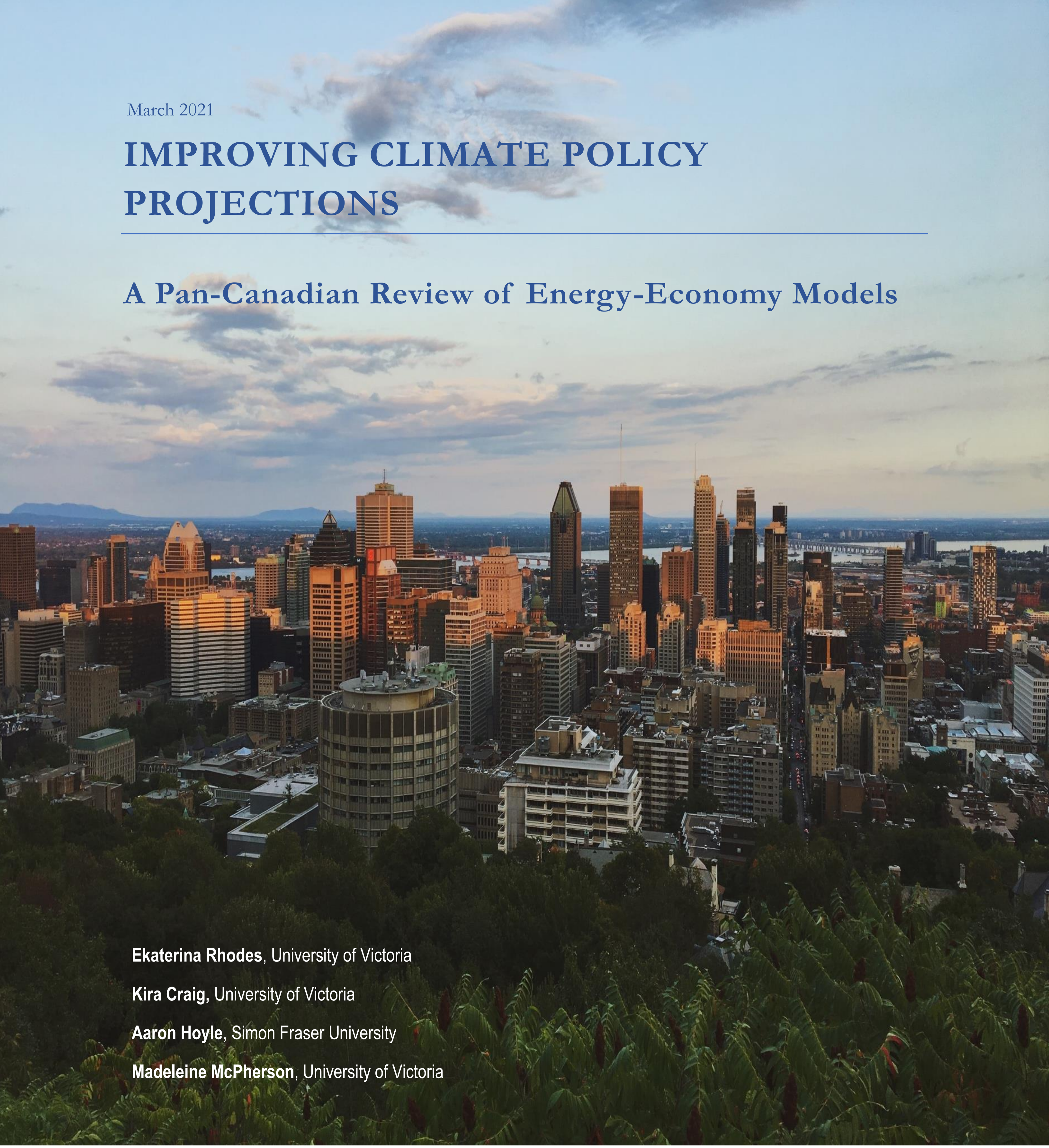

March 2021

IMPROVING CLIMATE POLICY PROJECTIONS

A Pan-Canadian Review of Energy-Economy Models

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EXECUTIVE SUMMARY

Canada has committed to reduce its greenhouse gas (GHG) emissions by 30 per cent by 2030 below 2005 levels and to net zero by 2050. To achieve these targets, the federal and many provincial and territorial governments implemented a variety of climate policies, including carbon pricing, sector-specific regulations, incentives for clean technologies, and low-carbon infrastructure investments. However, forecasted impacts of these policies vary dramatically across different energy-economy models in terms of GHG and economic outcomes. Understanding Canada's existing energy-economy modelling landscape can help select models suitable for specific policy questions, better assess progress to climate targets, and implement effective climate policy.

Over the past decade there have been increasingly disparate attempts to improve the accuracy of climate policy projections. Some of this work exists in academic literature, while the rest occurs in private and not-for-profit sectors with limited access to methodological information. This study develops a mixed-method review of the key strengths, gaps, and improvements in energy-economy models in the public, private, and not-for-profit sectors in Canada over the past ten years. The main objectives are to:

1. develop a publicly accessible inventory of energy-economy models in Canada;
2. develop best practices for modelling climate policies; and
3. engage stakeholders to synthesize and disseminate research results, including model critiques and best practices, to improve the overall accuracy of forecasted climate policy impacts.

To develop a publicly accessible inventory of models, we combine the use of a narrative literature review with a web-based 'expert' survey of Canadian model developers and users (n=14). First, we study academic peer-reviewed literature and open-access reports from public, private, and not-for-profit organizations, to identify the key characteristics for assessing the ability of energy-economy models to evaluate climate policy impacts, to develop a list of energy-economy models used across Canada, and to assess them against the identified characteristics. Energy-economy models are considered eligible for inclusion in the literature search based on their ability to evaluate economy-wide climate policies, specifically if (a) they were used to assess GHG and economic impacts of climate policies in Canada between 2009 and 2019 inclusive; and (b) if there is sufficient publicly available documentation to evaluate models against the assessment characteristics. We search for this information via ScienceDirect and Google Scholar databases. As a result, we identify 21 models and assess them qualitatively against the key four characteristics of treatment of technology, microeconomic realism, macroeconomic realism, and policy representation.

To enrich the narrative literature review, we implement a web-based survey instrument that helps update literature review results, identifies missing energy-economy models, describes models that lacked published information, and assesses all models against three new characteristics of uncertainty analysis, spatial and temporal representations, and data transparency, in addition to the four aforementioned characteristics. The survey analysis combined with the narrative literature review, results in a comprehensive modelling inventory that compares and contrasts 24 distinct energy-economy models against the seven assessment characteristics. These models fall under four categories: top-down (17%), bottom-up (25%), hybrid (41%), and integrated assessment models (17%).

We find that models that share similarities in over-arching methodological approaches are also similar in the way they represent technologies, market heterogeneity, trade effects, different policy types, and energy equilibrium. Conversely, there are quite diverse approaches used in the representation of technological change, non-financial microeconomic factors (e.g. lack of information, quality of service), financial or monetary features, and non-energy equilibrium. For the most part, models represent technology, micro- and macroeconomic characteristics according to the typology of bottom-up, top-down, hybrid, and integrated assessment models. However, several modelling evolutions have emerged. To varying extents, top-down models can explicitly represent technologies and some bottom-up models incorporate microeconomic characteristics. We find that models differ in the types of policies they can simulate, sometimes underrepresenting politically popular performance regulations, government procurement, and research and development programs. All models use at least one method to explore uncertainty, rarely incorporate detailed spatial and temporal representations, and lack transparent methodological documentation.

Based on our results, we suggest six best practices that can help researchers and policy-makers improve energy-economy models and better assess impacts of climate policies. Specifically, models should:

1. explicitly represent energy-related technologies and technological change dynamics;
2. capture both market heterogeneity and non-financial (behavioural) costs of technologies;
3. include a representation of trade and finance;
4. link energy supply-demand using price-quantity adjustments;
5. accurately represent different types of policies and policy interactions; and
6. explore uncertainty in forecasted economic and GHG impacts.

These suggestions do not determine which model is 'best' because model choice depends in part on the type of research and/or policy question posed. However, the inventory and the best practice suggestions can assist researchers, modellers, and policy-makers in choosing the most suitable modelling tools for their specific questions, and help identify methodological gaps to address in future research. Given that models continuously evolve through modifications by model developers and users, the inventory should be treated as a guide based on 2020 data.

Our knowledge mobilization activities engaged a variety of relevant stakeholders to validate and disseminate research results in the public, private, and not-for-profit sectors in Canada. First, we validated literature review results by asking model users and developers across the country to complete an 'expert' survey for the models they develop and/or use. Then we disseminated our findings through public presentations to climate policy-makers in the Government of British Columbia (December 9, 2020) and the Government of Canada (January 14, 2021), policy advocacy experts in a not-for-profit Canadian Climate Choices Institute (January 19, 2021), and interdisciplinary researchers in the Institute for Integrated Energy Systems at the University of Victoria (February 3, 2021). We have also submitted abstracts to two conferences to validate and disseminate results to wider audiences, including the private sector and academia. Specifically, we anticipate to present the results at the Canadian Society for Ecological Economics conference in May 2021 and the Canadian Economics Association conference in June 2021. We have submitted the literature review and survey results for publication in two high-impact peer-reviewed journals, Renewable and Sustainable Energy Reviews and Energy Research and Social Science, to further enhance the project's contributions to the state of academic modelling knowledge. In summary, the study represents the first pan-Canadian effort to systematically synthesize energy-economy model methodologies, facilitating the use and development of more accurate models to help Canadian policy-makers ensure GHG emissions remain within the Earth's carrying capacity.

1. BACKGROUND

1.1. ISSUE

As part of the global Paris Agreement, 189 nations pledged to reduce greenhouse gas (GHG) emissions to ensure the global average temperature does not exceed two degrees Celsius (United Nations Climate Change, 2020). Canada set a GHG emissions reduction target of 30 per cent by 2030 below 2005 levels and has recently committed to achieve a net zero economy by 2050 (Government of Canada, 2016; Government of Canada, 2020). To achieve these targets, the federal and many provincial and territorial governments implemented a variety of climate policies, including carbon pricing, sector-specific regulations, incentives for clean technologies, and low-carbon infrastructure investments. However, forecasted impacts of these policies across different energy-economy models vary dramatically in terms of GHG and economic outcomes (Vaillancourt et al., 2017; Environment and Climate Change Canada, 2018; Jaccard et al., 2016; Bataille et al., 2015). The discrepancy in modelling results highlights the need to better understand differences in modelling methodologies and develop best practices for improving climate policy projections.

> This review is a tool for researchers and decision-makers to help them understand why (or why not) a particular energy-economy model might be well-positioned to answer their research and policy questions.

Quantitative models of the energy-economy are widely used to understand and determine policy responses to climate change in the energy sector. Models are often applied to global energy system analysis, in addition to individual nations or sub-national regions (e.g. provinces and territories) to form an evidence base for climate policy analysis. Given the complexity and diversity of energy-economy models (also termed "energy-environment-economy" models in the literature), designed for a variety of purposes, this review is a tool for researchers and decision-makers to help them understand why (or why not) a particular energy-economy model might be well positioned to answer their research and policy questions.

Over the past decade there have been increasingly disparate attempts to improve climate policy projections in energy-economy models. Some of this work exists in academic literature (Jaccard et al., 2019; Ghersi, 2015; Cai et al., 2015; Murphy & Jaccard, 2011), while the rest occurs in private and not-for-profit sectors with limited access to methodological information (Navius Research, 2019; Pembina Institute, 2019; McPherson, 2019). Despite the growing attention to modelling improvements, there are also debates about the key modelling characteristics that help produce 'more realistic' climate policy forecasts (Pindyck, 2013; Hedenus et al., 2013). Furthermore, information about existing modelling tools, recent improvements, or their criticisms is not summarized against consistent methodological characteristics in a publicly accessible manner. Some of the published reviews focus exclusively on energy systems models (rather than energy-economy models) without incorporating economic agent behaviour and using different assessment characteristics and model classification schemes.

1.2. OBJECTIVES

Our study employs a mixed-method scoping review of the key strengths, gaps, and improvements in energy-economy models in the public, private, and not-for-profit sectors in Canada over the past ten years. The main objectives are to:

1. develop a publicly accessible inventory of energy-economy models in Canada;
2. develop best practices for modelling climate policies; and
3. engage stakeholders to synthesize and disseminate research results, including model critiques and best practices, to improve the overall accuracy of forecasted climate policy impacts.

In order to develop a modelling inventory, we conduct a narrative literature review and a web-based 'expert' survey of model developers and users (n=14) in Canada. The main objectives of the literature review are to (a) develop the main energy-economy modelling assessment characteristics, (b) identify all energy-economy models used in Canada in the last decade, and (c) initiate a cross-modelling assessment against the identified characteristics in (a). The survey's objectives are to (a) validate existing literature reviews of energy-economy models with up to date primary data, (b) identify any missing models in the literature review, and (c) assess all models across a broad range of assessment characteristics to capture model information that is not otherwise documented in a publicly accessible manner. We use the results of the narrative review and the survey to create a comprehensive inventory of all energy-economy models in Canada and to develop best practices for modelling climate policies.

The report is organized as follows. Section 2 reviews the key typologies of energy-economy models. Section 3 describes the methodology of our narrative literature review and survey. Section 4 summarizes results in regards to the model assessment characteristics and how energy-economy models in Canada score against these characteristics, developing a matrix tables inventory of energy-economy models in Canada (objective 1). Section 5 provides best practices for modelling climate policy (objective 2). Section 6 summarizes the key findings and outlines opportunities for future research. Section 7 describes the knowledge dissemination activities.

2. MODEL TYPOLOGY

Most energy-economy models can be grouped into three main categories: bottom-up, top-down, and hybrid, depending on the degree of incorporating methodological characteristics of technological explicitness, behavioural realism (microeconomic realism), and equilibrium (macroeconomic) feedbacks (Jaccard et al., 2003; Rivers & Jaccard, 2006) (Figure 1).

