Understanding Energy-Economy Models:
Survey Evidence from Model Users and Developers in Canada

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Abstract

Energy-economy models are important tools used by policy-makers and researchers to design effective climate policy. However, there has been limited research that compares models against consistent characteristics to understand their impacts on climate policy projections. This can make it difficult for policy-makers to identify suitable models for their specific policy questions and develop effective climate policies. A web-based survey of energy-economy model users and developers in Canada’s public, private, and non-profit sectors (n=14) was conducted to systematically compare seventeen models against a framework of seven characteristics: technology characteristics, micro-, and macro-economic characteristics, policy representations, treatment of uncertainty, high-resolution spatial and temporal representations, and data transparency. It was found that for the most part, models represent technology, micro-, and macro-economic characteristics according to the classic typology of bottom-up, top-down, and hybrid models. However, our findings show that several modelling evolutions have occurred. Some top-down models can explicitly represent technologies and some bottom-up models incorporate microeconomic characteristics. Models differ in the types of policies they can simulate, sometimes underrepresenting performance regulations, government procurement, and research and development programs. All models incorporate at least one type of uncertainty analysis, models infrequently have high-resolution spatial and/or temporal representations, and most models lack publicly accessible methodological documents. Implications for researchers and policy-makers that use energy-economy models and/or develop policies are discussed.

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Chapter 1. Introduction

1.1. Problem Statement

In a pledge to limit the rise of average global temperatures beyond two degrees Celsius, 189 nations signed the Paris Agreement in 2015 (United Nations Climate Change, 2020b, 2020c). As part of this pledge, countries have developed nationally determined contributions (NDCs) that outline their strategies to reduce greenhouse gas (GHG) emissions (United Nations Climate Change, 2020a). While some NDCs are supported by climate policy, the current efforts are projected to miss the global commitment (United Nations Environment Programme, 2019, p. 12). Current national strategies need to be strengthened to combat the continuing rise of GHG emissions. Developed countries, such as Canada, that have the financial capacity for GHG mitigation have a responsibility to progress national targets.

Energy-economy models aid policy-makers in understanding the effects of different policy proposals on GHG emissions and economic outcomes (Pollitt & Mercure, 2018, p. 185; Rivers & Jaccard, 2006, p. 2038). These models examine the linkages between the energy system and the economy of a region (Nakata, 2004, p. 420). However, the GHG and economic projections of a model varies based on how it incorporates certain methodological characteristics (Jaccard et al., 2003, pp. 56–58). These discrepancies make it difficult for policy-makers to choose amongst the various models to assess the impacts of existing and proposed climate policies. This is further exasperated by the lack of publicly available and consistent information on modelling methodologies. While some information on academic models exists in scholarly databases, other information has only been sporadically gathered across the public, private, and non-profit sectors (e.g., Jaccard et al. (2019), Murphy & Jaccard (2011), Navius Research (2019)). In addition, these sources do not use consistent characteristics to compare and contrast models systematically, making it difficult for policy-makers to choose the model best suited to answer their specific policy question(s). Understanding how different models perform against common methodological characteristics can help policy-makers choose a suitable model, improve existing and future models, and design effective climate policies.

1.2. Research Objectives

Using a web-based survey of energy-economy model users and developers in Canada (n=14), this study aims to compare and contrast energy-economy models used in the public, private, and non-profit sectors. Specifically, the study compares seventeen models in terms of their technology, micro-, and macro-economic characteristics, policy representation, treatment of uncertainty, high-resolution spatial and temporal representation, and data transparency. The objectives of this study are as follows:

1) update existing literature reviews of energy-economy models with current survey data,
2) collect model information that may not be publicly accessible, and
3) compare models against the identified seven characteristics, using modelling inventory tables, to identify strengths and gaps that ultimately impact climate policy projections.

1.3. Structure of the Thesis

Following the introduction, this thesis is structured as follows: Chapter 2 reviews the current energy-economy modelling classification and discusses the framework, consisting of seven model characteristics, for assessing and comparing energy-economy models. Chapter 3 outlines the methodology for survey data collection and analysis. Chapter 4 describes the results of the analysis. Chapter 5 discusses the results and limitations of the study. Chapter 6 discusses the key implications of findings for policy-makers and academic research. Finally, Chapter 7 concludes.

Chapter 2. Literature Review

2.1. Energy-Economy Model Classification

The energy-economy modelling literature suggests three model types based on analytical approach: “bottom-up” technological models, “top-down” macroeconomic models, and hybrid models that were developed to combine the strengths of the bottom-up and top-down modelling types (Hourcade et al., 2006, p. 4) (Figure 1). While model frameworks are diverse and do not always fit into these general categories, it is pedagogically useful to classify models in this way (Jaccard, 2009, p. 312).

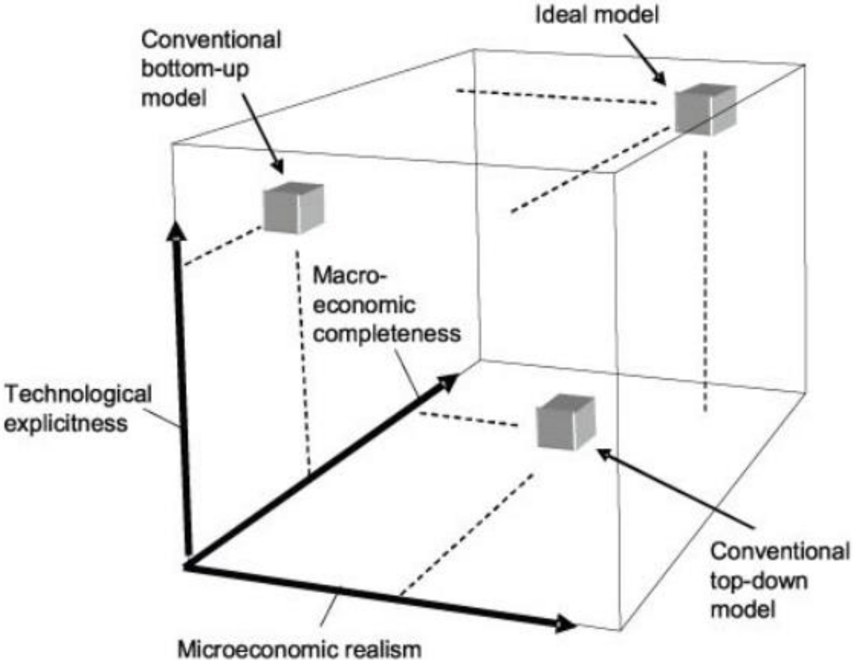

Figure 1: Three-dimensional assessment of energy-economy models. The ideal model is a hybrid model combining the strengths of top-down and bottom-up models. Reproduced from Hourcade et al. (2006, p. 4).

This model classification categorizes models based on their incorporation of three characteristics: explicit representation of technologies, microeconomic representations, and macroeconomic representations (Hourcade et al., 2006, p. 4; Jaccard et al., 2003, p. 57). Technology characteristics refer to the level of detail current and emerging technologies are represented (Mundaca et al., 2010, pp. 306–307). Microeconomic characteristics refer to the inclusion of intangible behavioural as well as non-intangible up-front costs, involved in technology purchasing decisions that can help account for individual preferences (Rivers &

Jaccard, 2006, p. 2040). Macroeconomic characteristics represent the interaction of the energy system with the larger macroeconomy through equilibrium feedbacks (Hourcade et al., 2006, p. 3; Rhodes et al., 2021b, p. 5).

A technologically-explicit bottom-up modelling approach represents supply- and demand-side technologies in detail, including market shares, operating costs, and performance attributes (Hourcade et al., 2006, p. 2; Jaccard, 2009, p. 312). However, they are criticized for their focus on financial costs alone, ignoring the intangible costs that are associated with technology purchasing decisions (Jaccard, 2009, p. 312; Rivers & Jaccard, 2006, p. 2039). This can result in the underestimation of the ease and cost of GHG abatement by bottom-up models (Hourcade et al., 2006, p. 4; Jaccard & Dennis, 2006, p. 91; Rhodes et al., 2021b, p. 5). In addition, the technologies in the energy sector are not interacting with the rest of the economy, limiting bottom-up models for policies with economy-wide feedbacks (Löschel, 2002, p. 107). However, bottom-up models are useful for determining the impacts of future technologies along with the technologies that can contribute to lower GHG emissions (Prina et al., 2020, pp. 2–3),

In contrast, a top-down approach aggregates technology representation and often represents detailed micro- and macroeconomic characteristics. Historical data is often incorporated to implicitly represent the intangible costs realised by firms and consumers in technology purchasing decisions. However, this historic data may not accurately reflect future decision-making processes (Jaccard, 2009, p. 313; Rivers & Jaccard, 2006, p. 2039). Top-down models estimate the broader macroeconomic effects of policies, which makes them useful for modelling large-scale policies such as taxes (Jaccard & Dennis, 2006, p. 92). However, the lack of technological explicitness and limited representation of technological change can cause top-down models to overestimate the cost of GHG abatement (Horne et al., 2005, p. 60).

