Energy Reports 9 (2023) 4380–4400

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Modeling the transition to a zero emission energy system: A cross-sectoral review of building, transportation, and electricity system models in Canada

M. McPherson [a,*], E. Rhodes [b], L. Stanislaw [a], R. Arjmand [a], M. Saffari [a], R. Xu [a], C. Hoicka [c], M. Esfahlani [d]

[a] Department of Civil Engineering and the Institute for Integrated Energy Systems at the University of Victoria, Canada
[b] School of Public Administration and the Institute for Integrated Energy Systems at the University of Victoria, Canada
[c] Department of Geography, Department of Civil Engineering at the University of Victoria, Canada
[d] National Research Council Canada, Canada

ARTICLE INFO

Article history:
Received 11 August 2022
Received in revised form 5 February 2023
Accepted 27 February 2023
Available online 24 March 2023

Keywords:
Energy systems integration
Energy system modeling
Electrification
Decarbonization pathways

ABSTRACT

Models have long been effective tools in the planning and policy making of energy systems, but low-carbon electrification—decarbonizing generation supply while expanding electrical demand—poses new challenges for the modeling community. At its core, electrification relies on integrating insights that span the supply *and* demand side of power systems, resolving operational characteristics *and* long-term climate change, and the integration of previously independent engineered systems. However, our modeling landscape consists of a suite of models that focus on distinct sectors (power, buildings, transport) and spatial–temporal scales (municipal, provincial, federal). This paper probes whether the existing suite of energy system models, which span sectors, disciplines, and jurisdictions, is up to the task of charting net-zero pathways, specifically in the Canadian context. To do so, we analyze an inventory of energy system models that are being used in practice using a recently assembled model database. Next, we supplement our analysis with a web-based search and literature review. For each model category, we describe the key modeling approaches, strengths and weaknesses, and typical ways and areas in which these models are applied. We find that by focusing on a specific scale and sector, these models by their very definition, omit out-of-scope interactions leaving critical information gaps. Many of the most imperative areas for future research straddle multiple sectors or multiple scales—electric vehicle charging, carbon policy coordination, regional electricity trading, to name a few. Future research should focus on identifying ways in which different models could be used together to produce policy-related conclusions that are as detailed but more holistic than conclusions that can be gleaned from an individual model.

1. Introduction

Energy system models are effective tools in the planning and policy making that is needed to chart a pathway to net-zero and reach the Paris Agreement pledges outlined in each country's nationally determined contributions (Environment and Climate Change Canada, 2022). Sector specific decarbonization strategies have been explored extensively in energy systems models: building system models quantify emissions reductions through energy efficiency and retrofit measures; transportation models quantify emissions reductions through mode shifting or (EV) technology adoption; power system models explore renewable energy integration and fossil phase outs. However, low-carbon electrification – simultaneously decarbonizing and expanding generation capacity – poses new challenges for modelers and their frameworks. Namely, electrification relies on integrating insights across several dimensions: the supply *and* demand sides of power systems, spatially and temporally resolved operations *and* long-term climate change, and the suite of previously independent engineered systems. For example, supply side questions such as *what is the optimal pathway for expanding low-carbon generation and transmission to meet increasing demand from previously fossil-dependent sectors* are inherently linked to demand side questions such as *how will electrification impact load profiles* and *what are the opportunities for demand side management to provide much needed grid flexibility?*

---

[*] Correspondence to: Faculty of Engineering, Department of Civil Engineering, ECS Building Room 304, PO Box 1700, STN CSC, Victoria, BC V8W 2Y2, Canada.
E-mail address: mmcpherson@uvic.ca (M. McPherson).

https://doi.org/10.1016/j.egyr.2023.02.090

Existing model frameworks are not necessarily context specific, however, the availability of data, resources and modeling skills in a particular context are the result of the unique co-evolution of energy systems and institutions of that jurisdiction. Furthermore, the sectors that require decarbonization to reach nationally determined contributions vary by country, as do the cross-sector interactions that models need to examine. Therefore, modeling suites are worth examining in a particular national context as they depend on their own particular sectors of focus in decarbonization pathways.

Canada provides a productive context in which to examine these questions. In its nationally determined contribution pledge to the UNFCCC, Canada has committed to reducing its greenhouse gas (GHG) emissions by 40–45% below 2005 levels by 2030 and to net-zero by 2050 (Environment and Climate Change Canada, 2021). This requires significant changes to Canada's energy infrastructure (Riehl and Peters, 2021). Low-carbon electrification – using low or zero carbon electricity to power traditionally fossil-intensive activities – is considered a key part of Canada's strategy. Currently, Canada's electricity supply is derived from hydro sources (Canadian Hydropower Association, 2008), eighty percent from non-emitting sources (Natural Resources Canada, 2020), and Canada has enough renewable energy resources based in current technology to fully decarbonize (Barrington-Leigh and Ouliaris, 2017); Canada is well positioned for low-carbon electrification. However, there is a gap: the transportation and buildings sectors are heavily dependent on fossil fuels, accounting for 38% of Canada's total emissions (Government of Canada, 2022), making decarbonization in these sectors a priority.

Energy-economy models tend to focus on the implications of policy changes on economic and GHG outcomes and/or technology adoption. For example, an analysis that employs an energy-economy model may probe which policy instruments best incentivize the uptake of electric vehicles, and/or what the implication of a particular policy has on economic growth and jobs. Another category of models that are often used for climate policy assessments and thus overlap with or extend energy-economy models are integrated assessment models. They link the dynamics of a jurisdiction's energy economy with biospheric and atmospheric systems. Rhodes et al. (2022) have detailed the strengths and weaknesses of Canada's suite of energy-economy and some integrated assessment models.

Yet, low-carbon electrification of the transportation and building sectors will require design and operation of expanded zero-emission generation, distribution, and transmission infrastructure—something that energy-economy models are not well-suited for. This type of electrification introduces a new category of policy and planning questions. Energy-economy models tell us the kinds of policies that we need to effectively reduce emissions (Rhodes et al., 2022; Mundaca et al., 2010; Cai et al., 2015); due to the complexities of power system operation and spatial and temporal dependent characteristics of energy demand and renewable resource potential, engineers need to develop the specific plans of what energy infrastructure to build and where, in order to operationalize the zero-carbon system.

Electrification of the building and transportation sectors requires a multi-sector, multi-spatial and multi-temporal perspective that Canada's existing modeling suite is ill-equipped to address. In general, integrated modeling platforms that can usefully address the integration of energy systems do not exist in most jurisdictions. Rather, there are discrete models for power *or* transport *or* buildings; planning *or* operations; planning/operations of supply *or* demand side. Therefore, this study is relevant to model assessments in other jurisdictions. Although not clearly defined in the literature, for the purposes of this study, operational models are distinct from energy-economy or integrated assessment models in that operational models represent the physical system: how much power will a wind facility produce; how electrons move from one location to another; which generators need to turn on (and off) and when in order for supply to match demand; how people travel around a city (and where will they charge their EVs); how frequently will the heat pump cycle on (and draw power) to keep a building in location Y at setpoint X. That is, energy flows (electrons, heat, renewable energy resources) with spatial granularity (nodes on a grid, a building in a specific weather climate, wind speed at a location, streets in a city) and temporal granularity (at hour X in year Y). For these reasons, this review seeks to complement the work of Rhodes et al. (2022) by detailing the suite of Canada's operational electricity models that answer distinct questions from energy-economy models.

Sector-specific models, such as those detailing power, transport and buildings, typically contain operational details, but (by definition) fail to provide insights that span multiple sectors or the relationship between the energy sector and the economy. Therefore, the challenge of electrification is that it is bringing together previously distinct sectors and energy carriers—buildings in Canada have been predominantly heated with natural gas, vehicles predominantly fueled by diesel and oil, and the power sector that, until recently, predominantly relied on thermal energy and hydropower. As buildings and transport electrify, and as we add in more variable renewable energy (VRE), all of which are temporally and spatially dynamic, there is a need to understand how these sectors of power, transport and buildings – and the operational models that represent them – interact.

While spatially scoped models appear to have the possibility of showing interactions between some of these sectors, they typically neglect to represent interactions between physical or political scales. For example, a tailored city-specific energy model may consider the interactions between the building, transportation, and electricity sectors, but neglect bulk power system scale capacity requirements. A transportation model typically represents a network at the city scale but omits imports/exports with the bulk power system. A building system model representing heating load demand response often neglects price implications in power markets. A provincial scale power system model may explore the requirements for flexibility resources to integrate variable renewable energy resources, but neglect operation of the transport system.

These issues in Canada's suite of models are of such importance that the Energy Modelling Hub (EMH) was created, funded by Natural Resources Canada with the mandate to convene modelers and decision makers across Canada to facilitate evidence-based policy making.

As we chart electrification pathways, the following question emerges: *is our current suite of energy modeling tools sufficient to chart low-carbon electrification and decarbonization pathways?* The analysis that follows describes the capabilities and gaps in our current suite of energy system models. More specifically, we address the question: *what improvements are needed to facilitate the development of holistic, multi-sector insights needed to represent electrification?*

To address these questions, this paper reviews *both* supply *and* demand models that are necessary for electrification analyses, specifically to identify how each category might contribute to creating a more holistic perspective of decarbonization pathways. By doing so, this paper contributes to a growing body of model review analyses that adopt a problem orientation. The model review presented in this paper is framed around the question of electrification, with applications that pertain specifically to the Canadian context. However, the approach adopted here could be applied to other jurisdictions as well. Charting low-carbon electrification requires the development of a holistic perspective that spans previously disparate sectors and scales. As such, this review spans the model landscape supply *and* demand sectors as well as detailed sector-specific models *and* long-term, pan-sector models. Economy-wide models do not offer an operational representation of the different sectors, and are excluded for this reason.

At the broadest level, authors such as van Beeck (1999) and Timmerman et al. (2014) set out to classify energy models. Other multi-model reviews orient around a specific research question, such as the framing that Connolly et al. (2010b), Ringkjøb et al. (2018) and Emmanuel et al. (2020) adopted focusing on the representation of variable renewable energy integration in energy planning models. Others have performed deep dives into specific model categories, such as those that focus on electricity markets (Ventosa et al., 2005) or a city scale analyses (Sola et al., 2018). Still others such as Pfenninger et al. (2014) and Huppmann et al. (2019) have reviewed the model landscape to identify areas that merit further software development work. Trutnevyte et al. (2014) and Hall and Buckley (2016) adopt a country-specific lens, focusing on energy system models application to energy system decarbonization specifically in the context of the UK. This paper contributes to this growing body of model review analyses that adopt a problem orientation to model classification. However, the key contribution of this paper is that we review the model landscape from a different (and increasingly important) perspective: energy systems integration.

2. Methods

In order to answer the research question, the suite of models being used in practice in Canada on both the supply and demand side was assessed by conducting a Canada-wide survey of energy model users and developers as part of the Canadian Energy Modelling Initiative (EMI) (now called the Energy Modelling Hub or EMH) supplemented with a web search for any models being used in Canada that may have been missed. EMH is a program coordinated by academic modelers and Natural Resources Canada (NRCan). The EMH convenes energy modeling stakeholders from public, private, and not-for-profit sectors to support political climate policy-making (Energy Modelling Initiative, 2021). Results from our survey populated an open-access model database for the Canadian energy modeling community (Energy Modelling Initiative, 2021).

To this end, this paper builds on a combination of research methods, namely an expert survey consisting of a structured questionnaire and a subsequent literature review to follow the leads and complement the scope of the findings of the survey. This combination is referred to in methodological literature as a facilitative combination of methods, where methods are used sequentially to extend the scope of a study and ensure that potential gaps of one method have been covered by another method. Such a combination of methods also offers the benefits of triangulation, in that results can be cross checked for consistency thereby offering enhanced confidence in the research findings (Neil, 2012). Expert surveys and direct communication have gained popularity in the study of energy models due to the ability to identify model nuances in a consistent manner otherwise not available in published literature. Chang et al.'s (2021) recent study of trends in approaches for modeling the energy transition reinforces the benefits of using surveys and other direct inputs of model developers and users. The authors argue that expert surveys help overcome the shortcomings of literature review methods, such as overlooking important aspects of models and their applications, misinterpreting model descriptions due to the lack of common model assessment language, and identifying novel models not covered in published literature. Surveys maintain "open lines of dialogue" and can be particularly useful to describe models that are used outside of academia to inform policy-making. Connolly et al. (2010b) have used a survey of model developers to identify and collect information on energy tools that could simulate renewable energy systems. The survey included iteratively tailored questions to obtain the most relevant data for the purpose of the study, providing common language for classifying models (Connolly et al., 2010a). A more recent study by Müller et al. (2018) collects primary data from a survey and an in-person meeting of stakeholders, in addition to literature review, to present and categorize models used in energy system analysis, improving the accuracy of model assessments and enhancing outreach to policy-makers and practitioners. Similarly, Ridha et al. (2020) administered an expert survey to develop a 'fact-based' large-scale review of energy system models in terms of their complexity across temporal, special, mathematical, and modeling dimensions.

2.1. Survey

Survey data were collected through the SurveyMonkey platform in 2020. Survey design was informed by a review of international literature (i.e., on model types, applications, scales, key inputs and outputs) (Chang et al., 2021; Ridha et al., 2020; Rhodes et al., 2021a). Questionnaire drafts were circulated for multiple rounds of feedback from the EMH advisory committee resulting in the final 16 open-ended and multiple choice questions. This committee consisted of 12 energy modeling academics and public service practitioners. The consultation process was essential to ensure the classification of energy models included the appropriate level detail as per the past studies that guided survey design (Chang et al., 2021; Rhodes et al., 2021a).

The questionnaire consisted of three sections:

- "basic information" asked participants to indicate their name, affiliations, employment sector, and relationship to modeling (e.g., model developer or user).
- "model(s) information" included questions about the model name, covered sectors, original developer(s), model type, model applications, scales, inputs and outputs—this section allowed for entries for up to three models, with the option of requesting follow-up communication by email for additional models.
- "model(s) usage information" included questions about specific policy assessment applications for up to three models.

The sampling approach for this survey resembles what methodological literature refers to as purposive sampling (Sovacool et al., 2018) combined with a snowball/network sampling approach (Clive, 2012). In the context of energy modeling studies, purposive sampling has been argued to enable access to a "variety of experiences to fit the purposes of the study" [20]; snowball sampling on the other hand, utilizes referrals and recommendations to access 'hidden' populations such as experts in professional networks that may not have their works published in academic venues (Clive, 2012). Initially, the survey invitation was sent to more than 500 contacts including several institutional mailing lists for events concerning energy modeling. The list was complemented by the contributions of staff, executive and advisory members of the EMH, amounting to a total of 773 unique contacts which received the survey invitation by January 2020. EMH staff and invited contacts expressed their efforts in "snowballing" the invitation and ensuring it has been disseminated to relevant participants. Before processing the data, several follow-up attempts were launched to clarify ambiguous and incomplete contributions of survey participants ensuring the validity and completeness of entries.