Technological explicitness is the level of detail to which current and emerging technologies are represented in a model (Mundaca et al., 2010). The level of behavioural realism depends on whether human preferences are accounted for, including intangible costs, or if decisions are only based on minimizing costs (Rivers & Jaccard, 2006). Equilibrium feedbacks are how the equilibrium of prices, demand, and supply level of goods in the macroeconomy are affected by a policy (Nika et al., 2019).

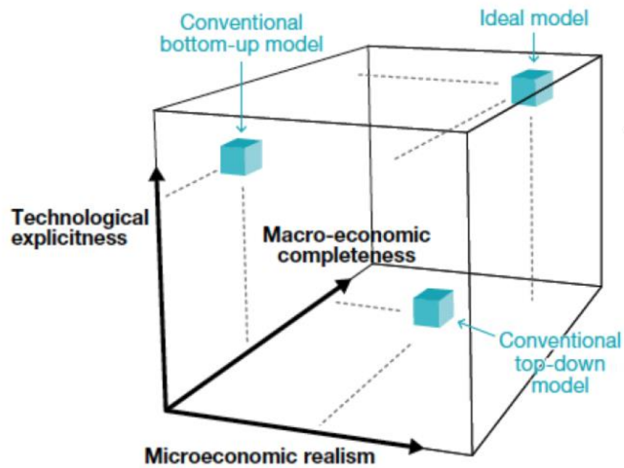


Figure 1. Three-dimensional assessment of energy-economy models. The ideal model is a hybrid model combining the strengths of top-down and bottom-up models. Reproduced from Hourcade et al. (2006).

The main strength of bottom-up energy-economy models is their high level of technological explicitness. Current and future technologies are characterized in detail including their market shares, capital and operating costs, emissions profile and energy use (Rivers & Jaccard, 2006; Jaccard, 2009). A criticism of bottom-up models is their lack of behavioural realism because they assume different technologies are perfect substitutes and that financial costs are the only factor in the estimate of the total social costs of technological change (Rivers & Jaccard, 2006). However, this is not an accurate depiction of reality as other behavioural (intangible) costs are included in technology purchasing decisions such as consumer preference, higher chance of premature failure, and differing financial costs between consumers (Jaccard et al., 2003). In addition, such models do not consider macroeconomic feedbacks, since energy sector technologies are not interacting with the rest of the economy (Löschel, 2002). As a result, bottom-up models underestimate the total cost of emissions abatement, which leads to overly optimistic GHG reductions under climate policy (Jaccard & Dennis, 2006). The high level of technological detail makes bottom-up models useful when policy-makers are trying to determine the potential impacts of emissions from future technologies and energy demands (Herbst et al., 2012), as well as to show the technological possibilities to meet environmental targets (Jaccard et al., 2003).

In contrast, top-down models take an aggregated approach by focusing on the interactions between the energy system and the rest of the economy (Assoumou et al., 2018). Top-down models, such as Computable General Equilibrium models, can assess the links between sectors to determine how a policy directly impacts the rest of the economy through macroeconomic equilibrium feedbacks (Nika et al., 2019). Top-down models are also able to incorporate behavioural realism as the parameters are based on historical data, so they contain the intangible behavioural costs consumers and businesses include in making technological purchasing decisions (Rivers & Jaccard, 2006). The problem with the use of historical data is that decision-making of the past may not be indicative of future decisions (Rivers & Jaccard, 2006; Jaccard, 2009). By focusing on the overall processes in the economy at a simplified level compared to bottom-up models, top-down models lack technological explicitness and neglect to account for technology preferences. The combination of these factors contributes to an overestimation in emissions abatement costs (Horne et al., 2005). Top-down models are useful when modelling large scale policies such as taxes,

but the absence of technological detail means they are inadequate at modelling technology specific polices such as subsidies (Jaccard & Dennis, 2006)

To overcome the challenges faced by bottom-up and top-down models, hybrid energy-economy models were developed. Hybrid models combine the strengths of top-down (equilibrium feedbacks and behavioural realism) and bottom-up (technological explicitness) models. This hybridization can be done through the addition of technological explicitness into a top-down model or incorporating behavioural realism and/or equilibrium feedbacks into a bottom-up model (Rivers & Jaccard, 2006). The application of a hybrid framework to a policy scenario typically results in more modest GHG reductions due to the inclusion of intangible non-financial costs compared to a bottom-up methodology (Murphy & Jaccard, 2011).

In addition to top-down, bottom-up, and hybrid models, system dynamics models (e.g. production cost, capacity expansion), and integrated assessment models are also used for the assessment of climate policies. System dynamics models are similar in their analytical approach to bottom-up models, including in their accounting of fuels, technologies, and intermediate energy flows, and calibration to historical data. However, there are consequential differences. Instead of simulating the evolution of an economy's energy system using empirically estimated parameters, many system dynamics models employ deterministic assumptions about flows of energy, and stocks of energy-related technologies. Integrated assessment models aim to link the dynamics of a region's energy-economy with those of the biosphere and atmosphere. The detail and extent to which models represent diverse systems vary widely, but all represent economic processes and activities that produce GHG emissions to some degree (Lopion et al., 2018; Savvidis et al., 2019).

3. METHODS

3.1. LITERATURE REVIEW

We conducted a scoping review to address the study's objectives. Scoping reviews "aim to map the key concepts underpinning a research area and the main sources and types of evidence available, and can be undertaken as standalone projects in their own right, especially where an area is complex or has not been reviewed comprehensively before" (Mays et al., 2001). Given the extent and complexity of the topic of climate policy modelling, as well as the lack of synthesis literature, the study uses an exhaustive scoping review method with pre-defined inclusion criteria (see below).

Although the terminology surrounding climate policy modelling can be varied, researchers' explanations of what constitutes an energy-economy model are generally consistent (Hedenus et al., 2013; Hourcade et al., 2006; Jaccard, 2009; Nakata, 2004). We define "energy-economy models" as those that examine the linkages between all energy sectors and the economy of a region. Thus, we exclude from our review models that focus only on a particular feature of the energy system (e.g. production cost, capacity expansion models).

To identify model assessment characteristics against which to compare energy-economy models, we examined peer-reviewed literature using a narrative review method, which synthesized evidence familiar to the authors (Sovacool, Axsen, & Sorrell, 2018). Several recent energy-systems reviews offered a useful starting point, in particular Lopion et al. (2018) and Savvidis et al. (2019). However, the characteristics used in recent reviews are quite diverse, and not constrained to energy-economy models. This study applies a tighter scope of characteristics.

To begin with, using the ScienceDirect and Google Scholar electronic databases, we identified potential literature using the following search string: ("energy-economy model" OR "energy-environment-economy model" OR "E3 model") AND ("review" OR "criteria" OR "assessment" OR "evaluation"). This search returned 3,982 publications across both databases. We scanned this literature for suggestions on how to improve the evaluation of GHG and economic outcomes of climate policies using energy-economy models. The aim was to be comprehensive and uncover nuances and themes in the literature (e.g. trade-offs in analytical approaches). Next, we used reference lists, particularly of recent articles and reviews, to lead to other useful papers. We also identified authors or research groups that were frequently mentioned, and scanned their peer-reviewed publications for suggestions potentially relevant to characteristics identification. The search results in forming four main characteristics: treatment of technology, microeconomic and macroeconomic realism, and policy representation with additional sub-characteristics (see Section 4).

To identify energy-economy models in Canada and initiate their assessment against the identified characteristics, we reviewed academic peer-reviewed literature and public reports from public, private, and not-for-profit organizations. Energy-economy models were considered eligible for inclusion based on their ability to evaluate economy-wide climate policies, specifically if (a) they were used to assess GHG and economic impacts of climate policies in Canada between 2009 and 2019 (inclusive), and (b) if there was sufficient publicly available documentation to evaluate the model against the characteristics discussed above. Models were identified via two electronic databases: ScienceDirect and Google Scholar, meaning that our review provides only a sample of literature on energy-economy models and their application to climate policy evaluation. We used the following search string: ("energy-economy model" OR "energy-environment-economy model" OR "integrated assessment model" OR "E3 model") AND ("Canada" OR "British Columbia" OR "Alberta" OR "Saskatchewan" OR "Manitoba" OR "Ontario" OR "Quebec" OR "New Brunswick" OR "Nova Scotia" OR "Newfoundland" OR "Prince Edward Island" OR "Northwest Territories" OR "Yukon" OR "Nunavut"). This search method returned a total of 961 results. Of this initial sample, we removed duplicates, and papers that did not qualify, particularly those that were not used to assess GHG and economic impacts of climate policies in Canada. The product was 54 publications, which included peer-reviewed articles and 'grey' literature (e.g. theses or government reports). These publications identified 21 unique models (several publications commonly used the same model) developed and/or used by 33 individuals across public, private, and not-for-profit sectors. Searches were conducted in June 2020.

Next, we compared models against assessment characteristics qualitatively. Our initial evaluation was based on answering guiding questions—binary and open-ended, based on the assessment characteristics identified in the search above (see Table 1). The guiding questions were based on our reading of the literature supporting the model assessment characteristics.

Table 1. Guiding questions for assessing energy-economy models against the assessment characteristics.

Assessment characteristics	Assessment sub-characteristics	Guiding questions
Treatment of technology	Representation	Are technologies represented explicitly or implicitly? If explicitly, how many are represented?
	Technological change	How does the model account for technological change?
Microeconomic realism	Market heterogeneity	How does the model account for market heterogeneity (differences in how different consumers and producers make choices between technologies)?
	Non-financial decision factors	How does the model account for non-financial decision factors?
Macroeconomic realism	Trade effects and finance	How is inter-regional and international trade treated? How are monetary and financial dimensions represented?
	Energy equilibrium	Are energy commodities supply-demand balanced through price-quantity adjustments?
	Non-energy equilibrium	Are non-energy commodities supply-demand balanced through price-quantity adjustments?
Policy representation	Policy interaction	How is policy interaction treated in the model? How does the model avoid double-counting emissions reductions?
	Policy types	How does the model represent the following policy types: carbon pricing, performance standards, prescriptive regulations, and government investments and subsidies?

We formed answers to the guiding questions using publicly available information on the model in question, using qualitative explanations. When information was not available with respect to certain characteristics, we flagged it for further exploration in a web-based 'expert' survey. This initial model assessment helped inform the survey design (see Section 3.2). We merged literature review results with survey results to create a comprehensive energy-economy model inventory in the form of matrix tables per each assessment characteristic (see Section 4).

3.2. SURVEY

3.2.1. SURVEY INSTRUMENT

To validate literature review results and collect model information that is not publicly available, we conducted a web-based synthesis survey of energy-economy model developers and users (n=14) identified in the literature review part of the project. We chose a purposive convenience sampling methodology to recruit the 'experts' (Sovacool et al., 2018) including model developers and model users because they tend to simulate the effects of climate policies and use the results to inform policy decisions (Needham & Vaske, 2008). Our population included experts from the narrative literature review (described in Section 3.1) that identified 33 model users and developers of energy-economy models in Canada. These 33 individuals represented 30 organizations consisting of 20 public organizations, six private companies, and four not-for-profit organizations. We identified email addresses of the 33 individuals through their organizations' open-access websites and sent electronic invitations. In our invites, we stated that different individuals from each organization could fill out the survey for different models developed or used in their organization.

We administered the survey in September 2020 using the University of Victoria's SurveyMonkey platform. We employed tailored survey design methods to ensure high quality of responses while minimizing the overall survey error (Dillman, Smyth, & Christian, 2014). We pre-tested the survey questions with a select group of energy experts and economists in academic institutions to reduce survey error. The average time for a respondent to complete the survey was 1 hour and 30 minutes but it is skewed by six respondents who completed the survey for more than one model.

To encourage participation and establish trust, we sent out personalized survey invitations explaining the purpose of the study and its benefits to the potential participant. Before beginning the survey, all respondents were presented with consent information outlining the terms of participation, including the risks and benefits to participating as well as how their data would be used, analyzed, and stored. To begin the survey, all respondents were required to agree to these terms.

We received complete survey responses from 14 individuals, ten model owners and four model users, resulting in a 42% response rate. These individuals reported on the total of 19 distinct models (eight individuals responded for one model, five responded for two models, and one responded for five models). Four models received responses from two individuals each. The individuals represented 13 organizations: five public organizations, six private companies, and two not-for-profit organizations, underrepresenting public organizations compared to the number of public sector modellers identified in the narrative literature review.

The survey contained a mix of closed-ended and open-ended questions in each of the sections. The questions were based on the seven assessment characteristics from Section 3. Specifically, the survey consisted of eight sections: (1) information about the respondent; (2) general model information; (3) the model's technology characteristics; (4) the model's inclusion of microeconomic characteristics; (5) the model's inclusion of macroeconomic characteristics; (6) the model's policy representation; (7) the model's treatment of uncertainty, inclusion of spatial and temporal representations, and transparency of modelling assumptions; and (8) final comments (see Appendix for the full survey questionnaire).

In the first section, respondents were asked general questions about their identity, organizational affiliation, and the number of models they use or run in their line of work. The subsequent sections and questions were repeated for each model based on the indicated number of models that are run or used by the respondent. The second section asked general questions about the model including the model name and owner/operator, model description to identify its type (i.e. top-down, bottom-up, integrated assessment, or hybrid) and other general information such as the jurisdictional application and simulation period.

In the third section on technology characteristics, respondents were asked questions about the level and dynamics of technology representation in their model. A definition for technology characteristics was provided at the beginning of the section. Respondents were asked questions about the number of represented technologies, types of included and excluded near-commercial and backstop technologies (i.e. defined in the survey as “an undefined processes used to limit abatement costs”), how technological change is represented, and how often technology parameters are updated.

The fourth section on microeconomic characteristics asked respondents questions on the model’s ability to realistically represent agent behaviour within the energy-economy. A definition of microeconomic characteristics was provided at the beginning of the section and other terms were defined throughout the questions. Respondents were asked about their model’s ability to capture perceptions of upfront costs, lack of information, quality of technology service, risks of new technology failure, and how often microeconomic parameters are updated.

