University of Victoria

Sustainable Energy Systems Integration & Transitions (SESIT) Group

An open-access integrated platform for visualizing Canadian's transition to a low-carbon energy system

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Abstract

Efforts to develop and apply modeling tools that explore Canada's energy system transition towards decarbonization have grown in recent years. Such analyses deal with topics ranging from technical to economic, resource and environmental issues, and social and behavioral topics. Given the scope of the transition at hand, each of these topics merits a place in the discussion. Furthermore, the scientific community faces the important challenge of reporting sustainable energy transition pathways both to decision-makers and the broader public. But the diversity of insights derived from models makes it challenging to have that conversation in a coherent and cohesive manner. Visualization dashboards can play an important role in presenting insights in a coherent way to facilitate the constructive dialogue that is necessary for navigating complex choices. This project presents an integrated modeling platform to facilitate a comprehensive yet consistent suite of Canada's low-carbon transition pathways. Importantly, the platform represents the output from multiple model types that span sectors (power, transport, buildings), as well as scales (provincial, national, international) in an interactive platform. This suite of modeling tools and data cuts across the boundaries of established fields of knowledge and covers multiple dimensions of the energy transition. By representing a suite of model outputs in an open-source and transparent way, the platform can facilitate and improve the dialogue between researchers, policymakers and industry when investigating key questions linked to the energy transition.

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List of Abbreviations

BESOS	Building and Energy Simulation, Optimization and Surrogate Modeling Platform
COPPER	Canadian Opportunities for Planning and Production of Electricity Resources model
CREST	Cost of Renewable Energy Spreadsheet Tool
EV	Electric Vehicle
GDP	Gross Domestic Droduct
GE MAPS	General Electric Multi Area Production Simulation Software program
GHG	Greenhouse Gas
GLOBIOM	GLobal BIOsphere Management
HERMES	Hydro Electric Reservoir Management Evaluation System
HVAC	Heating Ventilation and Air Conditioning
IAM	Integrated Assessment Model
IAMC	Integrated Assessment Modeling Consortium
IEA	International Energy Agency
IESD	Integrated Electricity System Dispatch Model
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
MACRO	Aggregated Macro-economic model
MAGMA	Multi-Area Grid Metric Analyzer
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact

NDC	Nationally Determined Contribution
NREL	National Renewable Energy Laboratory
NZEH	Near Zero Energy House
PLEXOS	An integrated energy system simulation software designed for energy market analysis
PROMOD	Generator Portfolio Modeling System
PyPSA	Python for Power System Analysis
ReEDS	Regional Energy Deployment System
SESIT	Sustainable Energy Systems Integration & Transitions group
SILVER	Strategic Integration of Large-capacity Variable Energy Resources model
SSP	Shared Socioeconomic Pathways
SWITCH	Solar, Wind, Conventional and Hydroelectric generation and Transmission model
TASHA	Travel Activity Scheduler for Household Agents
VRE	Variable Renewable Energy
WDCAS	Wind–Diesel Hybrid System with Compressed Air Energy Storage

1 Introduction

Following Canada's commitment to the Paris agreement and the establishment of clean energy targets [1], there has been an increased focus on energy systems management and optimization. The energy systems' transitions towards the clean energy future can be categorized by their research area and energy sector. Modeling exercises are helpful to produce policy insights into the energy systems for a broader community. Modeling exercises also include a capacity-building component that allows modelers to interact with stakeholders and share the results from models. These activities involve different types of data and depending on the scope of the project, and it can be pretty laborious. Visualization dashboards can play an important role in presenting insights in a coherent way to facilitate the constructive dialogue that is necessary for navigating complex choice

1.1 Visualization platforms in a broader context

Energy system models produce diverse model outputs or results, which can be difficult for non-modelers or non-experts to understand. Visualizations are an effective means to communicate model outputs in an accessible way, which can then foster meaningful insights and effective decision making. Options ranging from custom plotting scripts to proprietary visualization formats are currently implemented in the energy system modeling space. This section reviews some of the visualization platforms that are of particular relevance in the IAM and electricity system modeling fields and reviews the prevalence of integrated visualization platforms in both commercial modeling software and its open-source counterparts.

Within the broader energy modeling landscape, IAMs have enjoyed particular success in terms of their impact on policy. The reason for this stems, in part, from the effectiveness of their multi-model visualization platforms, which bread robustness, transparency, and trust. The IAM community has engaged in extensive efforts to compare the outputs of multiple models. Furthermore, representing IAM scenario outputs on a single visualization creates robust discussion about the differences between the different IAM models and their scenarios. The most common visualization platform for Integrated Assessment Modeling is the Scenario Explorer hosted by the International Institute for Applied Systems Analysis (IIASA) [3]. The IAM community has been outstanding about having a common visualization platform. The Scenario Explorer compares IPCC emission scenarios for established Integrated assessment models (IAMs). Users can upload model results or use existing results from established models to visualize the outputs of individual model scenarios and compare outcomes and scenarios. The platform is based around a workspace system where users set up dashboards based on their visualization needs. The dashboards consist of panels that display model results that can be filtered and cross-linked by a variety of metrics. A standardized model output format is required to utilize the platform.