Hybrid models were developed to combine the strengths of bottom-up and top-down models. This is often accomplished through the incorporation of the technological explicitness of bottom-up models and the micro- and macroeconomic characteristics of top-down models). A hybrid approach produces more accurate projections compared to bottom-up and top-down models (Hourcade et al., 2006, pp. 4–5; Jaccard, 2005, pp. 90–92; Rivers & Jaccard, 2006, p. 2040).

In addition to energy-economy models, policy-makers also have other modelling tools to assess different policy questions, including integrated assessment models (IAM) and energy systems models (IPCC, 2018; Pfenninger et al., 2014). IAMs aim to link key processes of the economy and energy system with the dynamics of the atmosphere and biosphere (Nika et al., 2019, pp. 2–3). Energy systems models focus on the energy system (i.e., the progression of acquisition to the final use of energy), within an economy to understand energy supply and demand and generally do not incorporate economic agent behaviour (Nika et al., 2019, pp. 30–

31; Pfenninger et al., 2014, pp. 75–76). While there have been examples of systematic reviews on IAMs (e.g., the Integrated Assessment Modeling Consortium (n.d.), Paris Reinforce (n.d.)) and energy systems models (e.g., Lopion et al. (2018), Pfenninger et al. (2014)), reviews of energy-economy models are lacking. Therefore, the scope of this review is restricted to the assessment of energy-economy models in Canada that examine the linkages between the energy system and the economy of a region.

2.2. Energy-Economy Model Assessment Framework

While the technology, microeconomic, and macroeconomic characteristics have been considered extensively in the modelling literature (e.g., Beugin & Jaccard (2012), Hourcade et al. (2006), Rivers & Jaccard (2006)), additional characteristics including policy representation, treatment of uncertainty, high-resolution spatial and temporal representations, and data transparency have been put forward as important in the assessment of energy-economy model projections (e.g., Lopion et al. (2018), Murphy & Jaccard, (2019), Pfenninger et al. (2014), Rhodes et al. (2021b)). While this study generally follows Hourcade et al's (2006, pp. 4-5) model assessment characteristics, it primarily employs an exploratory research approach to gather information on the key strengths and gaps in existing energy-economy models to help guide researchers and policy-makers in their model choices and interpretations of modelling results.

2.2.1. Technology Characteristics

Technology characteristics refer to the level of resolution about technology parameters and the representation of technological change dynamics (Jaccard, 2009, p. 316). A high degree of technological detail can allow policy-makers to assess future market responses of consumer and firm technology adoption rates caused by a specific policy (Rivers & Jaccard, 2006, p. 2046). Technology specific models can include commercial (e.g., hydroelectricity, nuclear, hybrid electric vehicles) and near-commercial (e.g., direct air capture, carbon capture and storage, hydrogen-fuel cell vehicles, first- and second-generation biofuels) technologies. These technologies can be characterized by their capital and operating costs in addition to performance attributes (Rivers & Jaccard, 2006, p. 2039). The evidence base for developing policies is often strengthened by the representation of technologies in adequate detail (Li et al., 2015, p. 292).

The representation of technological change dynamics can also affect modelling projections (Gillingham et al., 2008, pp. 2734–2735). The technologies in exogenous technological change are only dependent on the passage of time (Clarke et al., 2014, p. 423; Gillingham et al., 2008, p. 2736). Exogenous technological change can be represented by the use of an autonomous energy-efficiency improvement (AEEI) parameter in more aggregated models, the addition of new energy-efficient technology in more disaggregated models, or through backstop technologies (processes or technologies that are used to limit abatement costs) (Gillingham et al., 2008, p. 2736). In contrast, endogenous technological change is influenced by investments in research, expected prices, and policies in addition to the passage of time (Clarke et al., 2014, p. 423; Gillingham et al., 2008, p. 2737). The main three methods of incorporating endogenous technological change are direct price-induced, investments in research and development, and learning by doing (Gillingham et al., 2008, p. 2737).

2.2.2. Microeconomic Characteristics

Microeconomic characteristics give the model the ability to account for the non-financial (behavioural) choices of firms and consumers that can impact the effectiveness of policies (Hourcade et al., 2006, p. 3; Krysiak & Weigt, 2015, pp. 6–7). Microeconomic characteristics in energy-economy modelling can be represented through two main methods: market heterogeneity and non-financial decision costs (Rhodes et al., 2021b, p. 8).

Market heterogeneity reflects the reality that variation exists amongst consumers. This variation can include factors such as income stratification and/or other socio-economic and behavioural parameters (Mercure et al., 2016, p. 104). These variations can influence consumer technology purchasing decisions. The inclusion of market heterogeneity in energy-economy models is more likely to create a more realistic outcome of technology adoption and the distributive impacts of policies (Krysiak & Weigt, 2015, pp. 7–8). Non-financial/intangible costs are additional factors used by consumers when they are making the decision to acquire new technologies. Typically, models represent firms and consumers as “rational agents” in their decision making when choosing between technology alternatives (Hourcade et al., 2006, p. 2; McCollum et al., 2017, p. 323). Rational agents aim to maximize utility, have fixed and known preferences, as well as perfect information. However, real-world decision making is much more complex and agents do not always chose the most rational option that is cost-minimizing or utility maximizing (Gillingham et al., 2009, pp. 2–3). Non-financial costs include the risk of adopting new technologies, quality variations between technologies, and a lack of information (Clarke et al., 2014, p. 468; Jaccard et al., 2003, pp. 53–55). The exclusion of these non-financial costs can lead to the underestimation of GHG abatement costs (Murphy & Jaccard, 2011, p. 7147).

2.2.3. Macroeconomic Characteristics

Macroeconomic characteristics represent a region’s economy through the relationships of energy supply-demand to the structure of the economy (Hourcade et al., 2006, p. 3; Krysiak & Weigt, 2015, p. 2). Climate policies have the ability to cause economic benefits and costs, which can often occur at the same time (Mercure et al., 2019, p. 1031). These macroeconomic feedbacks can change both the structure and growth rate of the economy as well as its outputs

(Jaccard, 2009, p. 315). Therefore, understanding the influence of macroeconomic feedbacks caused by climate policies is important to policy-makers in the development of decarbonization pathways.

Macroeconomic feedbacks can be incorporated in energy-economy models through two approaches: full or partial equilibrium methods (Hedenus et al., 2013, p. 122). Full equilibrium methods link the whole economic output to energy supply and demand in a full equilibrium framework. The effects of policy instruments, price fluctuations, and resources on all sectors are examined (Hedenus et al., 2013, p. 122). In contrast, partial equilibrium methods only consider a part of the market, often with a focus on the energy sector.

Generally, both full and partial equilibrium methods link the energy-consuming sectors to the energy-producing sectors of the economy to represent the supply and demand of energy in the economy (Rhodes et al., 2021a, p. 5). Through price and quantity adjustments an equilibrium of energy commodities is achieved between the supply and demand of all energy sources. This can also be done for non-energy commodities, though it is not incorporated as often as it is for energy commodities (Rhodes et al., 2021b, p. 22). For example, due to the variable nature of renewable energy sources the representation of the electric grid is crucial to understanding the balance of supply and demand of electricity between economic sectors (Savvidis et al., 2019, p. 503).

Another important macroeconomic characteristic is the inclusion of trade and financial feedbacks due to the global nature of reducing GHG emissions (Hourcade et al., 2006, p. 3; Jaccard, 2009, pp. 314–315). Models can range from not incorporating any trade effects to assuming domestic goods are preferred over imports to assuming goods are globally homogenous and easily traded (Clarke et al., 2014, pp. 422–423). Additionally, energy-economy models can represent links to the financial and monetary sectors (Pollitt & Mercure, 2018, p. 186). Given that financial investment in clean energy is required to meet climate goals, understanding the origins of these investments and their effects on the economy is crucial to climate policy projections (Mercure et al., 2016, pp. 107–108).

2.2.4. Policy Representation

Models differ in their representation of different climate policies. Policies can be considered individually or in combination, and their modelled impacts can include the representation of emission abatement costs, economic impacts, and GHG emission reductions (Goulder & Parry, 2008, p. 152). A model’s ability to represent multiple climate policies can allow policy-makers to choose the best policy mix for a specific goal when interactions are considered to avoid the double-counting of emissions reductions (Schneider et al., 2015, pp. 473–474).

There is an extensive range of climate policy instruments including emission pricing, government investments and subsidies, performance standards, and prescriptive regulations (Goulder & Parry, 2008). Emission pricing policies can be a direct tax on emissions, a tradeable allowance system also known as “cap-and-trade,” or a hybrid combination of both. Emission pricing policies require the agent to either decrease their emissions or pay a carbon price (Goulder & Parry, 2008, p. 155). The revenue generated by emission pricing policies can then be recycled often to finance tax reductions or transferred to low income households (Goulder & Parry, 2008, pp. 160–161; 166). Government investment and subsidies are measures that provide financial aid or support to lower the barrier to accessing low carbon technologies. Research and development investments to advance technologies are a typical example of government investment, while rebates are a common subsidy. Performance standards do not prescribe specific technology requirements, which gives firms the flexibility in how they meet the standard (Goulder & Parry, 2008, p. 158). In contrast, prescriptive regulations do not give firms the flexibility to decide how to meet government standards and instead require them to adopt specific technologies (Peace & Ye, 2020, pp. 8–9).