The fifth section started with a definition of macroeconomic characteristics and asked questions about the model’s representation of equilibrium feedbacks, balances of energy and non-energy commodities, representation of the electric grid (due to electricity typically portrayed as its own sector), trade, the monetary and finance sectors, and how often macroeconomic parameters are updated.

The sixth section on policy representation asked questions about the model’s ability to accurately represent different types of climate policies and policy mechanisms, including government investments, subsidies, a carbon tax, cap-and-trade, hybrid carbon pricing (combining carbon tax with cap-and-trade), carbon revenue recycling, performance standards, and prescriptive regulations. The final question asked how often policy parameters are updated.

The seventh section asked questions about the uncertainty method(s) used by the modellers and the parameter(s) most often explored through uncertainty analysis. Respondents were also asked to answer questions about high-resolution spatial and temporal representations as well as the transparency of the model and data. The final section asked a single open-ended question to share any other model details.

3.2.2. SURVEY DATA ANALYSIS

The responses for four models (i.e. CIMS, GCAM, gTech, LEAP) with multiple survey participants were merged into one synthesized response per model through the use of the following methods: (1) for “I don’t know” answers from one respondent, any alternative response from another respondent would replace “I don’t know;” (2) questions that allowed multiple answers (e.g. the timeframe in which parameters are updated) were merged in the combined response; and (3) if both the developer and a user of a model submitted contradictory responses, the developer’s answers were used instead of the model user’s. We contacted four respondents by email to confirm information where the variation in responses could not be resolved using the aforementioned methods.

We categorized models into the main model types discussed in Section 2 – bottom-up, top-down, hybrid, and integrated assessment models, in order to examine the general trends in how they incorporate each of the seven characteristics. We used model description answers from the first part of the survey to assign models to either of the four categories. Specifically, macroeconomic top-down models included models described as “input-output” and “computable general equilibrium;” technological bottom-up models were described as “simulation,” “optimization,” “linear programming,” or “technology adoption;” integrated assessment models included “integrated assessment model,” “optimal growth;” and hybrid models included “hybrid” and “system dynamics” descriptors. We confirmed this model classification with past literature into these models (Wolinetz & Axsen, 2017; Zhu, Ghosh, Luo, Macaluso, & Rattray, 2018), though we acknowledge that some models may not be completely attributed to just one category.

We received one response for a macroeconomic model The Infometrica Model (TIM), but we did not analyze it as a stand-alone model because it does not meet the definition of an energy-economy model in Section 1. TIM represents as a sub-component of the E3MC model, composed of TIM and ENERGY 2020; therefore, we analyzed TIM as part of the entire E3MC model. Similarly, the Integrated Electricity Supply and Demand (IESD) model was not analyzed separately—it is used in conjunction with gTech to provide increased detail in the electricity sector, so we considered its characteristics in the analysis of gTech (Navius Research, 2019). As a result of merging the models, we analyzed the survey data for 17 models, not 19 as identified by respondents.

We analyzed responses using descriptive statistics to calculate frequencies in multiple-choice questions. The open-ended responses were manually scanned and analyzed to identify common themes to support and further explain multiple-choice responses. When respondents provided answers that did not align with the definition of a question, we reassigned the response to a more suitable section of the analysis. Where a model was described by only one respondent, we treated the "I don't know" responses as missing values. We used matrix tables to summarize our assessments for each model against the seven characteristics. Some of the details from the open-ended responses were also included in the assessment matrices to enhance the comparative analysis of models.

For the most part, the literature review and the survey covered the same models. However, the literature review assessed seven models unidentified in the survey (i.e. DICE, FUND, GEEM, MESSAGE-MACRO, MAPLE-C, PAGE, and SK-CGE). These seven models were merged with survey results to form joint model assessment matrices for the total of 24 models. For the first four characteristics of technology representations, micro- and macroeconomic realism, and policy representations, we use 24 models as a common denominator to calculate frequencies (Sections 4.1-4.4). Where values are missing due to methodological differences in literature review and survey design, we report on the percentage of missing values. For the additional three characteristics explored in the survey only—i.e. treatment of uncertainty, spatial and temporal representations, and data transparency, we use 17 models as a common denominator to calculate frequencies (Section 4.5). In other words, we exclude the seven models covered in the literature review only when performing the analysis against these three characteristics.

4. RESULTS

We found that energy-economy models are owned by mostly public organizations (54%), followed by private companies (33%), and non-for-profit groups (13%) in Canada (Table 2). These models use a diverse set of analytical approaches (Figure 2). A hybrid approach that combines the strengths of both bottom-up and top-down models was the most common, with this approach employed by ten models (41%): CIMS, CIMS-Urban, E3MC, ENERGY 2020, Energy Policy Simulator, GCAM, gTech, MAPLE-C, MESSAGE-MACRO, and NATEM-TIMES. Six models (25%) use a bottom-up approach: CanESS, CityInSight, LEAP, MEDEE, MESSAGE, and REPAC. An integrated assessment (i.e. DICE, EC-IAM, FUND, PAGE) and top-down approach (i.e. EC-PRO, EC-MSMR, GEEM, SK CGE) was each found in four models (17%).

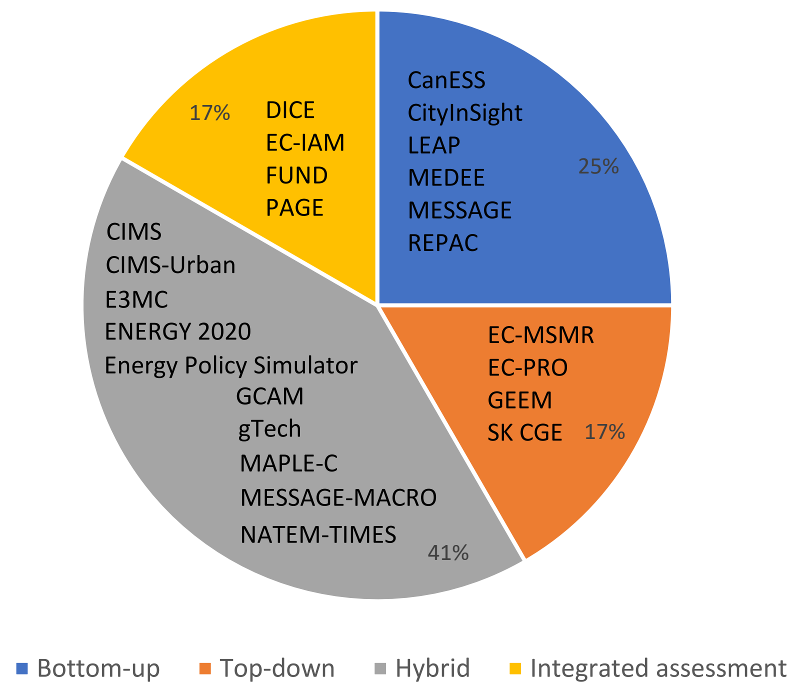


Figure 2. Analytical approaches employed in reviewed energy-economy models

Models' simulation periods range from a sub-annual time period to every 10 years, with a select group of four models having the ability to simulate multiple time periods (i.e. GCAM, LEAP, MESSAGE, NATEM-TIMES). The most common simulation period is every year (42%) or every 5 years (46%), with 29% of models missing this information (i.e. those not assessed in the survey: DICE, FUND, GEEM, MESSAGE-MACRO, MAPLE-C, PAGE, and SK-CGE). Fewer models use a simulation period of every 10 years (8%) or a simulation period of less than one year (13%). Models vary in their simulation timeframes with half of the models running to 2050 (29% of models were missing values). A smaller portion of models run to 2030 (25%) and 2100 (29%). The respondents for six models—CIMS, CIMS-Urban, CityInSight, EC-MSMR, gTech, and LEAP, indicated they can be run to multiple dates in the future.

There is a wide range of jurisdictional applications of models, from cities all the way up to an international level, depending on models' specific objectives. Just over half of models can be used in multiple jurisdictions with the provincial/territorial level being the most common application (50%), followed by a national application (38%) (29% of the models were missing values). Fewer models can be applied to regional (25%) and municipal scales (21%), as well as the broad international jurisdiction (25%).

About one third of the models (38%) represent multiple economic sectors at once ranging from buildings, to waste, transport, industry, electricity, and land use (29% were missing values). The least represented economic sector is land use with 46% of models including this sector. A few models include additional sectors, such as agriculture (e.g. CIMS, MEDEE) and the forestry sector (e.g. NATEM-TIMES). The transportation sector was the only sector to be included in all models that identified their economic sector coverage.

Table 2: General model information. *

Model	Model information					
	Owner	***Model description***	***Simulation period***	***Simulation targets***	***Jurisdictional application***	***Economic sector coverage***
CanESS	Sustainable Solutions Group (SSG) and whatIf? Technologies Inc.	Exploratory simulation model (treated as bottom-up)	Every year	2100	Provincial, national	All sectors
CIMS	Simon Fraser University (SFU), Energy and Materials Research Group	Hybrid (treated as hybrid)	Every 5 years	2030, 2050	Regional, provincial, national	Land use excluded; Agriculture included
CIMS-Urban	SFU, Energy and Materials Research Group	Hybrid (treated as hybrid)	Every 5 years	2030, 2050	Municipal	Electricity excluded
CityInSight	SSG and whatIf? Technologies Inc.	Exploratory simulation model (treated as bottom-up)	Every year	Any year – generally 2050-2070	Municipal, regional	All sectors
DICE	Yale University, William Nordhaus	Integrated assessment model (IAM), optimal growth (treated as IAM)	N/A	N/A	N/A	N/A
E3MC	Systematic Solutions, Inc.	Input-output, hybrid, system dynamics (treated as hybrid)	Every year	2050	Provincial, national	Land use excluded
EC-IAM	Government of Canada, Environment and Climate Change Canada (ECCC)	IAM (treated as IAM)	Every 5 years	2100	International by country and region	All sectors
EC-PRO	Government of Canada, ECCC	Computable general equilibrium (CGE) –small open-economy model (treated as top-down)	Every year	2050	Provincial, rest of the world	Land use excluded
EC-MSMR	Government of Canada, ECCC	CGE (treated as top-down)	Every 5 years	2050, 2100	International, flexible set of countries and region	All sectors
ENERGY 2020	Systematic Solutions, Inc.	Hybrid, system dynamics (treated as hybrid)	Every year	2050	Provincial	All sectors
Energy Policy Simulator	Energy Innovation, LLC	Input-output, hybrid, system dynamics (treated as hybrid)	Every year	2050	Municipal, regional, provincial, national	All sectors
FUND	University of Sussex: Richard Tol. University of California, Berkley Energy and Resources Group: David Anthoff	IAM, optimal growth (treated as IAM)	N/A	N/A	N/A	N/A
GCAM	University of Maryland, Joint Global Change Research Institute	IAM, hybrid (treated as hybrid)	Every year, every 5 years	2100	Regional, national, international	All sectors
GEEM	Navius Research	Top-down, general equilibrium (treated as top-down)	N/A	N/A	N/A	N/A

gTech	Navius Research	Optimization/linear programming, CGE (treated as hybrid)	Every 5 years	2030, 2050	Provincial, national, US, international	All sectors
LEAP	Stockholm Environment Institute	Optimization/linear programming (treated as bottom-up)	Sub-annual, every year, every 5 years, every 10 years	Any year	Municipal, regional, provincial, national, multi-national, international	All sectors
MAPLE-C	US Energy Information Administration	Hybrid, bottom-up, general equilibrium (treated as hybrid)	N/A	N/A	N/A	N/A
MEDEE	Government of Québec, Transition Energétique Québec	Simulation model (treated as bottom-up)	Every 5 years	2050	Provincial	Electricity and land use excluded; agriculture included
MESSAGE	The International Institute for Applied Systems Analysis (IIASA) Energy Program	Optimization/linear programming, IAM (treated as bottom-up)	Sub-annual, every year, every 5 years	2100	Regional, provincial, national, continental, international	Waste excluded
MESSAGE-MACRO	The International Institute for Applied Systems Analysis (IIASA) Energy Program	Hybrid - bottom-up, partial equilibrium (treated as hybrid)	N/A	N/A	N/A	N/A
NATEM-TIMES	Energy Super Modelers and International Analysts (ESMIA) Consultants	Optimization/linear programming, hybrid (treated as hybrid)	Any time period	2050	Municipal, provincial	Land use excluded; forestry sector included
PAGE	University of Cambridge, Judge Business School: Chris Hope	IAM, optimal growth (treated as IAM)	N/A	N/A	N/A	N/A
REPAC	Sustainable Transportation Action Research Team	Technology adoption (treated as bottom-up)	Every 5 years	2030	Provincial, national	Only transportation included
SK CGE	Government of Saskatchewan	Top-down - general equilibrium, static (treated as top-down)	N/A	N/A	N/A	N/A

* "N/A" stands for "not available," and represents both "I don't know" survey responses and missing values in the literature review. "All sectors" imply the sectors listed in the survey questionnaire, including buildings, waste, transportation, industry, electricity, and land use.

4.1. TREATMENT OF TECHNOLOGY

4.1.1. EXPLICIT REPRESENTATION

We found that the majority of the reviewed models explicitly represent technologies, albeit at different levels (Table 3). At one end of the spectrum, NATEM-TIMES, LEAP and CIMS explicitly represent thousands of technologies across all sectors, while Energy Policy Simulator and REPAC include tens of technologies. CanESS, CIMS-Urban, CityInSight, E3MC, ENERGY 2020, GCAM, gTech, MEDEE, MESSAGE, MESSAGE-MACRO, and MAPLE-C lay somewhere in between. In contrast to the majority, other "top-down" models, such as GEEM and SK CGE, implicitly represent technologies through the calibration of sector production functions, as do the DICE, FUND, and PAGE integrated assessment models.

Seven models (29%) explicitly represent both backstop and near-commercial technologies: CIMS, EC-IAM, EC-PRO, EC-MSMR, Energy Policy Simulator, GCAM, MESSAGE. Nine models (38%) explicitly represent technologies in all sectors, and nine models (38%) explicitly represent technologies in certain sectors. Backstop technologies include carbon capture and storage (i.e. CIMS, Energy Policy Simulator, GCAM), direct air capture (i.e. CIMS, Energy Policy Simulator), and biomass/bioliquids (i.e. GCAM).

