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# Exploring deep decarbonization pathways to 2050 for Canada using an optimization energy model framework

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## HIGHLIGHTS

- Study of deep decarbonization pathways for the Canadian energy sector to 2050.
- Use of a TIMES optimization energy model to derive minimum cost solutions.
- Key options are electrification, clean electricity supply and efficiency gains.
- Disruptive technologies are needed to meet ambitious targets at reasonable costs.

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## ABSTRACT

The main objective of this paper is to explore deep decarbonization pathways for the Canadian energy sector that would allow Canada to participate in global mitigation efforts to keep global mean surface temperatures from increasing by more than 2 °C by 2100. Our approach consists in deriving minimum cost solutions for achieving progressive emission reductions up to 2050 using the North American TIMES Energy Model (NATEM), a detailed multi-regional and integrated optimization energy model. With this model, we analyze a baseline and two 60% reduction scenarios of combustion related emissions by 2050 from 1990 levels, with different assumptions regarding projected demands for energy services and availability of technology options for carbon mitigation. The first reduction scenario includes only well-known technologies while the second one considers additional disruptive technologies, which are known but are not fully developed commercially. Results show that three fundamental transformations need to occur simultaneously in order to achieve ambitious GHG emission reduction targets: electrification of end-use sectors, decarbonization of electricity generating supply, and efficiency improvements. In particular, our results show that electricity represents between 52% and 57% of final energy consumption by 2050, electricity generating supply achieves nearly complete decarbonization by 2025 and final energy consumption decreases by 20% relative to the baseline by 2050.



## 1. Introduction

### 1.1. Context

The international scientific community has stated the need for deep decarbonization of the global economy in order to avoid irreversible damage from anthropogenic climate change. The Intergovernmental Panel on Climate Change (IPCC) has determined that atmospheric GHG concentrations should not exceed 450 ppm of carbon dioxide equivalent ($CO_2e$) in order to keep global mean surface temperatures from increasing by more than 2 °C by 2100, thus, minimizing dangerous anthropogenic interference with the climate. This translates to an emission reduction target range between 23% and 63% of global 1990 levels by 2050, and 71% to 124% by 2100[1] [1].

In 2014, total Canadian emissions were 732 Mt of $CO_2e$ with around 81% being energy-related and the rest being attributed to industrial processes and product use, agriculture, and waste [2]. Canada has recently announced a national GHG emission reduction goal of 30% reduction from 2005 levels by 2030 [3]. However, this target places it last (tied with Japan) concerning emission targets

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[1] Emission target range was converted from a 2010 base year to a 1990 base year using the fact that 2010 global emissions were 31% higher than 1990 emissions, data is taken from Table 3.1 in [1].

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amongst the G7 countries. One major obstacle impeding more ambitious reduction policies is Canada's role as one of the largest fossil fuel-exporting countries. In 2013, oil and gas production accounted for around 10% of Canadian GDP [4]. By comparison, in the United States, the share of oil and gas production in GDP was around 1.6% in 2011.

### 1.2. Objectives

The main objective of this paper is to explore possible deep decarbonization pathways and identify priority actions for the Canadian energy sector which would allow Canada to participate in these global mitigation objectives. Our approach is to derive minimum cost solutions for achieving progressive reductions in total greenhouse gas (GHG) emissions, from 2011 to 2050, for all of Canada. This is done using the North American TIMES Energy Model (NATEM), which is a highly detailed multi-regional optimization model [5]. NATEM is part of The Integrated MARKAL-EFOM System (TIMES) family of models supported by the *Energy Technology Systems Analysis Program* of the *International Energy Agency* [6].

A series of GHG reduction targets for 2050, varying from 30% to 70% reduction (in 10% increments) below the 1990 level, were first analyzed. The 60% reduction target was selected as the maximum realizable target for the combination of possible reduction options included in the model database. Any substantive increase in the target was not economically feasible with current technologies. For this paper, the goal of 60% reduction is set in order to delineate the most efficient mitigation measures and optimize the timing of their implementation.

Another objective of this paper is to show the impacts of considering disruptive technologies, which are known but are not fully developed commercially, on the optimal solutions and their costs. A series of scenarios were analyzed where additional disruptive technologies were included incrementally. This paper compares the two extreme cases: one scenario where only commercially proven technologies are included, and the other, where multiple disruptive technologies are also included in the model database.

