected, and, in most cases, have developed over time through a combination of organic growth, public planning, and the struggle to protect various interests. The central role of energy systems in our societies became evident following the first oil crises of the early 1970s. Sudden disruptions in oil supplies highlighted the need to understand energy systems, which spurred the development of the first models, based on bottom-up representations of these systems. These models, which describe in detail the technical and economic aspects and relationships from production to final use, play various roles in understanding and planning energy systems.

There are several families of energy system models: simulation models, which use various rules to assess how energy needs will evolve based on population and economic growth, as well as technological changes [3]; bottom-up optimization models, which start with the current state of the energy system (from production to utilisation technologies) [4] and—generally building on demand estimates derived from simulations—assess the optimal energy and technology choices that minimize system costs while meeting projected demand; and top-down systems [5], often based on classical general equilibrium theory, which start with a broad, high-level description of the economic system to assess the link between these transformations and the rest of the economy. In parallel, of course, more technical models have been developed to represent, among other things, electric grids, gas networks, and the petroleum system, in support of the planning and management of these complex networks.

After a relatively quiet period in the energy sector, interest in systemic models was reignited by major international climate treaties and the commitment expressed by many countries to significantly reduce their greenhouse gas emissions—and even, with the Paris Agreement signed in 2015, to aim for carbon neutrality by 2050 (Fig. 1) [5]. Since the energy sector is responsible for two-thirds of global emissions, it followed naturally that any reduction would require deep transformations of the energy system while broadening the range of variables considered in these models to include climate, environmental, and life-cycle issues, using integrated assessment models [6].

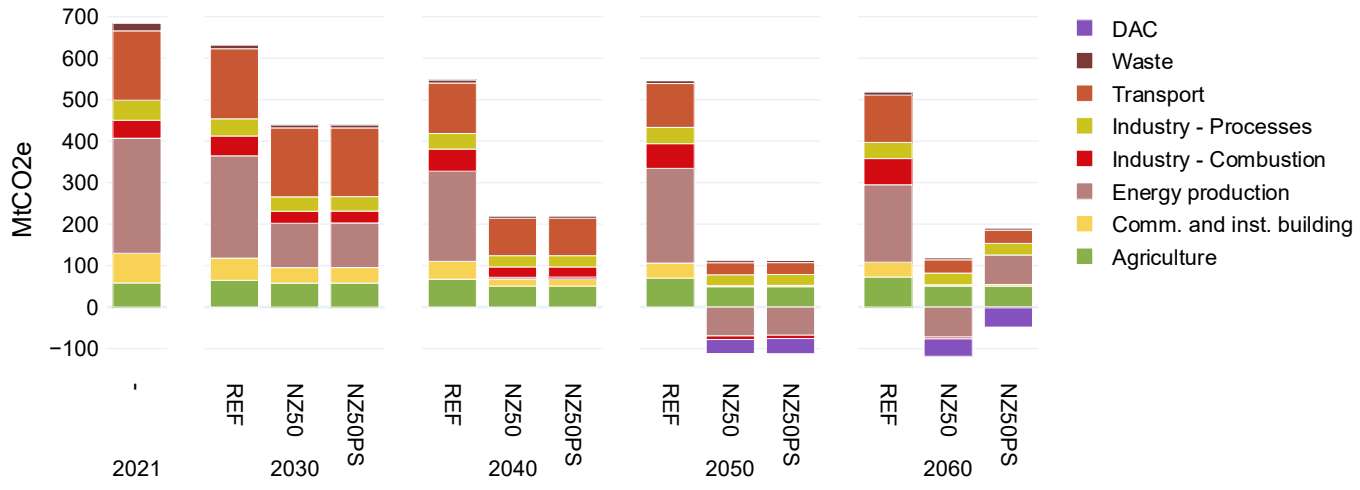


Figure 1. Total greenhouse gas emissions by sector between 2021 and 2060 for Canada under a carbon net-zero 2050 scenario, as calculated using the bottom-up techno-economic optimization model NATEM developed by ESMIA Consultants. Starting in 2050, there is a need for a significant amount of negative emissions—that is, emissions removed from the atmosphere, in order to reach net-zero. REF is the reference scenario with no greenhouse gas emission reduction targets. NZ50 aims for carbon neutrality by 2025, while NZ50PS adds the costs of small modular reactors to the NZ50 scenario (Source: Fig. 4.1 in Ref. [2])