Almost all of the models (79%) represent at least one near-commercial technology (17% were missing values). Near-commercial technologies are technologies that are used in a limited way and require some further development to achieve widespread adoption. Hydrogen fuel cell vehicles were the most common near-commercial technology, being represented in 63% of models. Other near-commercial technologies that were represented in the models include carbon capture and storage (58%), electrolysis-based hydrogen production (54%), and direct air capture (33%). Finally, just over half of models (58%) represent first and/or second-generation biofuels, with 71% of those models representing both categories of biofuels (33% of models were missing values).

4.1.2. TECHNOLOGICAL CHANGE

The majority of models (88%) represent technological change (4% were missing values) though they vary in their representation approach: exogenous, endogenous, or a combination of the two. Models most commonly (33%) represent technological change using both exogenous and endogenous methods depending on technology types. Three model types--bottom-up (i.e. LEAP, MEDEE), top-down (i.e. EC-PRO, EC-MSMR), and hybrid (i.e. E3MC, ENERGY 2020, Energy Policy Simulator, NATEM-TIMES) used this method. Exogenous technological change is represented in 29% of the models (i.e. CanESS, CityInSight, DICE, EC-IAM, FUND, GCAM, and GEEM). The CanESS and CityInSight models represent technological change exogenously by user specification of penetration rates, and declining capital costs for near-commercial technologies. Similarly, GCAM and GEEM represent technological change via exogenously specified capital costs. The DICE and FUND models take a slightly different approach by improving the efficiency of "carbon-saving technological change" (e.g. carbon capture and storage technologies), in addition to applying economy-wide efficiency gains through sector-specific production functions. The endogenous representation of technological change is found in 25% of the models (i.e. CIMS, CIMS-Urban, gTech, MAPLE-C, MESSAGE-MACRO, and REPAC), primarily by way of declining capital costs for near-commercial technologies based on technology market shares from previous model years. Fuel or maintenance operating costs are accounted for in 71% of the models (29% were missing values). Finally, we found that the models PAGE and SK CGE do not represent technological change.

Table 3. Representation of technologies and technological change in energy-economy models.*

Model	Technology representation				Technological change		
	Explicit technologies	**Backstop technologies**	**Near-commercial technologies**	**First and second-generation biofuels**	**Technological change**	**Declining capital costs**	**Annual operating costs**
CanESS	Certain sectors – 100 technologies	No	Includes CCS, electrolysis-based hydrogen production (H production), hydrogen fuel cell vehicles (H vehicles)	Both first (i.e. ethanol, biodiesel) and second (i.e. renewable diesel)	Exogenous	Yes	Fuel and maintenance
CIMS	All sectors – 1200 technologies	Yes – carbon capture and storage (CCS), direct air capture (DAC)	Includes DAC, CCS, H production, H vehicles	First (i.e. ethanol, biodiesel)	Endogenous	Yes	Fuel and maintenance
CIMS-Urban	All sectors – 500 technologies	No	Includes H vehicles	First (i.e. ethanol, biodiesel)	Endogenous	Yes	Fuel and maintenance
CityInSight	Certain sectors – 50+ technologies	No	Includes CCS, H production, H vehicles	Both first and second (i.e. generic biofuel category)	Exogenous	Yes	Fuel and maintenance
DICE	No	N/A	N/A	N/A	Exogenous	N/A	N/A
E3MC	Certain sectors – 79 technologies	No	Includes CCS, H production, H vehicles	Both first (i.e. ethanol, biodiesel) and second (i.e. HDRD)	Endogenous and exogenous	Yes	Fuel and maintenance
EC-IAM	All sectors	Yes	Includes DAC, CCS, H production, H vehicles	Both first and second	Exogenous	Yes	Fuel and maintenance
EC-PRO	Certain sectors	Yes	Includes DAC, CCS, H production, H vehicles	Both first and second	Endogenous and exogenous	Yes	Fuel and maintenance
EC-MSMR	All sectors	Yes	Includes DAC, CCS, H production, H vehicles	Both first and second	Endogenous and exogenous	Yes	Fuel and maintenance
ENERGY 2020	Certain sectors - 5 and 10 per sector	N/A	Includes CCS, H production, H vehicles	Both first (i.e. biofuel – corn, wheat, rapeseed) and second	Endogenous and exogenous	Yes	Fuel and maintenance
Energy Policy Simulator	All sectors - 50 technologies	Yes – CCS, direct air capture	Includes DAC, CCS, H production, H vehicles	First (i.e. biofuel, generic biomass)	Endogenous and exogenous	Yes	Fuel and maintenance
FUND	No	N/A	N/A	N/A	Exogenous	N/A	N/A
GCAM	All sectors - >100 technologies;	Yes – CCS and biomass/bioliquids	Includes DAC, CCS, H production, H vehicles	Both first and second	Exogenous	Yes	Fuel and maintenance
GEEM	No	No	Yes - implicitly	N/A	Exogenous	N/A	N/A
gTech	Certain sectors – 320 technologies	No	Includes DAC, CCS, H production, H vehicles	First (i.e. 3 drop-in fuels compatible with gasoline, diesel, and natural gas)	Endogenous	Yes	Fuel and maintenance

LEAP	All sectors– user selected number of technologies	No	Includes DAC, CCS, H production, H vehicles	Both first and second	Endogenous and exogenous	Yes	Fuel and maintenance
MAPLE-C	All sectors – several hundred technologies	N/A	Yes	N/A	Endogenous	Yes	N/A
MEDEE	Certain sectors (3) – 18 categories	No	No	No	Endogenous and exogenous	No	Fuel and maintenance
MESSAGE	All sectors – approx. 500 technologies	Yes	Includes CCS	N/A	N/A	Yes	Fuel and maintenance
MESSAGE-MACRO	~100 technologies	N/A	Yes	N/A	Endogenous	Yes	N/A
NATEM-TIMES	Certain sectors – 4000-5000 technologies	No	Includes CCS, H production, H vehicles	Both first and second	Endogenous and exogenous	Yes	Fuel and maintenance
PAGE	No	N/A	N/A	N/A	No	N/A	N/A
REPAC	Certain sectors – 5 technologies	No	Includes H vehicles	No	Endogenous	Yes	Fuel
SK CGE	No	N/A	N/A	N/A	No	N/A	N/A

* "N/A" stands for "not available," and represents both "I don't know" survey responses and missing values in the literature review.

4.2. MICROECONOMIC REALISM

4.2.1. MARKET HETEROGENEITY

With the exception of CanESS and CityInSight (and missing data for MESSAGE), all models represent market heterogeneity defined as differences in how different consumers and producers make choices between the same technologies (Table 4). We found that a group of models explicitly represent market heterogeneity by including a parameter that determines in part how much market share a given technology captures based on its relative costs. These models include CIMS, CIMS-Urban, gTech, E3MC, and ENERGY 2020. Another group, mostly made up of "top-down" full equilibrium models and integrated assessment models, represent market heterogeneity by calibrating their production functions to historical data (i.e. DICE, FUND, PAGE, MAPLE-C, SKE CGE), and/or to the outputs of "bottom-up" models (i.e. EC-PRO, GEEM). The models Energy Policy Simulator and REPAC represent market heterogeneity through choice methods. The models that do not address market heterogeneity are bottom-up models.

4.2.2. NON-FINANCIAL DECISION CHARACTERISTICS

The same models that address market heterogeneity also represent non-financial decision characteristics. The CIMS, CIMS-Urban, and gTech models use intangible cost parameters and revealed discount rates, while E3MC and ENERGY 2020 use logit functions in their calculation of energy service technology market shares. GCAM and MAPLE-C represent non-financial decision factors by way of a market share competition parameter, and MEDEE does the same for technology competition in heating systems (however, this is not addressed in the publicly available documentation with regards to other end-uses). NATEM-TIMES uses technology specific discount rates. The three integrated assessment models (i.e. DICE, FUND, PAGE), in addition to MESSAGE-MACRO and SKE CGE, implicitly represent non-financial decision factors in all scenarios through calibration to historical data, while EC-PRO and GEEM implicitly represent this dynamic through calibration to "bottom-up" models (i.e. ENERGY 2020 and CIMS, respectively).

The models that represent the full range of non-financial decision parameters use a hybrid approach (i.e. CIMS, CIMS-Urban, E3MC, and gTech). The most common parameters are upfront costs of technologies and associated discount rates, with fourteen (58%) models including these parameters (29% were missing values). Of those fourteen models, the majority (93%) represent this parameter by disaggregating technologies and representing the non-financial upfront costs of each technology.

Characteristics that represent the lack of technology information, varying quality of technology service, and risk of technology failure are included less frequently than non-financial upfront costs of technologies. The models that include these characteristics are often of a hybrid nature (e.g. CIMS, E3MC, gTech). Almost half the models acknowledge that firms and consumers do not have complete information about all technologies, with 80% of those models representing this characteristic explicitly and 20% representing it implicitly (38% of models were missing values). The quality of technology service is addressed in 33% of all surveyed models, and the risk of new technology failure in 25% (29% of the models were missing values). One third of the models contain additional non-financial decision-making characteristics including technology availability (i.e. REPAC), and externality values of pollution (i.e. LEAP) (38% were missing values).

Table 4. Representation of market heterogeneity and non-financial decisions factors in energy-economy models.*

Model	***Market heterogeneity***	**Non-financial decision characteristics**					
		Non-financial decision characteristics	***Upfront costs of technologies***	***Lack of information***	***Quality of technology service***	***Risk of new technology failure***	***Other non-financial decision-making parameters***
CanESS	No	No	No	No	No	No	No
CIMS	Yes –behavioural parameter	Yes – intangible cost parameter and revealed discount rate	Yes, by disaggregating technologies (i.e. explicitly representing the upfront costs of each of the included technologies)	Explicitly (e.g. through model's parameters) - intangible cost parameter	Yes – intangible cost parameter	Yes – weighted average time preference of decision-makers for a given energy service demand and intangible costs and benefits consumers/firms perceive	Yes – represented by the intangible cost parameter
CIMS-Urban	Yes –behavioural parameter	Yes – intangible cost parameter and revealed discount rate	Yes, by disaggregating technologies	Explicitly – intangible cost parameter	Yes – intangible cost parameter	Yes – weighted average time preference of decision-makers for a given energy service demand and intangible costs and benefits consumers/firms perceive	Yes – represented by the intangible cost parameter
CityInSight	No	No	No	No	No	No	No
DICE	Yes – implicitly through calibration	Yes – implicitly through calibration	N/A	N/A	N/A	N/A	N/A
E3MC	Yes –consumer choice theory	Yes - logit functions calibrated to historical data	Yes, by disaggregating technologies	Implicitly (e.g. through past data, proxies)	Yes – historical parameters	Yes – historical parameters	Yes – "non-price factor" parameter
EC-IAM	Yes	Yes	Yes, by disaggregating technologies	Explicitly	No	No	No
EC-PRO	Yes – CES function	Yes - implicitly through calibration	Yes, by aggregating production functions (i.e. representing upfront costs by combining related technologies that produce the same output)	No	No	No	No
EC-MSMR	Yes	Yes	No	Explicitly	No	No	No
ENERGY 2020	Yes – consumer choice theory	Yes - logit functions calibrated to historical data	Yes, by disaggregating technologies	Explicitly – qualitative choice methods	Yes	No	N/A
Energy Policy Simulator	Yes – choice models, elasticities	Yes	Yes, by disaggregating technologies	Explicitly – shadow market prices	No	No	Yes
FUND	Yes – implicitly through calibration	Yes – implicitly through calibration	N/A	N/A	N/A	N/A	N/A

GCAM	Yes	Yes - market share competition "cost penalty" parameter	Yes, by disaggregating technologies	No	Yes (e.g. speed in the transportation sector and time to travel)	No	No
GEEM	Yes – implicitly through calibration	Yes – implicitly through calibration	N/A	N/A	N/A	N/A	N/A
gTech	Yes – "lifecycle" cost of tech experience as a normal curve	Yes – intangible cost parameter and revealed discount rate	Yes, by disaggregating technologies	Implicitly - intangible costs	Yes – intangible costs	Yes – intangible costs	No
LEAP	Yes	Yes	Yes, by disaggregating technologies	N/A	No	No	Yes - (e.g. externality values of pollution)
MAPLE-C	Yes – "equipment weight" parameter in market share competition	Yes – "equipment weight" parameter in market share competition	N/A	N/A	N/A	N/A	N/A
MEDEE	Yes	Yes - technology competition in new heating systems	Yes, by disaggregating technologies	No	Yes – cost parameter	No	Yes – non-financial costs in the residential sector about inconvenience of different heating systems
MESSAGE	N/A	Yes	Yes, by disaggregating technologies	N/A	No	Yes	N/A
MESSAGE-MACRO	Yes – implicitly through calibration	Yes – implicitly through calibration	N/A	N/A	N/A	N/A	N/A
NATEM-TIMES	Yes	Yes - technology-specific revealed discount rates	Yes, by disaggregating technologies	Explicitly	No	Yes – parametric scenario analysis	Yes – exogenous user constraints (e.g. max limit on carbon sequestration, ban on nuclear)
PAGE	Yes – abatement cost specification	Yes – abatement cost specification	N/A	N/A	N/A	N/A	N/A
REPAC	Yes – consumer choice model	Yes	Yes, by disaggregating technologies	Explicitly – based on survey data	Yes – consumer choice model	No	Yes – technology availability, awareness of technology, access to home charging
SK CGE	Yes – implicitly through calibration	Yes – implicitly through calibration	N/A	N/A	N/A	N/A	N/A

* "N/A" stands for "not available," and represents both "I don't know" survey responses and missing values in the literature review.