2.2.5. Treatment of Uncertainty

Understanding the effects of uncertainty on modelling projections is important when assessing the range of possible real-life scenarios influenced by the complexity of modelling methodologies (Hedenus et al., 2013, pp. 127–128). However, the incorporation of uncertainty analyses are not found in all policy reports and academic literature (Hedenus et al., 2013, pp. 127–128). Uncertainty in energy-economy models can be broadly classified as parametric or structural. The former is the uncertainty in input parameters, while the later refers to the uncertainty in the model’s structure describing energy-economic systems (DeCarolis et al., 2017, p. 192; Webster & Sokolov, 1998, p. 1). A sensitivity analysis is a common method to address parametric uncertainty by understanding the relative influence each input parameter has on the final modelling results (DeCarolis et al., 2017, pp. 192–193; Samsó et al., 2020, p. 2). Another method to assess uncertainty is a Monte Carlo analysis, which determines the uncertainty range of a variable in addition to determining the parameters that are important to the final results (Hedenus et al., 2013, p. 128). The effects of uncertainty can be explored in economic growth rates, energy prices, and technological details to provide a range of economic and GHG impacts (Babonneau et al., 2010, pp. 4–9).

2.2.6. Spatial and Temporal Representations

High resolution temporal and spatial representations can account for the variability in the renewable energy supply, due to changing weather conditions, via representative time slices or real time data (Lopion et al., 2018, p. 157; Pfenninger et al., 2014, p. 80). High-resolution spatial representations assist in the development of local-scale policies that are not spatially uniform such as urban planning and transportation (Jaccard et al., 2019, p. 3).

2.2.7. Data Transparency

Finally, the transparency of the methods, data, and assumptions used in an energy-economy model is important for the reproducibility of results (Cao et al., 2016, pp. 10–11; DeCarolis et al., 2012, pp. 1850–1851). Model transparency can be increased when the model's source code, input data, and documentation is publicly available, while model accessibility can be increased through the use of free software tools (DeCarolis et al., 2012, pp. 1850–1851). Greater transparency allows third parties to reproduce and validate modelling results, which is important for models used in the development of public policy (DeCarolis et al., 2012, p. 1852).

Building upon previous literature reviews (e.g., Lopion et al. (2018), Pfenninger et al. (2014), Rhodes et al. (2021b), Savvidis et al. (2019)) an empirically-novel approach is employed to compare energy-economy models via a web-based survey instrument to collect primary 'expert' data from energy-economy model users and developers across Canada based on the previously mentioned seven characteristics. These characteristics include: technology characteristics, micro- and macroeconomic characteristics, policy representation, treatment of uncertainty, high-resolution spatial and temporal representations, and data transparency

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Chapter 3. Materials and Methods

3.1. Data Collection

A web-based survey of energy-economy model ‘experts’ (n=14) in the public, private, and non-profit sectors across Canada was implemented to collect primary data regarding the seven assessment characteristics outlined in Chapter 2.2. A convenience sampling methodology was chosen to recruit a sampling frame of energy-economy model ‘experts’ (Sovacool et al., 2018, p. 20), that consisted of model developers and users across Canada. These experts simulate the effects of climate policies and/or use modelling results to inform policy decisions. This sampling frame included a total of thirty-three energy-economy model developers and users in Canada that were identified in a scoping review by Rhodes et al. (2021b). These thirty-three individuals represent thirty organizations: twenty public organizations, six private companies, and four non-profit organizations. Email information for each respondent was found on their organization’s open-access website and was used to send electronic invitations. The invites stated that different people within their organization could respond for different models that were developed and/or run in their organization.

The survey was designed and administered using the University of Victoria’s SurveyMonkey platform. Tailored survey design methods were employed to ensure the high quality of responses while minimizing the overall survey error (Dillman et al., 2014, pp. 3–4). All aspects of the survey design were approved by the University of Victoria Human Research Ethics Board (approval reference # 20-0245). The survey questions were pre-tested with a select group of energy-economy modelling experts in academic institutions to reduce overall survey error. The average time for a respondent to complete the survey was 1 hour and 30 minutes, however this average survey completion length is skewed by six respondents that completed the survey for more than one model.

To encourage participation and establish trust, personalized survey invitations were sent out explaining the purpose of the study and its benefits to the potential participant. Before beginning the survey, all respondents were presented with a consent form outlining the terms of participation, including the risks and benefits to participating as well as how their data will be used, analyzed, and stored (see Appendix A for the full consent form). To begin the survey, all respondents were required to agree to these terms.

Responses were received from fourteen individuals (10 model owners and 4 model users) representing thirteen organizations (five public organizations, six private companies, and two non-profit organizations), producing a 42% response rate. These 14 respondents represent many of the top-energy-economy modellers in Canada, which is a small field comprised of specialized knowledge holders. Respondents provided information about nineteen distinct models, with four models each receiving responses from two individuals. The scoping literature review by Rhodes et al. (2021b) identified twenty-one energy-economy models used in Canada over the past decade. Therefore, the nineteen models that were identified in this study are representative of Canada's modelling landscape. Most respondents (eight) provided information about one model, while six respondents provided information for more than one model, five provided information for two models, and one for five models.

The survey contained of a mix of closed-ended and open-ended questions in each section based on the seven assessment characteristics from Chapter 2.2. Specifically, the survey consisted of eight sections: (1) information about the respondent; (2) 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 treatment of uncertainty, inclusion of high-resolution spatial and temporal representations, and the transparency of modelling assumptions; and (8) final comments (see Appendix B 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 in their line of work. For the six respondents who provided information on more than one model, sections 2-8 were repeated for each model they reported on (e.g., the maximum number of repeats in the sample was five). The second section asked questions about the model including the model name and owner, description of the model type, 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, included near-commercial technologies, representation of technological change, 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 about the upfront costs of technologies, lack of information, quality of technology service, risk of new technology failure, and how often microeconomic parameters are updated.

The fifth section on macroeconomic characteristics started with a definition, and then asked respondents questions about the model's representation of equilibrium feedbacks, balancing of energy and non-energy commodities, representation of the electric grid, trade, 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 climate policies and mechanisms. This included a carbon tax, cap-and-trade, hybrid carbon pricing (i.e., a combination of a carbon tax and cap-and-trade), carbon revenue recycling, prescriptive regulations, subsidies, performance standards, government procurement/investment, and research & development. They were also required to indicate if the model considered interactions between multiple policies and avoided double-counting emissions caused by multiple climate policies. Finally, respondents indicated how often policy representation parameters are updated.

The seventh section asked questions about the uncertainty method(s) used by the model and the parameter(s) most often explored through uncertainty analysis. Respondents also answered questions about the inclusion of high-resolution spatial and temporal representations as well as the model and data transparency. The final section was an open-ended question where the respondents could share any additional model information.

3.2. Data Analysis

The four models (i.e., CIMS, GCAM, gTech, LEAP) that received multiple responses were merged together to form one synthesized response per model using the following methods: 1) any alternative response would replace "I don't know" responses; 2) questions that allowed multiple answers (e.g., the timeframe in which parameters are updated) were merged in the combined response; 3) if there were contradictory responses from a developer and user of a model, the user's responses were excluded and only the developer's answers were used. When responses could not be resolved using the aforementioned methods, respondents were contacted by email to confirm their information. This process was completed for four respondents in the sample.

Models were categorized into the three main model types discussed in Chapter 2.1 (i.e., bottom-up, top-down, and hybrid) to examine the general trends in how they incorporate each of the seven characteristics. Responses from the question collecting descriptions of the model type were used to categorize models based on their analytical approach. Technology-explicit bottom-up models were described as "simulation", "optimization/linear programming", or "technology adoption;" macroeconomic top-down models used "computable general equilibrium" descriptors; and hybrid models were described as "input-output", "hybrid", or "system dynamics". This information was confirmed with the literature (Rhodes et al., 2021b; Wolinetz & Axsen, 2017;

Zhu et al., 2018), however it is acknowledged that models are very diverse and may fit into more than one category. Due to its explicit representation of the macroeconomy, the integrated assessment model EC-IAM was analyzed within the top-down category.

A response was received for the macroeconomic model The Infometrica Model (TIM); however, it was not analyzed as a stand-alone model as it is not considered an energy-economy model according to the definition in Chapter 2.1. However, because TIM in conjunction with ENERGY 2020 make up the model E3MC, TIM was indirectly analyzed. Similarly, the Integrated Electricity Supply and Demand (IESD) model was not analyzed separately. IESD is often used in conjunction with gTech to provide increased detail in the electricity sector (Navius Research, 2019, p. 12), therefore it was combined with gTech in the analysis. Therefore, a total of seventeen models were included in the final analysis compared to the original total of nineteen models.

The data was analyzed through descriptive statistics to calculate the frequencies of the multiple-choice questions. The open-ended responses were manually scanned and analyzed to identify common themes to support and further explain the results of the multiple-choice questions. When respondents provided answers that did not align with the definition of a question, the response was reassigned to a more suitable question. For models with only one respondent, “I don’t know” answers were treated as missing values in the calculation of frequencies. Modelling inventory tables were developed to summarize the responses for each of the seven characteristics. Some open-ended response details were also included in these inventory tables to further augment comparisons between models.