This resulted in 175 responses in March 2020. 153 responses were complete, identifying 128 unique models, 121 contacts who identify as modelers, 127 who identify as model users, and 11 who identify with multiple roles.

2.2. Model categorization

To ensure data consistency across the EMH database and the literature search, we categorized models based on their overarching goals and methodologies. From an electrification lens, we categorized our review of the EMH database according to electricity supply- and demand- side models, each with subcategories within.

2.2.1. Supply-side model categorization

On the electricity supply side, two perspectives of the electricity infrastructure are considered: capacity-expansion models take a long term design perspective to explore changes in capacity configuration, and production cost models take an operational perspective to explore the hour-by-hour dispatch of the power system to meet demand. The capacity expansion problem determines how investment can be used to expand electric generation and transmission capacity as a result of investments, policies, energy needs, and technological and economic conditions (Dagoumas and Koltsaklis, 2019; Gacitua et al., 2018; Koltsaklis and Dagoumas, 2018). Production-cost models take a short-term operational perspective to ensure power system reliability, particularly with increasing shares of variable and uncertain generation (Delucchi and Jacobson, 2011). While capacity expansion identifies how changes in energy infrastructure can be used to accomplish goals such as decarbonization and the expansion of low- or zero-emission generation, unit commitment simulates the operation of an electricity system's parts, allowing assessment of the system's day-to-day performance and associated emissions.

2.2.2. Demand-side model categorization

On the demand side, this paper focuses on the transportation and building sectors, because these sectors both currently have high emissions, but could reduce these emissions dramatically if carbon-intensive fuels are replaced with low-carbon electricity. Models describing either travel patterns or charging patterns in the transport sector are relevant to low-carbon electrification of the transportation sector, and thus were included in our review. However, models of commercial long-distance transportation were excluded for two reasons: (1) electrification of commercial long-distance vehicles is expected to lag passenger vehicles due to the longer distances and larger payloads of freight transport (Bloomberg, 2020); and (2) commercial long-distance transportation models are typically simpler than models of passenger transport, causing them to lack sufficient detail for exploring the effects of electrification (Hensher and Figliozzi, 2007). Similarly, buildings are electrified when their operational components (such as heating, ventilation, and air conditioning systems) are electrified, and they affect the electricity system by contributing to a load curve that is aggregated at the substation level. Therefore, this review focuses exclusively on models that represent multiple buildings in a single analysis and as the sum of their component processes, as opposed to models of individual buildings (e.g., United States Department of Energy, 2020), or models that correlate building energy use to socioeconomic factors (e.g., Hoicka and Das, 2020; Bernard et al., 2011).

For the purposes of our study, we selected 12 models from the EMH database that pertain to decarbonization through electrification across supply and demand sectors: the electricity sector (i.e., 3 production cost and 6 capacity expansion models), transportation (i.e., 2 models), and buildings (1 model), as long as the models were developed and/or applied in Canada.

2.3. Scoping review search

Following the survey-based selection of models from the EMH database, we conducted an additional search in Google Scholar to ensure that our list of energy models in Canada is complete. Similar to the EMH model inclusion criteria, we considered models that were developed and/or applied in Canada (i.e., the overarching inclusion criterion for all search strings below). The search was conducted in March 2020–July 2021 and included literature published up to July 2021 without restrictions for start publication dates.

- For production cost models, we used this search string: "dispatch model" OR "operation model" OR "production cost model" OR "unit commitment", OR "OPF model", AND "Canada electricity system", AND "VREs integration", AND "decarbonization."
- To identify capacity expansion models, we used the following search string: "electricity system planning" OR "electricity system transition" OR "electricity system model" OR "electricity system decarbonization" OR "electricity system generation mix" OR "future of Canada's electricity system."
- Transportation models were identified using this search string: ("transportation modelling", OR "transportation energy models", OR "electric vehicle models", OR "smart charging") AND ("Names of Canadian large cities" OR "Names of Canadian provinces and territories").
- For building energy models, we identified relevant literature using the following search string: "building energy modeling" OR "urban building energy modeling" OR "community building energy modeling" OR "multiple building energy modeling" OR "building energy consumption modeling" OR "city building energy modeling."

After applying the same inclusion criteria as in the EMH model selection process, these Google Scholar searches helped identify an additional 3 production-cost models, 2 capacity-expansion models, 6 transportation models, and 11 building models, resulting in a total of 34 models reviewed in this study. The models are listed in Tables 2–5.

2.4. Model assessment

After selecting a total of 34 models from the EMH dataset and additional literature, each model was assessed according to the criteria in Table 1, based on information contained in the survey results as well as the subsequent literature review.

Once the models were reviewed for these criteria, the identified suite of models from each model type (capacity expansion models, production cost models, transportation or building) were analyzed as a whole, and the following questions were asked of the suite:

Usage

- In what ways was each modeling approach relevant in identifying possible pathways to, or results of low-carbon electrification?
- What were the main electrification and/or decarbonization takeaways from the results of the reviewed models?
- What policies or research questions were most frequently explored by the reviewed models?
- How could these models better support low-carbon electrification planning?

Table 1
Specific model description and review criteria.

Model and citation	
Subcategory OR spatial scale	Electricity system Electricity Integrated energy Travel/Operational (activity based or four step) Charging Deterministic Probabilistic OR Provincial City/Municipality Isolated microgrid
Model goal	Least cost pathways Long term effects Pathways produced by various policies or design Parameters
Results	
Decarbonization technologies and strategies modeled	
Area of application	Specific location and scale of application, e.g., National Inter-provincial Intra-Provincial City or municipality Neighborhood Buildings

Limitations

- What were some important limitations or challenges associated with each model type?

Multi-Sector application

Finally, similarities and potential areas of information flow between the four different model types were identified, and suggestions were made for how future studies could answer electrification-related questions more accurately and in greater detail by combining models from different sectors.

3. Results

3.1. Power system (supply side) models

3.1.1. Capacity expansion models

Capacity expansion models (CEM) address the capacity expansion problem by simulating investment in generation and transmission capacity given future economic, technological, policy, and energy demand scenarios (Boyd, 2016). The reviewed CEMs that have been developed or applied in the Canadian context can be categorized by their sectoral scope: some focus exclusively on the power system, while others represent the energy system as a whole. Given the exclusion of energy-economy models from this study, in instances where this distinction is unclear, we defer to the broadest model capability. For example, the (Electric Power Research Institute, 2021) Regional Economy, Greenhouse Gas, and Energy (REGEN) model includes a detailed end use and power sector modules (which optimizes capacity expansion and dispatch), but also includes an energy-economy formulation and thus is considered beyond the scope of this analysis. Six electricity-only CEMs have been used to identify least-cost pathways towards decarbonization at different geographical scopes: ReEDS represents the US and Canada (Brown et al., 2019), SWITCH represents the Western Interconnection (Alberta, British Columbia, and several US states) (Nelson et al., 2012), CREST is pan-Canadian (Dolter and Rivers, 2018), COPPER models Canada at the national scale (Arjmand and McPherson, 2021), CERI study No. 174 studies Canada's western provinces (Doluweera et al., 2018), and IESD considers Canada as a whole (Navius Research Inc., 2020). The three energy-CEM developed or applied in Canada employ adaptable frameworks that can be tailored to represent various aspects of supply and demand, different policy scenarios, and alternative technologies suites (variable renewable energy (VRE), storage, immature technologies), depending on the user's intended purpose: OSeMOSYS is open-source and clearly documented enabling broad accessibility (Howells et al., 2011); NATEM-Canada has been used to investigate various future scenarios both nationally and in Quebec (Loulou et al., 2016); CanESS is a commercially model used by a consulting company on behalf of various government agencies (whatIF? Technologies, 2016); and the electricity model IESD can be linked with an energy-economy modeling tool developed by the same company (i.e., gTech). An overview of the reviewed models is shown in Table 2. Typical model objectives, considerations, inputs and outputs are listed in Fig. 2.

3.1.2. Usage

The Canadian CEMs were used for five main reasons:

- to plan for the future of energy system and electricity system,
- to assess impact of policy on the future of the energy system,
- to develop strategies for emission reductions in the future,
- to explore how uncertainties might impact the energy system, and
- to predict economic trends, such as how energy prices might change in the future.

Among these, some key considerations addressed by the models were the long-term implications of increasing both variable and non-variable renewable capacity, how emissions could be reduced through increased electrification, and how system flexibility can be maintained through a combination of battery storage, hydro storage, and transmission resources. The main investigated policy that almost all models consider was carbon pricing, but other modeled policies include renewable portfolio standards (RPS) (ReEDS, COPPER, CERI study No. 174, IESD, SWITCH, OSeMOSYS, Energy 2020) and coal phase-out (ReEDS, COPPER, CERI study No. 174, IESD, NATEM-Canada, OSeMOSYS, Energy 2020).

To summarize, Fig. 1 shows the most common CEM goals and most important model considerations.

The typical CEM inputs and outputs are displayed in Fig. 2.

Table 2
CEM models developed or applied in Canada, categorized according to scope (electricity only versus pan-energy). The purpose of each model is presented along with a description of policy-related results obtained using the model, the geographical area for which those results are obtained, and a list of technologies and strategies relevant to low-carbon electrification that are represented in the model.

Model goal	Sub- category	Results	Decarbonization technologies and strategies modeled	Area of Application	Model and citation
Identify least-cost pathways to decarbonize Canada's electricity sector	Electricity system	New inter-provincial transmission and a substantial expansion of wind power in SK and AB would allow Canada to reduce electricity sector emissions at the lowest cost; hydropower and inter-provincial trade provide balancing services that allow for greater integration of variable wind power; prices of $80/tonne CO2e (or greater) render the majority of Canada's coal-fired plants uneconomic.	Expansion of wind and solar generation; expansion of transmission and storage capabilities; use of hydro for storage/balancing; carbon pricing	Canada (nationally)	CREST (Dolter and Rivers, 2018)
"analyze least-cost generation, storage, and transmission capacity expansion for western North America under various policy and cost scenarios"	Electricity	Current renewable profile standards are not aggressive enough to meet climate targets; the transition to other sources is possible with stronger carbon policies, but is very expensive; costs can be reduced by reinvesting carbon tax revenues in the power sector.	Renewable portfolio standards define (including both variable and non-variable renewables); generation, storage, and transmission capacity expansion; carbon pricing	Western Interconnection (includes Alberta and British Columbia)	SWITCH (Nelson et al., 2012)
Investigate long-term effects of a wide range of technology and policy changes on any or all parts of the electric power sector	Electricity	Wind expansion in Canada is sensitive to economic conditions; higher natural gas prices lead to increased renewable generation capacity; local resource availability drives market conditions; more-detailed modeling of hydro would improve model results; Canada and the US could benefit from shared environmental and infrastructure goals; cross-border transmission increases under most favorable by what metric scenario.	Changing natural gas prices; renewable portfolio standards; expansion of hydro; transmission expansion including cross-border (US-Canada) expansion	North America	ReEDS (Avraam et al., 2021; Beiter et al., 2017; Brown et al., 2019; Siddiqui et al., 2020; Zinaman et al., 2015)
Providing insight into the future of Canada's electricity system under different carbon management policies	Electricity	Canada's recently announced carbon management policies (HEHE) are enough to meet 2030 commitments; to achieve the zero-emission target by 2050, Canada needs to increase the carbon tax after 2030; supplementary policies that target natural gas-powered power plants are required to achieve set targets.	Carbon pricing strategies; renewable portfolio standard; coal phase-out; natural gas power plants performance standard; small modular reactors, carbon capture and storage; storage; hydro renewable and greenfield development	Canada (nationally)	COPPER (Arjmand and McPherson, 2021)
Analyze emission and economic impact of the electricity system transition	Electricity	Under different scenarios, hydropower (in British Columbia and Manitoba) and natural gas-fired technologies (in Alberta and Saskatchewan) will be the primary source of electricity generation. Under the constrained emission scenario, a large renewable capacity is integrated into the Alberta and Saskatchewan generation mix.	Carbon pricing; carbon cap; renewable electricity targets; coal phase-out; transmission expansion	Canada's western provinces: British Columbia, Alberta, Saskatchewan, and Manitoba	CERI study No. 174 (Doluweera et al., 2018)

(*continued on next page*)

3.1.3. *Limitations*

CEMs represent large spatial and temporal scopes, spanning provinces or continents and extending decades into the future. CEMs can be divided into those that focus on the power sector and those that are pan-energy. The former category enables a detailed sector-specific representation of each included feature but excludes factors that may affect the electricity system. The latter category enables cross-sector analyses but compromises operational details. Refer to the sub-categorization column in Table 2 for further details. CEM's broad scope limits the amount of detail they can represent, which makes them better suited to high level analyses.

Beyond the inherent trade-offs between scope and detail, four issues that are particularly important in the Canadian context were observed. First, all of the reviewed models except COPPER and CREST are unable to model chronological hydro storage reservoir levels due to their temporal representation; instead, calculations are performed for specified time slices throughout the year. This representation is too infrequent to represent hydro storage, which changes at daily, monthly, and hourly intervals.

Second, both intra-provincial and interprovincial transmission are simplified in many of the models. For example, ReEDS and CERI study No. 174 aggregate supply and demand at the provincial level, effectively implying that power generated within each

Table 2 (*continued*).