4.3. MACROECONOMIC REALISM

The majority of models (71%) incorporate macroeconomic characteristics to some degree to represent the structural systematic relationships of a region's economy (8% were missing values) (Table 5). These models are almost all hybrid or top-down models due to their parameterization through historical macroeconomic data. The models EC-IAM, EC-PRO, EC-MSMR, gTech, and NATEM-TIMES include full and/or partial equilibrium methods, supply-demand balance both energy and non-energy commodities, and represent the electric grid. Five bottom-up models do not represent the macroeconomy (i.e. CanESS, CIMS-Urban, CityInSight, MEDEE, REPAC). More models use full equilibrium methods (50%) than partial equilibrium methods (29%). Full-equilibrium models are typically more of a top-down (i.e. EC-PRO, EC-MSMR) or hybrid nature (i.e. gTech).

4.3.1. ENERGY AND NON-ENERGY COMMODITIES

Most models (63%; 8% were missing values) represent the supply-demand balance of energy commodities through price-quantity adjustments, with fewer models (54%; 13% were missing values) balancing non-energy commodities. The models MEDEE and PAGE do not represent energy equilibrium, instead relying on exogenous energy supply assumptions. Of these models, ten (i.e. EC-IAM, EC-PRO, EC-MSMR, GCAM, GEEM, gTech, MAPLE-C, MESSAGE-MACRO, NATEM-TIMES, SK CGE) balance both energy and non-energy commodities, and two (i.e. Energy Policy Simulator, MESSAGE) partially balance both energy and non-energy commodities. Nine of these models that balance both energy and non-energy commodities are top-down (i.e. EC-PRO, EC-MSMR, GEEM) or hybrid models (i.e. GCAM, gTech, MAPLE-C, MESSAGE-MACRO, NATEM-TIMES, SK CGE). E3MC is the only model that balances energy commodities, but not non-energy commodities. One third of the models include a representation of regional electric grids (i.e. E3MC, EC-IAM, EC-PRO, EC-MSMR, ENERGY 2020, gTech, LEAP, NATEM-TIMES) (29% of the models were missing values). These are mostly full-equilibrium top-down or hybrid models.

4.3.2. TRADE EFFECTS AND FINANCE

The incorporation of trade effects was found in almost all the models that represent macroeconomic characteristics, while the representation of the monetary and financial sectors was rare. International trade is represented in 54% of the models (17% were missing values), while inter-regional trade is represented in fewer (45%) of the models (25% were missing values). Inter-regional and international trade are incorporated in the same manner in the 67% of the models that represent trade effects (8% were missing values), with 70% representing trade endogenously and 10% (i.e. one model, LEAP) exogenously. Model documentation for several models such as CIMS, GEEM, gTech, and SK CGE made clear that they use an Armington specification in their representation of trade whereby goods and services are treated as non-perfect substitutes. The DICE model does not represent trade; instead, it treats regional outputs of commodities as perfect substitutes. gTech, GEEM, and E3MC are the only models found to represent inter-regional and international trade as well as the monetary and finance sectors. The Energy Policy Simulator and DICE are the only models, among those that represent the macroeconomy, to not include trade effects. Overall, the monetary and finance sectors have little representation in the models surveyed, with only five models (i.e. E3MC, Energy Policy Simulator, GEEM, gTech, MAPLE-C), incorporating these sectors (21% of models were missing values). Three of these models represent government fiscal balances, monetary flows, and exchange rates, using diverse methods (i.e. GEEM, E3MC, MAPLE-C).

Table 5. Representation of macroeconomic characteristics, trade effects, and finance in energy-economy models.*

Model	Macroeconomic characteristics						Trade effects and finance			
	Macroeconomic characteristics	*Full equilibrium methods*	*Partial equilibrium methods*	*Energy commodities supply-demand balanced*	*Non-energy commodities supply-demand balanced*	*Electric grid*	*Trade*	*Inter-regional trade*	*International trade*	*Monetary and finance sectors*
CanESS	No	No	No	No	No	No	No	No	No	No
CIMS	Yes	No	Yes	Yes, through price-quantity adjustments	Partially, via own-price elasticities	No	Yes	Endogenous - inter-regional transfers as well as net exports	Endogenous – export price elasticities	No
CIMS-Urban	No	No	No	No	No	No	No	No	No	No
CityInSight	No	No	No	No	No	No	No	No	No	No
DICE	Yes	Yes	N/A	No	No	N/A	No	No	No	N/A
E3MC	Yes	No	Yes	Yes	No	Yes – annual/seasonal level	Yes	Endogenous - electricity	Endogenous – energy flow using ENERGY 2020 and non-energy trade with TIM	Yes
EC-IAM	Yes	Yes	Yes	Yes	Yes, through price-quantity adjustments	Yes – national grids with peak demands	Yes	Endogenous	Endogenous	No
EC-PRO	Yes	Yes	No	Yes	Yes	Yes – provincial/territorial by generating technologies	Yes	Endogenous	Endogenous	No
EC-MSMR	Yes	Yes	No	Yes	Yes	Yes – national/regional level using hourly load curves	Yes	Endogenous – bilateral trade between countries and regional blocks	Endogenous	No
ENERGY 2020	Yes	Yes	Yes	Yes	N/A	Yes	Yes	N/A	N/A	No
Energy Policy Simulator	Yes	No	N/A	Partially, via own-price elasticities	Partially	No	No	No	No	Yes
FUND	N/A	Yes	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
GCAM	Yes	N/A	Yes	Yes	Yes	No	Yes	Endogenous	Endogenous	No
GEEM	Yes	Yes	N/A	Yes	Yes	N/A	Yes	Yes – Armington formulation	Yes – Armington formulation	Yes

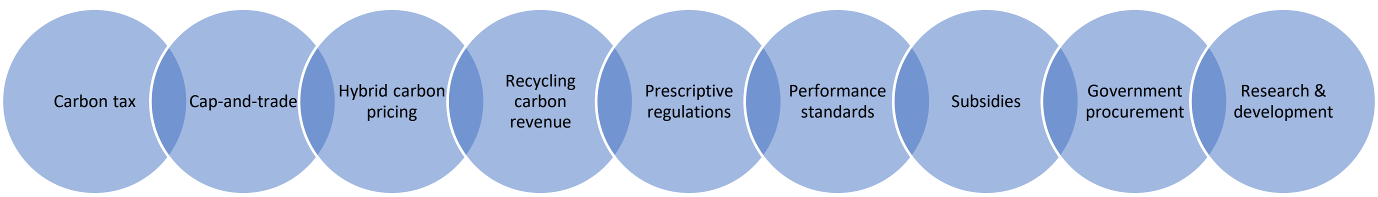
gTech	Yes	Yes	No	Yes	Yes	Yes	Yes	Endogenous – price and quantity used to balance supply and demand between regions	Endogenous – trade with US is explicit, simplified “rest of world” region trade	Yes
LEAP	Yes – to a point	No	Yes	N/A	N/A	Yes – detailed representation of generation and capacity expansion. Times slices can be seasons/ weeks/hours	Yes	Exogenous – only energy flows, not all economic trade	Exogenous – only energy flows, not all economic trade	No
MAPLE-C	Yes	Yes	N/A	Yes	Yes	N/A	Yes	N/A	Yes	Yes
MEDEE	No	No	No	No	No	No	No	No	No	No
MESSAGE	Yes	N/A	No	Partially	Partially	No	Yes	N/A	N/A	No
MESSAGE-MACRO	Yes	Yes	N/A	Yes	Yes	N/A	Yes	N/A	Yes	N/A
NATEM-TIMES	Yes	No	Yes	Yes	Yes	Yes – interconnections/ transmission explicit, distribution system represented by simple and aggregated tech. 16 annual time slices	Yes	Endogenous – optimizes trade flows of energy between model regions	Exogenous	No
PAGE	N/A	Yes	N/A	No	No	N/A	N/A	N/A	N/A	N/A
REPAC	No	No	No	No	No	No	No	No	No	No
SK CGE	Yes	Yes	N/A	Yes	Yes	N/A	Yes	Yes – Armington formulation	Yes – Armington formulation	N/A

* “N/A” stands for “not available,” and represents both “I don’t know” survey responses and missing values in the literature review.

14.4. POLICY REPRESENTATIONS

4.4.1. POLICY TYPES

Most models are able to represent at least one policy type, with the nine models – DICE, EC-IAM, EC-PRO, EC-MSMR, Energy Policy Simulator, FUND, gTech, LEAP, and NATEM-TIMES – having the ability to represent all tested policy types. The most represented policy type across all models is the carbon tax (88%; 4% were missing values) (Table 6). Five policy types: cap-and-trade, recycling carbon revenue, prescriptive regulations, performance standards, and subsidies are each represented by 75% of the models. This is followed by hybrid carbon pricing (63%), government procurement (50%), and research & development (38%). Most models that explicitly represent carbon pricing (i.e. carbon tax, cap-and-trade and a combination of thereof) are hybrid or top-down. Of the models that represent a carbon tax, all but two models (MEDEE and DICE) simulate this policy explicitly. Most of these models can also simulate the recycling of carbon revenue. We found that the GEEM and SK CGE models do not explicitly represent technology-specific regulations precisely because they do not explicitly represent technologies. However, both top-down models explicitly represent carbon taxes and associated revenue recycling. Cap-and-trade is represented by fewer models (75%; 13% were missing values) than a carbon tax, with 78% of those models simulating it explicitly and 22% implicitly (i.e. DICE, Energy Policy Simulator, FUND, MEDEE). Most of these models can also simulate hybrid carbon pricing due to their ability to represent cap-and-trade policy mechanisms.



The representation of prescriptive regulations is found in 75% of the models (17% were missing values), with three models (DICE, FUND, MEDEE) representing prescriptive regulations implicitly. The majority of models also represent subsidies (75%; 13% were missing values), with 22% (DICE, E3MC, FUND, MEDEE) of those models representing this policy type implicitly. Similarly, performance standard policies are also represented by the majority of models (75%; 17% were missing values), with 83% of those models representing this policy explicitly. Moels vary in their representation of government procurement and investment with 75% of those models representing it explicitly, and 25% implicitly (i.e. DICE, Energy Policy Simulator, FUND) (21% of models were missing values). Investment in research and development is the least represented policy, with only 38% of the models representing it either explicitly or implicitly (25% were missing values). Out of the models that include this policy type, 56% represent research and development explicitly, and 44% implicitly. The models that simulate investment in research and development explicitly (EC-IAM, EC-PRO, EC-MSMR, LEAP, NATEM-TIMES) are mostly top-down or hybrid models, with most of them (EC-IAM, EC-PRO, EC-MSMR) used by Canada's federal government. The DICE integrated assessment model aggregates the representation of all climate policies in its use of a single "emissions control" parameter, which limits global emissions. The FUND model takes almost an identical approach, by representing all climate policies as a single carbon price parameter.

4.4.2. POLICY INTERACTIONS

Regardless of model type, the majority of models explicitly consider the interactions between multiple climate policies (71%; 21% were missing values). The CIMS model (which uses a bottom-up partial equilibrium framework) treats policies as constraints in an optimization solver. Policies can become non-binding if more stringent policies are introduced. However, due to its partial equilibrium approach, CIMS does not simulate potential macroeconomic interactions such as capital movements between regions given stringent climate policy. The MAPLE-C and gTech models similarly represents policies as constraints. However, in contrast to the CIMS model, they do so within a full equilibrium framework, which allows them to capture interactive effects with regard to, for example, capital movements between regions, government taxation, and transfers between governments. The Canada Energy Policy Simulator model uses a method developed to explicitly avoid double counting GHG emissions reductions. It treats non-pricing policies (e.g. prescriptive regulations) as 'additive' relative to cross-sector pricing policies (e.g. carbon pricing). Some model documentation suggested that the representation of policy interaction had more to do with modellers' approaches, rather than the analytical frameworks of the models themselves. For example, model documentation for the E3MC, ENERGY 2020, and MAPLE-C models suggests that modellers often control for interaction by basing scenarios on incremental decision-making. Information required to assess models against the policy interaction criterion was not available for the models DICE, FUND, GEEM, PAGE, and SK CGE. Not all models that consider policy interactions also avoid double-counting emissions from multiple climate policies. The model E3MC implicitly accounts for policy interactions and avoids double-counting emissions at the same time.

Table 6. Representation of policy types and policy interactions in energy-economy models.*

Model	Policy types									Policy interaction	
	Carbon tax	***Cap-and-trade***	***Hybrid carbon pricing***	***Recycling carbon revenue***	***Prescriptive regulations***	***Subsidies***	***Performance standards***	***Government procurement/ investment***	***Research & development***	***Consider interactions between policies***	***Avoid double-counting emissions***
CanESS	No	No	No	No	No	No	No	No	No	No	No
CIMS	Explicitly (e. g. through model's parameters)	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	No	No	Explicitly	Explicitly
CIMS-Urban	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	No	No	Explicitly	Explicitly
CityInSight	No	No	No	No	No	No	No	No	No	No	No
DICE	Implicitly (e.g. through past data, proxies) – all policies represented by single "emissions control" parameter	Implicitly	Implicitly	Implicitly	Implicitly	Implicitly	Implicitly	Implicitly	Implicitly	N/A	N/A
E3MC	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Implicitly	Explicitly	Explicitly	No	Implicitly	Implicitly
EC-IAM	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly
EC-PRO	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly
EC-MSMR	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly
ENERGY 2020	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	No	Explicitly	Explicitly
Energy Policy Simulator	Explicitly	Implicitly	Implicitly	Explicitly	Explicitly	Explicitly	Explicitly	Implicitly	Implicitly	Explicitly	Explicitly

FUND	Explicitly – all climate policies represented as a single carbon price parameter	Implicitly	Implicitly	Implicitly	Implicitly	Implicitly	Implicitly	Implicitly	Implicitly	N/A	N/A
GCAM	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	No	No	Explicitly	Explicitly
GEEM	Explicitly	Explicitly	N/A	Explicitly	N/A	No	Explicitly	N/A	N/A	N/A	N/A
gTech	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Implicitly	Explicitly	Explicitly
LEAP	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly
MAPLE-C	Explicitly	Explicitly	N/A	Explicitly	N/A	Explicitly	Explicitly	N/A	N/A	Yes	N/A
MEDEE	Implicitly	Implicitly	Implicitly	No	Implicitly	Implicitly	Implicitly	No	No	Explicitly	Explicitly
MESSAGE	Explicitly	N/A	N/A	N/A	Explicitly	N/A	No	Explicitly	No	Explicitly	Explicitly
MESSAGE-MACRO	Explicitly	Explicitly	N/A	Explicitly	Explicitly	Explicitly	Explicitly	N/A	N/A	Yes	N/A
NATEM-TIMES	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly
PAGE	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
REPAC	Explicitly	No	No	No	Explicitly	Explicitly	N/A	No	N/A	Explicitly	N/A
SK CGE	Explicitly	N/A	N/A	Explicitly	N/A	N/A	N/A	N/A	N/A	N/A	N/A

* “N/A” stands for “not available,” and represents both “I don’t know” survey responses and missing values in the literature review.

