Energy Strategy Reviews 44 (2022) 100961

Contents lists available at ScienceDirect

Energy Strategy Reviews

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

Open-source modelling infrastructure: Building decarbonization capacity in Canada

Madeleine McPherson [a,c,*], Jacob Monroe [a], Jakub Jurasz [a,f], Andrew Rowe [a,b], Richard Hendriks [d], Lauren Stanislaw [a,c], Muhammad Awais [a,c,e], Madeleine Seatle [a,c], Robert Xu [a,c], Timothy Crownshaw [a], Mohammad Miri [a,c], Dustin Aldana [a], Moe Esfahlani [g], Reza Arjmand [a,c], Mohammadali Saffari [a,c], Tristan Cusi [a], Kanwarpreet Singh Toor [a], Joel Grieco [a]

[a] *Institute for Integrated Energy Systems, University of Victoria, Canada*
[b] *Department of Mechanical Engineering, University of Victoria, Canada*
[c] *Department of Civil Engineering, University of Victoria, Canada*
[d] *University of Toronto, 35 St. George Street, Toronto, ON, M5S 1A4d, Canada*
[e] *International Institute for Applied Systems Analysis, Schlossplatz 1, A-2361, Laxenburg, Austria*
[f] *Wrocław University of Science and Technology, Wrocław, Poland*
[g] *Institut de L'énergie Trottier, Polytechnique Montréal, Bureau A-520.40, 2900, Boul. Édouard-Montpetit, Campus de L'Université de Montréal, 2500, Chemin de Polytechnique, Montréal, Québec, H3T 1J4, Canada*

A R T I C L E I N F O

Keywords:
Energy systems modelling
Energy policy
Open source software
Decarbonization

A B S T R A C T

Actions that transform our energy system are the cornerstone of decarbonizing our economy but have been hindered by the ineffective interface between researchers and decision-makers in Canada. This paper begins by arguing for a more holistic perspective on energy system decarbonization modelling and exploring how insights can aid evidence-based decision making. We then respond with the development of a modelling platform that includes three core pillars: (1) a toolbox of models that together represent the integrated energy system, (2) a dataset containing the inputs required to populate those models, and (3) a visualization suite to analyze and communicate their outputs. The Spine Toolbox is leveraged to process these three components in an efficient workflow. Taken together, the platform promotes the usability of model results by fostering consistency, transparency, and timeliness. Furthermore, the epistemic limitations of energy systems modelling and implications for platform and model design, and engaging extended peer communities, are discussed. Our hope is that this platform can be a foundational resource that facilitates collaboration between energy system and decarbonization researchers, modelling teams and decision-makers, ultimately enabling the effective application of evidence-based policy.

1. Introduction

Models are useful tools when they illuminate the interactions within a complex system, and when those insights inform better decision making. The energy system is a prime example of a complex system for which models can be useful. Especially when a system is amid a transition, the abstraction that models provide is an effective means to explore 'what if' scenarios of possible futures. Such transitions have been a recurrent feature of energy systems, spurred by the oil crises in the 1970s, human-climate system interactions in the early 2000s, or the recent push for renewable energy integration and deep decarbonization, just to name a few. In tandem with each of these transitions, the formulation, usefulness, and objectives of energy systems models have shifted. The institutional landscape, suite of available technologies, and economic realities that were present during each transition played a foundational role in shaping the modelling landscape, and the formulations that underpin it. The resulting suite of modelling platforms that are currently available has been designed in response to needs as they emerged over time: to represent systems according to the prevailing jurisdictional boundaries; to explore topics that rose to the top of policy

* Corresponding author. Institute for Integrated Energy Systems, University of Victoria, Canada
E-mail address: mmcpherson@uvic.ca (M. McPherson).

https://doi.org/10.1016/j.esr.2022.100961
Received 28 July 2021; Received in revised form 24 August 2022; Accepted 5 September 2022
Available online 11 September 2022

agendas; to deliver insights on stakeholders' specific topics of interest. With the progression of the transition to decarbonize our energy system and more broadly our economy, energy system models must once more evolve, and rise to a new set of challenges.

In recent years, models have been used to inform energy and climate decision making in many jurisdictions. The United States Mid-Century Strategy for Deep Decarbonization [1] relied on analysis of quantitative energy methods, including a 24 model intercomparison study [2], and the EnergyPATHWAYS modelling tool for deep decarbonization assessment [3]. The latter was also used by the State of Washington to develop pathways for strengthening emission limits while growing its economy [4]. In the European Union (EU), a suite of interlinked models supports the European Commission's impact assessment and analysis of policy options [5], including the Commission's climate policy impact assessments [6]. The EU organizes the Energy Modelling Platform conference where 'modellers meet decision-makers' with the objective of narrowing the gap between scientific modellers and policy makers at all levels [7]. Initiatives such as these illustrate decision-makers' interests in energy system planning models and their outputs. But more importantly, examples such as these illustrate the impact that energy system modelling can have to improve decision making when the institutional structures and the stakeholders operating within them overcome the communication gap between modellers and decision-makers. Such examples stand out as successes that need to be replicated elsewhere including Canada.

However, there are several obstacles that impede the impact that models have on decision making. In some cases, obstacles stem from ineffective or incomplete communication of model-based analysis. For example, in their review of European modelling teams, Nikas et al. argue for the importance of transparency, harmonization of modelling parameters, and disclosure of input and output datasets [8]. Similarly, Huppmann et al. observe the need for a paradigm shift towards transparency, reproducibility, and intelligibility in modelling processes [9]. In other cases, obstacles stem from structural issues within the institutions engaged in modelling efforts. For example, Howells et al. highlight the imperative of good governance principles, in addition to rigorous analytics, when energy modelling is used to provide policy support (Howells et al., 2021). Howells et al. argue that modelling efforts should engage relevant stakeholders in a way that prioritizes accountability by following the U4RIA principles: Ubuntu ('*I am because you are*' interdependency), retrievability, repeatability, reconstructability, interoperability, and auditability (Howells et al., 2021). DeCarolis et al. suggests a formalization of the energy system modelling process by developing a series of best practices [10]. Open-sourcing modelling and other software components is one of the responses to these issues. The push towards open-source models and data is emerging as a reoccurring theme that is gaining momentum. Morrison finds that the number of energy system modelling projects that have made their source code public has increased from zero in 2000 to six in 2010 and 28 in mid-2017 (when the survey was conducted) [11]. Wiese et al. contend that open-source input data for modelling is similar in character to that of a public good [12], and launched the Open Power System Data platform to collect, verify, document and publish electricity system data [13]. Indeed, open-source is a paradigm that can make a significant contribution to overcoming some of the institutional barriers that surround modelling infrastructure.

In addition to these institutional barriers, the utility of a model is, in some cases, related to the structure or content of the model itself and, subsequently, the types of issues that models are equipped to address. For example, Aryanpur et al. demonstrate how the treatment of spatial dynamics impacts the results emerging from energy system analyses; in some cases, the modeller's selection leads to an under- or -over estimation in total system costs [14]. In a complementary review, Marcy et al. compare different approaches for selecting representative time segments (in capacity expansion models) in terms of their accuracy [15]. Pfenninger et al. focus on the evolution of issues over time, arguing that challenges including security, affordability, resilience, and environmental impact, as well as opportunities including markets for new technologies and competitive industries are driving a 'renewed effort to improve the model-based analysis of energy systems' [16]. To address this, Pfenninger et al. call for resolving details in time and space in energy system optimization models; representing uncertainty and transparency in energy system simulation models; handling complexity and optimization across scales in power systems and electricity market models; and capturing the human dimension in qualitative and mixed-methods scenarios [16]. DeCarolis et al. articulate similar challenges, and argue that macro-energy systems models face the challenges associated with projecting novel technology cost and performance characteristics over multiple decades, incorporating diverse objectives and preferences, considering the high spatial temporal resolutions required to adequately represent variable renewable energy (VRE) or storage technologies, and appropriately representing uncertainty [17]. In response, the authors founded the Open Energy Outlook for the United States as an interdisciplinary and inter-sectoral team of experts collaboratively developing novel approaches within a macro-energy modelling framework [17]. In their review, Pye et al. provide a compressive summary of the key challenges facing the energy modelling community: the representation of new mitigation options (especially in end-use sectors and carbon removal options), the development of relevant insights (focused on feasibility, behaviour and policy effectiveness), and the application of models for policy analyses (including incorporating uncertainty) [18]. Taking a step back, Huppmann et al. observe paradigm shifts in systems modelling: the increasing complexity of the systems being represented, and the rising importance of nexus issues and interaction across sectors [9]. The new set of issues facing decision makers is demanding a new set of capabilities from the models themselves, as well as how these models are applied in decision-making.

In this paper, we respond to both of these issues – the institutional infrastructure surrounding models, as well as the model content itself – with an integrated energy system platform. We focus our arguments and effort around the concept of *energy system integration (ESI)*. At its core, ESI proposes the coordination of planning and operation of energy systems across scales, sectors, and vectors [19]. The reality of our energy systems has shifted: energy production is no longer largely deterministic, demand growth is not occurring at a predictable rate, and *energy*, per se, is no longer planners' primary metric of concern. With the shift to electrification and increasing penetration of renewables, energy is only one of many characteristics of importance; managing uncertainty and inherent to renewables means shifting focus onto flexibility and reliability. Modelling ESI in such a way that it 'delivers insights not numbers' [20] has implications beyond the model formulations themselves. There is a growing tension between the need to increase the scope of transition modelling while simultaneously providing insight and confidence in model results to stakeholders. ESI considers the breadth of system infrastructure and how it is modelled, as well as the human dimension – individuals and institutional frameworks – across sectors, institutions, roles, and mandates. ESI pulls together the stakeholders working in the myriad of institutions across each economic sector (e.g., services, manufacturing, resources) and each jurisdictional scale (municipal, provincial, federal). Such a vast integration and coordination effort is daunting but is a core element of operationalizing energy system decarbonization. Models play a key role but, as articulated by others in the modelling community, we must revisit *what* energy models are representing, *how* they are used, and *by whom*.

The core contribution of this paper is the development and deployment of an integrated modelling platform that has been designed in direct response to the technical and institutional demands that ESI poses. The platform has been designed to provide a holistic perspective of the energy system that spans sectors (including sector-specific models and integrated assessment models) as well as scales (from municipal to global representations). More specifically, we adopt an *integration-of-multiple-models* approach, rather than focusing on a single-sector model (that lacks a holistic perspective) or an individual integrated model (that omits detail and sector specificity). The platform is then embedded in a stakeholder engagement process designed specifically for the Canadian context. This approach is a direct response to the issues raised in our review (above): the integrated platform approach addresses some of the issues pertaining to model content, while the stakeholder engagement process address some of the issues pertaining to the institutional infrastructure surrounding models.

In the following section (Section 1.1), we review common classes of energy system models and what these models typically represent to develop a sense of the current modelling landscape. We then (Section 1.2) discuss features that help make models and the insights that they generate useful to decision makers in the midst of the system transition. Section 1.3 reviews the key stakeholders that should be part of the modelling process, and what structures (process and software) facilitate their engagement and interactions. Section 2 then describes the technical aspects of the modelling platform including the overall structure (Section 2.1), the model input database (Section 2.2), the modelling tools themselves (Section 2), and the visualization suite (Section 2.4). These technical components are then contextualized within the modelling and institutional landscape in Canada in Section 3, followed by a discussion of the epistemic limitations with modelling in Section 4. Finally, we suggest for future work (Section 5) and draw conclusions (Section 6).

1.1. What: representing the integrated energy system

The energy modelling tools at our disposal form a rich landscape from which stakeholders draw relevant insights. Each has distinct capabilities and limitations that suit a particular research question or objective. Mixed-integer production cost models, for example, optimize the dispatch of generation assets to meet load throughout the day and across the system. Agent-based travel scheduling models, as another example, can be used to predict when and where electric vehicles need to charge. As the issues that are core to decarbonization continue to evolve, so too must the modelling platforms that seek to represent them. This section characterizes this evolution and proposes a novel framework in response to the core transition drivers that are underfoot.

The first stages of decarbonizing the energy system focused on the supply side: substituting carbon intensive forms of generation with low-carbon ones [21]. However, as power systems around the world made headway on decarbonizing, the conversation turned to the demand side: displacing end-users' reliance on fossil fuels with low-carbon electricity [22,23]. As we move beyond the limits of electrification towards deep decarbonization, broader energy systems integration comes to the fore [24]. Electrification, or more broadly energy systems integration, is now emerging as a core pillar of decarbonization; in lockstep, the value of integrating the range of modelling tools to generate a holistic platform is emerging as well. Returning to the example of electric vehicles, the planning and operation of both power and transport systems need to be coordinated. Electrified heating, as another example, requires that the design and operation of power systems account for building system operations and configuration. To move forward with operationalizing electrification, modelling platforms need to represent the integration of each energy system (power, transport, buildings).