Model goal	Sub- category	Results	Decarbonization technologies and strategies modeled	Area of Application	Model and citation
Determine long-term impact of economic conditions and policies such as capacity addition (change in supply) and technology implementation (change in demand) on consumption, generation mix, emissions, and costs	Electricity	Several policy pathways that can be used to achieve each of Canada's climate goals; the cheapest ways to reduce emissions include renewable-based electricity generation, using natural gas instead of coal and oil, and managing methane leaks; negative emission technology is essential to reach net-zero by 2050. Every major contributor of GHG emissions must participate in policies for Paris targets to be reached. ** results from a larger-scale model (into which IESD was incorporated) that encompasses both energy and the economy.	Increased renewable generation; carbon pricing; economic or industrial regulations	Canada, but can also be applied to smaller areas such as provinces	IESD (Melton et al., 2020; Navius Research Inc., 2020; Peters and Melton, 2019; Riehl and Peters, 2021)
Optimize and plan for long-term energy needs; model is open-source with express purpose to "extend the availability of energy modeling to the communities of students, business analysts, government specialists, and developing country energy researchers"	Integrated energy	Current renewable generation technologies require significantly increased land area. Market conditions determine whether storage reduces costs emissions; increased transmission between regions can reduce energy costs, but unless all regions have similarly strict policies, emissions may be shifted geographically instead of providing net reductions; carbon pricing can speed up decarbonization, but with diminishing returns; transitioning from coal to natural gas is economic and reliable in terms of consistent energy supply, but wind, solar, and nuclear have a much lower risk of exceeding desired emission levels.	Flexible and modular formulation allows representation of storage, all types of renewable generation, various constraints that could be used to represent any desired policy options	Alberta, British Columbia; other regions or scales possible	OSeMOSYS (English et al., 2020; Howells et al., 2011; Lyseng et al., 2016; Niet et al., 2017; Palmer-Wilson et al., 2019)
Detailed, scenario-based analysis of long-term energy trends	Integrated energy	Increased electrification, increased efficiency, and electricity system decarbonization are crucial; carbon taxes are effective if sufficiently aggressive, but renewable portfolio standards (RPS) may prove less ineffective; bioenergy could become an important low-emission fuel; transmission and coordination between regions with diverse system components can increase reliability and enable greater renewable use.	Bioenergy, carbon tax, renewable portfolio standards, end-use electrification, end-use efficiency, VRE integration, inter-provincial effects, immature technologies	Canada; Quebec	NATEM-Canada (Bahn and Vaillancourt, 2020; Loulou et al., 2016; Vaillancourt et al., 2018, 2; Vaillancourt et al., 2019a,b)
Integrated, multi-fuel, multi-sector representation with detailed accounting of sources and uses of energy and GHG for energy system planning and scenario exploration by clients from various regions.	Integrated energy	Most results are not published, but some examples include: scaling back Ontario's emission goals would not lead to lower energy prices; quantifying the effects of increased end-use efficiency; proposing pathways to emission reduction; assessing the viability of marine energy technologies.	Flexible: can incorporate policy mechanisms and infrastructure changes on both the supply and the demand side	Canada and provinces	CanESS (whatIF? Technologies 2016)
"Analyzing and forecasting the impacts of a variety of policy considerations on the energy market and resulting emissions"	Integrated energy	Strong market-based policies applied consistently across Canada are key to achieving emissions targets. Model has also been used by various government agencies for yearly or semi-yearly tasks such as predicting future emissions and air pollutants and forecasting energy supply and demand trends.	High level of technological detail: can include VRE, storage, emissions counting, various policy/pricing scenarios, end-use modifications, etc.	Applicable to Canada, the provinces, or any aggregation thereof	Energy 2020 (CER, 2019; Environment and Climate Change Canada, 2020,?; National Round Table – Table ronde nationale, 2006; Systematic Solutions, 2017b,a)

province can supply load anywhere in that province, regardless of the transmission infrastructure that exists within the province. CREST and COPPER do not model power flow, and instead assume power transfer based on the available transmission capacity. As a model category, CEMs tend to lack a representation of the distribution system.

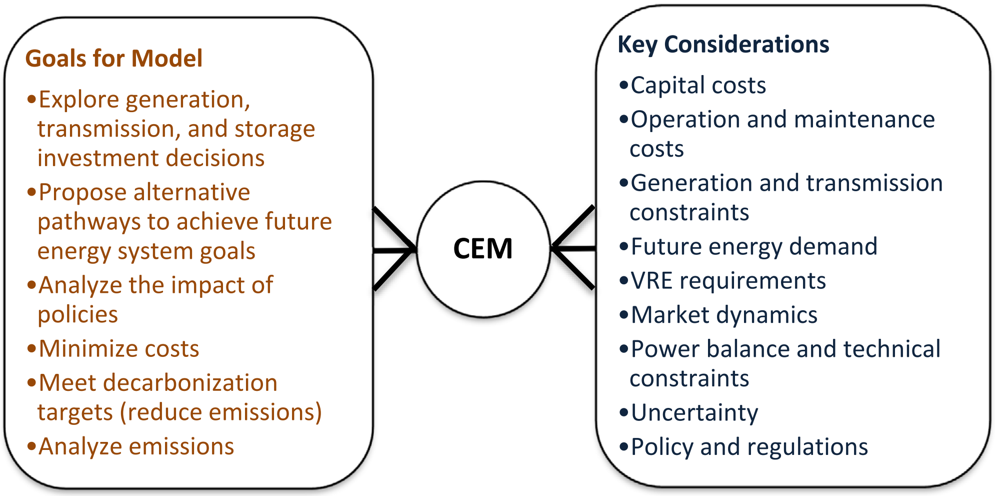

Fig. 1. General description of CEM in terms of what a model might be used to achieve, and some factors that constrain and influence the model results. The model goals are linked through the overarching goal to analyze the impact of policies to meet decarbonization targets at least cost. Note that individual models do not necessarily incorporate all of these factors and may explore only one or two big-picture goals. This figure is based on the information presented by Gacitua et al. (2018).

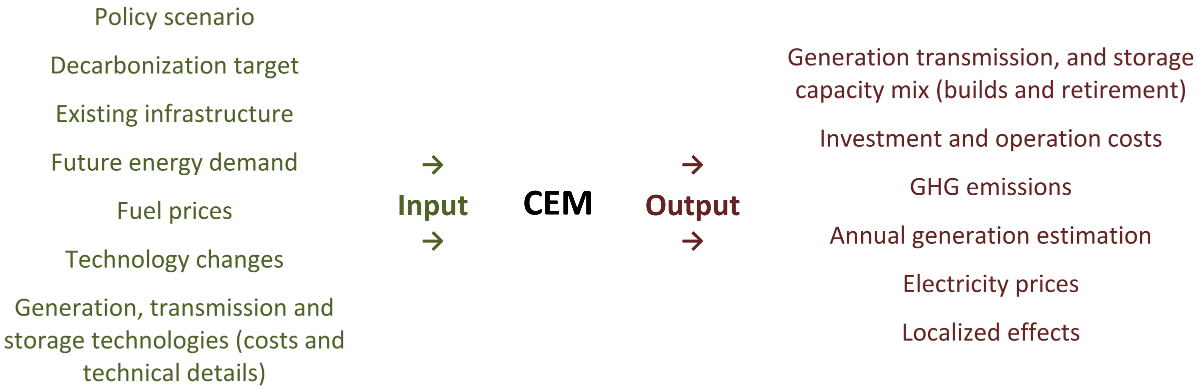

Fig. 2. Common inputs and outputs to CEM as defined by Boyd (2016). Again, individual models might not include every single listed input and output; rather, this represents the kinds of information that might be considered or obtained during the modeling process.

Third, none of the Canadian models capture market dynamics involving natural gas. While some models feature detailed representation of natural gas systems, each assumes that gas price will not change when more plants are built, when in reality, increasing demand for natural gas will lead to an increase in price. There is no integrated natural gas and power system model applied in the Canadian context (as far as we are aware). This issue has been addressed by some models that have been used in other jurisdictions, but not in any of the Canadian CEMs thus far.

Finally, although energy system models are the most comprehensive CEM frameworks, they do not account for outside factors that might also affect the energy sector, such as economic drivers, international trade, or markets for fossil fuel. While this is an inherent limitation due to computational requirements, it limits the comprehensiveness of the insights.

3.1.4. Production cost models

Production cost models (PCMs) optimize the least-cost dispatch of generation and transmission assets while meeting a series of operational constraints (Hummon et al., 2013). PCMs that have been developed or applied in the Canadian context can be differentiated by their spatial focus: those that focus on isolated microgrids, and those that consider bulk power systems (provincial or larger).

Canada has a significant number of isolated northern communities which must decarbonize for Canada to meet its net-zero goal. Four PCM models (listed in Table 3) focus on exploring how storage and other technologies can be used to integrate VRE onto isolated microgrids. Two PCM consider provincial or larger grids: SILVER focuses on assessing strategies to mitigate variability in grids with high levels of VRE penetration (McPherson and Karney, 2017), and HERMES is used by Manitoba Hydro to monitor the day-to-day operations of their grid, including predicting demand and determining hydro asset dispatch (Snell, 2020). Other provincial utilities no doubt also make use of production cost models, but details on their model frameworks were not found in either the EMH database or literature search. These models are discussed in Table 3 and in the following text.

3.1.4.1. Usage. While capacity expansion models illustrate alternative pathways for meeting decarbonization targets, PCMs demonstrate the operational challenges of VRE variability and uncertainty. In the context of decarbonization, PCM models (including all of those reviewed herein) focus on using flexible energy technologies to mitigate renewable generation variability. Both at the scale of microgrids as well as bulk power systems, variability and intermittency is a significant concern associated with VRE-based expansion of low-carbon electric capacity (Delucchi and Jacobson, 2011).

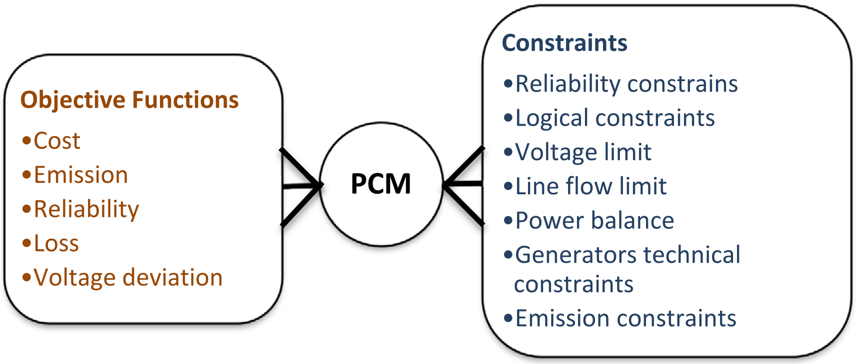

Fig. 3. Typical PCM objective functions and constraints.

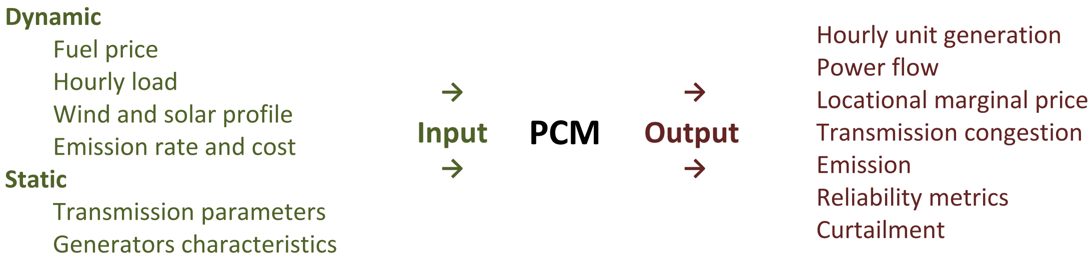

Fig. 4. Commonly seen inputs and outputs in PCM.

In the context of micro-grids, Sauter et al. (2019) and Wong and Pinard (2017) both simulated the optimal operation of microgrids supplemented with electric thermal storage systems and found that the proposed systems could be used effectively to balance against inconvenient VRE variations. Martinez et al. (2019) expanded on this work by including a diesel generator as a "transitional fuel" which has lower emissions than conventional generators and could be used to aid the transition to higher VRE penetration. Olivares et al. (2014) focused on improving PCM modeling in regards to specific issues associated with microgrids: they configured a new model formulation that improved representation of isolated microgrids by accounting for local system load imbalances.

In the context of bulk power systems, SILVER incorporates a wide suite of balancing options, is linked to a global renewable resource dataset, and can be tailored to represent various market structures and electricity system characteristics (McPherson and Karney, 2017). HERMES focuses on hydro reservoir and energy management on Manitoba's system (Association of Professional Engineers of the Province of Manitoba, 1995; Simonovic and Grahovac, 1991; Snell, 2020). The typical objective functions for a single objective PCM (Nekooei et al., 2013) and most important constraints (Iqbal et al., 2014) are shown in listed in Fig. 3 together with model inputs and outputs shown in Fig. 4.

The inputs and outputs from PCM are shown in Fig. 4 (Boyd, 2016).

3.1.4.2. Limitations. A key tradeoff that PCM modelers confront is balancing accuracy and runtime. PCMs consider higher resolution (e.g., hourly or even sub-hourly time steps) and more exhaustive constraints than CEMs, which increases accuracy but also increases computational burden. However, because PCM outputs are often used by utilities to make decisions in real time, model runtimes must be managed. In part because of their highly detailed model formulations, many PCMs exclude certain constraints, which increases runtime but compromises accuracy, or splits the model into multiple sub-problems.

Representing uncertainty in PCM models is also garnering attention due to the inherent uncertainty of renewable generation. To handle this, some PCMs incorporate probability functions into their model formulations which identify solutions that are acceptable under a range of conditions (Conejo et al., 2010; Saffari et al., 2019). While SILVER has a module to perform probabilistic optimization, it has not yet been applied in the Canadian context.

Similar to CEM, many PCMs suffer from shortcomings pertaining to their representation of hydro assets, despite its importance in the Canadian context. HERMES is clearly formulated to represent a hydro-dominated system (i.e., Manitoba's grid), however its formulation is not publicly available. SILVER represents several types of hydro facilities according to reservoir capacity, but would benefit from improvements in its representation of cascading hydro assets. None of the microgrids modeled in the aforementioned studies are connected with hydro resources.

The range of scenarios that have been implemented using PCMs have been limited, meaning that some avenues for easing the transition between current electricity systems and future VRE-heavy systems could be overlooked. Furthermore, individual models are typically not widely applied, and have not been subject to cross-comparisons.

Despite these issues, the high operational detail inherent to PCMs makes them useful for evaluating scenarios proposed by CEM and the grid-level effects of building or transportation sector electrification.

3.2. Demand-side models

3.2.1. Transportation models

The electrification of traditionally fossil-dependent activities, such as road transportation and heating, necessitates examining the supply side of energy systems in tandem with the demand sides. The previous two sections have focused on the design and operation of the supply side of power systems, respectively. The subsequent two sections focus on the two largest-emitting demand sectors: transportation and heating.

Table 3
PCM models in Canada. Models are categorized as described in the "Capacity Expansion Model Results" section, and the purpose of each model is presented along with a description of policy-related results obtained using the model, the geographical area for which those results are obtained, and a list of technologies and strategies relevant to low-carbon electrification that are represented in the model.