4.5. OTHER CHARACTERISTICS AND DATA MANAGEMENT

The survey explored three additional characteristics that were observed in the literature review but lacked publicly available information, including the treatment of uncertainty, high-resolution spatial and temporal representations, and data transparency. The following sub-sections describe the seventeen surveyed models against these three characteristics.

4.5.1. TREATMENT OF UNCERTAINTY

Uncertainty is explored in all models with 100% of model users using a sensitivity analysis, 41% using a Monte Carlo analysis, and 24% using other methods (Table 7). Just over half the model users use two or more methods to explore uncertainty. The use of a Monte Carlo analysis and/or other methods to explore uncertainty is most often found in hybrid models. Economic growth and energy prices are the most common characteristics explored through uncertainty analyses with 88% and 82% of modellers incorporating these parameters, respectively. The model NATEM-TIMES is the only model found to not explore either of these characteristics through uncertainty analysis. In addition, many modellers explored uncertainty in other parameters, including technology-related parameters (i.e. CanESS, CityInSight, E3MC, gTech, NATEM-TIMES, REPAC) and intangible costs (i.e. CIMS, CIMS-Urban).

4.5.2. HIGH-RESOLUTION REPRESENTATIONS

High-resolution spatial and/or temporal representations are included in only a small percentage of models, with more models including high-resolution temporal representations (35%) compared to high-resolution spatial representations (24%). The four models that include high-resolution spatial characteristics represent explicit geographic blocks (i.e. CIMS-Urban, CityInSight, LEAP) and water-related infrastructure (i.e. MESSAGE). Most of the models that include high-resolution spatial or temporal representations are bottom-up.

4.5.3. DATA MANAGEMENT

In terms of data management, most models (71%) are not freely available for public use, and most do not have open-source code (65%); these models are most often run by governments or private organizations. However, models are more likely to be transparent in their use of open-source data inputs and having at least some of their modelling equations and assumptions publicly accessible. Of the 29% of models that are freely available for public use, 40% are from academic institutions (i.e. CIMS, CIMS-Urban) and 60% from not-for-profit organizations (i.e. Energy Policy Simulator, LEAP, MESSAGE). Only four models (CIMS, CIMS-Urban, LEAP, MESSAGE) are both freely available and use open-source code. In contrast, 76% of models include at least some open-source data with certain inputs to the model being from publicly available sources such as Statistics Canada, ECCC, and Natural Resource Canada. Most models include a mixture of data from publicly available sources and confidential ones. More than half the models have at least some of their modelling equations (59%) and assumptions (65%) documented in a publicly-accessible manner. While some models do not currently have the equations and/or assumptions publicly available, several respondents indicated they are in the process of or plan to open source this information (i.e. CityInSight, NATEM-TIMES).

Table 7. Treatment of uncertainty, spatial and temporal resolutions in energy-economy models.

Model	Treatment of uncertainty		High-resolution representations		Data transparency				
	Uncertainty methods	***Parameters explored through uncertainty***	***Spatial***	***Temporal***	***Freely available for public use***	***Open-source code***	***Open-source data***	***Modelling equations publicly accessible***	***Modelling assumptions publicly accessible***
CanESS	Sensitivity analysis	Economic growth, population/employment projections, EV penetration rate, retrofit rates and depths, teleworking rates, petroleum extraction volumes	No	Yes – hourly demand and generation dispatch module	No	No	Yes – model calibration and "default" Business as usual (BAU) scenario	Yes – some on website	Yes – varies, in some cases assumptions are provided
CIMS	Sensitivity analysis, Monte Carlo analysis	Energy prices, economic growth, capital and intangible costs	No	No	Yes – available on request	Yes	Yes – from open sources (e.g. Statistics Canada (StatsCan), Natural Resources Canada (NRCan), ECCC)	Yes – in academic publications and reports. Manual under development	Yes – in academic publications and reports. Manual under redevelopment
CIMS-Urban	Sensitivity analysis, Monte Carlo analysis	Energy prices, economic growth, capital and intangible costs	Yes - linked to a GIS model to account for city policy impacts	No	Yes – available on request	Yes	Yes – from open sources (e.g. StatsCan, NRCan, ECCC)	Yes – in academic publications and reports. Manual under development	Yes – in academic publications and reports. Manual under redevelopment
CityInSight	Sensitivity analysis	Economic growth, population/employment projections, EV penetration rate, retrofit rates and depths, teleworking rates	Yes – city/region subdivided geographically into many zones	No – a planned feature	No – ambitions for the future	No – ambitions for the future	Yes – some inputs from public sources	No – ambitions to open-source the model	No – ambitions to open-source the model
E3MC	Sensitivity analysis, HYPERSENS	Energy prices, economic growth, technology improvement	No	No	No	No	Yes – some inputs from public sources	Yes – manuals on website	Yes – some published in reports and open data tables
EC-IAM	Sensitivity analysis, Monte Carlo analysis	Energy prices, economic growth, other	No	No	No	No	Yes - partially	No	No
EC-PRO	Sensitivity analysis	Energy prices, economic growth, other	No	No	No	No	Yes - provincial/ territorial Supply-Use Tables	No	No

EC-MSMR	Sensitivity analysis	Energy prices, economic growth, other	No	No	No	No	Yes – some inputs from public sources	No	No
ENERGY 2020	Sensitivity analysis, HYPERSENS	Energy prices, economic growth	No	No	No	No	No	Yes – model documentation on website	Yes – some published in reports and open data tables
Energy Policy Simulator	Sensitivity analysis, Monte Carlo analysis	Energy prices, economic growth	No	No	Yes	No	Yes - all data is included and cited in the model is downloadable	Yes – model guide on website	Yes – online guide on website
GCAM	Sensitivity analysis	Energy prices, economic growth, other	No	No	No	Yes	Yes	Yes - poorly	Yes
gTech	Sensitivity analysis, Monte Carlo analysis	Energy prices, economic growth, technology cost/availability of pre-commercial tech	No	Yes - IESD allows for flexible seasonal/weekly /hourly time slices	No	No	Yes	No	Yes – depends on the client
LEAP	Sensitivity analysis, Monte Carlo analysis, Scenario analysis	Energy prices, economic growth, demographics, policy	Yes – can model results to user-defined grid-squares	Yes – flexible seasonal/weekly/hourly time slices	Yes -free to users in low and lower-middle-income countries and all students	Yes – some code is open source (e.g. NEMO optimization framework)	N/A – depends on the model created	Yes – LEAP equations on website	N/A – depends on the model created
MEDEE	Sensitivity analysis	Energy prices, economic growth	No	Yes – passenger vehicle fleet characteristic on annual basis	No	No	No	No	Yes – in some reports and working sessions
MESSAGE	Sensitivity analysis	Energy prices, economic growth	Yes – can represent water-related infrastructure in high resolution	Yes - possibility to represent high resolution temporal data	Yes	Yes	Yes - most data from publicly available databases	Yes – model documentation on website	Yes – model documentation on website
NATEM-TIMES	Sensitivity analysis, Monte Carlo analysis, Stochastic modelling	Evolution of technology costs, future availability of emerging tech	No	Yes – at the time slice level	No	Yes	Yes – some inputs from public sources	Yes – basic TIMES equations on ETSAP website	No – website under development
REPAC	Sensitivity analysis	Energy prices, tech availability, tech awareness	No	No	No	No	No	No	Yes – open access journal article

4.5.4. PARAMETER UPDATES

Related to data management, we asked survey respondents to indicate how often each of the core model characteristics is updated. For each characteristics the most common update timeframe is every year, followed by every 2–5 years for all characteristics except for macroeconomic details (Table 8). Some models such as GCAM and gTech have more than one update timeframe due to different model end-users (e.g. clients and/or policy-makers) choosing to update at different times.

Table 8. Frequencies of model characteristics' updates in energy-economy models.*

Model	Model characteristics			
	Technology representations	***Microeconomic realism***	***Macroeconomic realism***	***Policy representations***
CanESS	Every year	No	No	No
CIMS	Every 2-5 years	Every 2-5 years	Every 5-10 years	Every year
CIMS-Urban	Every 2-5 years	Every 2-5 years	No	Every year
CityInSight	Every year	No	No	No
E3MC	Every 2-5 years	Every year	Every year	Every year
EC-IAM	Every year	Every year	Every year	Every year
EC-Pro	Every year	Every year	Every year	Every year
EC-MSMR	Every year	Every year	Every year	Every year
Energy 2020	Every 2-5 years	Every year	N/A	Every year
Energy Policy Simulator	Every year	Every year	Every year	Every year
GCAM	Every year; every 5-10 years	Every year; every 5-10 years	Every 5-10 years	Every year, every 2-5 years, every 5-10 years
gTech	Every 2-5 years	Every 2-5 years; every 5-10 years	Every 2-5 years	Every year, every 2-5 years
LEAP	Every 2-5 years	Every 2-5 years	N/A	Every 2-5 years
MEDEE	Every 5-10 years	Every year	No	Every 2-5 years
MESSAGE	Every year	N/A	Every year	Every year
NATEM-TIMES	Every year	Every year	Every year	Every year
REPAC	Every 2-5 years	N/A	No	Every 2-5 years

* "N/A" stands for "not available," and represents both "I don't know" survey responses and missing values in the literature review.

5. BEST PRACTICES FOR CLIMATE POLICY MODELLING

Based on our literature review and survey, we offer six 'best practice' suggestions to consider in modelling GHG and economic impacts of climate policies in policy-making as well as academic and private sectors. The suggestions do not determine which model is 'best' because model choice depends in part on the type of research and/or policy question posed.

Models should:

Explicitly represent energy-related technologies	Aim to capture both market heterogeneity & non-financial costs	Include a representation of trade and finance
Link energy supply-demand using price-quantity adjustments	Accurately represent different types of policies, & do so within an integrated framework that captures unintended policy interactions	Incorporate uncertainty analysis

First, models should explicitly represent energy-related technologies. This means that technologies that supply or demand energy services are disaggregated within a model. The explicit and detailed representation of technologies is desirable because (a) it allows for the representation of technological change dynamics; (b) it allows for technology-specific data to be used by the model, either directly as inputs or in model calibration; (c) it allows for tracking different vintages of technologies over time; and (d) it helps modelling technology-specific policies (Lopion et al., 2018; Prina et al., 2020). In addition, models should aim to represent technological change dynamics (i.e. how capital stocks of technologies evolve within the economy). This is particularly important for representing near-commercial technologies, because their attributes are not captured by historical data, and may also change over time (Edenhofer et al., 2011; Riahi et al., 2012; Clarke et al., 2014). The reviewed models represent technological change using a diverse range of exogenous and endogenous methods, and there is no consensus on the 'best' method. Ideally, the method(s) should be tailored to fit specific policy questions. For instance, representing technological change in one sector using exogenously specified declining capitals costs might be a reasonable approach if a climate policy is to be implemented exclusively in another. Models that use endogenous technological change can respond to socio-economic factors in addition to the passage of time. Therefore, the projected cost of abatement in these models can be considerably lower than projections from models that use exogenous technological change (Löschel, 2002).

Second, in terms of representing how consumer and firms make energy-related investment decisions, models should aim to capture both market heterogeneity and non-financial costs because (a) not all decision-makers will make the same decision given the same circumstances surrounding an energy-related investment, and (b) many non-financial factors can influence decisions involving energy service technologies, especially at the household level. We found that many models do not address the issues of imperfect information, quality of technology service, and risk of technology failure in their methodologies implying that many real-life behaviours are likely to be ignored in climate policy projections, resulting in underestimated mitigation costs and overly optimistic GHG reductions (Li et al., 2015;

Murphy & Jaccard, 2011). Incorporating these model characteristics improves the accuracy of climate policy evaluation because it allows for a more realistic representation of consumer and firm behavior, which in turn allows modellers to use technology acquisition data (Clarke et al., 2014; Li & Strachan, 2017; Mercure et al., 2019). There are many ways that models can represent these dynamics, including the use of revealed discount rates to account for non-financial factors and the use of market share competition parameters to account for market heterogeneity and/or differences in non-financial costs.

Third, models that seek to assess the economic effects of climate policy accurately should include a representation of trade and finance because GHGs are heavily affected by economic activity. In addition, providing information on key economic indicators such as changes in activity, changes in interprovincial or international trade, and structural shifts (e.g. labour shifting from high to low carbon intensity sectors) is likely to be useful to policy-makers (Bataille et al., 2006; Jaccard, 2009). While most models with macroeconomic feedbacks represent trade effects, they lack representation of the financial and monetary sectors potentially ignoring differences in costs of capital for low-carbon technology in different regions (Pollitt & Mercure, 2018). Models that take a general equilibrium analytical approach are best suited to represent trade and finance.

Fourth, energy-economy models used to evaluate the effects of climate policy should aim to link energy supply-demand using price-quantity adjustments, such that equilibrium is achieved for each energy source across all sectors (Balistreri & Rutherford, 2012; Savvidis et al., 2019). This provides a realistic representation of the interdependencies of energy systems, which is necessary to simulate stringent climate policy. A model that does not represent energy supply-demand is not able to capture dynamics that are central to climate policy analysis, such as changes in the composition of energy consumption given changing prices. However, it may be valid to represent energy equilibrium exogenously or endogenously, depending on the model's intended use.