Chapter 4. Results

4.1. General Model Information

The surveyed energy-economy models in Canada are primarily owned by public organizations (eight models), followed by private companies (seven models), and non-profit groups (two models) (Table 1). The models were found to use a diverse set of analytical approaches. The use of a hybrid approach that combines the strengths of both bottom-up and top-down approaches was the most common, with this approach employed by eight models: CIMS, CIMS-Urban, E3MC, ENERGY 2020, Energy Policy Simulator, GCAM, gTech, and NATEM-TIMES. A bottom-up approach was the next most common approach with six models (i.e., CanESS, CityInSight, LEAP, MEDEE, MESSAGE, REPAC) using it. A top-down approach (i.e., EC-PRO, EC-MSMR, EC-IAM) was the least common, being used in three models.

The simulation period of a model is ranges from sub-annual time periods 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). Most of the models use a simulation period of every year (ten models) or every 5 years (eleven models). Fewer models use a simulation period of every 10 years (two models) or more often than at an annual basis (three models). Models vary in their simulation timeframes with twelve models running to 2050. A smaller portion of models run to 2030 (six models) and 2100 (seven models). The respondents for six models (i.e., CIMS, CIMS-Urban, CityInSight, EC-MSMR, gTech, 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 up to an international level, depending on a models' specific objectives. Three-quarters of models can be used in multiple jurisdictions with the provincial/territorial level being the most common application (twelve models), followed closely by a national application (nine models). Fewer models can be applied to regional (six models) and municipal scales (five models) as well as the broad international jurisdiction (six models).

About half of the models represent multiple economic sectors at once ranging from buildings, to waste, transport, industry, electricity, and land use sectors. The least represented economic sector is land use with eleven models including this sector. A few models include additional sectors, such as agriculture (i.e., CIMS, MEDEE) and the forest sector (i.e., NATEM-TIMES). The transportation sector was the only sector to be included in all surveyed models.

The following sub-sections describe the surveyed models against the seven characteristics from Chapter 2.2.

Table 1: 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
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 top-down)	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
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
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
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
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; forest sector included
REPAC	SFU, Sustainable Transportation Action Research Team	Technology adoption (treated as bottom-up)	Every 5 years	2030	Provincial, national	Only transportation included

* "All sectors" imply the sectors listed in the survey questionnaire, including buildings, waste, transportation, industry, electricity, and land use.

4.2. Treatment of Technologies and Technological Change

All of the surveyed models were found to explicitly represent technologies (Table 2). Seven models explicitly represent both backstop and near-commercial technologies: GCAM, CIMS, EC-IAM, EC-PRO, EC-MSMR, Energy Policy Simulator, MESSAGE. Over half of models explicitly represent technologies in certain sectors, while the rest explicitly represent technologies in all sectors. The number of represented technologies ranges from five (i.e., REPAC) to thousands (e.g., CIMS, NATEM-TIMES). Backstop technologies exist in only seven models and 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).

Table 2: 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
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
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
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
MEDEE	Certain sectors (3) – 18 categories	No	No	No	Endogenous and exogenous	No	Fuel
MESSAGE	All sectors – approx. 500 technologies	Yes	Includes CCS	N/A	N/A	Yes	Fuel and maintenance
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
REPAC	Certain sectors – 5 technologies	No	Includes H vehicles	No	Endogenous	Yes	Fuel

* “N/A” stands for “not available,” and represents “I don’t know” survey responses.

With the exception of MEDEE, all of the models represent at least one near-commercial technology. Near-commercial technologies are technologies that are used in a limited way and require some further development to achieve widespread adoption. Of the near-commercial technologies surveyed, hydrogen fuel cell vehicles were the most common, being represented in fifteen models. Other near-commercial technologies that are represented in the surveyed models include carbon capture and storage (14 models), electrolysis-based hydrogen production (13 models), and direct air capture (8 models). Finally, the majority of models (i.e., 14 models) represent first and/or second-generation biofuels, with ten of those models representing both categories of biofuels.

Almost all models include representations of technological change, declining capital costs, and annual operating costs. Models most commonly represent technological change using both exogenous and endogenous methods depending on technology types (Figure 2). All three model types of 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) use this method. The models that represent technological change exogenously also consist of bottom-up (i.e., CanESS, CityInSight), top-down (i.e., EC-IAM), and hybrid (i.e., GCAM) approaches, while models that represent it endogenously mostly used a hybrid approach (i.e., CIMS, CIMS-Urban, gTech). The large majority of models (i.e., sixteen models) include declining capital costs in their representation of technologies. Only one model, MEDEE, does not include declining capital cost functions. Finally, fuel and maintenance costs are included as annual operating costs in almost all surveyed models.

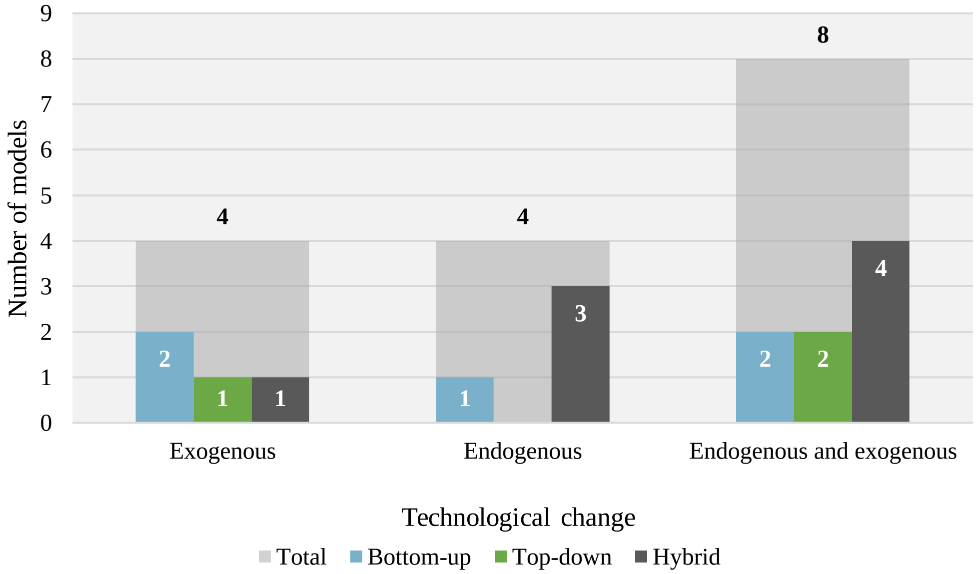

Figure 2: Models representing technological change by model type.

4.3. Representation of Microeconomic Characteristics

With the exception of the models CanESS and CityInSight, all models include some representation of microeconomic characteristics (Table 3). Four models represent a full range of microeconomic characteristics including upfront costs of technologies, lack of information, varying quality of technology service, risk of new technology failure and other non-financial characteristics. These tend to be hybrid models (i.e., CIMS, CIMS-Urban, E3MC, and gTech). Models address market heterogeneity through several methods including choice methods (i.e., E3MC, ENERGY 2020, Energy Policy Simulator, REPAC) and behavioural parameters (i.e., CIMS, CIMS-Urban). The models that do not address market heterogeneity are bottom-up models.

Table 3: 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 decisionmakers 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 decisionmakers 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
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
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
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)
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

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
MESSAGE	N/A	Yes	Yes, by disaggregating technologies	N/A	No	Yes	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)
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

* “N/A” stands for “not available,” and represents “I don’t know” survey responses.

The same models that address market heterogeneity also include at least one non-financial cost parameter. The most common parameter are upfront costs of technologies and associated discount rates, with fourteen models addressing this parameter. Of those fourteen models, the majority represent this parameter by disaggregating technologies and representing the non-financial upfront costs of each included 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 (Figure 3). The models that did include these characteristics often use a hybrid approach (e.g., CIMS, E3MC, gTech). Just over half of models acknowledge that firms and consumers do not have complete information about all technologies with eight models representing this characteristic explicitly and two representing it implicitly. The quality of technology service is addressed in eight of the surveyed models and the risk of new technology failure in six models. Almost half of the models contain additional non-financial decision-making characteristics including technology availability (i.e., REPAC) and externality values of pollution (i.e., LEAP).