At the same time, modelling tools have been designed with a diverse range of objectives: to design or operate power systems, to quantify a policy's impact on behaviour, to understand how the distribution of employment shifts, among many others. Such objectives inherently emerge out of different disciplinary perspectives: engineers focused on system design and operation, economists focused on policy impacts, or social scientists focused on human implications. At each stage along the decarbonization pathway, differing objectives are emphasized, which in turn shifts the model framework that is the most appropriate. For example, some jurisdictions that have succeeded in setting GHG emission targets (informed by climate models) and identified the policies necessary to achieving them (using energy-economy models) must now turn their attention to planning and operation of the low-carbon infrastructure fleet (i.e. capacity expansion and dispatch models).

Planning and operating an integrated system pose a challenging but imperative departure from the convention of representing isolated power, transport, and buildings systems. If we are to not only deeply decarbonize our energy systems (including power, heat, and transport), but also improve them (e.g., a 'Just Transition'), decision makers need a holistic perspective that captures a wider range of scenarios that encapsulate the broader suite of metrics that are involved a transitioning system. By building integrating insights that span disparate systems, scales and perspectives, energy modellers can inform holistic policy development. We need modelling frameworks that are commensurate with the scale and scope inherent to the decarbonization challenge.

1.2. How: making model insights accessible

Given the objective of representing an integrated energy system, the challenge becomes how to build an integrated modelling platform and then how to apply such a platform, once built, to aid decision making. The platform components – raw data, databases, visualization scripts, the models themselves, and the tools to link those models – must be revisited, reimagined, and redeveloped. Model usability relies on several key characteristics, which are facilitated by a series of supporting tools. First, models must deliver insights on a timescale that is consistent with the available policy-making window [25]. Doing so means that the data and models must be ready for immediate use: namely, they have been built, their code has been validated, their data inputs have been gathered, verified, and are well documented. Second, decision makers must have trust that the model outputs are robust [25]. Trust can be fostered by transparency (open-source code and data) and consistency (of the insights derived from models). Third, the modelling suite and scenario runs must be inclusive of a diverse range of disciplines, perspectives, and stakeholders, specifically in the problem definition stages [25]. Doing so can be established through a well-designed modelling process.

1.3. Who: the institutional landscape

Decarbonization has become a defining feature of 21st century discourse, engaging stakeholders both within and outside of the energy sector. Consequently, energy systems modelling efforts must communicate insights to actors working within and knowledgeable about the energy system, as well as individuals whose expertise lies outside of the energy system. Despite the growing complexity and interconnectedness of model platforms, there is a parallel need to deliver insights from energy systems models to a growing list of decision makers who are implicated in decarbonization.

In addition to the broadening audience of energy systems models, stakeholders from across the breadth of energy systems must be convened. Energy systems integration demands that stakeholders and institutions hailing from distinct sectors (e.g., power, transport, manufacturing, buildings) and scales (municipal, provincial, federal) co-design and co-operate in an integrated fashion outside of their silos. Electric vehicle integration, for example, demands cooperation between transportation planners often at the municipal scale, power system operators at the provincial scale, and federal agencies negotiating national emissions reduction commitments. The multi-sector, multidisciplinary, and multi-scale nature of energy systems demands that stakeholders convene across the breadth of sectors, vectors, and scales to engage in effective planning and operational dialogue.

However, while the optimal design and operation of an integrated system demands a holistic perspective, decisions and implementation occur within discrete institutions at specific scales. Effective modelling platforms must therefore balance the expanded scope of integrated energy systems with the need to deliver insights that are appropriate for specific decision makers. The decisions that are made at each jurisdictional scale – transportation and urban planning at the municipal scale, power system planning and operation at provincial scale, devising carbon targets at the federal scale – require insights that are jurisdiction-specific but aligned.

An appropriate institutional framework that fosters relationships, dialogue, and effective communication between researchers and decision makers is needed to achieve useful modelling results and insights.

1.4. In summary

With the recent shift towards open-source data and open-source tools, institutional barriers that have prevented effective collaboration are now collapsing. At the same time, the need for effective collaboration tools is becoming apparent. The growing literature regarding the merits of open-source data and models points to improving the quality of science, enabling collaboration between investigation and policy-making, improving productivity, and fostering societal trust and debate [26].

This paper is organized around the modelling workflow depicted in Fig. 1: the decision makers and their agenda (first row) inform the technical attributes needed from data, models, and tools (second row) which rely on a series of institutional attributes (third row).

The hierarchical depiction starts with the policy makers and their policy agenda – the list of example topics that could be aided by energy modelling. The system models themselves are only one part of the software capacity; a larger platform is needed to represent the fully integrated energy system, including the interactions between systems and scales. Other elements include the raw data, databases, and visualization platforms. To be effective, this software suite must be characterized by a series of non-technical attributes: trust in the modeller and the analysis, consistency in the messaging around priority areas, transparency within and outside the modelling community; timeliness; and reproducibility of results.

This section has described the need for an integrated modelling platform and the characteristics that foster effective communication. In the next section, we describe the development of a software platform that is designed to facilitate the development of integrated energy insights. In summary, the goal of this platform is to leverage the range of modelling tool capacity - the breadth of integrated assessment and energy-economy models, with the depth of sector-specific models - to provide a holistic perspective of the energy system. The standardized suite of data and data processing tools (Section 2.2), modelling platforms (Section 2.3), visualizations (Section 2.4), and platform management (Section 2.1) that we present in this paper are designed to enable more timely and efficient execution of energy systems modelling and research. Section 3 then describes the process of communicating these results with decision makers, who can then leverage their insights to take action to decarbonize our energy systems. Finally, we describe epistemic limitations with modelling (Section 3), our intended future work (Section 4) and conclude (Section 5).

2. Responding to the 'what' and the 'how' - platform development

In the first part of this paper, we respond to the 'what' and the 'how' with the development of a software platform consisting of three pillars – data (Section 2.2), models (Section 2.3), and visualisations (Section2.4), as well as the glue that holds them together (Section 2.1). Each pillar is a critical component of an overarching framework designed to deliver evidence-based insights. Simply publishing the open-source code, while valuable from a research perspective, does not go far enough from a policy making perspective where timeliness, trust, and consistency are paramount. Insights can be delivered in a timely fashion when researchers or policy makers are already equipped with software capacity to respond as policy opportunities arise. Results can be reproduced when insights are derived from common data sources. Inclusiveness requires that analyses emerge from processes that have carefully convened appropriate stakeholders. The proposed standing repository of resources can be expanded, adapted, and leveraged by anyone with the time, interest, and expertise.

2.1. Overview structure – spine toolbox[1]

The Spine Toolbox[2] offers an effective platform to structure, standardize, version control and share data [27], with applicability to a broad range of topics. The toolbox allows for customizing model development, advancing interoperability of energy modelling frameworks, bundling scenarios for model simulation, and communicating the underlying assumptions, components and sub-processes of models [28]. Spine facilitates the exchange of input data and model results that are at the core of interconnecting data and modelling tools. The platform establishes a common data storage structure that uses data processing tools to provide data to energy models of different scope, thus allowing for an efficient modelling workflow for complex interlinked systems. This approach facilitates efficient sharing of resources across modelling tools. More specifically, Spine allows users to:

- build data processing tools that other users can utilize, avoiding duplication of effort;
- use shared server-based databases that house data in a standardized format;
- implement version control tools in repositories and built-in metadata structures;
- interconnect models to the standardized format;
- use the shared data as a starting point with additional functionality for project-based modifications;
- use tools and models developed by others within and outside of Canada;
- execute the workflow in a computing cluster or in the cloud;
- provide simplified access and query capabilities for non-technical stakeholders.

Fig. 2 shows the workflow for a theoretical example with two data sources and importers, three databases and four modelling tools.

In this study, we use the Spine platform as an interface that connects our database (Section 2.2: Pillar 1 – CODERS Database) to our a set of energy systems models (Section 2.3 Pillar 2 – Modelling platforms), which then populate a set of standardized visualizations (Section 2.4 Pillar 3 – IDEA Visualization suite). In this context, the Spine Toolbox delivers a complete view of complex model executions that enables an efficient modelling workflow.

2.2. Pillar 1 – CODERS database[3]

One of the critical impediments to modelling and implementing action towards deep decarbonization is the slow and opaque flow of information across institutional, disciplinary and regulatory boundaries [28]. Input data lack transparency and accessibility or, in some cases, are simply unavailable. When compared to the United States and Europe, the accessibility of electricity data in Canada is limited and disjointed [29]. The Energy Information Administration (EIA) in the US publishes electricity data using standardized metrics at the scale of balancing authorities (of which there are 71 in the US) [30]. The

[1] This section has been reproduced (with permission) from a report previously published with the Energy Modelling Initiative; it can be downloaded here: https://emi-ime.ca/projects/modelling-projects-2/.

[2] https://github.com/Spine-project/Spine-Toolbox.

[3] This section has been reproduced (with permission) from a report previously published with the Energy Modelling Initiative; it can be downloaded here: https://emi-ime.ca/projects/modelling-projects-2/.

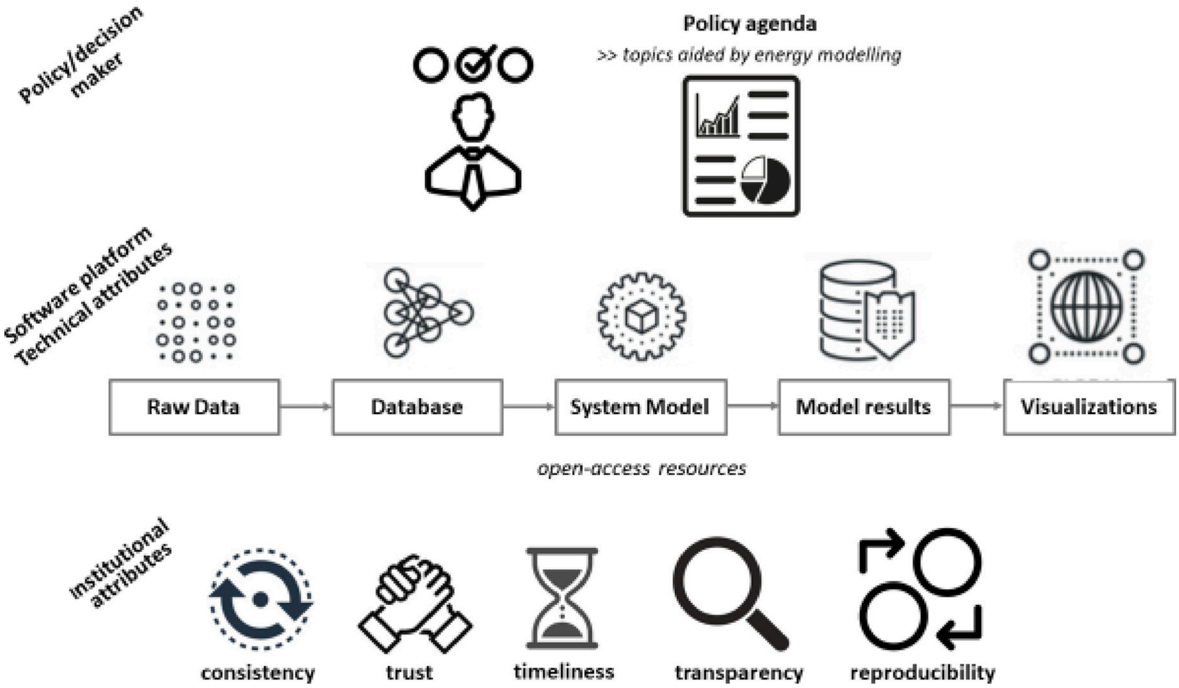

Fig. 1. Modelling workflow depiction.

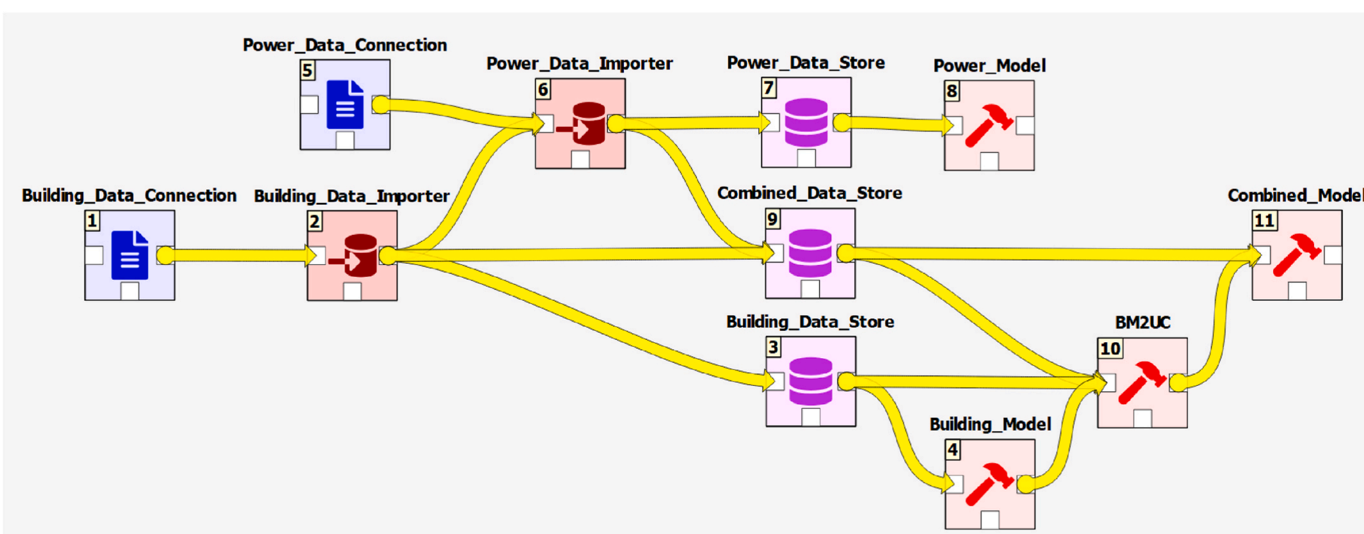

Fig. 2. Example Spine Toolbox workflow combining power system and building models.