Fifth, models should aim to accurately represent different types of policies, and do so within an integrated framework that captures unintended policy interactions (Savvidis et al., 2019; Bhattacharyya & Timilsina, 2010). Different model attributes are important for modelling particular types of polices, on a case-by-case basis. Thus, modellers should understand precisely how a given model represents each policy, and how interactive effects of multiple policies are represented. Modellers may also find value in controlling for policy interaction by basing scenarios on incremental decision-making. The models that are well suited to represent a diverse range of policies, in addition to how those policies might interact and avoid double-counting of emissions, contained an explicit representation of energy-related technologies within a full equilibrium framework.

Sixth, models should incorporate uncertainty analysis methods to allow policy-makers to compare a range of modelling projections, therefore contributing to more credible and politically acceptable policy decisions (Beugin & Jaccard, 2012). Uncertainty analyses can be particularly useful to policy-makers when estimating the world's transition out of the COVID-19 pandemic.

Besides the general six best practices above, our findings have useful implications for community-level and renewable energy policy questions. In particular, policy-makers and researchers aiming to assess the effectiveness of local-scale climate policy (e.g. land-use and community energy management) should look for models that incorporate high-resolution spatial representations, because the effects of those policies are not spatially uniform (Jaccard et al., 2019). Similarly, policy questions related to renewable energy generation and demand are better addressed in models with high-resolution temporal representations that account for the intermittency of renewable energy supply via real-time data and time slices (Lopion et al., 2018; Pfenninger et al., 2014).

6. CONCLUSIONS

The literature review and web-based survey of energy-economy model developers and users in Canada identifies 24 distinct models used across public, private, and not-for-profit sectors. Most of these models (41%) can be described as hybrid (CIMS, CIMS-Urban, E3MC, ENERGY 2020, Energy Policy Simulator, GCAM, gTech, MAPLE-C, MESSAGE-MACRO, NATEM-TIMES), followed by bottom-up (25%) (CanESS, CityInSight, LEAP, MEDEE, MESSAGE, REPAC). Finally, a top-down (EC-PRO, EC-MSMR, GEEM, SK CGE) or integrated assessment (DICE, EC-IAM, FUND, PAGE) approach was found in 17% of the models. We compare these models against seven assessment characteristics found to be important for projecting climate policy effects on GHG emissions and economic outcomes in the narrative literature review. These characteristics include technology representations, microeconomic and macroeconomic realism, policy representations, treatment of uncertainty, high-resolution spatial and temporal representations, and data transparency.

For the most part, models represent technology, micro- and macroeconomic characteristics according to the typology of top-down, bottom-up, and hybrid models, validating past modelling reviews (Hourcade et al., 2006; Rivers & Jaccard, 2006). In line with past literature, the surveyed top-down (e.g. EC-PRO, EC-MSMR) and hybrid (e.g. NATEM-TIMES, gTech) models include microeconomic (behavioural) and macroeconomic characteristics (Hourcade et al., 2006; Rivers & Jaccard, 2006). Bottom-up models (e.g. REPAC, MEDEE) explicitly represent technological characteristics, while excluding or poorly representing macroeconomic details (Jaccard, 2009; Löschel, 2002). However, the literature review and survey data suggest that models have evolved in several ways due to a growing variety and complexity of different policy tools used in climate policy mixes (Rogge, Kern, & Howlett, 2017). Some top-down models have evolved to include explicit representations of technologies in order to model technology-specific policies, while some bottom-up models have started to incorporate market heterogeneity and behavioural preferences to produce more realistic simulations.

Our study expands the three-characteristic based model typology (Hourcade et al., 2006) to include four additional characteristics of policy representations, treatment of uncertainty, high-resolution spatial and temporal representations, and data transparency. We find that while bottom-up models can simulate a carbon tax and prescriptive regulations, they do not generally represent macroeconomic policy mechanisms, such as the recycling of carbon revenues, adequately. Model users do address uncertainty, though often only through a sensitivity analysis. Bottom-up models are more likely than other models to include high-resolution spatial and/or temporal representations due to their explicit technological characteristics. In contrast, most hybrid and all top-down models can simulate the tested policy types due to a combination of explicit technology representations (to varying degrees in top-down models), and the incorporation of macroeconomic feedbacks (Jaccard & Dennis, 2006). Similar to bottom-up models, top-down models generally address uncertainty through a sensitivity analysis, while hybrid models almost always use other methods in combination with the sensitivity analysis, including Monte Carlo analysis. Top-down models lack the inclusion of high-resolution spatial and temporal representations due to their aggregated approach, while a small number of hybrid models include these representations. Differences in data transparency could not be attributed to model type, but rather to the organization type that uses and/or develops the model.

Our analysis has several limitations. First, the narrative literature review identified energy-economy models in Canada using only two databases, ScienceDirect and Google Scholar. Restricting the search to these databases, geography, and timeframe meant that our review provides only a sample of possible models and their application to climate policy evaluation. Our assessment of energy-economy models also relied in part on non-peer-reviewed 'grey' literature, the quality of which is uncertain. Second, there are potential biases that might have impacted survey responses. Because many respondents are model developers, they have a vested interest in promoting their model(s) and answering the survey questions in a way that reflects positively on their model and its assumptions. All respondents might have also been influenced by a social desirability bias whereby the capacity of the model or degree that characteristics are represented may have been overemphasized (e.g. several answers included “yes” and “explicitly” but failed to explain how exactly a characteristic was represented). In addition, the findings might have been affected by the varying levels of knowledge between model users and developers who completed the survey. For example, model users were more likely to choose the answer “I don’t know” or not answer an open-ended portion of the question, and sometimes provided a conflicting answer about the same model that was described by a model developer. Third, the survey used a convenience sampling method to recruit energy-economy model ‘experts’ in Canada as identified in the narrative literature review. This methodology might have limited the sample size and potentially affected the representation of the full model landscape in Canada. Finally, we chose the seven assessment characteristics using past literature on their general importance for modelling economic and GHG emission impacts of climate policy (Hourcade et al., 2006; Lopion et al., 2018; Savvidis et al., 2019). We did not conduct inferential analyses to suggest that some of these characteristics are more or less significant in influencing the quality of climate policy projections. Future research can employ a standard set of assumptions and climate policy scenarios to run different models and compare differences in results, in order to identify the relative importance of the seven assessment characteristics.

> No model is ideal for every policy question. Certain models or model types are better suited to answer certain questions than others.

Despite these limitations, this study offers important contributions to the existing body of modelling literature and climate policy-making. The comprehensive model assessment matrices help update past modelling reviews, and provide novel model information that is not otherwise publicly available, enabling more systematic comparisons of model strengths and gaps. Researchers and policy-makers can refer to these matrix tables when choosing a suitable model for their specific research or policy question. No model is ideal for every policy question, but rather certain models or model types are better suited to answer certain questions than others. All surveyed models seem to explicitly represent some technologies making them suitable to answer technology-specific policy questions. The high-resolution temporal representations in many bottom-up models (e.g. CanESS, LEAP) can further represent the fluctuations in renewable energy technologies caused by changing weather conditions. The evolution of explicit technology representations in all model types could reflect the fact that technology-specific policies such as subsidies and regulations are often preferred by policy-makers due to their higher political acceptability (Murphy & Jaccard, 2011). Almost all models are able to simulate carbon pricing; however, hybrid or top-down models (e.g. gTech or EC-PRO) would be more suited to this policy type due to their incorporation of macroeconomic feedbacks and the ability to represent carbon revenue recycling. All hybrid models can simulate a variety of prescriptive regulations, performance standards, and subsidies, because they incorporate the strengths of bottom-up and top-down methodologies. When developing climate policies at the municipal scale, using models that incorporate high-resolution spatial representations (e.g. CIMS-Urban, CityInSight) can help account for the non-spatial uniformity of land-use policies.

Finally, the observed lack of transparency in model data and assumptions/equations is a significant concern, and one that deserves the attention of academics and policy-makers. Non-transparent models can raise questions around credibility, especially if their results are used to inform public policy decisions. Without transparent and open access data, model results cannot be effectively reproduced and the implications of a policy scenario may not be fully understood and trusted (Pfenninger et al., 2014). More transparent and open access data can advance the accuracy of modelling results and lead to more informed and effective climate policy decisions (DeCarolis et al., 2012). One example of this in Canada is the Energy Modelling Initiative, which aims to provide open access tools and bridge the gap between model developers and users, similar to an Energy Modelling Forum in the United States (Beaumier et al., 2020; Energy Modelling Initiative, n.d.). Future research could explore governance mechanisms to amplify and sustain transparency in modelling.

The observed lack of transparency in model data and assumptions/equations is a significant concern, and one that deserves the attention of academics and policy-makers.

7. KNOWLEDGE MOBILIZATION ACTIVITIES

Our knowledge mobilization activities engaged a variety of relevant stakeholders to validate and disseminate research results in the public, private, and not-for-profit sectors in Canada. First, we validated literature review results by asking model users and developers across the country to complete an 'expert' survey for the models they develop and/or use. Survey respondents represented the following 13 organizations:

1. Public organizations:
    a. Government of Canada, Environment and Climate Change Canada
    b. Government of Québec, Transition Energétique Québec
    c. Government of New Brunswick, Climate Action Secretariat
    d. Simon Fraser University, Energy and Materials Research Group & Sustainable Transportation Action Research Team
    e. University of Maryland, Joint Global Change Research Institute
2. Private organizations:
    a. Energy Innovation, LLC
    b. Energy Super Modelers and International Analysts (ESMIA) Consultants
    c. Navius Research
    d. Sustainable Solutions Group
    e. Systematic Solutions, Inc.
    f. WhatIf? Technologies Inc.
3. Not-for-profit organizations:
    a. The International Institute for Applied Systems Analysis (IIASA)
    b. Stockholm Environment Institute

Following survey completion, we disseminated our findings through the following public presentations with dialogue-based questions and answer conversations:

1. Climate policy-makers at the British Columbia Climate Action Secretariat, Government of British Columbia (December 9, 2020);
2. Climate policy-makers at Environment and Climate Change Canada, Government of Canada (January 14, 2021);
3. Policy advocacy experts at the Canadian Climate Choices Institute, a not-for-profit (January 19, 2021);
4. Interdisciplinary researchers at the Institute for Integrated Energy Systems, University of Victoria (February 3, 2021).

This report and a supporting policy brief have been published on the University of Victoria website and distributed to our research collaborator at Environment and Climate Change Canada for further dissemination to national and sub-national climate policy-makers. We have also submitted abstracts to two conferences to validate and disseminate results to wider audiences, including the private sector and academia. Specifically, we anticipate to present the results at the Canadian Society for Ecological Economics conference in May 2021, and the Canadian Economics Association conference in June 2021. We have submitted the literature review and survey results to two high-impact peer-reviewed journals, *Renewable and Sustainable Energy Reviews* and *Sustainability*, to further enhance the project's academic contributions.

In summary, the study represents the first pan-Canadian effort to systematically synthesize energy-economy model methodologies, facilitating the use and development of more accurate models to help policy-makers ensure that Canada meets its commitments to reach net zero emissions by 2050.

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APPENDIX: SURVEY QUESTIONNAIRE “A REVIEW OF ENERGY-ECONOMY MODELS IN CANADA”

1. Your information

1.1 Personal information
Prefix/Title____________________
First Name____________________
Last Name____________________
Job Title/Position____________________
Division/Department/Program____________________
Organization____________________
City/Province____________________
Email____________________

1.2 What is the type of organization(s) you are associated with?

- Academia
- Government
- Industry
- Utility
- Consultant
- NGO
- Other. Please specify____________________

1.3 How many energy-economy models (i.e. a model that examines the linkages between all energy sectors and the economy of a region) do you use/run in your line of work? If you use more than one model you will be asked to fill out the survey for each model.

- 1
- 2
- 3
- 4
- 5
- More than 5

2. Model Information

2.1 Please provide the following information for the first model:

- Model name____________________
- Owner/Operator____________________

2.2 What type of model is it?

- Optimization/linear programming
- Input-output
- Computable general equilibrium (CGE)
- Hybrid
- Integrated assessment
- System dynamics
- Other. Please specify ____________________

2.3 What is the simulation period of the model? Please select all that apply.

- Every year
- Every 5 years
- Every 10 years
- Other. Please specify ____________________

2.4 How far into the future can the model be run? Please select all that apply.

- 2030
- 2050
- 2100
- Other. Please specify ____________________

2.5 What is the jurisdictional application of the model? Please select all that apply.

- Municipal
- Regional
- Provincial
- National
- Other. Please specify ____________________

2.6 What economic sectors are included in the model? Please select all that apply.

- Buildings
- Waste
- Transportation
- Industry
- Electricity
- Land use
- I don't know/I prefer not to answer
- Other. Please specify ____________________

3. Treatment of Technology

Treatment of technology refers to the level of resolution to which a model represents technological information, and how technological dynamics are captured.

3.1 Does the model explicitly represent technologies (e.g. their costs, availability, energy efficiency, and fuel compatibility)?

a) Yes
b) No [if selected, the survey will skip to question 4.1]
c) I don't know/I prefer not to say

3.2 What are the sectors where technologies are explicitly represented (e.g. their costs, availability, energy efficiency, and fuel compatibility)?

- All sectors. Please specify the approximate number of technologies _________
- Certain sectors. Please specify the approximate number of technologies _________

3.3 If you answered certain sectors, what sectors do explicitly represent technologies? Please select all that apply.

- Buildings
- Waste
- Transportation
- Industry
- Electricity
- Land use
- Not applicable (model explicitly represents technologies in all sectors)
- Other. Please specify ____________________

3.4 Does the model include any backstop technologies? A backstop technology can be represented as an undefined process used to limit abatement costs, or can refer to a particular technology or set of technologies.

- Yes
- No
- I don't know/I prefer not to say

If you answered yes, please explain which backstop technologies are included in the model.

____

The following questions are about the near-commercial technologies represented in the model. Near-commercial technologies are technologies that are used in a limited way and require some further development to achieve widespread adoption.