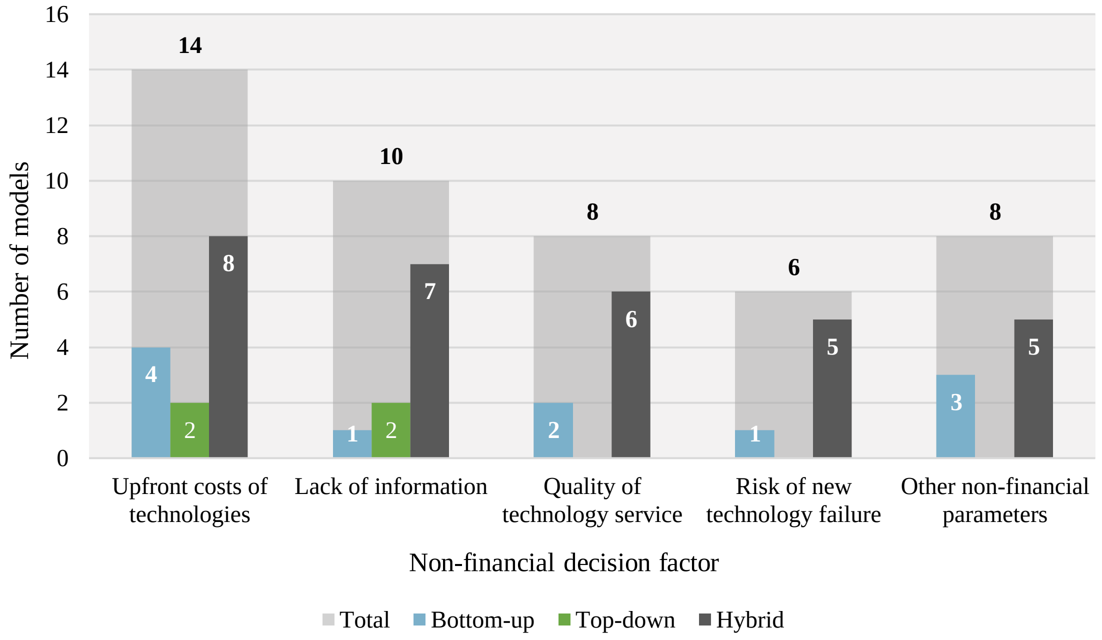

Figure 3: Models representing each non-financial decision factor by model type.

4.4. Representation of Macroeconomic Characteristics

The majority of models (i.e., twelve models) incorporate macroeconomic characteristics to some degree to represent the structural systematic relationships of a region's economy (Figure 4). These models are almost all hybrid or top-down models due to their parameterization through historical macroeconomic data (Table 4). The models EC-IAM, EC-PRO, EC-MSMR, gTech, and NATEM-TIMES include all the surveyed macroeconomic characteristics of 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). Of the twelve models that incorporate macroeconomic characteristics, slightly more models use partial equilibrium methods (seven models) than full equilibrium methods (five models). Full-equilibrium models are typically more of a top-down (i.e., EC-IAM, EC-PRO, EC-MSMR) and/or hybrid nature (i.e., gTech).

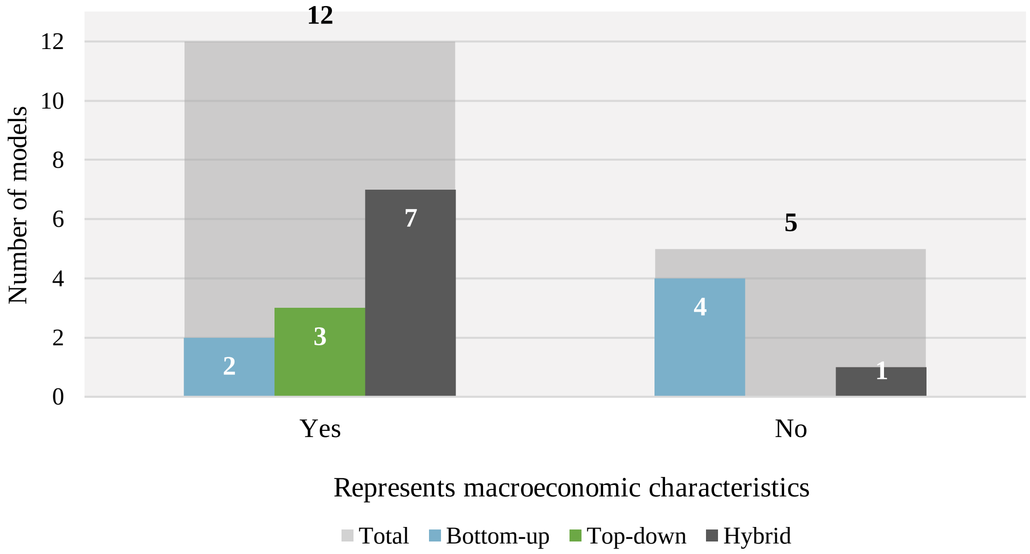

Figure 4: Models representing macroeconomic characteristics by model type.

Table 4: 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
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	N/A
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	N/A
Energy Policy Simulator	Yes	No	N/A	Partially, via own-price elasticities	Partially	No	No	No	No	Yes
GCAM	Yes	N/A	Yes	Yes	Yes	No	Yes	Endogenous	Endogenous	No
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
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
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
REPAC	No	No	No	No	No	No	No	No	No	No

* “N/A” stands for “not available,” and represents “I don’t know” survey responses

Most models represent the supply-demand balance of energy commodities through price-quantity adjustments, with fewer models balancing non-energy commodities. Of these models, six (i.e., EC-IAM, EC-PRO, EC-MSMR, GCAM, gTech, NATEM-TIMES) balance both energy and non-energy commodities and two (i.e., Energy Policy Simulator and MESSAGE) partially balance both energy and non-energy commodities. The six models that balance both energy and non-energy commodities are top-down (i.e., EC-PRO, EC-IAM, EC-MSMR) or hybrid models (i.e., GCAM, gTech, NATEM-TIMES). E3MC is the only model to balance energy commodities, but not non-energy commodities. Two thirds of the surveyed models include a representation of the electric grid (i.e., E3MC, EC-IAM, EC-PRO, EC-MSMR, ENERGY 2020, gTech, LEAP, NATEM-TIMES). These are mostly full-equilibrium top-down or hybrid models.

The incorporation of trade effects is found in almost all the models that represent macroeconomic characteristics, while the representation of the monetary and financial sectors is rare. gTech is the only model found to represent inter-regional and international trade as well as the monetary and finance sectors. Of the nine models that incorporate trade effects, inter-regional trade is represented endogenously in eight models and exogenously in one model, LEAP. Similarly, international trade is represented by more models endogenously (seven models) than exogenously (i.e., two models: LEAP and NATEM-TIMES). The Energy Policy Simulator is the only model, 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 two hybrid models, Energy Policy Simulator and gTech, incorporating these sectors.

4.5. Representation of Policies and Policy Interactions

All models except for CanESS and CityInSight are able to represent at least one policy type, with seven (i.e., EC-IAM, EC-PRO, EC-MSMR, Energy Policy Simulator, gTech, LEAP, and NATEM-TIMES) that are almost all hybrid or top-down models having the ability to represent all tested policy types (Table 5). The most represented policy types across all models are the carbon tax and prescriptive regulations, found in fifteen models (Figure 5). This is followed by subsidies (fourteen models), performance standards (thirteen models), cap-and-trade as well as hybrid carbon pricing (thirteen models), recycling carbon revenue (twelve models), government procurement (ten models), and research and development (seven models).

Table 5: Representation of policy types and policy interactions in energy-economy models. *

Model	**Policy Types**									**Policy Interactions**	
	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
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
GCAM	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	No	No	Explicitly	Explicitly
gTech	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Implicitly	Explicitly	Explicitly
LEAP	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly
MEDEE	Implicitly (e.g., through past data, proxies)	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
NATEM-TIMES	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly	Explicitly
REPAC	Explicitly	No	No	No	Explicitly	Explicitly	N/A	No	N/A	Explicitly	N/A

* "N/A" stands for "not available," and represents "I don't know" survey responses.

Most models that explicitly represent carbon pricing (i.e., carbon tax, cap-and-trade and a combination of thereof) are hybrid or top-down (Figure 5). Of the models that represent a carbon tax, all but one model (i.e., MEDEE) simulate this policy explicitly. Most models can also simulate the recycling of carbon revenue, with the exception of REPAC. A cap-and-trade policy is represented by fewer models than a carbon tax, with eleven models simulating it explicitly and two simulating this policy type implicitly (i.e., Energy Policy Simulator, MEDEE). The same models can simulate hybrid carbon pricing due to their ability to represent cap-and-trade policy mechanisms.