Model goal	Spatial scale	Results	Decarbonization strategies	Area of application	Model and citation
Evaluate electric grid operation under various energy system decarbonization scenarios	City, Provincial or larger	Evaluation of storage remuneration mechanisms (McPherson and Tahseen, 2018); decarbonization of Ontario's power system (McPherson and Karney, 2017); EV integration at the city-scale (McPherson et al., 2018); evaluation of integration strategies according to VRE characterization (McPherson et al., 2017).	High VRE penetration (based on spatially and temporally resolved resource database); demand response; energy storage; EV integration; hydro asset classification	Can be applied at the city, provincial, or national scale. The represented system is defined by the user, and can represent either areal or hypothetical system	SILVER (McPherson and Karney, 2017)
Short-term planning for utility company	Provincial or larger	Planning and operation of Manitoba Hydro's system of reservoirs, generating stations, and interconnections with other utilities; informs daily dispatch including monitoring and forecasting load, water supplies, hydraulic performance and power-system prices.	Detailed representation of hydro assets as well as other generation and storage assets; import/export to neighboring power systems (with VREs)	Manitoba Hydro power system	HERMES (Association of Professional Engineers of the Province of Manitoba, 1995; Simonovic and Grahovac, 1991; Snell, 2020)
Develop reliable solutions for VRE integration into isolated microgrids	Isolated microgrid	Conclude that electric thermal storage system "significantly reduces operating costs, and allows for better integration of intermittent wind and solar sources."	Electric thermal storage; VRE integration; distributed generation on an isolated microgrid	Kasabonika Lake First Nation isolated microgrid	Thermal Storage Systems in Northern Communities (Sauter et al., 2019)
Improve modeling techniques to better represent the unique reliability requirements of isolated microgrids	Isolated microgrid	Decomposition of model formulation is less computationally expensive than commercial solvers. The optimal dispatch strategy produced better results than traditional modeling methods, since it accounted for local system imbalances.	VRE integration; distributed generation on an isolated microgrid; fuel cell and electrolyzer storage; battery storage; backup diesel generator	Conceptual grid based on European network benchmark with similar characteristics to those seen in isolated Northern communities	Centralized Energy Management System for Isolated Microgrids (Olivares et al., 2014)
Identify and quantify the opportunities for electric thermal storage on electric grids with high penetrations of renewable energy	Isolated microgrid	Despite high capital costs, electric thermal storage can help balance the variability of wind while also reducing emissions.	Thermal energy storage, wind, smart grids, distributed generation/isolated microgrid	Yukon electric grid	Smart Electric Thermal Storage (Wong and Pinard, 2017)
Evaluate performance of an experimental system that supports VRE integration through storage and an additional fuel source	Isolated microgrid	System performance depends on wind speed, wind generation availability, and pressure within the storage system. Model results were consistent with-established software.	Wind–diesel hybrid system; storage; distributed generation/isolated microgrids	Remote area in Newfoundland and Labrador	Wind–Diesel Hybrid System with Compressed Air Energy Storage (Martinez et al., 2019)

The decarbonization of the transportation sector is driven primarily by the electrification of passenger vehicles. The rapid growth in electrified vehicles (EVs), both in recent years as well as projected in coming decades, will fundamentally change both the shape and the magnitude of bulk power systems' load curves. Models that represent vehicle transportation can be useful tools for characterizing the impact that electric vehicles will have on bulk power systems. In our review of transportation models that have been developed and/or applied in Canada, two distinct categories of transportation models have emerged: operational models that have traditionally been used to examine travel patterns (how people move from point to point), and a newer category of models focused on EV charging patterns (when and where people refuel their electric vehicles). Given our focus on the operational implications of low-carbon electrification, we have excluded models that focus on EV adoption rather than the operational implications of EVs on demand profiles (e.g., such as the REPAC model Wolinetz and Axsen, 2017).

Operational models have been used by jurisdictions to predict travel patterns which in turn inform overall energy use. Within the category of operational models, two sub-classifications emerged from the reviewed models: four-step operational models and activity-based operational models. Cities including Edmonton (pbConsult Inc., 2003) and Vancouver (City of Vancouver, 2015) use a four-step operational model, which aggregates data, such as traffic flow rates, to predict how transportation infrastructure will be utilized in the future (Ahmed, 2012; Hensher and Button, 2007). Meanwhile, cities including Calgary (The City of Calgary, 2001) use activity-based operational models, which simulate traffic patterns based on the activities of individual vehicles (National Academies Press, 2014).

In contrast, charging models take travel patterns as a static model input and focus on how EV charging can be optimized around travel patterns in order to provide the maximum benefit (or least disruption) to the electric grid. Charging models have been used to environmental and social dimensions of EV integration: Kamiya et al. study the GHG intensity associated with increased EV penetration in grids of varying compositions (Axsen et al., 2015); while Wolinetz et al. (2018) examine how consumer preferences effects of demand-response and EV-as-battery storage and the subsequent impact on grid configuration and operation. Starting from the opposite position, Tu et al.

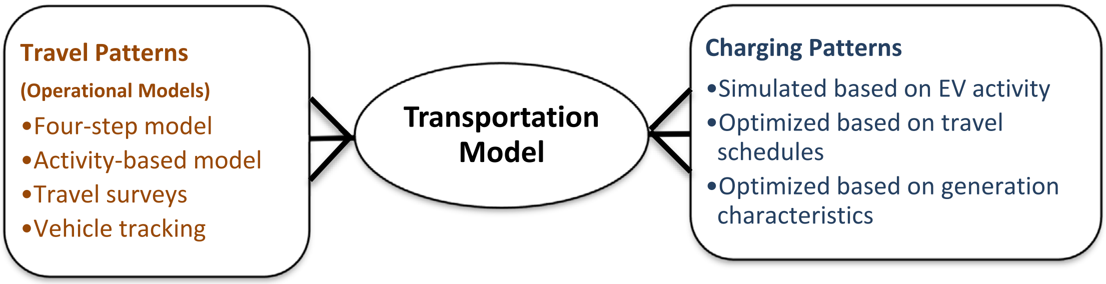

Fig. 5. Travel patterns and charging patterns are the two main factors that cause EVs to affect the electric grid. The slanted bars describe how each of these factors can be modeled or represented. "Four-Step Models" and "Activity-Based Models" are two specific model types and are described in greater detail during the discussion of specific Canadian transportation models.

optimized charging patterns and assessed the infrastructure requirements necessary to enable these patterns (Tu et al., 2020). Similarly, Yu developed modeling techniques (incorporating a rolling scheduling horizon for charging based on weather predictions) to optimize short-distance business vehicles charging (Danilo et al., 2019). Finally, Doluweera et al. developed a vehicle simulation model to study the impacts on electricity generation in the province of Alberta (Doluweera et al., 2020). The details of each of the reviewed models are presented in Table 4 and in the following text.

3.2.1.1. Usage. Operational models of travel patterns describe day-to-day vehicle activities and traffic conditions over the short-term and long-term, as well as how those patterns would be impacted by infrastructure changes such as new roads or increased public transportation. As seen in Table 4, operational models are used by municipalities to evaluate policies and plan for travel infrastructure and traffic flow. These models did not directly study EVs and their impacts on emissions and electricity demand. In addition, these models were not used to explore how expanding public transportation systems could be used to reduce emissions. However, operational models can be used in conjunction with data to describe the charging constraints imposed on EVs (based on each vehicle's travel schedule) and to understand how new transportation policies would affect travel patterns (and associated charging requirements).

Charging models, on the other hand, are directly applicable to low-carbon electrification. In addition to exploring how the timing of charging impacts emissions, charging models are used to investigate whether EVs could be used as grid storage devices, what charging infrastructure would be needed to support optimal charging patterns, and how willing consumers were to charge their vehicles in response to signals from the grid. Beyond analyzing how vehicle electrification will impact electricity grids, these models can be used to determine how EVs can be used to actively reduce emissions.

The impact of electrified vehicles (EVs) on the grid is influenced by **both** the travel paths and the charging requirements of each vehicle. The different ways in which each of these considerations can be modeled is summarized in Fig. 5 (Delle Site and Filippi, 2009; National Academies Press, 2014).

A general overview of the possible inputs and outputs of each model type (Delle Site and Filippi, 2009; National Academies Press, 2014) is shown in Fig. 6.

3.2.2. Limitations

The reviewed transportation models tended to ignore commercial transportation and long-distance private vehicle transit, meaning that some energy requirements and charging patterns that would impact total sector decarbonization are unaccounted for. This result is likely an underestimate of low-carbon electric capacity requirements. Similarly, the focus on transportation charging alone ignores interaction with other load categories (e.g., building loads), which may lead to underestimation of capacity requirements (e.g., if load profiles were coincident). These issues could be addressed by expanded studies and data collection, or by incorporating EV modeling into a multi-sector exploration of decarbonization.

The documentation that is available for most operational models is limited compared to that of the charging models. Furthermore, the models are built on travel surveys from 5–10 years ago, when there was not a significant number of EVs in use. Until better data is available, these models are limited by their implied assumption that EV travel patterns are/will be similar to the travel patterns of gasoline vehicles. Nonetheless, operational models are useful for understanding how travel patterns might impact infrastructure requirements and travel times.

Charging models suffer from a lack of reliance on appropriate data: Kamiya and Wolinetz use traditional (gasoline) travel patterns in their studies; and Tu and Yu perform optimization from a utility perspective (excluding considerations of consumer preferences). Datasets are emerging to help fill this gap: the Canadian Plug-In Electric Vehicle Survey collected travel diaries including comments on EV charger availability (Axsen et al., 2015); the ongoing Charge the North Project tracks the travel and charging patterns of EV drivers via GPS (FleetCarma, 2018; Goody et al., 2020).

3.2.3. Building system models

Like the transportation sector, the electrification of the building sector, and heating loads in particular, is a critical part of many decarbonization plans. The electrification of heating loads will have an impact on the bulk power system, both in terms of overall demand, the shape of that demand, and the flexibility in the load profile. Like transportation modeling, building systems models are important tools for characterizing heating loads and their electrification. We limit our review of building system models to those that contain sufficient operational detail to be useful in electrification analyses. In other words, our review is limited to engineering models that have been developed and/or applied in a Canadian context and have detailed physics-based representations of the causes of building energy consumption. These causes can be broken into two categories: thermal exchange between the buildings and the environment, and loads caused directly by human activities such as lighting and appliance use (Swan and Ismet Ugursal, 2009).

Each of the reviewed models incorporate both thermal exchange and human activities in their calculations of energy consumption. However, because human behavior is often unpredictable, the models can be sorted based on the level of complexity used to represent behavior: "deterministic" models assume

Table 4
Summary of Canadian transportation models. Models are categorized as travel/operational models versus charging models. The purpose of each model is presented along with a description of policy-related results obtained using the model, the geographical area for which those results are obtained, and a list of technologies and strategies relevant to low-carbon electrification that are represented in the model.

Model goal	Results	Decarbonization strategies	Sub-category	Area of application	Model and citation
Predict travel patterns	Documentation is limited; modeling is used by the city to support transportation policy and planning.	None: model is built on data from gasoline vehicles, but can be applied to EV integration analyses if one assumes EV travel behavior will be similar to that of gasoline travel behavior.	Travel/ operational (activity-based)	City of Calgary	Calgary Operational Model (The City of Calgary 2001)
			Travel/ operational (four-step)	City of Edmonton	Edmonton Operational Model (pbConsult Inc 2003)
			Travel/ operational (activity-based)	City of Toronto	Greater Toronto Area Model (Miller et al., 2015; Miller and Roorda, 2003)
			Travel/ operational (four-step)	City of Vancouver	Vancouver Operational Model (City of Vancouver 2015)
Determine how EVs impact grid GHG emissions in both the short term and the long term for three different grids typologies	When considering both short-term and long-term timescales, the impact that EV have on grid emissions varies by province according to the carbon intensity of the provincial grid; low-carbon generation is crucial to ensuring that EVs lead to reduced emissions; marginal emissions (the emissions of the highest-cost generator that would turn on given increased demand) are more important than average emissions (averaged over all utilized generators) in determining the effects of changing load on grid emissions.	Electric Vehicles; policies including carbon tax and renewable portfolio standards (RPS) with minimum EV penetration	Charging model	British Columbia, Alberta, Ontario	Kamiya: short-term and long-term perspectives (Kamiya et al., 2019)
Determine how consumer preferences and behavior will influence EV adoption rates and the impact of vehicle-grid integration (including EV demand-response and EVs for grid energy storage)	When realistic, survey-based consumer participation rates are taken into account, demand-response strategies such as utility control of charging times are less effective than previous studies have suggested, both in terms of reducing costs and reducing emissions. Electricity prices may decrease slightly as a result of these strategies, but the effect is too small for profit-maximizing utilities to provide increased financial incentives for consumer EV adoption.	Electric Vehicles; Demand Response; use of EV batteries as energy storage	Charging model	British Columbia; Alberta	Wolinetz: Behaviorally-realistic EV–grid integration (Wolinetz et al., 2018)
Determine optimal EV charging patterns, compare emissions across charging patterns (against the baseline gasoline vehicles), and determine the charging infrastructure requirements needed to support each proposed charging pattern	Optimized charging outperforms off peak charging by 50%; however, significant increases in EV chargers in public and at workplaces may be needed to ensure large emission reductions.	Electric Vehicles, demand-response	Charging model	Greater Toronto and Hamilton	Tu: charging optimization (Tu et al., 2020)
Simulate large-scale EV activity and charging patterns based on real data, and then optimize charging in real-time via a 4-hour rolling horizon	Smart scheduling of EVs results in lower peak load; mid-morning charging load by business vehicles (who may travel from site to site during a work day, but do not include long-distance transportation) cannot be shifted to another time period; wind is more reliable on average, but solar is better-timed for meeting mid-morning load.	Electric Vehicles, demand-response	Charging model	Theoretical population based on data taken from business vehicles in Western Australia	Yu: Charging Impacts (Danilo et al., 2019)
Develop a simulation model to assess energy and emissions impacts of the use of EVs in Alberta	Adoption of EVs in Alberta can contribute to provincial emissions reduction targets, through reduction of electricity generation emissions and EV adoption. However, electricity demand increase due to EVs is relatively small.	Electric Vehicles, demand-response	Charging model	Province of Alberta	Doluweera: Charging Impacts (Doluweera et al., 2020)

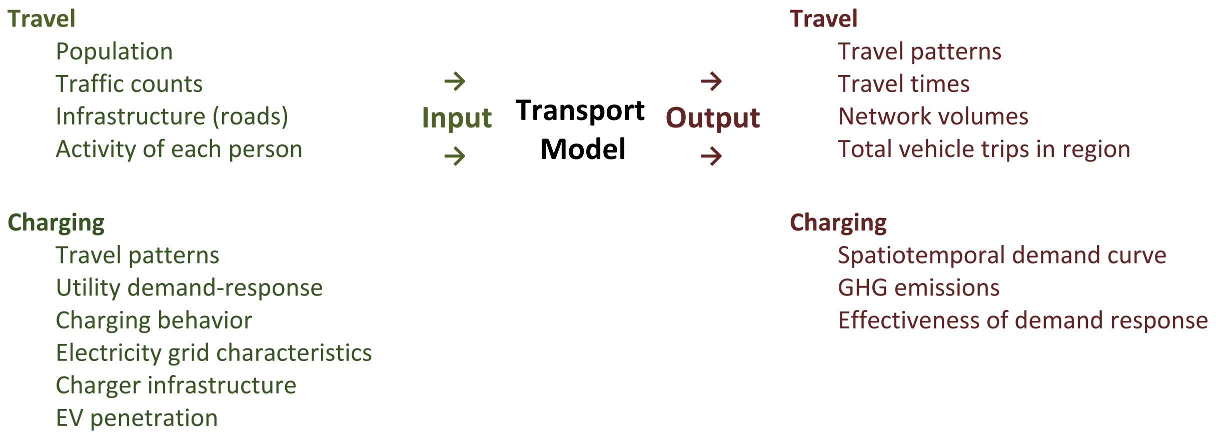

Fig. 6. List of possible inputs and outputs that could be used for modeling EV travel patterns and EV charging patterns. Individual models are not necessarily associated with all of the inputs and outputs pertaining to their model type.

that humans in the same situation will always follow the same behavioral patterns, while "probabilistic" models seek to simulate or characterize the underlying patterns, and can represent behavioral variations in greater detail.