3.5 Does the model include direct air capture?

- Yes
- No
- I don't know/I prefer not to say

3.6 Does the model include carbon capture and storage?

- Yes
- No
- I don't know/I prefer not to say

3.7 Does the model include electrolysis-based hydrogen production?

- Yes
- No
- I don't know/I prefer not to say

3.8 Does the model include hydrogen fuel cell vehicles?

- Yes
- No
- I don't know/I prefer not to say

3.9 Does the model include first generation biofuels (i.e. derived from food crop sources such as starch, sugar, animal fats, and vegetable oil)?

- Yes
- No
- I don't know/I prefer not to say

If you answered yes, please explain which first generation biofuels are included in the model.

____

3.10 Does the model include second generation biofuels (i.e. derived from non-food biomass sources such as waste from food crops, agricultural residue, wood chips, and waste cooking oil)?

- Yes
- No
- I don't know/I prefer not to say

If you answered yes, please explain which second generation biofuels are included in the model.

____

3.11 Are any near-commercial technologies excluded from the model? Near-commercial technologies are technologies that are used in a limited way and require some further development to achieve widespread adoption (e.g. carbon capture and storage, plug-in electric vehicles, hydrogen fuel cells vehicles, heat pumps, solar, and wind).

- Yes
- No
- I don't know/I prefer not to say

If you answered yes, please explain which near-commercial technologies are excluded from the model.

____

3.12 Is technological change in the model represented as endogenous or exogenous? Technological change is the evolution of capital stocks of energy-related technologies within the economy.

- Endogenous
- Exogenous
- Endogenous and exogenous
- Not represented
- I don't know/I prefer not to say

If you answered endogenous and/or exogenous, please explain how the technological change is represented in the model. ______________________

3.13 Are technologies represented in the model subject to declining capital costs?

- Yes
- No
- I don't know/I prefer not to say

If you answered yes, please explain how declining cost are represented in the model. _________

3.14 What annual operating costs are included in the model? Please select all that apply.

- Fuel
- Maintenance
- No operating costs
- I don't know/I prefer not to answer
- Other. Please specify. ________

3.15 How often are most technology parameters updated in the model?

- Every year
- Every 2-5 years
- Every 5-10 years
- Every 10 years or longer
- Never
- I don't know/I prefer not to say

If certain technology parameters are updated at different times, please explain which parameters and how often.

____

4. Microeconomic Characteristics

Microeconomic characteristics refers to the ability of a model to realistically represent agent behavior within the energy-economy, including the heterogeneity of consumer preferences, and non-financial decision factors.

4.1 Is market heterogeneity (i.e. differences in how different consumers and producers make choices between technologies) addressed in the model?

- Yes
- No
- I don't know/I prefer not to say

If you answered yes, please explain how market heterogeneity is addressed in the model.

____

4.2 Is the risk of new technology failure addressed in the model (i.e. that new technologies have higher risk of failure than conventional ones)?

- Yes
- No
- I don't know/I prefer not to say

If you answered yes, please explain how the risk of new technology is addressed in the model.

____

4.3 Is the quality of technology service addressed in the model (e.g. convenience and comfort associated with driving a personal vehicle versus taking transit)?

- o Yes
- o No
- o I don't know/I prefer not to say

If you answered yes, please explain how the quality of technology service is addressed in the model. ______________________

4.4 Is the lack of information (i.e. firms and consumers do not have complete information about all available technologies) addressed in the model?

- o Yes, explicitly (e.g. through model's parameters)
- o Yes, implicitly (e.g. through past data, proxies)
- o No
- o I don't know/I prefer not to say

If you answered yes, please explain how the lack of information is addressed in the model. ______________________

4.5 Are upfront costs (i.e. capital investments) of technologies and associated discount rates represented in the model?

- o Yes, by disaggregating technologies (i.e. explicitly representing the upfront costs of each of the included technologies)
- o Yes, by aggregating production functions (i.e. representing upfront costs by combining related technologies that produce the same output)
- o Yes, other
- o No
- o I don't know/I prefer not to say

If you answered yes - other, please explain how upfront costs of technologies and associated discount rates are addressed in the model. ______________________

4.6 Besides the parameters listed above, are there other consumer and firm non-financial decision-making parameters?

- o Yes
- o No
- o I don't know/I prefer not to say

If you answered yes, please explain any other consumer and form non-financial decision-making parameters included in the model. ______________________

4.7 How often are most microeconomic/behavioural parameters updated in the model?

- o Every year
- o Every 2-5 years
- o Every 5-10 years
- o Every 10 years or longer
- o Never
- o I don't know/I prefer not to say

If certain microeconomic/behavioural parameters are updated at different times, please explain which parameters and how often. ______________________

5. Macroeconomic Characteristics

Macroeconomic characteristics refers to the ability of a model to represent the structural systematic relationships of a region's economy. This includes feedbacks such as trade, financing, and links between energy supply-demand and the economy's structure and output.

5.1 Does the model incorporate macroeconomic characteristics (i.e. represents the structural systematic relationships of a region's economy)?

- Yes
- No. [If selected the survey will skip to question 6.1]
- I don't know/I prefer not to say

If you answered yes, please explain how macroeconomic characteristics is incorporated in the model.
____

5.2 Does the model use general equilibrium methods to link economic feedbacks in a full equilibrium framework? A full equilibrium framework estimates aggregate relationships between the relative costs and markets shares of energy and other inputs to the economy, and links these estimates to sectoral and economic output.

- Yes
- No
- I don't know/I prefer not to say

If you answered yes, please explain how the model uses full equilibrium methods to link economic feedbacks in a full equilibrium framework. ______________________

5.3 Does the model use partial equilibrium methods to partially link major equilibrium feedbacks? Partial equilibrium methods do not simulate the entire economy, but instead only considers a specific part of the market or sector where the economic equilibrium is determined independently from the prices, supply and demand from other markets.

- Yes
- No
- I don't know/I prefer not to say
- Not applicable (model uses full equilibrium methods)

If you answered yes, please explain how the model uses partial equilibrium methods to partially link major equilibrium feedbacks. ______________________

5.4 Are energy commodities supply-demand balanced through price-quantity adjustments? Examples of energy commodities include electricity, refined petroleum products, and/or natural gas.

- Yes
- Partially, via own-price elasticities
- No
- I don't know/I prefer not to say

5.5 Are non-energy commodities supply-demand balanced through price-quantity adjustments? Examples of non-energy commodities include agriculture, metal, and/or livestock.

- o Yes
- o Partially, via own-price elasticities
- o No
- o I don't know/I prefer not to say

5.6 Is the electric grid represented in the model (e.g. hourly supply and demand and/or voltage and frequency of the electricity transmission and distribution system by province or other region)

- o Yes
- o No
- o I don't know/I prefer not to say

If you answered yes, please explain how the electric grid is represented in the model. ______________________

5.7 Is trade (i.e. the flow of goods and services between regions) represented in the model?

- o Yes
- o No [If selected the survey will skip to question 5.10]
- o I don't know/I prefer not to say

5.8 How is inter-regional trade treated within the model bounds?

- o Endogenously
- o Exogenously
- o Other
- o Inter-regional trade is not represented
- o I don't know/I prefer not to say

If you answered endogenously, exogenously, or other, please explain how inter-regional trade is treated within the model. ______________________

5.9 How is international trade treated within the model bounds?

- o Endogenously
- o Exogenously
- o Other
- o International trade is not represented
- o I don't know/I prefer not to say

If you answered endogenously or exogenously or other, please explain how international trade is treated within the model. ______________________

5.10 Are the monetary and finance sectors represented in the model?

- o Yes
- o No
- o I don't know/I prefer not to say

If you answered yes, please explain how the monetary and financial sectors are represented in the model.

____

5.11 How often are most macroeconomic parameters updated in the model?

- Every year
- Every 2-5 years
- Every 5-10 years
- Every 10 years or longer
- Never
- I don't know/I prefer not to say

If certain macroeconomic parameters are updated at different times, please explain which parameters and how often. ______________________

6. Policy Representation

Policy representation refers to the ability of a model to accurately represent different types of climate policies, whether implemented individually or in combination with each other.

6.1 Can the model simulate a carbon tax?

- Yes, explicitly (e.g. through model's parameters)
- Yes, implicitly (e.g. through past data, proxies)
- No
- I don't know/I prefer not to say

If you answered explicitly or implicitly, please explain how the model can simulate a carbon tax.

____

6.2 Can the model simulate a cap-and-trade policy?

- Yes, explicitly (e.g. through model's parameters)
- Yes, implicitly (e.g. through past data, proxies)
- No
- I don't know/I prefer not to say

If you answered explicitly or implicitly, please explain how the model can simulate a cap-and-trade policy.

____

6.3 Can the model simulate hybrid carbon pricing policies (e.g. carbon tax and cap-and-trade features combined)?

- Yes, explicitly (e.g. through model's parameters)
- Yes, implicitly (e.g. through past data, proxies)
- No
- I don't know/I prefer not to say

If you answered explicitly or implicitly, please explain how the model can simulate hybrid carbon pricing policies.

____

6.4 Can the model simulate recycling carbon revenue?

- Yes, explicitly (e.g. through model's parameters)
- Yes, implicitly (e.g. through past data, proxies)
- No
- I don't know/I prefer not to say

If you answered explicitly or implicitly, please explain how the model can simulate recycling carbon revenue.

____

6.5 Can the model simulate investment in Research and Development?

- Yes, explicitly (e.g. through model's parameters)
- Yes, implicitly (e.g. through past data, proxies)
- No
- I don't know/I prefer not to say

If you answered explicitly or implicitly, please explain how the model can simulate investment in Research and Development. ______________________

6.6 Can the model simulate prescriptive regulations, such as an emissions standard and/or a technology mandate?

- Yes, explicitly (e.g. through model's parameters)
- Yes, implicitly (e.g. through past data, proxies)
- No
- I don't know/I prefer not to say

If you answered explicitly or implicitly, please explain how the model can simulate prescriptive regulations.

____

6.7 Can the model simulate performance standards, such a low carbon fuel standard and/or a zero-emissions mandate with market credit trading mechanisms?

- Yes, explicitly (e.g. through model's parameters)
- Yes, implicitly (e.g. through past data, proxies)
- No
- I don't know/I prefer not to say

If you answered explicitly or implicitly, please explain how the model can simulate performance standards.

____

6.8 Can the model simulate subsidies for specific technologies?

- Yes, explicitly (e.g. through model's parameters)
- Yes, implicitly (e.g. through past data, proxies)
- No
- I don't know/I prefer not to say

If you answered explicitly or implicitly, please explain how the model can simulate specific technologies.

____

6.9 Can the model simulate government procurement/investments into low-carbon technologies?

- Yes, explicitly (e.g. through model's parameters)
- Yes, implicitly (e.g. through past data, proxies)
- No
- I don't know/I prefer not to say

If you answered explicitly or implicitly, please explain how the model can simulate government procurement/investments into low-carbon technologies. ______________________

6.10 Can the model represent multiple climate policies and consider interactions between these different policies?

- Yes, explicitly (e.g. through model's parameters)
- Yes, implicitly (e.g. through past data, proxies)
- No
- I don't know/I prefer not to say

If you answered explicitly or implicitly, please explain how the model can represent multiple climate policies and consider interactions between these different policies. ______________________

6.11 Does the model avoid double-counting emissions reductions caused by multiple climate policies?

- Yes, explicitly (e.g. through model's parameters)
- Yes, implicitly (e.g. through past data, proxies)
- No
- I don't know/I prefer not to say

If you answered explicitly or implicitly, please explain how the model avoids double-counting emissions reductions caused by multiple climate policies. ______________________

6.12 How often are policy representation parameters updated in the model?

- Every year
- Every 2-5 years
- Every 5-10 years
- Every 10 years or longer
- Never
- I don't know/I prefer not to say

If certain policy representation parameters are updated at different times, please explain which parameters and how often. ______________________

7. Other modelling considerations

7.1 What method(s) does the model use to explore uncertainty? Please select all that apply.

- Sensitivity analysis
- Monte Carlo analysis
- Gaussian process
- Bayesian model averaging
- Other methods
- No methods
- I don't know/I prefer not to say

If you answered other methods, please list which method(s) the explore uncertainty are used in the model.

____

7.2 What parameter(s) are most often explored through uncertainty analysis? Please select all that apply.

- Energy prices
- Economic growth
- Other parameters
- No parameters
- I don't know/I prefer not to say

If you answered other parameters, please list which parameter(s) are most often explored through uncertainty analysis. ______________________

7.3 Is the model freely available for public use?

- Yes
- No
- I don't know/I prefer not to say

If you answered yes, please provide a link/source where the model is available. ______________________

7.4 Does the model use open source code?

- Yes
- No
- I don't know/I prefer not to say

If you answered yes, please explain which code is used in the model. ______________________

7.5 Does the model use open source data?

- Yes
- No
- I don't know/I prefer not to say

If you answered yes, please explain how the data is open source. ______________________

7.6 Are the modelling equations documented in a publicly accessible manner (e.g. user manual)?

- Yes
- No
- I don't know/I prefer not to say

If you answered yes, please explain how the modelling equations are documented in a publicly accessible manner. ______________________

7.7 Are the modelling assumptions documented in a publicly accessible manner (e.g. assumption book)?

- Yes
- No
- I don't know/I prefer not to say

If you answered yes, please explain how the modelling assumptions are documented in a publicly accessible manner. ______________________

7.8 Does the model include high-resolution spatial representations of any technologies and/or methods (e.g. electric vehicles, hydrogen fuel cells, infrastructure)?

- Yes
- No
- I don't know/I prefer not to say

If you answered yes, please explain which technologies and/or methods are included and how they are represented in the model. ______________________

7.9 Does the model include high-resolution temporal representations of any technologies and/or methods (e.g. hourly renewable energy supply)?

- Yes
- No
- I don't know/I prefer not to say

If you answered yes, please explain which technologies and/or methods are included and how they are represented in the model. ______________________

8. Final Comments

Is there anything else you would like to share about the model not addressed in answers above?

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