While efforts initially focused on making better use of energy sources and related technologies—with modest GHG reduction targets—in line with the energy efficiency policies developed in the wake of the first two oil crises, such an approach is no longer appropriate when aiming for carbon neutrality: it is necessary to switch to different energy sources, rather than simply reducing marginally the use of fossil fuels. The adoption of carbon neutrality goals, coupled with the massive integration of new energy sources—primarily wind and solar, which have characteristics very different from traditional sources—has therefore reignited interest in energy system modeling, including the development of new tools,

approaches, and parameterization methods, as well as new energy technologies for transportation, heating, etc., with the aim of facilitating planning and the development of public policies. This renewed effort to model energy systems comes as the scientific community increasingly turns toward the development of open-source models—from codes to data—whereas historical codes are predominantly proprietary and closed-source.

In recent years, we have therefore witnessed a resurgence in the energy modeling community, with the participation of many new players. Long reserved for specialists in operations research, economists, and engineers—particularly those in electrical engineering—this field now attracts researchers from several other disciplines, including physicists, while simulation methods are diversifying to include, for example, stochastic and agent-based models [7], which complement the approaches traditionally developed by physicists, but also draw on their experience with larger-scale computations.

The new modeling philosophy offers the possibility of better integrating nonlinear approaches or those based on complex systems and of going beyond the standard optimization models in the field, which rely primarily on the minimization of discrete choices—that is, which require choosing one technology or the other, rather than a continuous mix of the two. This type of optimization does not allow for the use of calculus and often requires a linear re-formulation of the problem and the use of proprietary, closed-source tools for their solution.

Despite the considerable efforts we have seen in this field in recent years, many challenges remain for the community—challenges that may, in part, be of interest to physicists. On the technical front, the development of methods that go beyond linear solutions for discrete variables would certainly facilitate the development of more complex systems. One can imagine, for example, that stochastic approaches or even quantum computers would allow for a much richer exploration of problems of this type. Similarly, historically, energy system models have been designed to run on relatively lightweight computing infrastructures, often local servers. Rethinking these problems and the accompanying code for use on supercomputers would certainly make it possible to tackle more complex issues.

At the heart of these technical challenges lies the issue of data. How can we generate this data when it is often not publicly available? Would approaches that allow us to separate aggregated data, remove noise, and use statistical methods similar to those employed in various branches of physics enable us to reconstruct some of this data?

Finally, there is the question of modeling approaches and the issues addressed. By design, energy system models tend to focus on large-scale systems—provinces, countries, and continents. However, the transformation of the energy system is also taking place at the very local level, with impacts that can sometimes be very different. The integration of new technologies for energy consumption, as well as for decentralized energy production and storage, requires solutions and analyses that operate in both directions and involve highly nonlinear interactions. Would methods developed by physicists—whether for atomistic modelling or the multiscale approach to complex problems—be relevant here? In this context, the analysis of these complex systems aligns with that conducted by physicists who specialize in complex systems.

In addition to these technical issues, some behavioral and individual factors must also be considered. All too often, models tend to overlook the choices and behaviors of consumers, whether they are individuals or legal entities. Yet, in today's bidirectional contexts, these factors play a crucial role. Rather than imposing behaviors on citizens that merely replicate the models' optimized solutions, we need to revise algorithms and simulation methods to incorporate individual realities, thereby enabling more realistic planning for future transformations.

HERE IN CANADA

Over the decades, Canadian researchers have made significant contributions to the development of numerous models, including the MARKAL-TIMES model. As elsewhere in the world, the renewed importance of energy modeling for energy transition planning has strengthened governments' interest in energy modeling. This interest led to the creation of the Energy Modeling Hub [8] in 2022, an initiative initially led by Louis Beaumier and myself at the Institut de l'énergie at Polytechnique Montréal, Madeleine MacPherson of the Institute for Integrated Energy Systems at the University of Victoria, and Blake Shaffer of the School of Public Policy at the University of Calgary. Funding from Natural Resources Canada was renewed for four years in 2025, with the addition of partners from York University and Carleton University. In addition to bringing together researchers and stakeholders interested in energy modeling, this organization develops and maintains an open energy database and models accessible to the entire Canadian community. At the same time, Natural Resources Canada has issued several calls for proposals in recent years to promote the development of open models, many of which will be integrated, at various levels, into the CME's tools.

This collaborative Canadian environment allows researchers with an interest in the field to easily join and participate in the development of tools without having to start from scratch. This is therefore an excellent time for physicists interested in these issues to become part of this growing community and help advance a field that is crucial to the transformation of not only Canada's energy system but also that of the entire planet.

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