3.2.3.1. Usage. The reviewed papers tend to focus on reducing the energy footprint of buildings on the environment and the grid. Many of the reviewed papers seek to reduce building energy consumption through building envelope upgrades (Kim et al., 2017; Salter et al., 2020), optimized neighborhood planning (e.g., increasing population density Webster and Korteling, 2013, or facilitating walking or public transportation Hachem, 2016). Another recurring topic is supporting distributed generation through strategies such as adding storage to local distributed-generation systems (Yu et al., 2018) or varying building shapes to spread out the timing of solar generation (Bucking and Dermardiros, 2018; Hachem et al., 2013). The CHREM model (Bucking and Dermardiros, 2018) was used to investigate new electric heating systems in addition to other building-side modifications. While the physically detailed model formulations used in many of the reviewed works *could* be adapted to explore the performance of different electric technologies, only one (the CHREM model) directly explored decarbonization by electrification.

Among the reviewed deterministic models, two imposed changes to building features and then quantified how these changes would influence energy use. The CHREM model used this method to explore the economic costs, technological feasibility, and impact on energy use and GHG emissions associated with various envelope and equipment upgrades across the entire Canadian housing stock. Meanwhile, Kim et al. (2017) performed controlled experiments on a number of different buildings to determine the effects of building envelope parameters on energy use and solar potential. The approach in both cases entails simulating energy use in a small number of buildings and then summing the resulting load curves (United States Department of Energy 2020). As well, because buildings are likely to be owned individually or in relatively small groups, making changes on a building-by-building basis mirrors what building policy rollout might realistically be.

However, most of the deterministic models also explored the emergent energy consumption properties that resulted from changes in a community of buildings. For example, Yu et al. investigated the optimal control strategies for using a community of buildings to balance the load of an electric grid; in this model, the coordination of multiple buildings was necessary to enable a reasonable amount of energy could be shifted. Similarly, in addition to exploring changes made to individual building features, Salter, Hachem, and SCEC3 (Salter et al., 2020, 2017) also examined how the spatial arrangement of groups of buildings could impact energy use, and as a result were able to draw conclusions about the importance of building density and the ability of building locations to influence transportation requirements and energy consumption. Finally, the Bucking and Dermadios model optimized a district energy system to provide heat to multiple buildings, and noted that the system performed better when it was designed to take the entire group of buildings into account. For all these models, taking a community-perspective rather than merely aggregating the results of individual building upgrades enabled the exploration of additional avenues of impactful change.

These categories are explored in further detail in Fig. 7.

The general types of inputs and outputs to building energy models and the differences between inputs band outputs for each of these two model types are shown in Fig. 8.

3.2.3.2. Limitations. The deterministic assumptions of building occupant preferences and behavior can be problematic since human "perception and response" (Bourgeois et al., 2006) to conditions inside the building can significantly influence energy consumption (Gunay et al., 2016). To address this, several models explored the influence of human behavior on building loads using randomness or probability to simulate human variation. For example, Gunay et al. (2016) and the Newsham and Birt (2010) paper each used a different statistical method to look at the factors that most strongly influenced energy use. Similarly, Armstrong, Wills, and Rouleau all used probability to generate stochastic load curves based on factors such as appliance ownership, appliance characteristics, building occupancy, and other factors. And finally, Bourgeois et al. (2006) predicted how people will react to physical conditions within a building and explored the difference in load curves as a result of different reactionary behaviors. Understanding the impacts of behavioral variability on building energy use on time scales relevant to the electric grid is very important because falsely assuming temporal uniformity of energy use can significantly heighten load peaks and valleys and exaggerate the effects of particularly timing-dependent policies. However, in terms of their research questions and model applications, almost all of the behavioral models were more applicable to the advancement of modeling methodology than to the investigation of strategies to impact decarbonization via behavioral changes.

Considering all the reviewed models, there a mismatch between the strategies explored by the models and the concerns most related to low-carbon electrification. As described above, deterministic models oversimplify the effects of human behavior, while stochastic models were not really used for policy analysis;

Table 5
The reviewed Canadian building models. Models are categorized as described in the "Building Model Results" section, and the purpose of each model is presented along with a description of policy-related results obtained using the model, the geographical area for which those results are obtained, and a list of technologies and strategies relevant to low-carbon electrification.

Model goal	Sub-category	Results	Decarbonization strategies	Area of application	Model and citation
Simultaneously optimize building and district energy systems via an evolutionary algorithm (machine learning)	Deterministic (emergent)	Optimal solutions were different from a system in which building design was optimized without considering district system configuration. Energy storage and varied building orientations were important for balancing and diversifying load.	Net-zero energy building; district energy system	Three-building conceptual community in southern Ontario; multiple building types	Distributed Evolutionary Algorithm (Bucking and Dermardiros, 2018)
Represent residential energy use on a national level and explore retrofit scenarios	Deterministic (single building)	Many retrofit strategies explored. Results vary depending on the province and the technologies involved, so it is critical that policies are targeted to specific regions. However, "substantial energy savings and GHG emission reductions are techno-economically feasible for the CHS through careful selection of retrofit options."	Envelope modifications, appliance/lighting upgrade, internal combustion engine and Sterling engine cogeneration, solar combi-system, air to water heat pump, solar assisted heat pump, building integrated photovoltaic and thermal system	National; residential buildings	Canadian Hybrid Residential End-Use Model (CHREM) (Asaee, 2018; Asaee et al., 2019c; Asaee et al., 2017a,b; Asaee, Ugursal, and Beausoleil-Morrison 2017; Swan et al., 2009; Swan et al., 2011; Swan et al., 2008)
Explore future development scenarios	Deterministic (emergent)	Denser land use saves both money and energy. These effects increase when existing buildings are retrofitted, which has a relatively short payback period. Renewable generation is expensive, but can significantly reduce emissions and does pay back over larger time periods. Combining these strategies is essential to maximize energy and emissions savings.	Solar domestic hot water (DHW), solar photovoltaic (PV), biomass district energy, sustainable urban planning	City of Prince George, BC; residential	Spatial Community Energy Carbon and Cost Characterization (SCEC^3) model (Webster et al., 2011; Webster and Korteling, 2013)
Investigate and compare relationships among building [envelope] design variables and energy consumption by building type	Deterministic (single building)	Different building retrofit variables (i.e., thermal capacity of components, rate of air exchange with the environment, and efficiency of internal equipment) have different levels of importance depending on building type and location.	Envelope modifications	Five commercial, institutional, and residential reference buildings in Vancouver	Kim et al. (2017)
Assess the effectiveness of energy and emissions strategies to inform planners and urban designers	Deterministic (emergent)	Changing land use was found to be more effective than building envelope retrofits in reducing energy usage and GHG emissions.	Envelope modifications, sustainable urban planning	Entire neighborhoods (including all building types) in six cities in BC	Iterative "What-If" Neighborhood Simulation (Salter et al., 2020, 2017)
Determine how community design parameters impact energy performance	Deterministic (emergent)	Certain house shapes can generate significant amounts of solar energy; L-shaped buildings consume more energy but more than offset this with increased solar generation; varying orientations can spread peak solar generation over a 6-hour period; large or hard-to-get-out-of neighborhoods with high transportation requirements lead to increased energy use even when buildings are more efficient; design protocols suggested for solar communities.	"Smart" design of buildings/communities to reduce energy use or increase generation potential: unit shape and orientation, neighborhood density, street design, relative location of commercial versus residential centers; PV generation and passive solar heating	Conceptual community with weather from either Montreal or Calgary, meant to represent a "northern mid-latitude" location	Hachem et al: Solar Communities Hachem, 2016; Hachem et al., 2012, 2013

(continued on next page)

as a result, among all the models there is limited investigation of how real-time building-side strategies such as demand-response could be used to mitigate VRE variability. Another limitation is the segregation of sectors between different building model types. In general, the deterministic models were mostly residential and behavioral models were mostly commercial; however, ideally both of these sectors would be examined within a single model, because all building types contribute emissions and are therefore a focus for decarbonization.

Table 5 (*continued*).

Model goal	Sub-category	Results	Decarbonization strategies	Area of application	Model and citation
Understand how energy generation and consumption in communities can be used to help balance the electric grid	Deterministic (emergent)	Energy consumption decreased by 5%–9% when excess energy was used to run HVAC systems and produce DHW before battery storage systems charged. Demand-response strategies were more effective when real-time building temperature was taken into account. Varied PV orientation reduced grid imports by spreading out the timing of the generation, but fully south-facing PV saved money by generating more power when grid imports were expensive.	Battery energy storage; residential PV; demand-side management	Conceptual community based on model house near Toronto	Transactive Control Strategies (Yu et al., 2018)
Understand how occupancy in a building impacts energy use	Probabilistic	Accuracy of a regression model of building energy use improved when occupancy was included as a significant independent variable.	Demand-response or advance control of building energy load	A three-story building in eastern Ontario; Canada comprising laboratories and 81 individual work spaces	ARIMA (Newsham and Birt, 2010)
Assess the factors contributing to the plug-in equipment load patterns were investigated through an office equipment survey"	Probabilistic	In private offices, 75% of the plug-in equipment electricity use takes place during unoccupied periods.	Changing appliance usage patterns	Based on survey of people working in an office environment—most from North America (particularly Canada)	Plug-In Load Patterns (Gunay et al., 2016)
Create representative occupant-driven electric load profiles for Canadian residential households	Probabilistic	Electric load profiles were generated probabilistically, successfully incorporated into a whole-building simulation, and shown to match available data; "occupant-driven or discretionary electrical loads" are not as well-understood in the literature as are "temporal thermal demands."	Distributed generation	Canada: based on national-level data and compared against measurements from Quebec	Armstrong et al. (2009)
Depict occupancy behavior in building simulations more accurately; capture variability in building energy use patterns due to human preferences	Probabilistic	Probabilistic behavioral models from other countries could be scaled to Canada with reasonable accuracy, but tended to under-represent diversity; operational practices can impact building energy use significantly; collecting enough data to model behavioral patterns is a challenge.	Scaled a DHW system (generalize); "applicability to predictive control, demand-side management, etc."	Residential; models from US, UK, and Canada; data from Quebec City and national-level statistics	Rouleau et al.
Determine whether "daily, seasonal, and inter-dwelling variation" of non-HVAC loads predicted probabilistically are realistic compared to measured data	Probabilistic	Predicted loads were reasonably realistic, although seasonal variation was under-represented; lack of measured data was a challenge for model robustness and accuracy.	Distributed generation; "design and analysis of community-scale energy systems and incentives"	Residential homes; model developed in UK; data from 22 houses in Ottawa	Wills et al. (2018)

(*continued on next page*)

Across the three main strategies explored in building system models, some important policy-based takeaways stood out. Both CHREM and Kim found that buildings of different types or in different locations can respond very differently to the same energy-saving measures; this implies that it is important to target retrofit strategies to individual buildings and that environmentally-friendly building codes should vary across geographical regions according to local climates. Similarly, Bucking, Hachem, and Yu all found that varying building properties and orientations was important for leveling both energy demand and distributed generation; thus, community planning when new communities are developed is important for ensuring that building energy use and building strain on the electric grid can be reduced in the long term. Finally, Salter, Hachem, and SCEC3 [77,83] all noted that increasing building density was far more effective than building retrofits alone in reducing energy consumption; this indicates that long-term social behaviors such as sharing

Table 5 (*continued*).

Model goal	Sub-category	Results	Decarbonization strategies	Area of application	Model and citation
Incorporate a dynamic model of occupant behavior (i.e., "perception and response to environmental stimuli") into a detailed technical model of building energy use (in this case both a lighting module and a whole-building module are used)	Probabilistic	Daylighting can reduce energy use, but effects depend on proportions of participating residents, and daylighting could increase energy use in cold climates (light as heat) – also, "building occupants that actively seek daylighting rather than systematically relying on artificial lighting can reduce overall primary energy expenditure by more than 40%, when compared to occupants who rely on constant artificial lighting. [However,] depending on the proportion of buildings occupants that actively seek out daylighting, reduced lighting use through automated control may not always produce anticipated savings in primary energy for indoor climate control. In some cases, reduced lighting use is shown to increase primary energy expenditure for indoor climate control, trimming down initial primary energy savings in lighting alone. This reveals the superiority of integrated design approaches over simpler daylighting guidelines or rules of thumb."	Daylighting (using sunlight for processes inside of buildings)	Simple office building in Quebec City (heating dominated) and in Rome (cooling dominated)	Bourgeois et al. (2006)

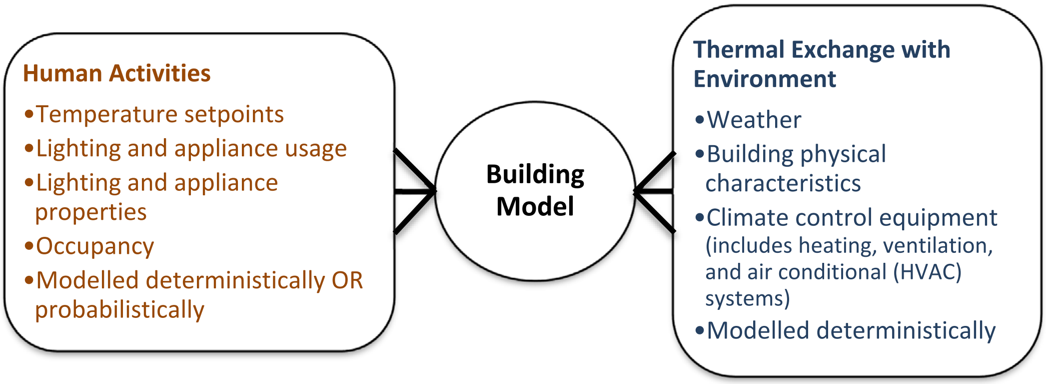

Fig. 7. Main causes of building energy use are human activities such as lighting and appliance use, and thermal exchange (heat transfer) between buildings and the environment. The factors that contribute to each of these causes are listed, followed by how each can be modeled (far right). "Deterministic" refers to a framework in which consistent inputs lead to the same predicted energy use, while "probabilistic" captures the fact that the energy use differs among people.