European Network of Transmission System Operators (ENTSO) collects and distributes supply and demand data in real time for each country in the European Union [31]. Electricity data in Canada are primarily published at the provincial level, in an inconsistent and sometimes incomplete manner [29].

While there is no single reliable and standardized source for electricity data that would support electricity systems or integrated energy systems modelling in Canada, there are several federal government databases that host data pertaining to various aspects of Canada's energy system. Statistics Canada (StatCan) publishes data on electricity supply, demand and prices [32]. The Canadian Energy Regulator (CER) tracks and publishes electricity import and export data [33]. Several more recent initiatives, led by a variety of institutions, have involved efforts to fill gaps in the Canadian energy data landscape. The Canadian Centre for Energy Information (CCEI) was recently formed within StatCan with an overall investment of $15 million over 5 years [34] as an independent, one-stop shop for comprehensive energy data and expert analysis [35]. The real-time electricity data (RTED) dashboard is being developed by NRCan, the CER, and StatCan to provide granular data on near-real time electricity systems operations, including high frequency electric system data by province and territory (phase one) and a national statistical framework (phase two) [36]. The CER commodity tracking system contains monthly energy trade (imports, exports, volumes, prices) data for natural gas and LNG, crude oil, refined petroleum products, natural gas liquids, and electricity [37]. The CER's annual Canada's Energy Future report provides a conceptually consistent “Reference Case” of long-term supply and demand projections that incorporates the current economic outlook, a moderate view of energy prices and technological improvements, while considering announced climate and energy policies [38].

Though standardized and high-quality, the target data of these federal initiatives are of insufficient scope and granularity to support the existing and evolving electricity systems models that are necessary to informing grid decarbonization policy imperatives (e.g., dispatch modelling of electrification). While provincial utilities and independent electricity system operators (ISOs) across Canada do collect and maintain data of sufficient scope and granularity, there typically is no standardized approach to this data collection or provision. For example, hourly electricity demand data are only publicly available at real or near real time for BC, Alberta, Ontario, Québec, Nova Scotia and New Brunswick, but not the remaining provinces [29]. Data at the plant-level on the supply side of electricity systems are even more limited and difficult to obtain [29]. High-frequency electricity supply data are only available for participating facilities in the electricity markets in Ontario and Alberta, while the other provinces publish supply data with monthly or annual frequency [29]. Oftentimes, data is made available by utilities in response to intervener requests during regulatory proceedings or provided for a fee by system operators in response to requests from market participants and stakeholders [39].

The reasons for such data gaps are manifold, including individual, organizational, commercial and legal requirements that hinder the development of open-source databases and models [26]. Hirth (2020) elaborates on the legal aspect, explaining how researchers often infringe upon the intellectual rights of data holders, due to the unclear legal status of many energy systems databases [40]. The resulting data gaps leave modellers with inadequate resources to perform in-depth and timely analyses of Canada's low-carbon energy transition, which in turn frustrates the efforts of policy-makers while depriving the public of complete information [29]. Instead, individual institutions within Canada often develop their own datasets and tools, leading to overlapping and wasted effort as well as significant delays to policy and project implementation timelines. Furthermore, the lack of data and model openness often leads to unnecessary debate, wrongful conclusions, errors repetition and errors propagation (e.g., as observed in the case of land availability for renewable sources in Europe [41].

The dataset, Canadian Open-source Database for Energy Research and Systems-Modelling (CODERS), consolidates the existing national and provincial databases made public by utilities, system operators, independent power producers, regulators, government agencies and energy associations. Data contained in CODERS relates to generation facilities, transmission networks, substations and other system assets, as well as to system operations, demand, forecasts, imports, exports and costs. As the database evolves in response to a broader set of modelling and policy requirements, it is anticipated that the scope of data contained in CODERS will also evolve and expand. Table 1 provides a high-level summary of the current status of data collection for CODERS.

The database is built with a standardized and common structure across all 10 Canadian provinces and is designed to interface with a range of energy systems models. More specifically, CODERS contains the data required to populate energy systems models that span sectors (power, transport, buildings), scales (municipal, provincial, federal) and vectors (electricity, heat, water) (see section 2.3). CODERS is structured to be flexible, so that data can be added as they become available, removed when no longer relevant, or modified as circumstances change. By assembling such a database, we seek to support the development of *accessible* models and the production of *useful* analyses that depend on high quality, accessible and transparent data inputs. CODERS has been linked to a suite of energy systems models to support a broad suite of modelling activities developed (discussed in the next section).

2.3. Pillar 2 – modelling platforms[4]

There is a plethora of energy systems models that vary in their objectives, scope, formulation, and pre-analytic problem framings. Such characteristics are typically determined by the research question or policy objective that they are designed to address. The underlying principles driving model formulation range from physical laws in the case of engineering-based models, to price formation or adoption behaviour in the case of economic models, to resource flows and feedbacks in the case of multi-disciplinary models.

At one edge of the model landscape, integrated assessment models and energy-economy models take a broad perspective on energy, human, and environmental systems. Such models are typically developed and applied to explorations that require a high-level understanding of interactions between sectors: how resource availability impacts commodity prices which in turn impact human behaviour and demand; energy conversion processes from primary resources to secondary energy carriers and energy services. Their main strength lies in their ability to develop an appreciation of the entire energy system, often with a long-term perspective, including its coupling to the economy, interactions with human behaviour, the environment, and so on [42]. However, the breadth of such inter-system and inter-generational representations comes with an inherent trade-off. These models do not contain: (a) sufficient detail to capture the nuances within specific systems (e.g., how power flows through the transmission system); (b) sufficient spatial granularity to capture location-specific parameters (e.g., geospatial wind and solar resource availability); or (c) sufficient temporal granularity to capture various operational aspects (e.g., the generation fleet's ramping capacity).

At the other edge of the model landscape, sector-specific models represent greater system detail, providing temporal and spatial granularity but, by definition, omitting the dynamics or interactions between the modelled system or sector and its broader context. Their narrow scope enables a robust and thorough representation of an individual system with the necessary details to inform investment and operational decisions within the context of that given system. Sector-specific *design* models, on one hand, can address problems such as identifying optimal types and locations of generation assets, and the modes and configuration of transportation infrastructure, including GHG emissions and cost advantages and disadvantages across competing options. Sector-specific *operational* models, on the other hand, represent how systems could be utilized to meet demand, based on their physical system limitations (e.g., maximum power flow through a given transmission line) or should be utilized (e.g., the least cost way to supply electricity demand with the available grid assets). Such models offer the granularity, practicality, and specificity needed by planners and operators of such systems. Technology-specific models go even further. A storage degradation model, for example, can represent electro-chemical processes, and is suited to the exploration of technical design questions. However, this granularity and detail comes at the expense of providing only narrow perspectives specific to each individual system. The existence of other systems is ignored entirely or represented in such a highly simplified way that interactions, especially under changing circumstances, are impossible to capture accurately.

2.3.1. Model review – the canadian landscape

To provide context for the specific models included in our modelling suite, we briefly describe the model categories and review the modelling landscape in Canada using a recent survey conducted as part of the nation-wide Energy Modelling Initiative (EMI) [43]. Over 100 respondents detailed their model development and activities ranging from transportation to buildings, oil and gas to electricity, and river systems

[4] This section is a summary of a more extensive review paper which is currently under review.

Table 1
Data availability status in CODERS.

Generation / Storage	Name	Obtained
Generation / Storage	Owner	Obtained
Generation / Storage	Location	Obtained
Generation / Storage	Lat/long	Obtained
Generation / Storage	Region	Obtained
Generation / Storage	Substation	Obtained
Generation / Storage	Start Year	Obtained
Generation / Storage	End Year	Not available – calculated
Generation / Storage	Type	Obtained
Generation / Storage	Capacity	Obtained
Generation / Storage	Energy	Obtained
Generation	Heat Rate	Not available – calculated
Generation	Min. Capacity	Not available – calculated
Generation	Max Capacity	Not available – calculated
Generation	Min. Up Time	Not available – calculated
Generation	Min. Down Time	Not available – calculated
Generation	Ramp Rates	Not available – calculated
Generation	Must Run	Not available – calculated
Generation	Outage Rates	Not available – calculated
Generation	Start Up Cost	Not available – calculated
Generation	Shut Down Cost	Not available – calculated
Generation	O&M Costs	Under development
Storage	Technology	Obtained
Storage	Duration	Obtained
Storage	Associated Generation	Obtained
Storage	Cost	Obtained
Storage	Outage Rates	Under development
Storage	O&M Costs	Under development
Hydro	Development Potential	Obtained
Hydro	Reservoirs	Under development
Transmission	Circuit ID	Obtained
Transmission	Owner	Obtained
Transmission	Region	Obtained
Transmission	Current	Obtained
Transmission	Length	Not available – calculated
Transmission	Voltage	Obtained
Transmission	Reactance	Not available – calculated
Transmission	Rating	Not available – calculated
Transmission	Capacity	Not available – calculated
Transmission	Start Node	Obtained
Transmission	End Node	Obtained
Provincial Annual Demand	Historical Peak Capacity	Obtained
Provincial Annual Demand	Historical Annual Energy	Obtained
Provincial Annual Demand	Forecasted Peak Capacity	Obtained
Provincial Annual Demand	Forecasted Annual Energy	Obtained
Provincial Annual Demand	Before DSM	Obtained
Provincial Annual Demand	After DSM	Obtained
Provincial Annual Demand	Imports/Exports	Obtained
Provincial Hourly Demand	Historical Energy	Need
Provincial Hourly Demand	Interprovincial Transfers	Obtained
Provincial Hourly Demand	International Transfers	Obtained
Provincial Hourly Demand	International Prices	Obtained
System	Reserve Reqs.	Obtained
System	System Losses	Obtained

Obtained | Not available – calculated | Under development | Need

to climate change.

Capacity expansion models were the most prevalent model category in the EMI survey, when defined broadly to include (engineering) optimization formulations as well as (economic) equilibrium formulations. Engineering capacity expansion models, like energy-economy models, are useful for exploring the implications of policies (such as carbon taxes) but focus on infrastructure requirements rather than human preferences and behaviour. Such capacity expansion models treat electricity demand as a fixed constraint and focus on determining the least-cost capacity and infrastructure mix. Energy-economy models investigate future energy systems, including technology mix, considering factors such as costs, accessibility, and convenience; such tools are appropriate for evaluating the impacts of policies considering consumer behaviour, typically under conditions of market equilibrium. While both have relevance for policy makers, the differences in their formulations and assumptions are driven by the nature of the explorations they are designed to perform; neither can answer all research questions pertinent to decarbonization. Capacity expansion models have been applied across a range of geographic scales. The ReEDS [44] and Energy 2020 [45] models have been applied to case studies of the combined Canadian and US grids. CREST [46], the Integrated Electricity System Dispatch (IESD) model [47], gTech [48], CanESS [49], CIMS [50,51], TIMES-Canada [52], and COPPER [53,54] have been applied at the pan-Canadian scale. At the sub-national scale, the SWITCH model [55] has been applied to the Western Electricity Coordinating Council (WECC) region; OSeMOSYS [56] has been applied to select provinces, including Alberta [57]; and the North American TIMES Energy Model (NATEM)-Canada model has been applied to the Province of Quebec [58]. Such models have employed various methodologies, ranging from linear programming (CREST, ReEDS, IESD, OSeMOSYS, NATEM-Canada) to mixed integer linear programming (SWITCH, COPPER), simulation (CanESS, Energy 2020), and computable general equilibrium (CIMS, gTech), as well as various temporal resolutions (hourly, select time slices, monthly or annual averages) and modelling environments (GAMS or Python). These models also differ in their representations of transmission, storage, power flow, reserve requirements, and demand response, typically determined by the research applications the model is designed to represent. ReEDS is robust from a standpoint of technology differentiation, incorporating each major technology category in extensive technical and operational detail. However, it lacks a robust representation of hydroelectric resources that are of particular importance in the Canadian context. Like ReEDs, CREST and COPPER include representations of transmission and pumped hydro storage assets as well as a spatial and temporal resolution well-suited for representing VRE technologies and (theoretical) hydro resources. However, CREST's static time horizon (representing a given future year) omits development pathways, while its exclusion of demand response, mixed-integer dispatch, and reserve requirements limit its ability to delve into power system dynamics and electrification. COPPER has a limited technology suite and does not represent Canada's provincially distinct carbon policies. OSeMOSYS is a hybrid capacity expansion and dispatch model: it can be used in a traditional capacity expansion or in operational mode (i.e., hourly optimal dispatch with specified technology mixes) including nodal/spatial representations for transmission and trade. For example, it has been run as an hourly optimization for a one-year study period to examine VRE, storage, ramping requirements, and associated regulations [59]. CanESS, CIMS, and Energy 2020 represent the full energy system (beyond the electricity sector), enabling analyses of sectoral interdependence, but omit detail regarding electrification processes. Lengthier reviews of energy-economy models and of energy systems models can be found in Refs. [60,61], respectively.