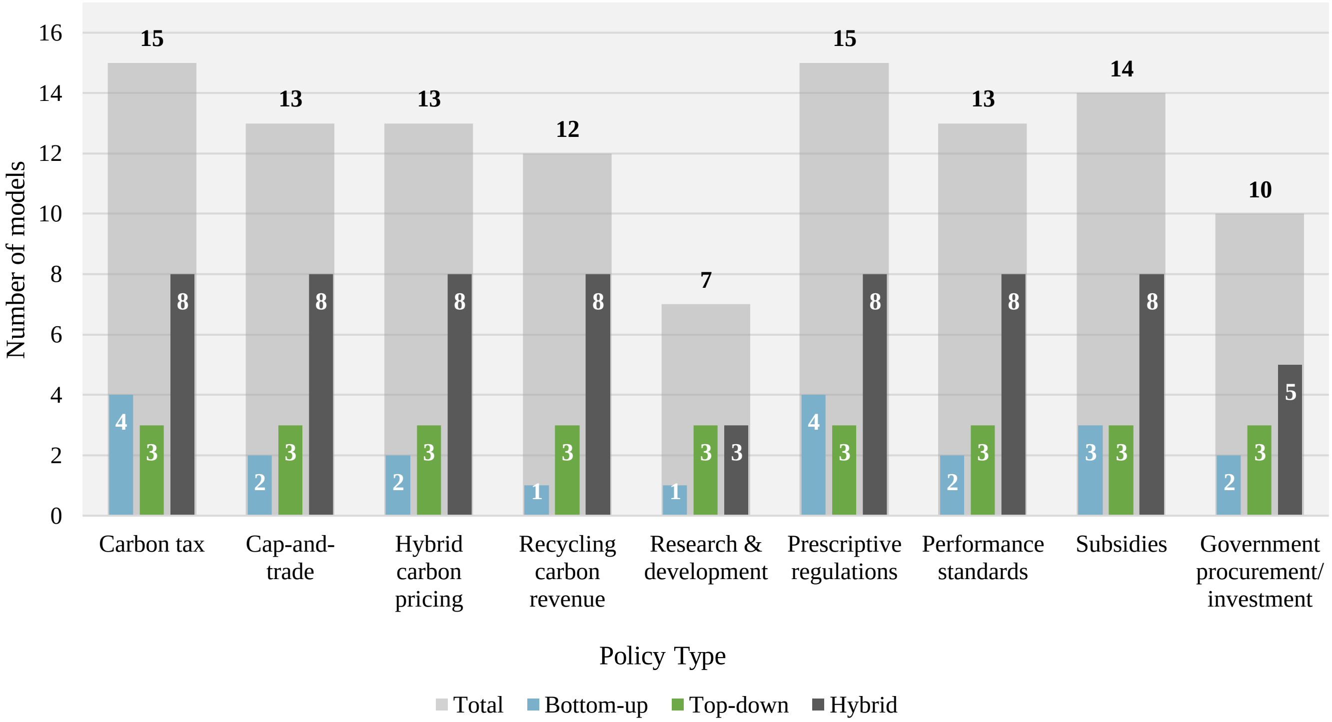

Figure 5: Models representing each policy type by model type.

The representation of prescriptive regulations mirrors the results of the carbon tax with fifteen models representing this policy type. MEDEE is the only model to represent prescriptive regulations implicitly. The majority of models represent subsidies (fourteen models), with only two (i.e., E3MC, MEDEE) of those models representing this policy type implicitly. Performance standard policies were also represented by most models (thirteen models), with twelve of those models representing this policy type explicitly. The models that do not represent either prescriptive regulations or performance standards are bottom-up models. Models vary in their representation of government procurement and investment with nine models representing it explicitly and one implicitly (i.e., Energy Policy Simulator). Investment in research and development is the least represented policy type, with only seven models representing it either explicitly or implicitly. Out of the models that include this policy type, five models represent research and development explicitly and two models represent it implicitly. The models that simulate investment in research and development explicitly (i.e., EC-IAM, EC-PRO, EC-MSMR, LEAP, NATEM-TIMES) are mostly top-down or hybrid models and three (i.e., EC-IAM, EC-PRO, EC-MSMR) are used by Canada's federal government.

Regardless of model type, the majority of models (i.e., fourteen models) explicitly consider the interactions between multiple climate policies. However, not all models that consider these interactions also avoid double-counting emissions that can be caused by multiple climate policies. The model E3MC was the only model found to implicitly represent both of these sub-characteristics.

4.6. Treatment of Uncertainty

Uncertainty is explored in all models with all models using a sensitivity analysis, seven using a Monte Carlo analysis, and four using other methods (Table 6). Just over half of the models 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 with fifteen and fourteen models incorporating these parameters, respectively. The model NATEM-TIMES was the only model to not explore either of these characteristics through uncertainty analysis. In addition, many models explore other 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).

Table 6: Treatment of uncertainty in energy-economy models.

Model	Treatment of uncertainty	
	Uncertainty methods	**Parameters explored through uncertainty**
CanESS	Sensitivity analysis	Economic growth, population/employment projections, EV penetration rate, retrofit rates and depths, teleworking rates, petroleum extraction volumes
CIMS	Sensitivity analysis, Monte Carlo analysis	Energy prices, economic growth, capital and intangible costs
CIMS-Urban	Sensitivity analysis, Monte Carlo analysis	Energy prices, economic growth, capital and intangible costs
CityInSight	Sensitivity analysis	Economic growth, population/employment projections, EV penetration rate, retrofit rates and depths, teleworking rates
E3MC	Sensitivity analysis, HYPERSENS	Energy prices, economic growth, technology improvement
EC-IAM	Sensitivity analysis, Monte Carlo analysis	Energy prices, economic growth, other
EC-PRO	Sensitivity analysis	Energy prices, economic growth, other
EC-MSMR	Sensitivity analysis	Energy prices, economic growth, other
ENERGY 2020	Sensitivity analysis, HYPERSENS	Energy prices, economic growth
Energy Policy Simulator	Sensitivity analysis, Monte Carlo analysis	Energy prices, economic growth
GCAM	Sensitivity analysis	Energy prices, economic growth, other
gTech	Sensitivity analysis, Monte Carlo analysis	Energy prices, economic growth, technology cost/availability of pre-commercial tech
LEAP	Sensitivity analysis, Monte Carlo analysis, Scenario analysis	Energy prices, economic growth, demographics, policy
MEDEE	Sensitivity analysis	Energy prices, economic growth
MESSAGE	Sensitivity analysis	Energy prices, economic growth
NATEM-TIMES	Sensitivity analysis, Monte Carlo analysis, Stochastic modelling	Evolution of technology costs, future availability of emerging tech
REPAC	Sensitivity analysis	Energy prices, tech availability, tech awareness

4.7. Spatial and Temporal Representations

Only a few models include high-resolution spatial and/or temporal representations, with more models including high-resolution temporal representation (i.e., six models) compared to high-resolution spatial representations (Table 7). 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 use a bottom-up approach.

Table 7: Spatial and temporal representations in energy-economy models.

Model	**High-resolution representations**	
	Spatial	**Temporal**
CanESS	No	Yes – hourly demand and generation dispatch module
CIMS	No	No
CIMS-Urban	Yes - linked to a GIS model to account for city policy impacts	No
CityInSight	Yes – city/region subdivided geographically into many zones	No – a planned feature
E3MC	No	No
EC-IAM	No	No
EC-PRO	No	No
EC-MSMR	No	No
ENERGY 2020	No	No
Energy Policy Simulator	No	No
GCAM	No	No
gTech	No	Yes - IESD allows for flexible seasonal/weekly /hourly time slices
LEAP	Yes – can model results to user-defined grid-squares	Yes – flexible seasonal/weekly/hourly time slices
MEDEE	No	Yes – passenger vehicle fleet characteristic on annual basis
MESSAGE	Yes – can represent water-related infrastructure in high resolution	Yes - possibility to represent high resolution temporal data
NATEM-TIMES	No	Yes – at the time slice level
REPAC	No	No

4.8. Data Transparency

In terms of data management, most models (i.e., eleven models) are not freely available for public use and do not have open-source code (eleven models) – these models are most often run by governments and private organizations (Table 8). However, models are more likely to be transparent in their use of open-source data inputs and have at least some of their modelling equations and assumptions publicly accessible. Of the six of models that are freely available for public use, two are from academic institutions (i.e., CIMS, CIMS-Urban) and four are from or developed by non-profit organizations (i.e., Energy Policy Simulator, GCAM, LEAP, MESSAGE). Only five models (CIMS, CIMS-Urban, GCAM, LEAP, MESSAGE) are both freely available and use open-source code (Figure 6). In contrast, thirteen models include at least some open-source data with certain inputs to the model being from publicly available sources such as Statistics Canada, Environment and Climate Change Canada, and Natural Resource Canada. Most models include a mixture of data from publicly available sources and confidential ones. More than half of models were found to have at least some of their modelling equations and assumptions documented in a publicly accessible manner. While some models do not have the equations and/or assumptions currently publicly available, several respondents indicated that they are in the process of or planning to open source this information (i.e., CityInSight, NATEM).

Table 8: Data transparency in energy-economy models.