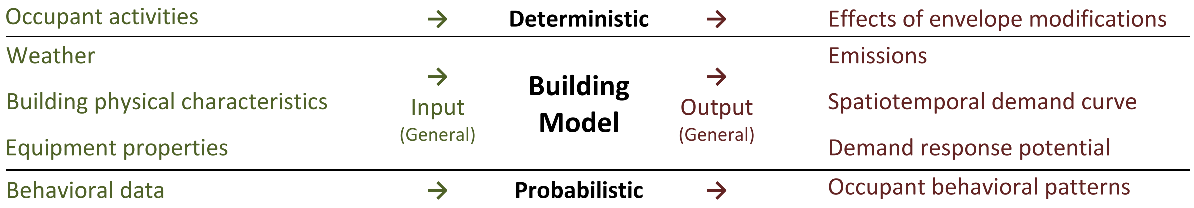

Fig. 8. Some inputs and outputs that are commonly seen in building models. Most of these are used in both deterministic and probabilistic model frameworks; however, some unique inputs and outputs for each type are also listed.

Table 6
Summary of model objective, constrains, inputs and outputs for each of the four reviewed model categories: capacity expansion, production cost, transportation, and buildings.

	Capacity expansion models	Production cost models	Transportation models	Building models
Model goal/objective	Explore generation, transmission, and storage investment decisions; propose alternative pathways to achieve future energy system goals; analyze the impact of policies; assess decarbonization pathways & targets	Minimize the dispatch of the power system; calculate the GHG emissions associated with the operation of the power system; analyze the reliability of the power system	Predict travel patterns; analyze the impact of EV integration; analyze the impact of consumer preferences; optimize EV charging patterns	Optimize building and/or district energy systems; represent residential energy use; explore retrofit scenarios; assess the effectiveness of energy and emissions policies/regulations; quantify design decisions on energy performance; assess the potential of demand response measures; assess the impact of occupancy on energy use.
Model considerations/ constraints	Capital costs; operation and maintenance costs; generation and transmission constraints; future energy demand; VRE requirements; market dynamics; power balance and technical constraints; explore uncertainty; policy and regulation	Power balance constraint; generator technical constraints; emissions constraints; reliability constraints; line flow limits	Travel patterns (modeled with Four-Step Models, and Activity-Based models, travel surveys, and vehicle tracking) and charging patterns (based on EV activity, travel schedules, or generation characteristics) both affect EV integration.	Two key causes of building energy use are human activities (temperature set points, lighting and appliance use, lighting and appliance properties, occupancy), and the thermal exchange (heat transfer) between buildings and the environment (weather, physical building characteristics, climate control equipment).
Model inputs	Policy scenario; decarbonization target; existing infrastructure; future energy demand; fuel prices; technology changes; generation, transmission and storage technologies (costs & technical details)	Fuel price; hourly load; wind and solar generation profile; emission rates and costs; transmission parameters; generator characteristics	Travel inputs (population, infrastructure, traffic counts, human activity) and charging inputs (travel patterns, charging behavior, charging infrastructure, demand response, EV penetration, power system characteristics).	Model inputs include: occupant activities, weather, building physical characteristics, equipment properties, and behavioral data.
Model outputs	Generation, transmission, and storage capacity mx (builds and retirements); investment and operation costs; GHG emissions; annual generation estimation; electricity prices; localized effects	Hourly unit generation; power flow; locational marginal price; transmission congestion; emissions; reliability metrics; curtailment rates	Travel outputs include: travel patterns, network volumes, travel times, total vehicle trips in a region. Charging outputs include spatiotemporal demand curves, effectiveness of demand response, GHG emissions.	Model outputs include: the effects of envelope modifications, emissions, spatiotemporal demand curve, demand response potential, occupant behavioral patterns.

living and working spaces and occupying smaller homes and offices is an important step towards a low-energy building future.

3.3. Model category summary

Table 6 summarizes the core aspets of the four model categories that we have reviewed in this paper, according to the model objectvice, constraints, input parameters, and output parameters.

4. Limitations and future work

This study has several limitations, some of which are justified according to the purpose of the paper, and some of which should be addressed in future work.

4.1. Scope of included models and sectors

This paper only considers the transportation and building sectors, thereby excluding some parts of the economy that also need to be weaned off fossil fuels, such as heavy industry. This focus keeps the paper to a reasonable length while still investigating some of the largest contributors to increased electric demand, but focuses on the areas of model development that are most mature.

4.2. Model search process

Survey social desirability and strategic bias may have led some experts to overstate their model's abilities, knowing that the results would inform the EMH database and potential policy-making, as well as unintentionally exclude some models (Rhodes et al., 2021b). In addition, differences between the model types led to non-uniform inclusion criteria: very few published Canadian CEM and PCM models were found leading to a straightforward set of categorization criteria; but a breadth of transportation and building energy modeling were found, some of which did not fit within the model definitions and thus could have been excluded. Future work could build on this study as a starting point of model categorization to inform more systematic literature reviews as well as model type-specific surveys.

5. Discussion

Each of the model categories deliver valuable insights that pertain to the sector and scope of the category in question. These insights, derived from sector and spatially specific models, provide useful information on the sector/scale at hand. Power system models have shown that aggressive carbon pricing was necessary to speed the adoption of VREs, that carbon pricing led to reduced emissions more quickly than did renewable portfolio standards, or how market design impacts resource dispatch. Demand side models have emphasized that infrastructure changes and consumer incentives are necessary to ensure reduced emissions. However, by focusing on a specific scale and sector, these models by very definition omit interactions with other sectors or scales. This leaves an information gap and many unanswered questions. Studies that apply sector or spatially specific models inevitably reach the extent of their defined scope, and point to the potential ramifications outside the scope boundary as an area for future work. Many of the most critical areas for future research now span across multiple sectors or multiple scales/jurisdictions. For example, several studies noted that jurisdictions should coordinate their carbon policies in order to ensure that emissions are reduced rather than shifted, or highlighted the role of interregional trade.

Critical areas of future research also span multiple sectors. For example, transportation models emphasized that total emissions associated with EVs depend on when and where charging can occur: the most substantial emission reductions occur when charging is optimized to align with renewable production. The issue of EV charging extends beyond the field engineering and into economics, urban and regional planning, and behavior. Together, these results stress the importance of expanding low-carbon generation resources (power system modeling), without which EV charging will either remain responsible for significant emissions, or be subject to constraints that are difficult to enact (behavioral modeling).

Returning to our initial question *'is our current suite of energy modeling tools sufficient to chart low-carbon electrification and decarbonization pathways'*, we find that the current suite of modeling tools has been designed to represent specific sectors and scales and provides useful insights within these bounds, but a gap exists in modeling holistic representations that span multiple sectors or scales. Our review demonstrates the robust modeling capability that represents specific energy system sectors or specific jurisdictional scales. However, there is a clear gap in our modeling landscape when it comes to understanding the interactions *between* systems or *between* scales.

This leads us to our next question: *what improvements are needed to facilitate the development of holistic, multi-sector insights needed to represent electrification?* This analysis has demonstrated that critical improvements are required exchange insights from one sector to the next and to develop pathways that take advantage of potential cross-sector synergies. This work has identified several potential areas of information flow between different model types, but future work is required to implement such capacity. Future electrification strides will be able to more accurately define pathways forward by integrating models from different sectors.

6. Conclusions

Energy system models are often relied on as tools to inform planning and policy making and chart energy system transformations. The paramount transformation is now to chart a pathway to net-zero—a transformation that relies heavily on low-carbon electrification. Electrification, in turn, brings together previously distinct sectors and energy carriers—transitioning away from heating with natural gas and transportation fueled by diesel and oil. As such, electrification relies on integrating insights across several dimensions: the supply *and* demand sides of power systems, spatially and temporally resolved operations *and* long-term climate change impacts, and the suite of previously independent engineered systems. Simultaneously representing this increasingly interconnected system poses new challenges for modelers and their frameworks.

This analysis contributes a novel review of the energy modeling landscape in the Canadian context, framed specifically around the issue of low-carbon electrification. While the reviewed model types span a diverse range of formulations, policies, and represented systems, several similarities and common issues emerge from our analysis. By representing energy demand, transportation and building models attempt to formulate human behavior, making them susceptible to assumptions and ensuing inaccuracies. Such assumptions and formulations can be improved through the incorporation of rigorous data describing consumers' behavior using revealed (historical) preferences or survey-based discrete choice experiments (Rivers and Jaccard, 2006). On the other hand, CEM and PCM are affected by incompatibilities with the timescales involved in design versus operational decisions. For example, PCMs representation of hydro storage assets is limited by the reservoir duration that exceeds PCM's hourly (or sub-hourly) resolution, and requires a chronological water level tracking beyond the capacity of many CEMs. These examples derive from the same fundamental issue: the tension between simplified, broad scope or detailed, narrow scope.

After taking stock of the current modeling landscape and the tensions therein, our next contribution is to propose a strategy for future modeling efforts. Namely, overcoming these intrinsic tensions could be aided by employing different model types in tandem. A more robust suite of policies might utilize insights from the breadth of outputs provided by combinations of models: CEMs with dispatch validation provided by PCMs and the sector specificity provided by building and transport models. For example, the simplified representation of transmission infrastructure in CEMs could be assessed using detailed PCM analyses. Electricity load's changing profile and flexibility potential that is informed by transportation or building models could be used to improve dispatch decisions in PCMs. The grid requirements mandated by building and transportation electrification should be represented in CEM infrastructure expansion assessments. The co-optimization of building fleets and transportation networks together with community shapes might catalyze urban energy efficiency potential.

As our model review highlights, each model type by itself can lead to a number of important insights for decision makers. However, a siloed model landscape lacks the sectoral scope and detailed operational perspective that is needed to understand the physical and technical implications of low-carbon electrification. Modeling frameworks must be able to represent cross sector and cross scale interactions. What can we learn from looking at all of these different model frameworks together, both in terms the individual model categories themselves, as well as the best path forward economy-wide decarbonization? Using a broader suite of modeling tools might allow the same problem to be explored from multiple perspectives, leading to impactful results that might not have been realized by any one model type. In fact, such results can be most useful in policy trade-off decisions where governments face multiple objectives of deep decarbonization.

CRediT authorship contribution statement

M. McPherson: Conceptualization, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **E. Rhodes:** Methodology, Writing – review & editing, Supervision. **L. Stanislaw:** Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **R. Arjmand:** Conceptualization, Formal analysis, Investigation, Resources, Writing – original draft,

Writing – review & editing, Visualization. **M. Saffari:** Conceptualization, Formal analysis, Investigation, Resources, Writing – original draft; Writing – review & editing, Visualization. **R. Xu:** Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing. **C. Hoicka:** Writing – review & editing. **M. Esfahlani:** Methodology, Data curation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dr. Madeleine McPherson reports financial support was provided by Mitacs. Dr. Madeleine McPherson reports financial support was provided by Energy Modelling Initiative.

Data availability

Data will be made available on request.

Acknowledgments

We would like to thank Normand Mousseau, Louis Beaumier and the Energy Modelling Initiative team for their invaluable work developing the model inventory and supporting this work. We would also like to thank Caroline Lee from the Canadian Institute for Climate Choices for her thorough and thoughtful review of the paper. Finally, we would like to thank Jack Pawlyna and Tim Crownshaw for their help crafting the figures. This work has been supported by funding from MITACS Accelerate (IT14846), NSERC (RGPIN-2019-04004) and the Energy Modelling Initiative.

References

Ahmed, Bayes, 2012. The traditional four steps transportation modeling using simplified transport network: A case study of dhaka city, Bangladesh. www.setscholars.org.

Arjmand, Reza, McPherson, Madeleine, 2021. Canada's electricity system transition under alternative policy scenarios. Energy Policy under review.

Armstrong, Marianne M., Swinton, Mike C., Ribberink, Hajo, Beausoleil-Morrison, Ian, Millette, Jocelyn, 2009. Synthetically derived profiles for representing occupant-driven electric loads in Canadian housing. J. Build. Perform. Simul. 2 (1), 15–30. http://dx.doi.org/10.1080/19401490802706653.

Asaee, S. Rasoul, 2018. Potential to reduce energy consumption and GHG emissions by using renewable energy technologies in the conversion of existing houses into net-zero and near net-zero energy buildings. http://dx.doi.org/10.1145/3234698.3234771.

Asaee, S. Rasoul, Nikoofard, Sara, Ugursal, V. Ismet, Beausoleil-Morrison, Ian, 2017a. Techno-economic assessment of photovoltaic (PV) and building integrated photovoltaic/thermal (BIPV/T) system retrofits in the Canadian housing stock. Energy Build. 152 (October), 667–679. http://dx.doi.org/10.1016/j.enbuild.2017.06.071.

Asaee, S. Rasoul, Ugursal, V. Ismet, Beausoleil-Morrison, Ian, 2017b. Techno-economic assessment of solar assisted heat pump system retrofit in the Canadian housing stock. Appl. Energy 190 (March), 439–452. http://dx.doi.org/10.1016/j.apenergy.2016.12.053.

Asaee, S. Rasoul, Ugursal, V. Ismet, Beausoleil-Morrison, Ian, 2019c. Development and analysis of strategies to facilitate the conversion of Canadian houses into net zero energy buildings. Energy Policy 126 (March), 118–130. http://dx.doi.org/10.1016/j.enpol.2018.10.055.

Association of Professional Engineers of the Province of Manitoba, 1995. Certificate of engineering acheivement for the development of the hydro-electric resource management evaluation system (HERMES).

Avraam, Charalampos, Bistline, John E.T., Brown, Maxwell, Vaillancourt, Kathleen, Siddiqui, Sauleh, 2021. North American natural gas market and infrastructure developments under different mechanisms of renewable policy coordination. Energy Policy 148, 111855. http://dx.doi.org/10.1016/j.enpol.2020.111855.

Axsen, J., Goldberg, S., Bailey, J., Kamiya, G., Langman, B., Cairns, J., Wolinetz, M., Miele, A., 2015. Electrifying vehicles: Insights from the Canadian plug-in electric vehicle study. Vancouver.

Bahn, Olivier, Vaillancourt, Kathleen, 2020. Implications of EMF 34 scenarios on renewable deployment and carbon abatement in Canada: Insights from a regionalized energy model. Energy Policy 142, 111518. http://dx.doi.org/10.1016/j.enpol.2020.111518.

Barrington-Leigh, Christopher, Ouliaris, Mark, 2017. The renewable energy landscape in Canada: A spatial analysis. Renew. Sustain. Energy Rev. 75 (August), 809–819. http://dx.doi.org/10.1016/j.rser.2016.11.061.