### 1.3. Optimization of decarbonization scenarios

Optimization models provide a rigorous analytical basis for defining decarbonization pathways and deriving minimum cost solutions that meet both growing demands for energy-related services and progressive reductions in combustion emissions. At a global level, the *Global Energy Assessment* [7] explores three alternative sets of transformation pathways using two integrated assessment modeling frameworks including the Model of Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE). In addition, every two years the *Energy Technology Perspectives* [8] of the *International Energy Agency* provides a comprehensive analysis of possible energy futures to 2050, including more than 500 technology options, using the TIMES cost-optimization model and stock accounting simulation models. Finally, the *World Energy Scenarios* of the *World Energy Council* [9] presents three exploratory scenarios representing alternative energy transition futures to 2060 using the Global Multi-Regional MARKAL (GMM) energy model.

At a national or regional level, numerous decarbonization studies have been carried out using cost-optimization models, in a stand-alone manner or in combination with other models. In particular, scenarios achieving an 80% GHG reduction goal of 1990 levels by 2050 employing the TIMES methodology were analyzed, for instance, in California [10,11], Ireland [12], Scotland [13] and the United Kingdom [14]. Some studies rather focus on pathways directly compatible with meeting the 2 °C target and their impacts on the energy system of various regions such as China and India [15,16] or globally [17,18]. Other studies on emission reduction pathways using similar tools include analysis for Macedonia [19], Austria [20] and Taiwan [21]. Comparable studies look at sector-specific decarbonization pathways such as for the electricity sector in Portugal [22] and Switzerland [23], and for the cement [24], steel [25] and building sector [26] in China. Finally, several studies propose decarbonization pathways through renewable penetration targets rather than emission targets such as for the power sectors in France [27] and Greece [28].

Based on the literature review, the work presented in this paper brings significant new information on this topic. Indeed, this is the first time in Canada that such a comprehensive integrated multi-jurisdictional approach, in a multi-time period context, has been undertaken for deriving minimum cost solutions for meeting ambitious GHG mitigation targets [5]. While global optimization models handle Canada as an aggregated region or even as part of the North American region, no other studies have been carried out for Canada specifically using a cost optimization, multi-regional and technology-rich approach. The *Deep Decarbonization Pathways Project* [29] looks at substantial reduction targets for fifteen different countries including Canada. The Canadian chapter of the project looks at an 88% reduction from 2015 levels by 2050, excluding agriculture, using a simulation model and a computable general equilibrium model [30,31]. However, it does not explicitly take cost minimization into consideration as part of a complete energy system approach. Similarly, two more studies carried out at *Environment and Climate Change Canada* [31] reports on a net 80% GHG emission reduction from 2005 levels using the Global Change Assessment Model (GCAM), a dynamic-recursive computable general equilibrium model.

Consequently, the work presented in this paper can: (i) provide more detailed Canadian-specific insights to global studies on deep decarbonization and their impacts on other regions; and (ii) help the Canadian authorities in defining long-term GHG strategies that are aligned with international agreements with a minimum impact on the energy system cost.

The remainder of this paper is organized as follows. Section 2 presents our methodological approach. Section 3 presents the different scenarios and their underlying assumptions. Section 4 consists of an overview of the main results as well as more detailed results by sector. Section 5 proceeds with a discussion of policy implications and limitations of the study. Section 6 concludes with a summary of key points and lessons learned.

## 2. Methodology

Our approach consists in deriving minimum cost solutions that satisfy both growing demands for energy-related services and progressive reductions in GHG emissions up to 2050. For this, we use the Canadian portion of the NATEM multi-regional energy model (NATEM-Canada) [5]. It offers a comprehensive representation of the energy system of each of the 13 Canadian provincial and territorial jurisdictions. It also models inter-jurisdictional and international flows of energy commodities, as well as the various options for meeting the prescribed GHG mitigation targets in 2050. NATEM has been soft-linked with a detailed simulation model of the Canadian energy systems (CanESS) [32] to provide consistency checks in particular for the turnover of the energy technology stocks.

### 2.1. The NATEM optimization energy model

NATEM was developed based on the TIMES optimization model generator [6]. A TIMES model is a representation of one or multiple region's entire integrated energy system through specific technolo-