On the supply side, **production cost models** of the bulk power system (i.e. excluding microgrids) include SILVER (Strategic Integration of Large-scale Variable Energy Resources) [62] which has been applied throughout Canada [63], HERMES (Hydro-electric Resource Management Evaluation System) which has been applied in Ontario [64], and PLEXOS which has been applied in BC [65] and Alberta [66]. The SILVER and PLEXOS formulations are similar, including unit commitment and optimal power flow formulations which allow representations of demand response and VRE resources. HERMES focuses on river systems and detailed hydro generation modelling but excludes demand response and non-hydro energy storage. In addition to these models, all electric utility companies have proprietary generation, transmission, and distribution system models, employing various optimization and simulation approaches, used in electricity system operation, planning, and scheduling.

Demand-side models tend to focus on smaller scales (neighbourhoods, cities, or provinces) than their supply-side counterparts. While transportation is often included as a demand sector in integrated models, the EMI survey identified four transportation-specific models whose methodologies range from agent-based approaches based on survey data to regression models utilizing traffic count data. Transport Quebec developed the MADIGAS model to simulate agent-based urban passenger transport and estimate traffic volumes for distinct transport modes within a given region [67,68]. The TASHA model also uses agent-based simulation, but focuses on transportation activities at the household level [69]. The Transportation Emissions Prediction Scheme (TEPS) model [70] estimates traffic count data for various regions based on regression and interpolation of historical traffic count data. Finally the ILUTE model [71] focuses on land use changes over a longer period (20 years) based on exogenous demographic data.

Like transportation, energy demand in buildings is often included in integrated models, but can also be modelled as a stand-alone sector, usually to represent or predict energy usage at either the individual building or community scales. The CHREM model represents physical system characteristics and occupant-specific energy use in households using a building archetype approach, including the impact of new technologies (e.g. retrofits, renewable generation) on energy use [72, 73], and has been applied at the national scale. The SCEC[3] model uses GIS to aggregate houses into groups (i.e. building archetypes, including commercial buildings) based on their neighborhood to model the outcomes of various policies in the town of Prince George, BC [74]. The BESOS model is a cloud-based front-end software that uses a machine learning approach, surrogate modelling, to reduce the computational burden associated with running the EnergyPlus building simulation software, designed to simulate the impacts of new technologies at the scale of individual buildings [75–78]. As in other areas of modelling, developing techniques to reduce computational burden and thereby facilitate the scale and timeliness of analysis is a common theme.

This review is intended to provide an illustrative perspective of the strengths and gaps in the Canadian energy modelling landscape and is by no means comprehensive. For example, diverse modelling efforts focused on energy management for isolated microgrids in remote communities, rate assessment, power flow, oil and gas supply, and climate have not been addressed here.

2.3.2. Modelling priorities and platform development

Upon analysis, we find that the lack of model integration is a major obstacle in the Canadian context. More specifically, we lack an integrated modelling platform which is designed to provide multi-scale, multi-sector, and multi-vector insights. This gap has several important consequences: sector specificity is required to enable electrification research, linkage to the gas system is needed to explore the potential of renewable natural gas and hydrogen, and linkage to global models is needed to enable exploration into questions regarding the water-energy-land nexus. This observation motivates our work to develop of a modelling suite that spans infrastructure systems and spatial-temporal scales, as shown in Fig. 3. Fig. 3 illustrates the models that have been incorporated into the modelling suite to date using bubbles spanning their sectoral representation (water, power, transport, fuels; shown on the y-axis) and their spatial-temporal representation (building, city, provincial, regional, national, or global; shown on the x-axis). Several of the models (EnergyPlus, City-scale, TASHA, and MESSAGEix) incorporate representations of multiple infrastructure systems (spanning multiple infrastructure systems shown on the y-axis) while others (SILVER and COPPER) focus on a single sector. Similarly, several of the models (TASHA, SILVER, COPPER, and MESSAGEix) have flexible spatial-temporal representations: TASHA can represent an individual city or collection of cities; SILVER can represent an individual city, province, or collection of provinces; COPPER can represent multi-provincial regions or Canada as a whole; MESSAGEix can represent a nation or the globe. The models illustrated by blue bubbles (SILVER and COPPER) have been developed by the co-authors, while those shown by green bubbles have been developed by other teams and integrated into the platform. The City-scale tool shown in pink compiles information from distinct models (building, transport, power) but is not a stand-alone model. Finally, arrows represent linkages established between the models allowing information (model inputs or outputs) to be exchanged.

To address this gap, we are integrating energy systems models by developing a series of linkage tools with the long-term vision of developing a comprehensive modelling platform shown in Fig. 3. Such linkage tools transfer data (model inputs and outputs) between models. For example, Seatle et al. (2021) linked the building, transportation, and electricity dispatch model to explore 100% renewable energy scenarios in the City of Regina [80]. Alternatively, Miri et al. (2022) linked the SILVER electricity dispatch model with the COPPER capacity expansion model to evaluate the flexibility of power systems across Canada [81]. With their power system focus, SILVER and COPPER often find themselves at the centre of decarbonization analyses, particularly as electrification dominates the current policy discourse. As such, COPPER and SILVER were selected as the first two components of the larger platform (shown in Fig. 3).

The COPPER framework [53] builds upon the CREST model developed by Dolter and Rivers [46] with several important modifications. Like CREST, COPPER is an optimization-based capacity expansion model that co-optimizes investment in thermal generation, VRE generation, transmission and storage technologies to investigate long-term electricity system planning options. However, unlike CREST, COPPER

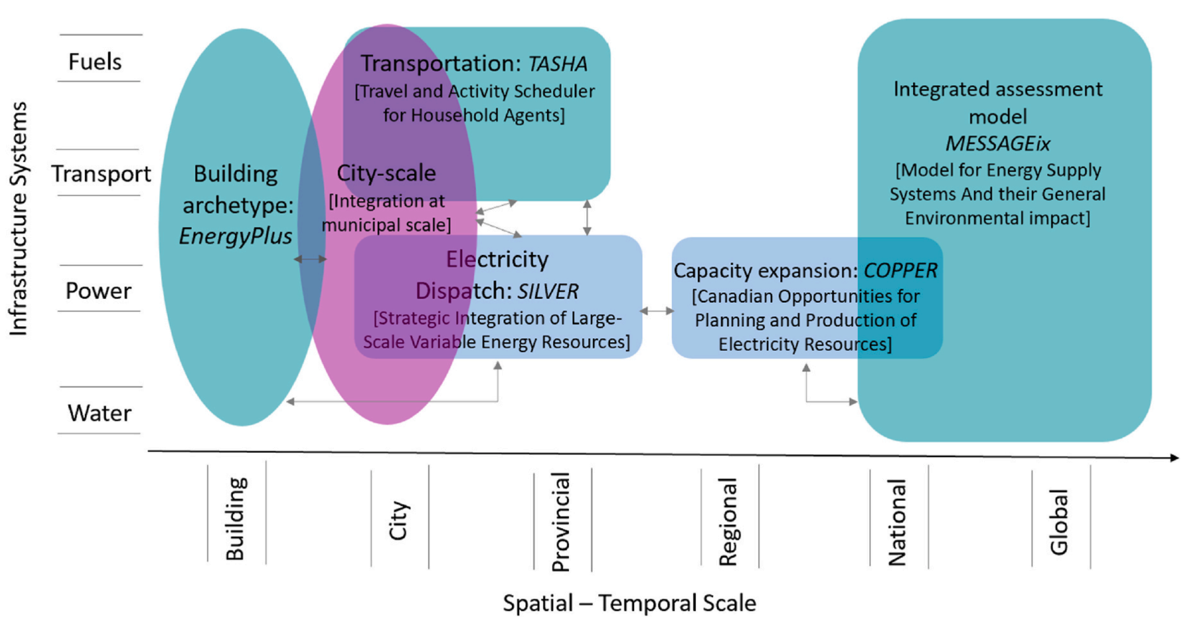

Fig. 3. The integrated modelling platform suite spanning infrastructure systems and spatial-temporal scales (adapted from Ref. [79]).

can be run as either a linear program or mixed-integer linear program; the latter allowing for the representation of binary decisions, such as whether to build a large hydro generation asset or not. Furthermore, CREST is formulated as a static, single period model, while COPPER covers multiple sequential periods. COPPER builds on CREST's rich representation of generation and storage technologies, with expanded representation of hydro assets, and adds several technology categories including small modular reactors, coal and gas with carbon capture and storage, and electrochemical storage. COPPER is based on a series of 'representative days', rather than running a full year chronologically, for reasons of computational tractability. Furthermore, COPPER incorporates up-to-date provincial and federal carbon policies as constraints on capacity expansion. Finally, COPPER is scripted in the Python language, allowing for greater interoperability with other modelling platforms. Open-sourcing COPPER gives energy modellers an extensible framework that can be applied to evaluate the implications of decarbonization policy measures, hydro asset renewal and greenfield development, technological improvements, and operational conditions on electricity system capacity planning in Canada.

The SILVER framework is an electricity system production cost and dispatch model with the requisite spatial and temporal granularity to represent the trade-offs among alternative balancing strategies for high VRE electricity grids [62]. SILVER has been applied to study the operational implications of high VRE penetrations for a series of provincial-level scenarios in Ontario [62] and at the city-level in Lusaka, Zambia [82]. SILVER has also been implemented to evaluate the utility of storage assets for different electricity system configurations and market paradigms [83]; the potential for VRE integration across Canada's power systems [63]; and pathways to a zero-emissions electricity across Canada by 2035 [54]. Open-sourcing SILVER provides the energy modelling community with an accessible production cost modelling and economic dispatch framework with high spatial and temporal resolution. This release provides energy modellers with an adaptable tool that can be readily applied to simulate policy-relevant scenarios with varying levels of demand response, storage, transmission expansion, and EV integration.

The open-source code repositories for both SILVER and COPPER will include full programming frameworks with permissive, open-source licenses. Additionally, user-manuals, tutorials for model implementation and execution, and multiple simulation test cases to validate model outputs are provided.

2.4. Pillar 3 – IDEA visualization suite[5]

The diversity and complexity of insights derived from individual models, and to a greater extent multi-model platforms, can make the interpretation of results challenging. Visualization dashboards play an important role in coherently presenting insights to facilitate the constructive dialogue necessary for navigating complex policy issues. Within the broader energy modelling landscape, IAMs have enjoyed particular success in terms of their impact on policy [84]. The reason for this stems in part from the effectiveness of their multi-model visualization platforms, which fosters robustness, transparency, and trust [84]. Representing IAM scenario outputs within a single visualization platform allows the IAM community to compare the outputs of multiple models, fostering robust discussions about the differences between model formulations and their respective scenarios. A notable visualization platform in this vein is the *Scenario Explorer* hosted by the International Institute for Applied Systems Analysis (IIASA) [85].

Within the electricity system modelling community, visualization platforms have not had the same impact, in large part because they are often tied to proprietary modelling software specific to the model for which it was created. Capacity expansion models such as Aurora [85], Hitachi ABB System Optimizer [86], and production cost models such as GE MAPS [87], PROMOD [88], and PLEXOS [89] have visualizations within graphical user interfaces integrated with their modelling functions. However, the rigidity of these visualization platforms limits their customization and frustrates comparison between distinct models. Some open-source electricity system models, such as PyPSA [90] and Switch 2.0 [91], have custom implementations of open-source plotting functions to visualize model outputs, but many exclude visualizations from their frameworks and leave it to the user to parse and plot data as required. Several open-source tools present commercial energy system model outputs, such as the National Renewable Energy Laboratory's (NREL) Multi-Area Grid Metric Analyzer (MAGMA) [92] and KALEIDOSCOPE [93] visualizations of PLEXOS model outputs. These tools benefit from transparent, open-source code and the ability to extend their capabilities using publicly available software libraries and packages.

High-resolution models beyond electricity systems can influence decision making, but also tend to lack visualization capabilities to efficiently communicate to stakeholders. There is a need for a flexible, general-purpose platform that can handle a range of energy model types, from high-resolution sector-specific models to national scale models and international IAMs. To the authors' best knowledge, aside from those developed for IAMs, there is a lack of generic platforms that can parse diverse energy system model outputs and visualize the results.