Model	Data transparency				
	Freely available for public use	**Open-source code**	**Open-source data**	**Modelling equations publicly accessible**	**Modelling assumptions publicly accessible**
CanESS	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	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	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	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	No	No	Yes – some inputs from public sources	Yes – manuals on website	Yes – some published in reports and open data tables
EC-IAM	No	No	Yes - partially	No	No
EC-PRO	No	No	Yes - provincial/ territorial Supply-Use Tables	No	No
EC-MSMR	No	No	Yes – some inputs from public sources	No	No
ENERGY 2020	No	No	No	Yes – model documentation on website	Yes – some published in reports and open data tables
Energy Policy Simulator	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	Yes	Yes	Yes	Yes - poorly	Yes
gTech	No	No	Yes	No	Yes – depends on the client
LEAP	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	No	No	No	No	Yes – in some reports and working sessions
MESSAGE	Yes	Yes	Yes - most data from publicly available databases	Yes – model documentation on website	Yes – model documentation on website
NATEM-TIMES	No	Yes	Yes – some inputs from public sources	Yes – basic TIMES equations on ETSAP website	No – website under development
REPAC	No	No	No	No	Yes – open access journal article

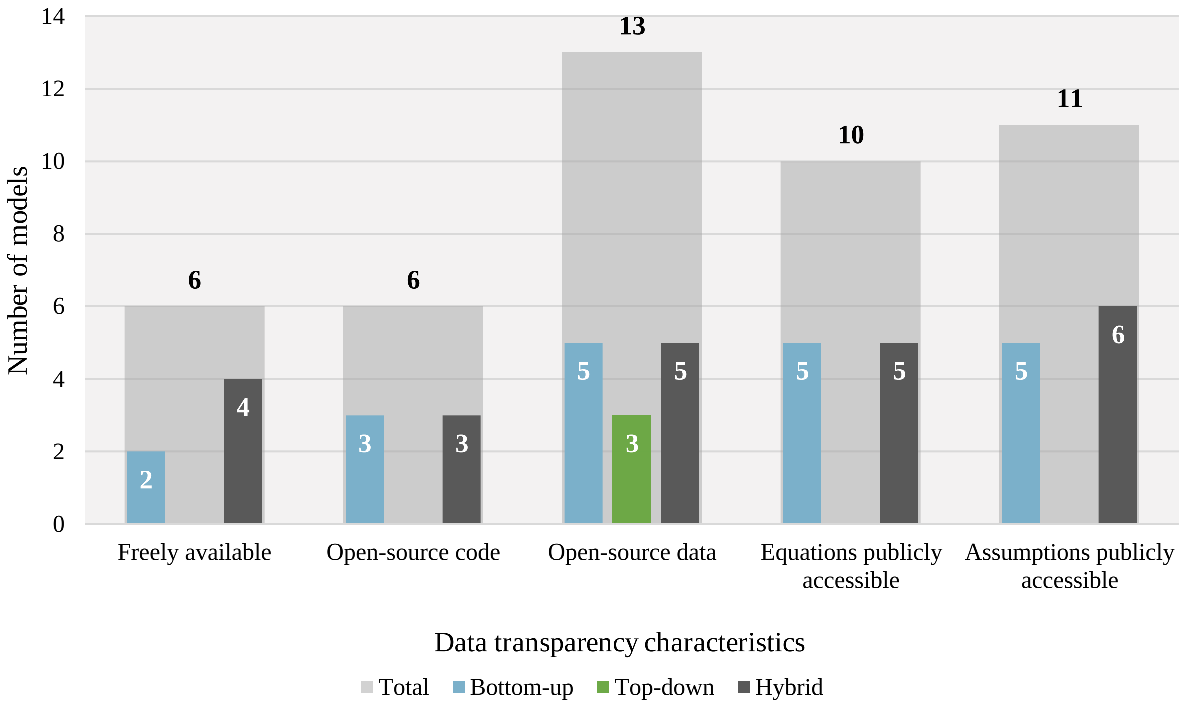

Figure 6: Models representing each data transparency characteristic by model type.

Related to data management, all respondents were asked to indicate how often each of the core model characteristics are updated (Table 9). For each characteristic, the most common update timeframe is every year, followed by every 2–5 years for all characteristics except for macroeconomic details. 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 9: Frequencies of model characteristics' updates.*

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 "I don't know" survey responses.

Chapter 5. Discussion and Conclusion

5.1. Discussion and Conclusion

The economic and GHG projections of energy-economy models vary based on the incorporation of methodological characteristics. The lack of consistent and publicly available information on modelling methodologies can make it challenging for policy-makers to choose a suitable model for their specific policy question. Using a web-based survey of energy-economy model developers and users (n=14) in Canada, 17 distinct models were identified as being used across the public, private, and non-profit sectors. The majority of these models (i.e., 8 models) use a hybrid approach (i.e., CIMS, CIMS-Urban, E3MC, ENERGY 2020, Energy Policy Simulator, GCAM, gTech, NATEM-TIMES), followed by models using a bottom-up approach (six models: i.e., CanESS, CityInSight, LEAP, MEDEE, MESSAGE, REPAC), and finally models with a top-down approach (three models: i.e., EC-PRO, EC-MSMR, EC-IAM). The models were compared against a framework of seven assessment characteristics that are considered important in the literature to the economic and GHG emission outcome projections of a climate policy. Specifically, these seventeen models were assessed against technology characteristics, micro- and macroeconomic characteristics, policy representations, treatment of uncertainty, high resolution spatial and temporal representations, and data transparency.

For the most part, models represent technology, micro-, and macro-economic characteristics according to the classic typology of bottom-up, top-down, and hybrid models (Hourcade et al., 2006, p. 3; Rivers & Jaccard, 2006, p. 2038). Top-down (e.g., EC-PRO, EC-MSMR) and hybrid (e.g., CIMS, NATEM-TIMES) models include representations of both micro- and macro-economic characteristics (Hourcade et al., 2006, pp. 2–3; Rivers & Jaccard, 2006, pp. 2039–2040). In contrast, bottom-up models (e.g., CanESS, MEDEE) explicitly represent technological characteristics, while excluding or poorly representing macroeconomic details (Jaccard, 2009, p. 312). However, this study suggests the emergence of several modelling evolutions that reflect the growing variety and complexity of climate policies in addition to the multitude of governmental priorities (Rogge et al., 2017, p. 3). Top-down models have evolved to include explicit representations that allow them to model technology-specific policies, while bottom-up models have started to include representations of market heterogeneity and behavioural preferences that produce more realistic projections.

This study expands upon the three characteristic classic model typology to include the four additional characteristics of policy representation, treatment of uncertainty, high-resolution spatial and temporal representations, and data transparency. The findings show that bottom-up models can simulate a carbon tax and prescriptive regulations, however they generally cannot represent macroeconomic policy mechanisms such as the recycling of carbon revenues. Model users do address uncertainty, though often only through a sensitivity analysis. Bottom-up models were more likely than other model types to include high-resolution spatial and/or temporal representations. In contrast, most top-down and hybrid models can represent the majority of the surveyed policy types due to a combination of explicit technology representation and incorporation of macroeconomic feedbacks (Jaccard & Dennis, 2006, p. 92). Similar to bottom-up model users, top-down model users generally address uncertainty through a sensitivity analysis, while hybrid model users almost always use other methods in combination with a sensitivity 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 type of organization that uses and/or develops the model.

5.2. Limitations and Contributions

There are several limitations to this analysis. Firstly, there are potential biases that might have impacted the survey responses. As many of the respondents are model developers, they have a vested interest in promoting their model(s) and might have responded to the survey questions in a way that reflects positively on their model and its assumptions. In addition, all respondents could have 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., when a respondent answered “yes” or “explicitly” but failed to explain how that characteristic was represented in the model). The nature and wording of prior questions or the survey consent form could establish an anchoring bias, where the previous information influences the respondent’s subsequent answers. Moreover, another source of bias might have come from 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 a question to expand their multiple-choice answer. As well, model users sometimes provided a conflicting response regarding the same model that was described by the model developers.

Secondly, this study used a convenience sampling method to approach ‘experts’ in the field of energy-economy models in Canada identified through the scoping review by Rhodes et al. (2021b). This methodology might have limited the sample size of the study, therefore potentially affecting the representation of the model landscape in Canada. Finally, the seven assessment characteristics were determined by a review of past literature that described their general importance on the economic and GHG emission impacts of climate policies (e.g., Hourcade et al. (2006), Lopion et al. (2018), Rhodes et al. (2021b), Savvidis et al. (2019)). This study did not conduct an inferential analysis to suggest that any of these characteristics are more or less significant to the quality of climate policy projections. Further research can use a standard set of assumptions to run a climate policy scenario with different models to assess the relative importance of each characteristic to the final modelling result.

This study offers an important contribution to the body of modelling literature and climate policy development, despite these limitations. The use of a survey instrument to collect primary ‘expert’ data from energy-economy model users and developers builds upon previous modelling reviews and explores the representation of four additional characteristics that impact the GHG emissions and economic impacts of climate policies. The comprehensive modelling inventory tables outline novel information that may not have been publicly accessible and allows for the comparison of energy-economy models to identify their key strengths and gaps. Researchers and policy-makers can refer to this model inventory when choosing a suitable model for their specific research and/or policy question. No model is ideal for every policy question, but rather certain models or model types are more well-suited to answer certain questions compared to others. All surveyed models explicitly represent technologies to some degree; therefore, they would be 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 representation 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, p. 7153).

Top-down and hybrid models (e.g., CIMS, EC-MSMR) that include several non-financial decision factors and macroeconomic feedbacks would be more well-suited to answer questions around large-scale policies (e.g., taxes) while accounting for human behaviour. Almost all models can represent carbon pricing, however hybrid and top-down models (e.g., gTech or EC-PRO) would be more suited to modelling this policy type due to their incorporation of macroeconomic feedbacks. All top-down and hybrid models (e.g., EC-IAM, GCAM, NATEM-TIMES) can represent a variety of prescriptive regulations, performance standards, and subsidies. Top-down and hybrid models are also more suited to the policy types that were not as adequately represented, such as research and development or government procurement and investment in low-carbon technologies. When developing climate policies at the municipal scale, using models that incorporate high-resolution spatial representations (e.g., CIMS-Urban, CityInSight) helps to account for the non-spatial uniformity of land-use policies. All models analyze uncertainty through a sensitivity analysis, however hybrid models (e.g., E3MC) would be more well-suited for a more detailed understanding of model uncertainty as many incorporate additional uncertainty analyses. While data transparency does not vary based on a certain model type, it is an important factor for researchers and policy-makers to consider in order to make their results more credible and politically acceptable.