Beiter, Philipp, Cole, Wesley J., Steinberg, Daniel C., 2017. Modeling the value of integrated U.S. and canadian power sector expansion. Electricity J. 30 (2), 47–59. http://dx.doi.org/10.1016/j.tej.2017.01.011.

Bernard, Jean Thomas, Bolduc, Denis, Yameogo, Nadège Désirée, 2011. A pseudo-panel data model of household electricity demand. Resour. Energy Econ. 33 (1), 315–325. http://dx.doi.org/10.1016/j.reseneeco.2010.07.002.

Bloomberg, 2020. BNEF EVO report 2020. BloombergNEF. https://about.bnef.com/electric-vehicle-outlook/.

Bourgeois, Denis, Reinhart, Christoph, Macdonald, Iain, 2006. Adding advanced behavioural models in whole building energy simulation: A study on the total energy impact of manual and automated lighting control. Energy Build. 38 (7), 814–823. http://dx.doi.org/10.1016/j.enbuild.2006.03.002.

Boyd, Erin, 2016. Overview of power sector modeling. Presented at the Department of Energy: Technical Assistance Website.

Brown, Maxwell, Cole, Wesley, Eurek, Kelly, Becker, Jon, Bielen, David, Chernyakhovskiy, Ilya, Cohen, Stuart, et al., 2019. Regional energy deployment system (ReEDS) model documentation: Version 2019. Natl. Renew. Energy Lab. (NREL) (November), www.nrel.gov/publications.

Bucking, Scott, Dermardiros, Vasken, 2018. Distributed evolutionary algorithm for co-optimization of building and district systems for early community energy masterplanning. Appl. Soft Comput. J. 63, 14–22. http://dx.doi.org/10.1016/j.asoc.2017.10.044.

Cai, Yiyong, Newth, David, Finnigan, John, Gunasekera, Don, 2015. A hybrid energy-economy model for global integrated assessment of climate change, carbon mitigation and energy transformation. Applied Energy (148), 381–395. http://dx.doi.org/10.1016/j.apenergy.2015.03.106.

Canadian Hydropower Association, 2008. Hydropower in Canada: Past Present and Future=L'hydroélectricité Au Canada : Passé, Présent et Avenir. Canadian Hydropower Association, Ottawa.

CER, 2019. Canada's energy future 2019.

Chang, Miguel, Thellufsen, Jakob Zink, Zakeri, Behnam, Pickering, Bryn, Pfenninger, Stefan, Lund, Henrik, Østergaard, Poul Alberg, 2021. Trends in tools and approaches for modelling the energy transition. Appl. Energy 290 (May), 116731. http://dx.doi.org/10.1016/j.apenergy.2021.116731.

City of Vancouver, 2015. Northeast false creek transportation study phase 2 transportation multi-modal assessment.

Clive, Seale, 2012. Sampling. In: Seale, Clive (Ed.), Researching Society and Culture, 3rd Ed. Sage Publication, London, pp. 134–152.

Conejo, Antonio J., Carrion, Miguel, Morales, Juan M., 2010. Decision Making under Uncertainty in Electricity Markets. vol. 1. Springer, New York.

Connolly, D., Lund, H., Leahy, M., 2010a. A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl. Energy http://dx.doi.org/10.1016/j.apenergy.2009.09.026.

Connolly, D., Lund, H., Leahy, M., 2010b. A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl. Energy 87 (4), 1059–1082. http://dx.doi.org/10.1016/j.apenergy.2009.09.026.

Dagoumas, Athanasios S., Koltsaklis, Nikolaos E., 2019. Review of models for integrating renewable energy in the generation expansion planning. Appl. Energy 242 (May), 1573–1587. http://dx.doi.org/10.1016/j.apenergy.2019.03.194.

Danilo, Yu, Adhikari, Min Prasad, Guiral, Aurélien, Fung, Alan S., Mohammadi, Farahnaz, Raahemifar, Kaamran, 2019. The impact of charging battery electric vehicles on the load profile in the presence of renewable energy. In: 2019 IEEE Canadian Conference of Electrical and Computer Engineering, CCECE, 2019. pp. 14–17. http://dx.doi.org/10.1109/CCECE.2019.8861730.

Delle Site, P., Filippi, F., 2009. Weighting methods in multi-attribute assessment of transport projects. Eur. Transp. Res. Rev. 1, 199–206. http://dx.doi.org/10.1007/s12544-009-0018-1.

Delucchi, Mark A., Jacobson, Mark Z., 2011. Providing all global energy with wind water, and solar power, part II: Reliability, system‘and policies. Energy Policy 39, 1170–1190. http://dx.doi.org/10.1016/j.enpol.2010.11.045.

Dolter, Brett, Rivers, Nicholas, 2018. The cost of decarbonizing the Canadian electricity system. Energy Policy 113 (February), 135–148. http://dx.doi.org/10.1016/j.enpol.2017.10.040.

Doluweera, Ganesh, Hahn, Fabian, Bergerson, Joule, Pruckner, Marco, 2020. A scenario-based study on the impacts of electric vehicles on energy consumption and sustainability in alberta. Appl. Energy 268 (June), 114961. http://dx.doi.org/10.1016/j.apenergy.2020.114961.

Doluweera, Ganesh, Hosseini, Hossein, Umeozor, Evar, Lucas, Duncan, Hyder, Ammar, 2018. Economic and environmental impacts of transitioning to a cleaner electricity grid in western Canada. Canadian Energy Res. Inst. https://ceri.ca/assets/files/Study_174_Full_Report.pdf.

Electric Power Research Institute, 2021. Canadian national electification assessment - electrification opportunities for Canada's energy future. https://www.epri.com/research/programs/109396/results/3002021160#:#:~:text=The%20Canadian%20National%20Electrification%20Assessment,place%20of%20fossil%2Dfueled%20alternatives.

Emmanuel, Michael, Doubleday, Kate, Cakir, Burcin, Marković, Marija, Hodge, Bri Mathias, 2020. A review of power system planning and operational models for flexibility assessment in high solar energy penetration scenarios. Solar Energy 210 (November), 169–180. http://dx.doi.org/10.1016/j.solener.2020.07.017.

Energy Modelling Initiative, 2021. Energy modelling initiative – bringing the tools to support Canada's energy transition. https://emi-ime.ca/.

English, Jeffrey, Niet, Taco, Lyseng, Benjamin, Keller, Victor, Palmer-Wilson, Kevin, Robertson, Bryson, Wild, Peter, Rowe, Andrew, 2020. Flexibility requirements and electricity system planning: Assessing inter-regional coordination with large penetrations of variable renewable supplies. Renew. Energy 145 (January), 2770–2782. http://dx.doi.org/10.1016/j.renene.2019.07.097.

Environment and Climate Change Canada, 2020. Canada's Greenhouse Gas and Air Pollutant Emissions Projections 2020. Government of Canada.

Environment and Climate Change Canada, 2021. Canada's climate actions for a healthy environment and a healthy economy. EC21125. https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/climate-plan-overview/actions-healthy-environment-economy.html.

Environment and Climate Change Canada, 2022. Canada's enhanced nationally determined contribution. https://www.canada.ca/en/environment-climate-change/news/2021/04/canadas-enhanced-nationally-determined-contribution.html.

FleetCarma, 2018. Charge the north - Results from the world's largest electric vehicle charging study.

Gacitua, L., Gallegos, P., Henriquez-Auba, R., Lorca, M. Negrete-Pincetic, Olivares, D., Valenzuela, A., Wenzel, G., 2018. A comprehensive review on expansion planning: Models and tools for energy policy analysis. Renew. Sustain. Energy Rev. 98 (December), 346–360. http://dx.doi.org/10.1016/j.rser.2018.08.043.

Goody, M., Lepold, S., Koke, H., Smallacombe, K., 2020. Charge the north : Findings from the complete data set of the world's largest electric vehicle study. In: 33rd Electric Vehicle Symposium (EVS33). Portland, Oregon.

Government of Canada, 2022. Greenhouse gas emisisons - Canadian environmental sustainability indicators. https://www.canada.ca/en/environment-climate-change/services/environmental-indicators/greenhouse-gas-emissions.html#transport.

Gunay, H. Burak, O'Brien, William, Beausoleil-Morrison, Ian, Gilani, Sara, 2016. Modeling plug-in equipment load patterns in private office spaces. Energy Build. 121 (June), 234–249. http://dx.doi.org/10.1016/j.enbuild.2016.03.001.

Hachem, Caroline, 2016. Impact of neighborhood design on energy performance and GHG emissions. Appl. Energy 177 (September), 422–434. http://dx.doi.org/10.1016/j.apenergy.2016.05.117.

Hachem, Caroline, Athienitis, Andreas, Fazio, Paul, 2012. Evaluation of energy supply and demand in solar neighborhood. Energy Build. 49 (June), 335–347. http://dx.doi.org/10.1016/j.enbuild.2012.02.021.

Hachem, Caroline, Fazio, Paul, Athienitis, Andreas, 2013. Solar optimized residential neighborhoods: Evaluation and design methodology. Solar Energy 95 (September), 42–64. http://dx.doi.org/10.1016/j.solener.2013.06.002.

Hall, Lisa M.H., Buckley, Alastair R., 2016. A review of energy systems models in the UK: Prevalent usage and categorisation. Appl. Energy 169 (May), 607–628. http://dx.doi.org/10.1016/j.apenergy.2016.02.044.

Hensher, David A., Button, Kenneth J. (Eds.), 2007. Handbook of Transport Modelling. 1. Handbooks in Transport. Emerald Group Publishing Limited, http://dx.doi.org/10.1108/9780857245670.

Hensher, David, Figliozzi, Miguel Andres, 2007. Behavioural insights into the modelling of freight transportation and distribution systems. Transp. Res. B 41 (9), 921–923. http://dx.doi.org/10.1016/j.trb.2007.04.002.

Hoicka, Christina E., Das, Runa, 2020. Ambitious deep energy retrofits of buildings to accelerate the 1.5 °C energy transition in Canada. Canadian Geogr. Le Géographe Canadien http://dx.doi.org/10.1111/cag.12637, Cag.12637.

Howells, Mark, Rogner, Holger, Strachan, Neil, Heaps, Charles, Huntington, Hillard, Kypreos, Socrates, Hughes, Alison, et al., 2011. OSeMOSYS: The open source energy modeling system: An introduction to its ethos structure and development. Energy Policy 39 (10), 5850–5870. http://dx.doi.org/10.1016/j.enpol.2011.06.033.

Hummon, Marissa, Palchak, David, Denholm, Paul, Jorgenson, Jennie, Olsen, Daniel J., Kiliccote, Sila, Matson, Nance, et al., 2013. Grid integration of aggregated demand response, part 2: Modeling demand response in a production cost model. www.nrel.gov/publications.

Huppmann, Daniel, Gidden, Matthew, Fricko, Oliver, Kolp, Peter, Orthofer, Clara, Pimmer, Michael, Kushin, Nikolay, et al., 2019. The MESSAGE ix integrated assessment model and the ix modeling platform (ixmp): An open framework for integrated and cross-cutting analysis of energy climate, the environment, and sustainable development. Environ. Model. Softw. 112 (2018), 143–156. http://dx.doi.org/10.1016/j.envsoft.2018.11.012.

Iqbal, M., Azam, M., Naeem, M., Khwaja, A.S., Anpalagan, A., 2014. Optimization classification algorithms and tools for renewable energy: A review. Renew. Sustain. Energy Rev. 39 (November), 640–654. http://dx.doi.org/10.1016/j.rser.2014.07.120.

Kamiya, George, Axsen, Jonn, Crawford, Curran, 2019. Modeling the GHG emissions intensity of plug-in electric vehicles using short-term and long-term perspectives. Transp. Res. Part D Transp. Environ. 69 (April), 209–223. http://dx.doi.org/10.1016/j.trd.2019.01.027.

Kim, Ju Chan, Jonathan, Salter, Kellett, Ronald, Girling, Cynthia, 2017. Relationships between variables and energy consumption in different building types. In: 2017 Proceedings of the Symposium on Simulation for Architecture and Urban Design. pp. 167–170.

Koltsaklis, Nikolaos E., Dagoumas, Athanasios S., 2018. State-of-the-art generation expansion planning: A review. Appl. Energy 230 (November), 563–589. http://dx.doi.org/10.1016/j.apenergy.2018.08.087.

Loulou, Richard, Wright, Evelyn, Giannakidis, George, Noble, Ken, 2016. Energy technology systems analysis programme. http://www.iea-etsap.org/web/Documentation.asp.

Lyseng, B., Rowe, P., Wild, J., English, T., Niet, A., Pitt, L., 2016. Decarbonising the alberta power system with carbon pricing. Energy Strategy Rev. 10 (May), 40–52. http://dx.doi.org/10.1016/j.esr.2016.05.001.

Martinez, Nicolas, Benchaabane, Youssef, Silva, Rosa Elvira, Ilinca, Adrian, Ibrahim, Hussein, Chandra, Ambrish, Rousse, Daniel R., 2019. Computer model for a wind–diesel hybrid system with compressed air energy storage. Energies 12 (18), 3542. http://dx.doi.org/10.3390/en12183542.

McPherson, M., Harvey, L.D. Danny, Karney, Bryan, 2017. System design and operation for integrating variable renewable energy resources through a comprehensive characterization framework. Renew. Energy 113, 1019–1032. http://dx.doi.org/10.1016/j.renene.2017.06.071.

McPherson, Madeleine, Ismail, Malik, Hoornweg, Daniel, Metcalfe, Murray, 2018. Planning for variable renewable energy and electric vehicle integration under varying degrees of decentralization: A case study in Lusaka. Zambia. Energy 151, 332–346. http://dx.doi.org/10.1016/j.energy.2018.03.073.

McPherson, Madeleine, Karney, Bryan, 2017. A scenario based approach to designing electricity grids with high variable renewable energy penetrations in ontario Canada: Development and application of the SILVER model. Energy 138 (November), 185–196. http://dx.doi.org/10.1016/j.energy.2017.07.027.

McPherson, Madeleine, Tahseen, Samiha, 2018. Deploying storage assets to facilitate variable renewable energy integration: The impacts of grid flexibility renewable penetration, and market structure. Energy 145, 856–870. http://dx.doi.org/10.1016/j.energy.2018.01.002.

Melton, Noel, Riehl, Brianne, Peters, Jotham, 2020. What are Canada's most promising options for reducing greenhouse gas emissions? Navius Res..

Miller, Eric J., Roorda, Matthew J., 2003. Prototype model of household activity-travel scheduling. Transp. Res. Rec. 114–121.

Miller, Eric J., Vaughan, James, King, David, Austin, Matthew, 2015. Implementation of a 'Next Generation' activity-based travel demand model: The toronto case. In: 2015 Conference of the Transportation Association of Canada. Charlottetown.