IDEA, the Integrated Dashboard for Energy transition Analysis, is a platform in development to facilitate the consistent and comprehensive visualization and comparison of low-carbon transition pathways. Importantly, the platform interactively presents output from multiple model types that span sectors (power, transport, buildings) and spatial-temporal scales (provincial, national, international), and cuts across the boundaries of established research fields and various dimensions of transition pathways. By representing model outputs in a consistent, open-source, transparent manner, the platform can facilitate and improve the energy transition dialogue between researchers, policy-makers and industry. The suite of models discussed above, focusing on the Canadian context, are one application for the IDEA platform.

Currently, IDEA produces visualizations for five different model types: IAMs (MESSAGE), capacity expansion models (COPPER), production cost models (SILVER), transportation system models (TASHA), and building system models (EnergyPlus). A unified platform allows decision-makers to analyze model outputs applying various user-defined criteria using interactive plotting features, enabling comparisons across sectors and studies. Fig. 4 illustrates the planned graphical user interface, including: scenario selection; tabs detailing distinct aspects of energy systems; chart, table, and map visualization capabilities; time display functions; comparison details; model explorer and sensitivity modes; and comparison validity warnings. The final IDEA platform will be structured around four main query types: stand-alone (one scenario for the variable of interest), comparison (multiple scenarios for the variable of interest), model exploration, and multi-variate sensitivity analysis.

The visual interface is designed to increase the visibility and intelligibility of aspects of energy transitions scenarios that are frequently omitted or obscured, and therefore often misapprehended by stakeholders. IDEA has been designed to be forward compatible with emerging modelling best-practices (including probabilistic ensemble modelling, comprehensive sensitivity auditing, and transparency regarding qualitative problem framings) and data management principles (accessibility, transparency, usability) at the forefront, to facilitate:

- The integration of insights from different model types;
- The comprehensive exploration of energy transition scenarios, including qualitative and research design aspects;

[5] Portions of this section has been reproduced (with permission) from a report previously published with the Energy Modelling Initiative; it can be downloaded here: https://emi-ime.ca/projects/modelling-projects-2/.

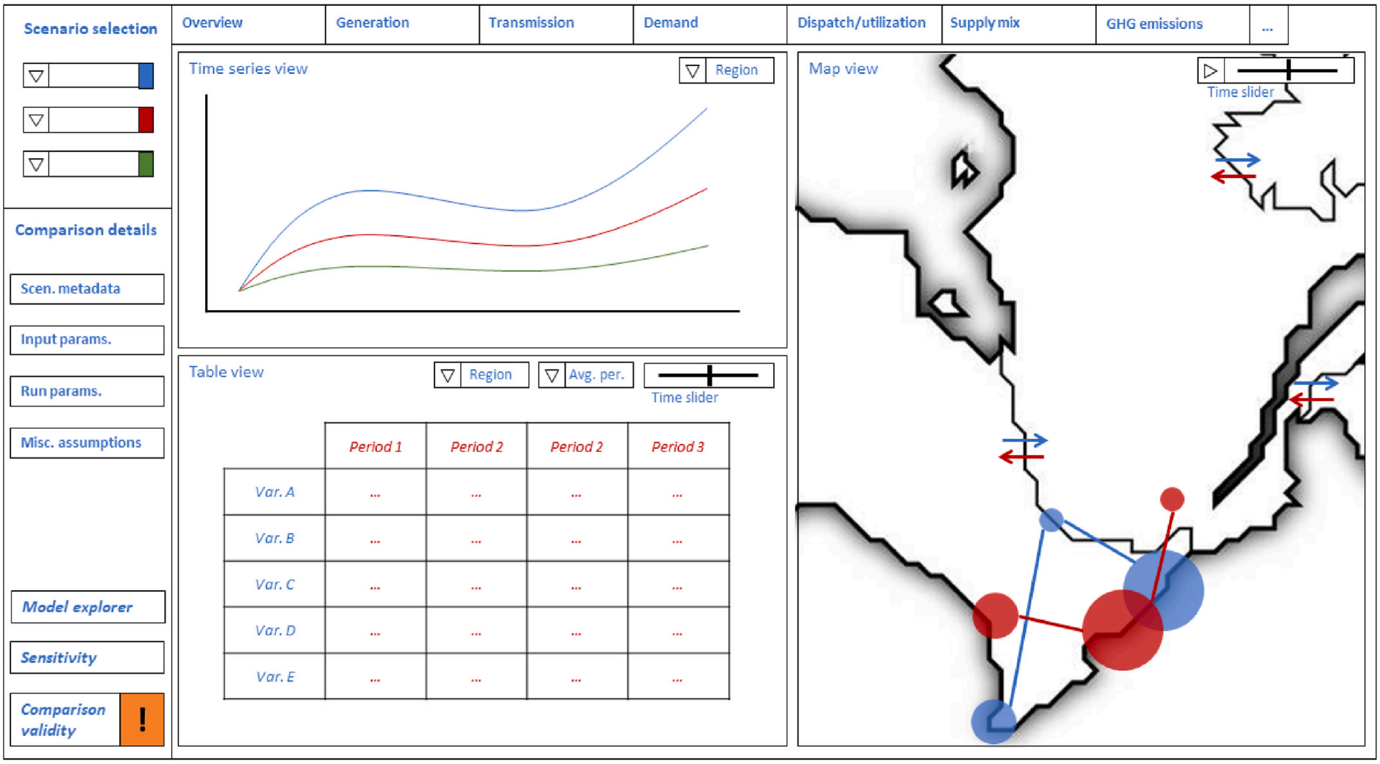

Fig. 4. Planned graphical user interface for the IDEA platform.

- Explicit comparison of energy system model formulations, boundaries, and corresponding limitations; and
- Mapping the solution space for energy system decarbonization with the requisite contextual framing.

continues to be developed via new releases to improve its capabilities and address limitations, including ongoing expansion of supported models, enumeration of visualized results, improving documentation and tutorials, and launching the platform in the form of a readily accessible web application.

3. Responding to 'the who' – the institutional landscape

Despite a focus on technology often overshadowing the conversation, Canada's energy system transition is also hindered by institutional barriers. Policy actions and investments have been burdened by entrenched interests and a lack of attention on pathways that consider disrupting employment, moderating economic growth, or imposing higher energy prices that disproportionately harm low-income households [94]. Modelling can help decision-makers navigate such political and policy decisions by clarifying potential complex socio-economic-technical interactions and identifying the likely impacts of public investments. However, the lack of a coordinated body mandated to convene stakeholders, including policy-makers from multiple jurisdictions, researchers from multiple disciplines, and citizens from across Canada, has stalled progress. In Canada, the slow and often ineffective interface between modellers and decision-makers has emerged as a particularly important but weak link, despite the commitment to evidence-based decision making that was emphasized in the Prime Minister's Mandate Letters for Infrastructure [95], Environment [96], and Natural Resources (NRCan) [97]. Canada is unique among advanced economies in its lack of a permanent institutional mandate to bridge the modelling-policy interface; in fact, the called for sustained R&D funding to support capacity in national laboratories and other institutions in Canada [98]. Our failure to leverage Canada's modelling expertise in decision making processes is a substantial missed opportunity. Other efforts to convene researchers and decision makers in decarbonization pathway design are being undertaken around the world. For example, Costa Rica's Minister of Environment and Energy collaborated with researchers from several universities in Costa Rica and Europe to develop and assess a national decarbonization plan that is technically possible and delivers financial and socioeconomic benefits (Godínez-Zamora et al., 2020). Initiatives such as this provide a valuable framework for how collaborative modelling processes occur outside of a formalized institutional structure. Energy modelling programs, such as those in the UK and California, have played a critical role in achieving climate targets while maintaining economic prosperity [99].

3.1. United Kingdom – a global benchmark of climate policy

Over the last 15 years, the UK has become a world leader on climate change, systematically meeting and exceeding its goals while developing policies that are reference points for the rest of the world [100]. This success owes credit to the Energy Research Centre (), which is mandated with four "national capabilities": (1) leveraging energy modelling capability to deliver evidence for decision making, (2) engaging a broad suite of stakeholders, (3) hosting energy data, and (4) supporting and maintaining energy models. The Committee on Climate Change (CCC), in turn, develops evidence-based climate change policy based on modelling work procured from the UKERC, performed in-house and/or through collaboration with a wide range of modellers and stakeholders. In particular, the CCC's highly effective Carbon Budgets policy marked a milestone in the use of energy and climate modelling in policy making [101,102]. The clear direction derived from the legal obligation to adopt the Carbon Budget twelve years ahead of time was instrumental in the policy's success, as it provided the time required to develop and implement policies, grow nascent markets, adapt consumer behaviour, and support infrastructure and innovation investments. Furthermore, CCC and UKERC modelling work has led to electricity market reform (implemented in 2013) [103], a ban on the sale of new internal combustion engines by 2035 (currently in the public consultation process) [104], and targeted heating systems decarbonization by 2050 [105]. The UK's evidence-based approach, resting on energy and climate modelling, has helped to achieve the UK's world leader status.

3.2. California – evidence-based approach to meeting climate and economic goals

The California Air Resources Board (CARB) and the California Energy Commission (CEC) have a history of successfully implementing evidence-based policy built on a multi-model approach [106]. The CARB develops and updates the Climate Change Scoping Plan, which identifies and evaluates emission reduction measures and mechanisms for "feasible and cost effective GHG reductions" [107] using the Energy 2020 bottom-up model and E-DRAM top-down model [108]. In parallel, the CEC is responsible for ensuring adequate and cost-effective energy supply. As part of this mandate, the CEC publishes the biannual Integrated Energy Policy Report (IEPR), which forecasts emission reductions pathways using the PATHWAYS model [109]; these forecasts are then used for planning by the California Public Utilities Commission (CPUC) and the California Independent System Operator (CAISO). The IEPR is an impactful example of the applications of energy modelling to policy. These coordinated efforts have played a key role in charting California's climate mitigation and economic growth path, while positioning California as a climate policy leader both within the United States and internationally [110].

3.3. Canada and the energy modelling hub

Several studies have used models to explore decarbonization policy options in Canada, and the interest for further studies is growing rapidly. The memorandum of understanding between the British Columbia and Canadian governments on the electrification of the gas sector [111], the Atlantic Canada Clean Energy Growth roadmap [112], the Regional Electricity Cooperation and Strategic Infrastructure Initiative (RECSI) [113] and the RECSI internal evaluation [114] were each informed by modelling efforts. However, until recently, Canada lacked an institutional mandate, such those in the UK or California, that bridges the policy-modelling interface. This posed a major obstacle to implementing evidence-based policy, transitioning our energy system, and ultimately decarbonizing our economy. The reason for this may derive from the fact that Canada's natural abundance of hydroelectric resources (approximately 60% of total electricity supply) means that we *already have* a largely decarbonized power system; many other countries have been developing institutional capacity (increasing levels of human resources, strengthening organizations, enhancing interactions between organizations [115]) to more effectively pursue concerted decarbonization activities. However, this gap has nevertheless proven to be problematic in the Canadian context in which federalism necessitates coordinated actions from levels of government with both complementary and overlapping policy levers. The extant diversity in terms of provincial energy markets, from deregulated, competitive wholesale markets to regulated Crown Corporations and hybrid structures, and access to primary resources, from fossil fuels to hydro resources, further strengthens the need for an inclusive and strategic approach to policy making. Strengthening the modelling-policy interface, distinct from strengthening the field of energy model development, depends on capacity building within a framework that convenes stakeholders in a structure suited to Canada's decentralized energy systems.

In response to their Mandate Letter, emphasizing engagement with experts to operationalize energy efficiency, climate resilience, and electrification, NRCan funded the Energy Modelling Initiative (EMI) (in 2019 and 2020) which was then renamed the Energy Modelling Hub (EMH) (funded from 2021 to 2025) to mobilize modellers, policy-makers, utilities and other stakeholders from across Canada in energy transition discourse. The EMI stakeholder consultation process identified four core tenets of an effective modelling-policy workflow that are currently lacking in the Canadian context: it must be sufficiently agile to respond during the timeframe in which the relevant policy making window is open; it must be open, transparent, and inclusive to foster trust and confidence; it must convene multiple disciplines (engineering, economics, public policy), levels of government (municipal, provincial, federal), and stakeholders (academic, public, private sector, government, utilities, NGOs) throughout the scenario definition, modelling, and analysis process; and it must develop holistic insights that span systems, scales, and vectors [25]. The Energy Modelling Hub aims to fill this gap.

3.4. The Scenario Bundling Process

For model-based studies to have an impact on decision- or policy-making, the pre-analytic process associated with building or applying the models is just as important as the technical aspects of the modelling platforms. Each of the four core tenets of an effective modelling-policy workflow that were identified by the EMI – agile, transparent, pluralistic, holistic – have both technical and institutional implications. The proposed *Scenario Bundling Process* is an iterative workflow that aims to operationalize these core tenets. The process itself is still a nascent idea, especially when compared to the mature field of energy modelling, and subject to constant iteration and improvement. The proposed *Scenario Bundling Process* centers on the co-development (by the appropriate suite of stakeholders) and execution (by the appropriate modelling teams) of '*Scenario Bundles*' that explore a selected decarbonization project, policy, or target through the series of activities shown in Fig. 5.