Chapter 6. Recommendations and Implications for Policy

This study has some applied uses for researchers and policy-makers that use energy-economy models and/or develop policies based on their results. First, all models explicitly represent technologies and technological change. This explicit representation strengthens the evidence base of policies (Li et al., 2015, p. 292) and allows them to make better predictions of future energy demands (Herbst et al., 2012, p. 118). While all models represent technological change, the diverse methods of modelling technological change can produce different results. 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, p. 106).

Second, most models represent at least one microeconomic characteristic such as market heterogeneity and non-financial costs, which results in more realistic projections (Rivers & Jaccard, 2006, p. 2040). However, the upfront cost of technologies is the most frequent and often only microeconomic characteristic represented. The less frequent representation of other characteristics (e.g., lack of technology information, quality of technology service, and risk of technology failure) could mean that agent behaviour is not properly considered, which can lead to the underestimation of GHG mitigation costs (Murphy & Jaccard, 2011, p. 7147).

Third, the inclusion of macroeconomic characteristics in all top-down and hybrid models allows policy-makers to understand the economic costs and benefits of a policy (Mercure et al., 2019, p. 1031). This can include the effects on energy prices, economic development, employment, gross domestic product, trade, and sectoral output. These costs and benefits are important for policy-makers to consider, as they try to balance ethical and socio-economic impacts with effective emission reductions (Bhardwaj et al., 2020, p. 315; Kolstad et al., 2014, p. 235). Most models with macroeconomic feedbacks represent trade effects, however the infrequent representation of the financial and monetary sectors can decrease the accuracy of modelling projections, notably regarding the financing of investments in low-carbon technologies (Pollitt & Mercure, 2018, pp. 107–108).

Fourth, some of the most frequent and popular policies used by governments including performance standards, research and development, and government investment are not represented in all models. The strong political support for these underrepresented policies extends from their implicit abatement costs and higher chances of long-term implementation (Rhodes et al., 2017, p. 65). While all models consider interactions between policies, they do not all avoid double-counting emission reductions caused by multiple climate policies. To improve modelling projections, models should aim to represent a wide range of policy types and explore the extent to which different models double-count GHG reductions.

Fifth, the incorporation of uncertainty analyses allows policy-makers to compare a range of modelling projections to develop more credible, useful, and politically acceptable policies (Beugin & Jaccard, 2012, p. 90). Analyses to explore parametric uncertainty (e.g., a sensitivity analysis and/or Monte Carlo analysis) can test the robustness of the results and provide an understanding of the influence that individual parameters have on the results. Uncertainty analyses could be particularly useful to policy-makers when estimating the world's transition out of the COVID-19 pandemic.

Sixth, high-resolution spatial and/or temporal representations are rarely incorporated in the surveyed models. This lack of spatial representation can impact the effectiveness of local-scale climate policy development regarding land-use issues (Jaccard et al., 2019, p. 3), while the lack of temporal representation can affect projections that incorporate the demand for electricity and renewable energy (Lopion et al., 2018, p. 157; Pfenninger et al., 2014, p. 80). However, the inclusion of high-resolution spatial and/or temporal representations does increase the overall computation time (Lopion et al., 2018, p. 160).

Finally, the low levels of transparency in model data and assumptions/equations that are observed can impact the perceived credibility of the modelling results, which is particularly problematic when results are used to inform public-policy decisions. Without transparent and open access data, model results cannot be effectively replicated and the implications of a policy scenario may not be fully understood (Pfenninger et al., 2014, pp. 77–78). The movement to 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, p. 1852). A recent example of this in Canada is the Energy Modelling Initiative, which aims to facilitate communication between modellers, governments, and other model users to produce evidence-based policy decisions (Beaumier et al., 2020; Energy Modelling Initiative, n.d.).

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Appendix A: Consent Form

A Review of Energy-Economy Models in Canada

Introduction and Participant Consent

You are invited to participate in a survey study entitled “A Review of Energy-Economy Models in Canada” that is being conducted by Dr. Katya Rhodes. The purpose of this research project is to identify the key improvements, critiques and best practices of energy-economy models in the academic, public, private, and not-for-profit sectors in Canada over the past decade. The results will help facilitate the use of more accurate energy-economy modelling practices to improve the design of Canada’s climate policies.

Researchers

This study is conducted by Dr. Katya Rhodes, Assistant Professor in the School of Public Administration at the University of Victoria, British Columbia. Kira Craig is a graduate research assistant implementing and analyzing survey results. You may also contact the University of Victoria to verify the ethical approval of this study and to ask other questions.

Participant Involvement

If you agree to participate, completing the survey should take approximately 15-20 minutes of your time. The survey will be distributed to energy-economy modellers and policy-makers in public, private, and non-profit sectors in Canada. If there are any questions you do not feel comfortable answering, please feel free to choose “I don’t know/prefer to not answer/other". You are able to change or remove any of your responses prior to our analysis of survey results.

Risks

There are possible but very limited social and economic risks to you by participating in this research. Social risks may include potential loss of privacy, as there are a limited number of individuals working on energy-economy models in your type of organization, which means it may be possible for those who know the field well to guess your identity. We will minimize the social risks to you by protecting your anonymity as much as possible. Economic risks may include potential loss of paid work time associated with completing the survey during work hours. You can minimize these risks by choosing when and how you complete the survey, including outside of work hours.

Benefits

You will have the opportunity to provide your insights, knowledge, and experiences with energy-economy models currently being used in Canada. This research has the potential to help policy-makers in Canada better assess their progress to climate targets and implement effective climate policy through more accurate modelling and evaluation frameworks. We will develop a report describing all stages and results of the study, including the inventory of models, latest modelling improvements, knowledge/data strengths and gaps, opportunities for future research, and best practices for modelling climate policy impacts.

Voluntary Participation

Your participation in this research is completely voluntary. If you decide to participate, you may withdraw at any time without consequence or explanation.

Anonymity

Your name will not be disclosed to anyone at any time. However, due to the nature of this research it is impossible to guarantee your anonymity. Anonymity may be compromised because we will be naming your type of organization in our report and a potential student thesis, and the number of the individuals within it who fit my selection criteria are small.

Confidentiality

The confidentiality of your data will be protected. Survey responses will not identify you by name, and electronic copies will be stored on a password-protected project laptop while data is being collected. The laptop will be kept as secure as possible throughout the research. When the research is complete, the interviews will be burned onto CDs and stored in a locked filing cabinet in Dr. Rhodes' office at the University of Victoria until May 2030. The survey results will then be removed from the project laptop.

Dissemination of Results

It is anticipated that the results of this study can be shared with others in the following ways: the created inventory will be shared in an open-access data repository (Mendeley Data), published articles, theses, books, presentations at scholarly meetings and conferences, and class workshops. Potential theses produced with this research will be available online through the University of Victoria's D-space.

Use of Data

Survey responses will be stored in an electronic form. In the end of the survey you will have an opportunity to review/ edit responses before they are being used as data by researchers. Data from this study may be used by the investigators for future scholarly research building on/expanding on the current project. It will not be used for any other purpose whatsoever. Any future use of data obtained through the survey will be bound by the terms outlined in this form (dissemination, confidentiality, disposal, anonymity).

Appendix B: Survey Questionnaire

A Review of Energy-Economy Models in Canada

1. Selecting the "yes" button below indicates that you understand the above conditions of participation in this study and that you have had the opportunity to have your questions answered by the researchers.
    - Yes (I consent to the aforementioned terms of the survey)
    - No (I do not consent to the aforementioned terms of the survey)

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

For each model identified the following questions will be asked:

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)?

- Yes
- No [if selected, the survey will skip to question 4.1]
- 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)?

- Yes
- No
- 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?

- 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 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?

  - Yes, by disaggregating technologies (i.e., explicitly representing the upfront costs of each of the included technologies)
  - Yes, by aggregating production functions (i.e., representing upfront costs by combining related technologies that produce the same output)
  - Yes, other
  - No
  - 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?

  - Yes
  - No
  - 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?

  - 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 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.

- Yes
- Partially, via own-price elasticities
- No
- 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)

- Yes
- No
- 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?

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

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

- Endogenously
- Exogenously
- Other
- Inter-regional trade is not represented
- 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?

- Endogenously
- Exogenously
- Other
- International trade is not represented
- 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?

- Yes
- No
- 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

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

[QUESTIONS 2.1 TO 8 WILL BE REPEATED FOR EACH MODEL PARTICIPANTS IDENTIFY IN QUESTION 1.3]

THANK YOU FOR THE PARTICIPATION!

Please feel free to contact Dr. Katya Rhodes or Kira Craig should you wish to expand or edit the responses at a later date and/or if you have questions.