Müller, Berit, Gardumi, Francesco, Hülk, Ludwig, 2018. Comprehensive representation of models for energy system analyses: Insights from the energy modelling platform for europe (EMP-E) 2017. Energy Strategy Rev. 21 (August), 82–87. http://dx.doi.org/10.1016/j.esr.2018.03.006.

Mundaca, Luis, Neij, Lena, Worrell, Ernst, McNeil, Michael, 2010. Evaluating energy efficiency policies with energy-economy models. Annu. Rev. Environ. Resour. 35, 305–344. http://dx.doi.org/10.1146/annurev-environ-052810-164840.

National Academies Press, 2014. Activity-Based Travel Demand Models: A Primer. National Academies Press, http://dx.doi.org/10.17226/22357.

National Round Table – Table ronde nationale, 2006. Getting to 2050: Canada's Transition to a Low-Emission Future. Government of Canada, http://nrt-trn.ca/climate/getting-to-2050/getting-to-2050-research.

Natural Resources Canada, 2020. Electricity facts. Government of Canada website. 2020. https://www.nrcan.gc.ca/science-data/data-analysis/energy-data-analysis/energy-facts/electricity-facts/20068#wb-cont.

Navius Research Inc., 2020. Electricity modeling 2020. https://www.naviusresearch.com/services/electricitymodeling/.

Neil, Spicer, 2012. Combining qualitative and quantitative methods. In: Seale, Clive (Ed.), Researching Society and Culture, 3rd Ed. Sage Publications, pp. 479–493.

Nekooei, Komail, Farsangi, Malihe M., Nezamabadi-Pour, Hossein, Lee, Kwang Y., 2013. An improved multi-objective harmony search for optimal placement of DGs in distribution systems. IEEE Trans. Smart Grid 4 (1), 557–567. http://dx.doi.org/10.1109/TSG.2012.2237420.

Nelson, James, Johnston, Josiah, Mileva, Ana, Fripp, Matthias, Hoffman, Ian, Petros-Good, Autumn, Blanco, Christian, Kammen, Daniel M., 2012. High-resolution modeling of the western North American power system demonstrates low-cost and low-carbon futures. Energy Policy 43 (April), 436–447. http://dx.doi.org/10.1016/j.enpol.2012.01.031.

Newsham, Guy R., Birt, Benjamin J., 2010. Building-level occupancy data to improve ARIMA-based electricity use forecasts. http://laws.justice.gc.ca/en/showtdm/cs/C-42http://lois.justice.gc.ca/fr/showtdm/cs/C-42.

Niet, T., Lyseng, J., English, V., Keller, K., Palmer-Wilson, I., Moazzen, B., Robertson, P., Wild, B., Rowe, A., 2017. Hedging the risk of increased emissions in long term energy planning. Energy Strategy Rev. 16 (June), 1–12. http://dx.doi.org/10.1016/j.esr.2017.02.001.

Olivares, D.E., Cañizares, C.A., Kazerani, M., 2014. A centralized energy management system for isolated microgrids. IEEE Trans. Smart Grid 5 (4), 1864–1875.

Palmer-Wilson, Kevin, Donald, James, Robertson, Bryson, Lyseng, Benjamin, Keller, Victor, Fowler, McKenzie, Wade, Cameron, Scholtysik, Sven, Wild, Peter, Rowe, Andrew, 2019. Impact of land requirements on electricity system decarbonisation pathways. Energy Policy 129 (June), 193–205. http://dx.doi.org/10.1016/j.enpol.2019.01.071.

pbConsult Inc., 2003. City of edmonton regional travel model overview and summary.

Peters, Jotham, Melton, Noel, 2019. Meeting Canada's climate mitigation commitments under the Paris agreement. Navius Research, on behalf of Canada's Ecofiscal Commission.

Pfenninger, Stefan, Hawkes, Adam, Keirstead, James, 2014. Energy systems modeling for twenty-first century energy challenges. Renew. Sustain. Energy Rev. 33 (May), 74–86. http://dx.doi.org/10.1016/j.rser.2014.02.003.

Rhodes, Ekaterina, Craig, Kira, Hoyle, Aaron, McPherson, Madeleine, 2021a. How do energy-economy models compare? A survey of model developers and users in Canada. Sustainability 13 (11), 5789.

Rhodes, Ekaterina, Craig, Kira, Hoyle, Aaron, McPherson, Madeleine, 2021b. IMPROVING CLIMATE POLICY PROJECTIONS a Pan-Canadian Review of Energy-Economy Models. University of Victoria.

Rhodes, Ekaterina, Hoyle, Aaron, McPherson, Madeleine, Craig, Kira, 2022. Understanding climate policy projections: A scoping review of energy-economy models in Canada. Renew. Sustain. Energy Rev. 153 (January), 111739. http://dx.doi.org/10.1016/j.rser.2021.111739.

Ridha, Elias, Nolting, Lars, Praktiknjo, Aaron, 2020. Complexity profiles: A large-scale review of energy system models in terms of complexity. Energy Strategy Rev. 30 (July), 100515. http://dx.doi.org/10.1016/J.ESR.2020.100515.

Riehl, Brianne, Peters, Jotham, 2021. Achieving net zero emissions by 2050 in Canada. Navius Research, on behalf of Canadian Institute for Climate Choices.

Ringkjøb, Hans Kristian, Haugan, Peter M., Solbrekke, Ida Marie, 2018. A review of modelling tools for energy and electricity systems with large shares of variable renewables. Renew. Sustain. Energy Rev. 96 (November), 440–459. http://dx.doi.org/10.1016/j.rser.2018.08.002.

Rivers, Nic, Jaccard, Mark, 2006. Useful models for simulating policies to induce technological change. Energy Policy 34 (15), 2038–2047. http://dx.doi.org/10.1016/j.enpol.2005.02.003.

Rouleau, Jean, Ramallo-González, Alfonso P., Gosselin, Louis, Blanchet, Pierre, Natarajan, Sukumar, 2019. Energy Build. 202 (November), 109375. http://dx.doi.org/10.1016/j.enbuild.2019.109375.

Saffari, M., Misaghian, M., Kia, A., Heidari, D., Zhang, P., Dehghanian, M.S., Aghaei, J., 2019. Stochastic robust optimization for smart grid considering various arbitrage opportunities. Electr. Power Syst. Res. 174, http://dx.doi.org/10.1016/j.epsr.2019.04.025.

Salter, Jonathan, Kellett, Ronald, Girling, Cynthia, Inomata, Fausto, 2017. Modeling energy for urban form archetypes. In: 2017 Proceedings of the Symposium on Simulation for Architecture and Urban Design. pp. 365–368.

Salter, Jonathan, Lu, Yuhao, Kim, Ju Chan, Kellett, Ronald, Girling, Cynthia, Inomata, Fausto, Krahn, Alix, 2020. Iterative 'what-if' neighborhood simulation: Energy and emissions impacts. Build. Cities 1 (1), 293–307. http://dx.doi.org/10.5334/bc.51.

Sauter, Patrick S., Solanki, Bharatkumar V., Cañizares, Claudio A., Bhattacharya, Kankar, Hohmann, Sören, 2019. Electric thermal storage system impact on northern communities' microgrids. IEEE Trans. Smart Grid 10 (1), 852–863. http://dx.doi.org/10.1109/TSG.2017.2754239.

Siddiqui, Sauleh, Vaillancourt, Kathleen, Bahn, Olivier, Victor, Nadejda, Nichols, Christopher, Avraam, Charalampos, Brown, Maxwell, 2020. Integrated North American energy markets under different futures of cross-border energy infrastructure. Energy Policy 144 (September), 111658. http://dx.doi.org/10.1016/j.enpol.2020.111658.

Simonovic, Slobodan P., Grahovac, Jovan, 1991. Evolution of a decision support system for reservoir operations: Manitoba hydro case study. Decision Support Syst. 485–526. http://dx.doi.org/10.1007/978-3-642-76048-8_23.

Snell, Jacob, 2020. HERMES. Energy modelling initiative (EMI) 2020. https://emi-ime.ca/inventory-model/hermes/.

Sola, Alaia, Corchero, Cristina, Salom, Jaume, Sanmarti, Manel, 2018. Simulation tools to build urban-scale energy models: A review. Energies 11 (12), 3269. http://dx.doi.org/10.3390/en11123269.

Sovacool, Benjamin K., Axsen, Jonn, Sorrell, Steve, 2018. Promoting novelty rigor, and style in energy social science: towards codes of practice for appropriate methods and research design. Energy Res. Soc. Sci. 45 (November), 12–42. http://dx.doi.org/10.1016/J.ERSS.2018.07.007.

Swan, Lukas G., Ismet Ugursal, V., 2009. Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. Renew. D Sustain. Energy Rev. 13 (8), 1819–1835. http://dx.doi.org/10.1016/j.rser.2008.09.033.

Swan, Lukas G., Ismet Ugursal, V., Beausoleil-Morrison, Ian, 2011. Occupant related household energy consumption in Canada: Estimation using a bottom-up neural-network technique. Energy Build. 43 (2–3), 326–337. http://dx.doi.org/10.1016/j.enbuild.2010.09.021.

Swan, L.G., Ugursal, V. Ismet, Beausoleil-Morrison, Ian, 2008. A new hybrid end-use energy and emissions model of the Canadian housing stock. In: Third SBRN and SESCI 33rd Joint Conference, vol. 8.

Swan, Lukas, Ugursal, V. Ismet, Beausoleil-Morrison, Ian, 2009. Implementation of a Canadian residential energy end-use model for assessing new technology impacts. In: IBPSA 2009 - International Building Performance Simulation Association 2009. pp. 1429–36.

Systematic Solutions, 2017a. ENERGY 2020 documentation. Beavercreek, ohio.

Systematic Solutions, 2017b. ENERGY 2020 overview. Beavercreek, ohio.

The City of Calgary, 2001. Transportation modelling in calgary. Calgary.

Timmerman, Jonas, Vandevelde, Lieven, Eetvelde, Greet Van, 2014. Towards low carbon business park energy systems: Classification of techno-economic energy models. Energy 75 (October), 68–80. http://dx.doi.org/10.1016/j.energy.2014.05.092.

Trutnevyte, Evelina, Barton, John, O'Grady, Áine, Ogunkunle, Damiete, Pudjianto, Danny, Robertson, Elizabeth, 2014. Linking a storyline with multiple models: A cross-scale study of the UK power system transition. Technol. Forecasting Soc. Change 89 (November), 26–42. http://dx.doi.org/10.1016/j.techfore.2014.08.018.

Tu, Ran, Gai, Yijun (Jessie), Farooq, Bilal, Posen, Daniel, Hatzopoulou, Marianne, 2020. Electric vehicle charging optimization to minimize marginal greenhouse gas emissions from power generation. Appl. Energy 277 (November), 115517. http://dx.doi.org/10.1016/j.apenergy.2020.115517.

United States Department of Energy, 2020. About building energy modeling. 2020. https://www.energy.gov/eere/buildings/about-building-energy-modeling.

Vaillancourt, Kathleen, Bahn, Olivier, Levasseur, Annie, 2019a. The role of bioenergy in low-carbon energy transition scenarios: A case study for quebec (Canada). Renew. Sustain. Energy Rev. 102 (March), 24–34. http://dx.doi.org/10.1016/j.rser.2018.11.025.

Vaillancourt, Kathleen, Bahn, Olivier, Levasseur, Annie, 2019b. The role of bioenergy in low-carbon energy transition scenarios: A case study for quebec (Canada). Renew. Sustain. Energy Rev. 102 (March), 24–34. http://dx.doi.org/10.1016/j.rser.2018.11.025.

Vaillancourt, Kathleen, Bahn, Olivier, Sigvaldason, Oskar, 2018. The Canadian contribution to limiting global warming below 2°c: An analysis of technological options and regional cooperation. Lecture Notes Energy 64, 227–244. http://dx.doi.org/10.1007/978-3-319-74424-7_14.

van Beeck, 1999. Classification of Energy Models, 777, FEW Research Memorandum.

Ventosa, Mariano, Baıllo, Álvaro, Ramos, Andrés, Rivier, Michel, 2005. Electricity market modeling trends. Energy Policy 33 (7), 897–913. http://dx.doi.org/10.1016/j.enpol.2003.10.013.

Webster, Jessica, Korteling, Brett, 2013. Evaluating residential energy, emissions and cost scenarios for prince george's official community plan: ICEM approach, methods and SCEC3 model results. Canmet Energy https://www.fraserbasin.bc.ca/_Library/ClimateToolkit/Evaluating_Residential_EE_Cost_Scenarios_PG.pdf.

Webster, Jessica, Korteling, Brett, Gilmour, Brent, Margerm, Katelyn, Beaton, John, 2011. Integrated community energy modelling: Developing map-based models to support energy and emissions planning in Canadian communities. In 315, 3–60. http://dx.doi.org/10.3384/ecp110573153.

whatIF? Technologies, 2016. Canadian energy systems simulator (caness). http://www.whatiftechnologies.com/caness.

Wills, A.D., Beausoleil-Morrison, I., Ugursal, V.I., 2018. Adaptation and validation of an existing bottom-up model for simulating temporal and inter-dwelling variations of residential appliance and lighting demands. J. Build. Perform. Simul. 11 (3), 350–368. http://dx.doi.org/10.1080/19401493.2017.1369570.

Wolinetz, M., Axsen, J., 2017. How policy can build the plug-in electric vehicle market: Insights from the respondent-based preference and constraints (REPAC) model. Technol. Forecast. Soc. Change 117, 238–250.

Wolinetz, Michael, Axsen, Jonn, Peters, Jotham, Crawford, Curran, 2018. Simulating the value of electric-vehicle-grid integration using a behaviourally realistic model. Nat. Energy 3 (2), 132–139. http://dx.doi.org/10.1038/s41560-017-0077-9.

Wong, Steven, Pinard, Jean Paul, 2017. Opportunities for smart electric thermal storage on electric grids with renewable energy. IEEE Trans. Smart Grid 8 (2), 1014–1022. http://dx.doi.org/10.1109/TSG.2016.2526636.

Yu, Danilo, Brookson, Aidan, Fung, Alan S., Raahemifar, Kaamran, Mohammadi, Farahnaz, 2018. Transactive control of a residential community with solar photovoltaic and battery storage systems. In: IOP Conference Series: Earth and Environmental Science. Hong Kong. http://dx.doi.org/10.1088/1755-1315/238/1/012051.

Zinaman, Owen, Ibanez, Eduardo, Heimiller, Donna, Eurek, Kelly, Mai, Trieu, 2015. Modeling the integrated expansion of the Canadian and U.S. power sectors with the regional energy deployment system (ReEDS). www.nrel.gov/publications.