The *Process* begins with a series of pre-forum 'listening sessions' in which stakeholders with topic-relevant expertise (including policy makers and modellers) assemble in a forum-style workshop to: (a) define the policy issue, question and objectives; (b) develop the *Scenario Bundles*, including the input datasets and reference scenario data, 'what-if' pathways, topic scale, scope and methods; (c) prioritize the uncertainties that are most relevant to the topic at hand (technological, societal, political) and define the scenario matrix accordingly; and, (c) select the appropriate suite of models. The term 'bundling' articulates the assembly of components within the modelling workflow, including the input and reference scenario data, scenario matrix, visualization suite and models themselves. These inputs would then populate the *IDEA Visualization Suite*. After the research teams have performed their integrated modelling work, a second forum is be convened to: (a) discuss the initial model results focusing on cross-model synergies, consistencies (common themes and robust implications), and inconsistencies (where further debate is required); (b) determine if subsequent rounds of modelling is required to coalesce divergent results or redefine the *Scenario Bundle* (reverse arrow in Fig. 5); and (c) brainstorm questions and scenarios for subsequent rounds. Subsequent consultations occur with additional stakeholders identified in the first forum, extending beyond modellers and decision-makers to ensure that multiple perspectives are incorporated and that the process is inclusive and transparent. While this process represents an initial organizational template, individual contexts and circumstances may demand modifications to this workflow, such as limiting the list of stakeholders, engaging in virtual meetings, or expediting the timeline (e.g., due to a short policy window).

The *Scenario Bundling Process* is an evolving proposal that is subject to learnings from ongoing research and testing. The process has been applied in several case studies across a range of spatial scales including national, provincial, and municipal. The first case study, entitled *Clean Power Pathways* [116] explored pan-Canadian decarbonization pathways, including zero-emissions electricity and aggressive electrification, in collaboration with a range of contributors and collaborators from academia, government, the private sector, led by the David Suzuki Foundation [54]. The study linked the COPPER capacity expansion and SILVER production cost models to test the effectiveness and technical feasibility of Canada's recently proposed decarbonization policies. The

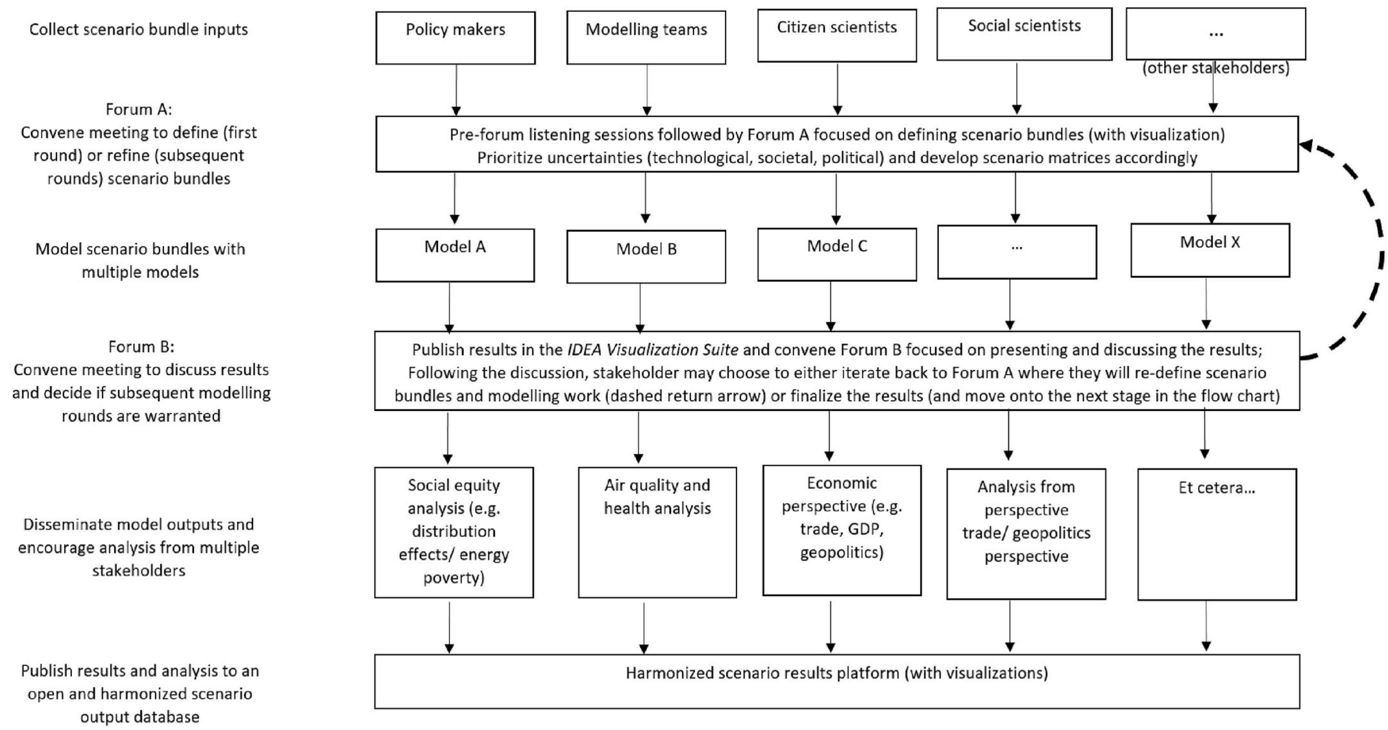

Fig. 5. Proposed *Scenario Bundling Process:* formalizing the policy-modelling workflow.

second in-progress case study delves into the role of inter-provincial transmission expansion, whereby hydro-dominated provinces balance wind and solar expansion in neighbouring fossil-dependent provinces, through a cost-benefit analysis across Canada's four western provinces. This study also links COPPER and SILVER, but focuses on transmission infrastructure, both in terms of the technical aspects of the modelling and analysis as well as the group of stakeholders who are engaged in the project. Finally, the third case study integrates power (represented by SILVER), transport (represented by TASHA), and building system (represented by EnergyPlus) models applied to the City of Regina with a 100% renewable energy target [80]. Further information can be found in Ref. [117]. All case studies have adopted the *Scenario Bundling Process* to co-develop the scenario matrix and analysis framework in a distinct way; each entailed a distinct list of stakeholders, adopted a different model implementation and approach, and engaged in a distinct series of forums and processes. While the specifics of each case study differ, the *Scenario Building Process* has thus far proven to be a useful approach to transparent, participatory modelling.

4. Addressing epistemic limitations in energy systems modelling

Beyond the accessibility issues of energy system modelling in Canada and the consistency, transparency, and timeliness of model results, discussed in the preceding sections, attention must also be given to the epistemic foundations of quantitative modelling and how this should influence the development of new platforms designed to improve the overall quality of the energy transition dialogue. Due to the highly complex and interdependent nature of today's major socio-ecological challenges, including energy system transitions, research approaches rooted in reductionism are no longer defensible, as argued by Refs. [118, 119]. Instead, these challenges require holism, systems-based approaches, and a research orientation of epistemic humility.

Ravetz (1990) and (2003) suggests that a shift away from expert monopolies on knowledge, which often suffer from reductionism and conceptual rigidity, and towards participatory approaches to modelling, including stakeholder policy design and extended peer communities, can play a vital role in building better models [121]. However, as described by Ref. [122], modelling outcomes can be impeded by insufficient popular understandings of the pertinent system, which can result in "negotiated nonsense". Therefore, an appropriate balance must be established between prioritizing demonstrated expertise and fostering greater participation.

Both the development of energy system models and the interpretation of their results must embrace transparency and reflexivity. Effective modelling must reject a common emphasis on prediction and instead embrace greater attention towards understanding qualitative problem framings and exploring of areas of ignorance. In fact, establishing appropriate problem framings is generally more important than, and must occur prior to, consideration of technical or methodological details in modelling [123–125]. The *Scenario Bundling Process* is one example of an approach to establishing alternative problem framings via participatory modelling. As noted by van Der Sluijs et al. (2005), "the main problem characteristic is that unquantifiable uncertainties dominate the quantifiable ones. Unquantifiable uncertainties include those associated with problem framings, model structures, assumptions, system boundaries, indeterminacies, and value ladenness" [123]. Special attention must be paid to the common pitfall of allowing the qualitative problem framing to be conditioned by available models and established methodological choices, as described by Ref. [126].

Knowledge produced by any given model is necessarily contingent, imperfect, and only meaningful within a finite descriptive domain. As Saltelli et al. (2020) caution, "Mathematical models are a great way to explore questions. They are also a dangerous way to assert answers" [124, 126]. Funtowicz and Ravetz (1990) note that quantitative computer models are particularly sensitive to the "garbage in, garbage out", or GIGO principle [120]. Quantification, through the language of mathematics, can give a false sense of concreteness which often serves to reinforce perceptual uniformity and rigidity. Floyd et al. (2020) argue that energy system models built on principles of pluralism and epistemic humility are needed, and the proper interpretation of results requires transparency regarding the limitations of the chosen modelling approach [127].

This research orientation suggests a greater focus on emerging modelling best practices, widely applied in climate modelling but still under-developed in energy systems modelling, such as ensemble and probabilistic methods, and comprehensive sensitivity analysis. As described by van Der Sluijs et al. (2005) and Berner and Flage (2016), this shift requires the quantification of output sensitivity (i.e., the impact of estimation error), input data pedigree ("strength of knowledge", i.e., the likelihood of estimation error), and finally, diagnostic analysis summarizing both impact and likelihood and thereby identifying key research priorities for iterative model improvement [123, 128]. As a prerequisite to such methods, model input parameters subject to epistemic uncertainty must be specified via probability distributions where possible, rather than specified as deterministic point estimates. Repeated sampling and simulation can then be used to build up arbitrarily large ensembles of plausible model outcomes, with results presented probabilistically. Achieving this shift is necessarily a gradual and involved process, as the associated data gathering, analytical, and computational requirements are substantial – legacy modelling formulations are often not immediately amenable to such a shift. However, research efforts aimed at better understating the implications of epistemic limitations in energy systems research will tend to produce more robust outcomes over time, including improved and more nuanced understanding of energy transition solution space among decision makers and other stakeholders.

5. Future work

The development of the Spine platform described in this paper, as well its implementation, are ongoing processes. Our next platform development steps include: (1) integrating a growing suite of models into the platform, (2) expanding dynamic linkages between models within the platform, and (3) developing the capacity to perform advanced visualizations and multi-model comparisons. Future development work will be guided by the demands identified by stakeholder-driven studies alongside a long-term goal of strengthening the epistemic foundations of energy systems modelling in Canada, including building capacity to both perform probabilistic and ensemble modelling and visualize the corresponding outputs where practicable, as discussed above. Incorporating an expanded suite of models – including novel methodologies – into the platform will drive energy modellers to tackle a diverse range of increasingly complex issues such as inter-sectoral policy implications or water-energy-land nexus issues, among many others, from a growing set of research perspectives. A new set of linkages must be developed for each study depending on the nature of the research question, the sectoral coverage and spatial-temporal scope, and the availability of data. As the complexity of energy issues grows, it becomes increasingly important to perform cross-study comparisons, including both same-model comparisons and multi-model compilations. Contemporaneously, the growing repositories that store the models and their results must continue to be maintained and made accessible to the energy modelling community. In addition to the model and platform developments, the *Scenario Bundling Process* will undergo further research and development. Each engagement session offers new insights regarding the participatory modelling process, convening modellers, and empowering policy makers. As new models are added onto the platform, new research questions will inevitably be posed; as energy systems become increasingly integrated, new linkages will be developed; as issues become increasingly interdisciplinary, a variety of workflows and processes will emerge. Ultimately, this platform and process aims to become the foundation for multitudinous avenues for future improvements in energy systems modelling in Canada.

6. Conclusions

This paper discusses the software and institutional infrastructure requirements for reimagining energy systems decarbonization: core energy modelling tools including an extensive database of Canadian energy system information (CODERS); a suite of models that spans the power, transport and building sectors; and a cutting-edge visualization platform to illustrate model results and identify avenues toward deep decarbonization. Integrating these three software components will allow researchers to expand the modelling scope and descriptive domain of Canadian deep decarbonization pathways. In addition, the Spine environment abstracts the workflow process in a simple way, which improves the ability of modellers to both explain their work and connect individual parameters of their models to the appropriate stakeholder during policy development sessions. Further, the design environment lowers the barrier to entry to participation in the decarbonization dialogue, allowing for a more diverse range of disciplines, perspectives, and stakeholders to interact during the modelling and policy formulation processes. The visualization platform provides a versatile toolkit to communicate model results in a manner that is understandable, interactive, and pleasing to the eye, which both engages the audience and makes model findings more accessible. In addition, the development process will unfold with an eye to the epistemic basis of energy systems modelling and emerging best practices, seeking to leverage the successes of quantitative modelling in other scientific fields while promoting pluralistic energy transition research. The modelling tools outlined in this paper can be implemented for a diverse range of objectives such as charting decarbonization transition pathways, investigating the spatial and temporal implications of decarbonization policies, the planning and operation of low-carbon generation assets, or evaluating water-energy-land nexus impacts, among others. Our ultimate goal is to assemble the requisite modelling components to explore the vast solution space of integrated energy systems through a holistic lens.

Credit author statement

Madeleine McPherson – intro, energy modelling landscape, discussion, conclusions. Jacob Monroe - open source models & Spine architecture. Andrew Rowe – paper review. Jakub Jurasz, Dustin Aldana, Tristan Cusi – software development, writing original draft (CODERS Database section). Richard Hendriks – data collection; writing original draft (CODERS Database section). Muhammad Awais, Mohammad Miri, Kanwarpreet Singh Toor, Joel Grieco – software development; writing original draft (IDEA Visualization section). Reza Arjmand – software development (COPPER model). Mohammadali Saffari – software development (SILVER model). Lauren Stanislaw, Robert Xu, Madeleine Seatle – writing original draft (model review section). Moe Esfahlani – writing original draft (model review section). Timothy Crownshaw – contributing content on epistemic limitations and IDEA visualization suite, and paper review

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to thank Normand Mousseau, Professor at the University of Montreal and Scientific Director of the Trottier Energy Institute and Louis Beaumier, Executive Director of the Trottier Energy Institute for supporting this work. We would also like to thank the Energy Modelling Initiative (invoice numbers: RA046775, RA046776) and Natural Resources Canada (agency award number: 6549) for funding our software development efforts, as well as MITACS (application reference number: IT14846) and NSERC (award number: NFRFE-2018-00338) for funding our research efforts.

References

[1] The White House, United States Mid-Century Strategy for Deep Decarbonization, 2016.
[2] L. Clarke, A. Fawcett, J. Weyant, J. McFarland, V. Chaturvendi, Y. Zhou, Technology and US emissions reductions goals: results of the EMF 24 modeling exercise, Energy J. 35 (Special Issue) (2014).
[3] J. Williams, B. Haley, F. Kahrl, J. Moore, Pathways to Deep Decarbonization in the United States. Retrieved from USDDPP Reports, 2014.
[4] Washington Governor Jay Inslee, Deep Decarbonization. (T. O. Washington, Producer), 2016.
[5] European Commission, Modelling Tools for EU Analysis, 2021.
[6] European Commission, EU 2030 Climate and Energy Framework, 2021.
[7] Energy Modelling Platform For Europe, EMP-E 2020 Modelling Climate Neutrality for the European Green Deal, 2020.
[8] A. Nikas, et al., Perspective of comprehensive and comprehensible multi-model energy and climate science in Europe, Energy 215 (Jan. 2021) 119153, https://doi.org/10.1016/j.energy.2020.119153.
[9] D. Huppmann, et al., 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. Software 112 (March 2018) (2019) 143–156, https://doi.org/10.1016/j.envsoft.2018.11.012.
[10] J. DeCarolis, et al., Formalizing best practice for energy system optimization modelling, Appl. Energy 194 (2017) 184–198, https://doi.org/10.1016/j.apenergy.2017.03.001.
[11] R. Morrison, Energy System Modeling: Public Transparency, Scientific Reproducibility, and Open Development vol. 20, Energy Strategy Rev., Apr. 2018, pp. 49–63, https://doi.org/10.1016/j.esr.2017.12.010.
[12] F. Wiese, et al., Open power system data – frictionless data for electricity system modelling, Appl. Energy 236 (December) (2019) 401–409, https://doi.org/10.1016/j.apenergy.2018.11.097.
[13] E. Z. and D. B. Neon Neue Energieökonomik, Technical University of Berlin, "Open Power System Data - A Free and Open Data Platform for Power System Modelling, 2021. https://open-power-system-data.org/. (Accessed 27 June 2021).
[14] V. Aryanpur, B. O'Gallachoir, H. Dai, W. Chen, J. Glynn, A review of spatial resolution and regionalisation in national-scale energy systems optimisation models, Energy Strategy Rev. 37 (Sep. 2021) 100702, https://doi.org/10.1016/j.esr.2021.100702.
[15] C. Marcy, T. Goforth, D. Nock, M. Brown, Comparison of temporal resolution selection approaches in energy systems models, Energy 251 (Jul. 2022) 123969, https://doi.org/10.1016/j.energy.2022.123969.
[16] S. Pfenninger, A. Hawkes, J. Keirstead, Energy systems modeling for twenty-first century energy challenges, Renew. Sustain. Energy Rev. 33 (May 2014) 74–86, https://doi.org/10.1016/j.rser.2014.02.003.
[17] J.F. DeCarolis, et al., Leveraging open-source tools for collaborative macro-energy system modeling efforts, Joule 4 (12) (2020) 2523–2526, https://doi.org/10.1016/j.joule.2020.11.002.
[18] S. Pye, et al., Modelling net-zero emissions energy systems requires a change in approach, Clim. Pol. 21 (2) (Feb. 2021) 222–231, https://doi.org/10.1080/14693062.2020.1824891.
[19] M. O'Malley, B. Kroposki, Unlocking Flexibility: Energy Systems Integration, February, 2017.
[20] R. Hamming, Numerical Methods for Scientists and Engineers, McGraw-Hill, New York, 1962.
[21] T. Morita, J.R. Robinson, J. Alcamo, N. Nakicenovic, K. Riahi, Greenhouse Gas Emission Mitigation Scenarios and Implications, 2001, ISBN 0-521-01502-2. Cambridge.
[22] S. Sakamoto, et al., Demand-side decarbonization and electrification: EMF 35 JMIP study, Sustain. Sci. 16 (2) (2021) 395–410, https://doi.org/10.1007/s11625-021-00935-w.
[23] G. Luderer, et al., Residual fossil CO2 emissions in 1.5-2 °c pathways, Nat. Clim. Change 8 (7) (2018) 626–633, https://doi.org/10.1038/s41558-018-0198-6.
[24] Deep Decarbonization Pathways Project, Pathways to Deep Decarbonization 2015 Report, SDSN - IDDRI, 2015.
[25] L. Beaumier, M. Esfahlani, M.-M. Roy, N. Mousseau, M. McPherson, Energy Modelling Centre – Long-Term Plan Proposal, a Report by the Energy Modelling Initiative, 2020.
[26] S. Pfenninger, J. DeCarolis, L. Hirth, S. Quoilin, I. Staffell, The importance of open data and software: is energy research lagging behind? Energy Pol. 101 (2017) 211–215.
[27] Spine Project, Spine Toolbox, 2020. https://github.com/Spine-project/Spine-Toolbox.
[28] R.M. Hendriks, et al., CODERS : Introducing an Open Access Dataset for Decarbonizing Canada ' S Energy System, 2021.
[29] A. Leach, N. Rivers, B. Shaffer, Canadian Electricity Markets during the COVID-19 Pandemic: an Initial Assessment, Can. Public Policy, 2020, pp. S145–S159, https://doi.org/10.3138/CPP.2020-060.
[30] U.S. Energy Information Administration, EIA, 2021. https://www.eia.gov/. (Accessed 17 February 2021).
[31] ENTSOE, Transparency Platform, 2021.
[32] Statistics Canada, Electricity and Renewable Energy, 2021. https://www150.statcan.gc.ca/n1/en/subjects/energy/electricity_and_renewable_energy.
[33] Canada Energy Regulator, International Power Lines Dashboard, 2021. https://www.cer-rec.gc.ca/en/data-analysis/facilities-we-regulate/international-power-lines-dashboard/index.html.
[34] Natural Resources Canada, Government of Canada Launches the Canadian Centre for Energy Information Website, 2020.
[35] Government of Canada, Canadian Center for Energy Information, 2021. https://energy-information.canada.ca/en.
[36] S. Préfontaine, Real-time Electricity Data (RTED), 2021.
[37] Canada Energy Regulator, Energy Commodities, 2021. https://www.cer-rec.gc.ca/en/data-analysis/energy-commodities/.
[38] Canada Energy Regulator, Canada's Energy Future, 2021.
[39] Alberta Electricity System Operator, Data Requests, 2021.
[40] L. Hirth, Open data for electricity modeling: legal aspects, Energy Strategy Rev. 27 (100433) (2020).
[41] D.S. Ryberg, M. Robinius, D. Stolten, Evaluating land eligibility constraints of renewable energy sources in Europe, Energies 11 (5) (2018) 1246.
[42] A.S. Dagoumas, N.E. Koltsaklis, Review of models for integrating renewable energy in the generation expansion planning, Appl. Energy 242 (March) (2019) 1573–1587, https://doi.org/10.1016/j.apenergy.2019.03.194.
[43] Energy Modelling Initiative, Energy Modelling Initiative Inventory, 2020. https://emi-ime.ca/inventory/. (Accessed 10 April 2020).
[44] National Renewable Energy Laboratory, Regional Energy Deployment System Model, 2019. https://www.nrel.gov/analysis/reeds/. (Accessed 18 March 2019).
[45] I. Systematic Solutions, Energy 2020 - Publications, 2019. https://www.energy2020.com/publications. (Accessed 19 October 2020).
[46] B. Dolter, N. Rivers, The cost of decarbonizing the Canadian electricity system, Energy Pol. 113 (February 2017) (2018) 135–148, https://doi.org/10.1016/j.enpol.2017.10.040.
[47] Navius Research, Integrated Electricity System Dispatch (IESD) Model, 2020. https://www.naviusresearch.com/services/electricitymodeling/. (Accessed 19 October 2020).
[48] Navius Research, Introducing gTech, 2020. https://www.naviusresearch.com/gtech/. (Accessed 19 October 2020).
[49] whatIF? Technologies, Canadian Energy Systems Simulator (CanESS), 2016. http://www.whatiftechnologies.com/caness. (Accessed 19 October 2020).
[50] M. Jaccard, International Handbook on the Economics of Energy: combining top down and bottom up in energy economy models, Int. Handb. Econ. Energy (2009) 311–331.
[51] R. Murphy, M. Jaccard, Energy efficiency and the cost of GHG abatement: a comparison of bottom-up and hybrid models for the US, Energy Pol. 39 (11) (2011) 7146–7155, https://doi.org/10.1016/j.enpol.2011.08.033.
[52] K. Vaillancourt, et al., A Canadian 2050 energy outlook: analysis with the multi-regional model TIMES-Canada, Appl. Energy 132 (Nov. 2014) 56–65, https://doi.org/10.1016/j.apenergy.2014.06.072.
[53] R. Arjmand, M. McPherson, Canada's electricity system transition under alternative policy scenarios, Energy Pol. 163 (Apr. 2022) 112844, https://doi.org/10.1016/j.enpol.2022.112844.
[54] Stephen Thomas, Shifting Power: Zero-Emissions Electricity across Canada by 2035, David Suzuki Foundation, May 2022, 978-1-988424-85–9.
[55] Renewable & Appropriate EnergyLaboratory, SWITCH-WECC- Desining Low-Cost, Low-Carbon Power Sstems Using the SWITCH Optimization Model, 2020. http://rael.berkeley.edu/old_drupal/switch/. (Accessed 19 October 2020).
[56] M. Howells, et al., OSeMOSYS: the open source energy modeling system: an introduction to its ethos, structure and development, Energy Pol. 39 (10) (Oct. 2011) 5850–5870, https://doi.org/10.1016/j.enpol.2011.06.033.
[57] K. Palmer-Wilson, et al., Impact of land requirements on electricity system decarbonisation pathways, Energy Pol. 129 (February) (2019) 193–205, https://doi.org/10.1016/j.enpol.2019.01.071.
[58] K. Vaillancourt, O. Bahn, A. Levasseur, The role of bioenergy in low-carbon energy transition scenarios: a case study for Quebec (Canada), Renew. Sustain. Energy Rev. 102 (December 2017) (2019) 24–34, https://doi.org/10.1016/j.rser.2018.11.025.
[59] J. English, et al., Flexibility requirements and electricity system planning: assessing inter-regional coordination with large penetrations of variable renewable supplies, Renew. Energy 145 (2020) 2770–2782, https://doi.org/10.1016/j.renene.2019.07.097.
[60] E. Rhodes, K. Craig, A. Hoyle, M. McPherson, Survey of energy-economy model developers and users in Canada, Mendeley Data V1 (2021) 1–39.
[61] L. Stanislaw, et al., Modeling the transition to an electric economy in Canada: a cross-sectoral review of building, transportation, and electricity system models, Prog (2021).
[62] M. McPherson, B. Karney, 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 (1) (2017) 185–196.
[63] M. Saffari, M. McPherson, Assessment of Canada's electricity system potential for variable renewable energy integration, Energy 250 (123757) (2022) 12.
[64] J. Snell, HERMES, Energy Modelling Initiative (EMI), 2020. https://emi-ime.ca/inventory-model/hermes/. (Accessed 23 March 2021).
[65] I. Moazzen, B. Robertson, P. Wild, A. Rowe, B. Buckham, Impacts of large-scale wave integration into a transmission-constrained grid, Renew. Energy 88 (Complete) (2016) 408–417, https://doi.org/10.1016/j.renene.2015.11.049.
[66] V. Keller, et al., Coal-to-biomass retrofit in Alberta - value of forest residue bioenergy in the electricity system, Renew. Energy 125 (2018) 373–383, https://doi.org/10.1016/j.renene.2018.02.128.

[67] Transports Québec, Modèles d'affectation en transport en commun, 2018. https://www.transports.gouv.qc.ca/fr/ministere/Planification-transports/modeles-transport/modeles-affectation-transport-commun/Pages/modeles-affectation-transport-commun.aspx. (Accessed 19 October 2020).

[68] Transports Québec, Concepts généraux des modèles de transport urbain des personnes, 2017.

[69] E.J. Miller, M.J. Roorda, Prototype model of household activity-travel scheduling, in: Transportation Research Record, vol. 1831, 2003, pp. 114–121, https://doi.org/10.3141/1831-13.

[70] A. Ganji, M. Shekarrizfard, A. Harpalani, J. Coleman, M. Hatzopoulou, Methodology for spatio-temporal predictions of traffic counts across an urban road network and generation of an on-road greenhouse gas emission inventory, Comput. Aided Civ. Infrastruct. Eng. (Nov. 2019), https://doi.org/10.1111/mice.12508 p. mice.12508.

[71] E.J. Miller, B. Farooq, F. Chingcuanco, D. Wang, Historical validation of integrated transport–land use model system, Transp. Res. Rec. J. Transp. Res. Board 2255 (1) (Jan. 2011) 91–99, https://doi.org/10.3141/2255-10.

[72] L.G. Swan, V.I. Ugursal, I. Beasuoleil-Morrison, A new hybrid end-use energy and emissions model of the Canadian housing stock, in: Third SBRN and SESCI 33rd Joint Conference, 2008, p. 8.

[73] L. Swan, V.I. Ugursal, I. Beasuoleil-Morrison, Implementation of a canadian residential energy end-use model for assessing new technology impacts, in: IBPSA 2009 - International Building Performance Simulation Association 2009, 2009, pp. 1429–1436.

[74] J. Webster, et al., Evaluating Residential Energy, Emissions and Cost Scenarios for Prince George's Official Community Plan: ICEM Approach, Methods and SCEC 3 Model Results, March, 2012.

[75] G. Faure, T. Christiaanse, R. Evins, G.M. Baasch, BESOS: a collaborative building and energy simulation platform, in: BuildSys 2019 - Proceedings of the 6th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation, Nov. 2019, pp. 350–351, https://doi.org/10.1145/3360322.3360995.

[76] P. Westermann, C. Deb, A. Schlueter, R. Evins, Unsupervised learning of energy signatures to identify the heating system and building type using smart meter data, Appl. Energy 264 (Apr. 2020) 114715, https://doi.org/10.1016/j.apenergy.2020.114715.

[77] G.M. Baasch, A. Wicikowski, G. Faure, R. Evins, Comparing gray box methods to derive building properties from smart thermostat data, in: BuildSys 2019 - Proceedings of the 6th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation, Nov. 2019, pp. 223–232, https://doi.org/10.1145/3360322.3360836.

[78] B. Morvaj, R. Evins, J. Carmeliet, Decarbonizing the electricity grid: the impact on urban energy systems, distribution grids and district heating potential, Appl. Energy 191 (Apr. 2017) 125–140, https://doi.org/10.1016/j.apenergy.2017.01.058.

[79] M. McPherson, T. Akhtar, Introducing a flexible platform for modelling energy systems integration, in: Presented at the 18th International Workshop on Large-Scale Integration of Wind Power into Power Systems as Well as on Transmission Networks for Offshore Wind Power Plants, Dublin, Ireland, 2019 [Online]. Available: https://windintegrationworkshop.org/dublin2019/.

[80] M. Seatle, L. Stanislaw, R. Xu, M. McPherson, Integrated transportation, building, and electricity system models to explore decarbonization pathways in Regina, saskatchewan, Front. Sustain. Cities 3 (Nov. 2021) 674848, https://doi.org/10.3389/frsc.2021.674848.

[81] M. Miri, M. Saffari, A. Reza, M. Madeleine, Integrated Models in Action: Analyzing Flexibility in the Canadian Power System toward a Zero-Emission Future, Energy, 2022.

[82] M. McPherson, M. Ismail, D. Hoornweg, M. Metcalfe, Planning for variable renewable energy and electric vehicle integration under varying degrees of decentralization: a case study in Lusaka, Zambia, Energy 151 (2018) 332–346, https://doi.org/10.1016/j.energy.2018.03.073.

[83] M. McPherson, S. Tahseen, Deploying storage assets to facilitate variable renewable energy integration: the impacts of grid flexibility, renewable penetration, and market structure, Energy 145 (2018) 856–870, https://doi.org/10.1016/j.energy.2018.01.002.

[84] M. Awais, M. Miri, J. Monroe, K.S. Toor, J. Grieco, M. McPherson, An Open-Access Integrated Platform for Visualizing Canadian ' S Transition to a Low-Carbon Energy System, 2021.

[85] D. Huppmann, J. Rogelj, E. Kriegler, V. Krey, K. Riahi, A new scenario resource for integrated 1.5 °C research, Nat. Clim. Change 8 (12) (2018) 1027–1030, https://doi.org/10.1038/s41558-018-0317-4.

[86] Hitachi, Capacity Expansion, 2021. https://www.hitachiabb-powergrids.com/offering/product-and-system/energy-portfolio-management/market-analysis/capacity-expansion. (Accessed 6 March 2021).

[87] GE Energy Consulting, GE MAPS, 2021. https://www.geenergyconsulting.com/practice-area/software-products/maps. (Accessed 6 March 2021).

[88] Hitachi, PROMOD, 2021. https://www.hitachiabb-powergrids.com/offering/product-and-system/energy-portfolio-management/market-analysis/promod. (Accessed 6 March 2021).

[89] Energy Exemplar, PLEXOS Market Simulation Software, 2021. https://energyexemplar.com/solutions/plexos/. (Accessed 6 March 2021).

[90] T. Brown, J. Hörsch, D. Schlachtberger, PyPSA: Python for power system Analysis, Open Res. Softw. 6 (1) (2018), https://doi.org/10.5334/jors.188.

[91] J. Johnston, R. Henriquez-Auba, B. Maluenda, M. Fripp, Switch 2.0: a modern platform for planning high-renewable power systems, Software 10 (2019), 100251, https://doi.org/10.1016/j.softx.2019.100251.

[92] National Renewable Energy Laboratory, Releases - NREL/MAGMMA, 2021. https://github.com/NREL/MAGMA/releases. (Accessed 6 March 2021).

[93] National Renewable Energy Laboratory, Kaleidoscope, 2021. https://github.com/NREL/kaleidoscope. (Accessed 6 March 2021).

[94] M. Jaccard, The Citizen's Guide to Climate Success, Cambridge University Press, Cambridge, United Kingdom, 2020, https://doi.org/10.1017/9781108783453.

[95] Government of Canada, Minister of Infrastructure and Communities Mandate Letter, 2020. https://pm.gc.ca/en/mandate-letters/minister-infrastructure-and-communities-mandate-letter. (Accessed 3 February 2020).

[96] Government of Canada, Minister of Environment and Climate Change Mandate Letter, 2020. https://pm.gc.ca/en/mandate-letters/minister-environment-and-climate-change-mandate-letter. (Accessed 3 February 2020).

[97] Government of Canada, Minister of Natural Resources Mandate Letter, 2020. https://pm.gc.ca/en/mandate-letters/minister-natural-resources-mandate-letter. (Accessed 3 February 2020).

[98] IEA, Energy Policies of IEA Countries - Canada 2015 Review, 2015.

[99] L. Beaumier, N. Mousseau, S.-P. Breton, M. Purdon, For a Sustained Canadian Energy Systems Modelling Initiative, 2017.

[100] Climate Action Tracker, United Kingdom Current Policy Projections, 2020. https://climateactiontracker.org/countries/uk/current-policy-projections/. (Accessed 14 April 2020).

[101] Committee Climate Change, The Fourth Carbon Budget – Reducing Emissions through the 2020s, 2010. London, UK.

[102] Committee on Climate Change, The Fifth Carbon Budget - the Next Step towards a Low-Carbon Economy, 2015.

[103] UK Government, Energy Act 2013 Chapter 32, 2013. United Kingdom.

[104] UK Government, Open Consultation: Consulting on Ending the Sale of New Petrol, Diesel and Hybrid Cars and Vans, 2020.

[105] UK Government, Clean Growth - Transforming the Heating: Overview of Current Evidence, 2018.

[106] California Energy Commission, 2015 Integrated Energy Policy Report, Sacramento, 2015.

[107] California Legislative Assembly, Bill 32, 2006. Chapter 488, Section 1, Division 25.5. CALIFORNIA GLOBAL WARMING SOLUTIONS ACT of 2006, 2006.

[108] California Air Resources Board, Economic Models, Sacramento, 2010.

[109] E3, Tools: PATHWAYS Model, 2017. San Francisco.

[110] Energy Futures Initiative, Optionality, Flexibility & Innovation: Pathways for Deep Decarbonization in California, 2019. Washington D.C.

[111] Government of Canada, Memorandum of Understanding between the Government of Canada and the Government of British Columbia on the Electrification of the Natural Gas Sector, 2020. https://pm.gc.ca/en/news/backgrounders/2019/08/29/memorandum-understanding-between-government-canada-and-government.

[112] Government of Canada, Atlantic Canada Growth Strategy - Clean Energy, 2019.

[113] Natural Resources Canada, Clean Energy and Electricity Infrastructure, 2021.

[114] Government of Canada, Evaluation of the Regional Electricity Cooperation and Strategic Infrastructure (RECSI) Initiative, 2019. https://www.nrcan.gc.ca/nrcan/plans-performance-reports/strategic-evaluation-division/reports-plans-year/evaluation-reports-2019/evaluation-regional-electricity-cooperation-and-strategic-infrastructure-recsi-initiative/22363. (Accessed 8 January 2021).

[115] S. Willems, K. Baumert, Institutional Capacity and Climate Actions, 2003.

[116] David Suzuki Foundation, Clean Power Pathways, 2022. https://davidsuzuki.org/project/clean-electricity/. (Accessed 12 August 2022).

[117] Madeleine McPherson, Stakeholder engaged energy systems modelling: three Canadian case studies, in: Presented at the 21st Wind & Solar Integration Workshop, the Hauge, Netherlands, Oct. 2022 [Online]. Available: https://windintegrationworkshop.org/.

[118] I. Prigogine, I. Stengers, Order Out of Chaos: Man's New Dialogue with Nature, Bantam Books, Toronto, Canada, 1984.

[119] F. Capra, P.L. Luisi, The Systems View of Life: a Unifying Vision, Cambridge University Press, Cambridge, UK, 2014.

[120] S. Funtowicz, J. Ravetz, Post-normal science: a new science for new times, Sci. Eur. 266 (10) (1990) 20–22.

[121] J.R. Ravetz, Models as metaphors, in: B. Kasemir, J. Jäger, C.C. Jaeger, M. T. Gardner (Eds.), Public Participation in Sustainability Science: A Handbook, Cambridge University Press, Cambridge, 2003, p. xxix, https://doi.org/10.1017/CBO9780511490972.

[122] Matthias Ruth, Innovation, technology, and economic growth, in: Handbook on Growth and Sustainability, Cheltenham, Gloucestershire, UNITED KINGDOM, Edward Elgar Publishing, 2017, pp. 213–231, https://doi.org/10.4337/9781783473564.00018.

[123] Jeroen P. van der Sluijs, Matthieu Craye, Silvio Funtowicz, Penny Kloprogge, Jerry Ravetz, James Risbey, Combining quantitative and qualitative measures of uncertainty in model-based environmental assessment: the NUSAP system, Risk Anallysis 25 (2) (2005) 481–484.

[124] A. Saltelli, et al., Five ways to ensure that models serve society: a manifesto, Nature 582 (7813) (2020) 482–484, https://doi.org/10.1038/d41586-020-01812-9.

[125] M. Giampietro, K. Mayumi, A. Şorman, Energy Analysis for a Sustainable Future: Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism, Routledge, London, 2013, https://doi.org/10.4324/9780203107997.

[126] A. Saltelli, et al., The technique is never neutral. How methodological choices condition the generation of narratives for sustainability, Environ. Sci. Pol. 106 (2020) 87–98, https://doi.org/10.1016/j.envsci.2020.01.008.
[127] J. Floyd, et al., Energy descent as a post-carbon transition scenario: how ‘knowledge humility’ reshapes energy futures for post-normal times, Futures 122 (Sep. 2020) 102565, https://doi.org/10.1016/j.futures.2020.102565.
[128] C.L. Berner, R. Flage, Comparing and integrating the NUSAP notational scheme with an uncertainty based risk perspective, Reliab. Eng. Syst. Saf. 156 (2016) 185–194.