Within the electricity system modeling community, visualization platforms have not had the same impact as they have done in the IAM space. The main reason for this is the fact that many data visualization platforms are tied to proprietary software specific to the model it was created for. There are limited options for presenting visualizations from different models in a single space and limited options for common platforms that generate comparisons between models. Capacity expansion models such as Aurora [3], Hitachi ABB System Optimizer [4], or production cost models such as GE MAPS [5], PROMOD [6], have visualizations and a graphical user interface built into their modeling functions. There are also integrated electricity sector models that utilize both capacity expansion and production cost modeling, such as PLEXOS [7], which also has visualizations tied to its modeling frameworks. However, these visualization methods for commercial energy models are rigid: , the outputs cannot be parsed into the visualizations, and thus limit their customizability and the comparison between different models.

Open-source energy modeling visualizations also are limed by their rigidity with being tied to single models. Open-source electricity system models such as PyPSA [8] and Switch 2.0 [9] and others rely on custom implementations of open-source plotting functions implemented on the resulting outputs. Many of these models do not provide visualizations as part of their frameworks and leave it to the user to parse and plot the data as required. There are generic, open-source programs that parse commercial energy system model outputs, such as the National Renewable Energy Laboratory's (NREL) Multi-Area Grid Metric Analyzer (MAGMA) [10]. MAGMA produces plots of PLEXOS outputs that can compare dispatch and load for different zones and scenarios across various plots. MAGMA was produced for the NREL Eastern Renewable Generation Integration Study [11]. MAGMA is released as a standalone open-source package developed in R programming utilizing the typical plotting packages [12]. KALEIDOSCOPE [13] is also a platform developed by the NREL that visualizes PLEXOS scenarios in a geographic diagram, a chord diagram, and dispatch charts. KALEIDOSCOPE is also produced in R and is built to run locally and does not have web hosting functionality. MAGMA and KALEIDOSCOPE are not written for generic inputs and are bound to receiving PLEXOS outputs. They parse data with a rplexos [14] an open-source R package that interprets PLEXOS outputs. As with other open-source projects, these platforms benefit from the transparent nature of open-source code and the ability to extend the platform's capabilities using openly available software libraries and packages. However, at the current time, the platforms are still only for representing the outputs from a single model (PLEXOS).

Several data templates and visualization dashboards have been developed within the energy modelers community for regional and global studies in response to these challenges. However, those mainly involve the Integrated Assessment Models (IAMs) results to explore scenarios for accessing sustainable pathways. Results from other sectoral and high-resolution models can make a significant impact on a local and sub-national scale. Still, those are not currently visualized and communicated to stakeholders efficiently. There is a need for a platform that can handle a suite of energy model types, varying from high-resolution sector-specific models to national scale capacity expansion models and international IAMs.

1.2 Research Objective

To the authors' best knowledge, there are not any generic platforms that parse standard energy system model outputs and visualize the results othet than IAMs. In this project, we develop an integrated modeling platform that includes five different types of models: IAM (MESSAGE), capacity expansion (COPPER), grid operation (SILVER), transportation systems (TASHA), and building systems (an archetype model). A single consistent platform allows decision-makers to analyze model outputs for various user-defined criteria using interactive plotting features, which enable comparison among and benchmarking across sectors and studies. The current study addresses the research gap by streamlining the visualization process. Specifically, this project makes the following contributions:

- Develops a process flow to convert the results of the models into a standard data format
- Develops a set of plotting functions that use the standardized results to create figures with interactive widgets that allow for quick multi-platform comparisons
- Accommodating a standardized but flexible format for reporting model outputs

- Publishes the code in an open, accessible, and transparent manner, complete with appropriate documentation.

1.3 Outline

The remainder of this report is organized as follows. Following in Section 1, other visualization platforms and their importance are discussed. This research project objectives are also discussed in Section 1.4. Section 2 describes each model type, including their input and outputs. Also, it includes and reviews cases from models that has been developed by the Sustainable Energy Systems Integration & Transitions group (SESIT) team [2] at the University of Victoria. Section 3 discusses the workflow and methodologies used to create a visualization platform. The visualization platform results are discussed in Section 4. Finally, Section 5 discusses the limitations of the current work and future plans.

2 Overview of Included model and model types

In this section, all the modeling framework typologies are discussed. Then, a case study of the model type which is developed by the SESIT team at the University of Victoria. The outputs from these models are contributing to present the showcase from the visualization platform.

2.1 Integrated Assessment Models

Integrated Assessment Models (IAMs) help researchers and policymakers understand the long-term consequences of varying socio-economic development and climate change scenarios across various scales [15]. IAMs are widely used for accessing the cost and benefits of climate change impacts and mitigation strategies. Results from IAMs have been used widely amongst the community to answer critical questions on climate change transition and to set ambitious global warming goals at the least possible cost [16].

An IAM for Canada has been built from the MESSAGEix-GLOBIOM framework. The IAM combines different modeling frameworks to assess multi-disciplinary policy decisions. The energy mix outlook in the IAM is generated with MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact). MESSAGE is a Linear Programming (LP) energy engineering model that minimizes the total discounted costs for supplying future energy demands [17].

The MESSAGE implementation in the IAM represents the entire world as 14 regions, with trade flows (imports and exports) between regions included in the decision variables. A future time horizon of 2020 or 2025 to 2100 in 10-year steps is considered in the MESSAGE cost optimization. To assess economic implications and to address feedback on economic policies, MESSAGE is linked to the aggregated macro-economic model MACRO. The macro-economic model is solved iteratively with MESSAGE until shared prices and demands converge (Krey et al., 2016).

2.1.1 Case Study: MESSAGE- Canada

The IAM simulates subregion energy mix outlooks based on exogenously defined demands for energy in the industrial, residential/commercial, and transport sectors. The demands are calculated on the basis population, urbanization, and GDP projections consistent with the Shared Socioeconomic Pathways (SSP) [19]. The subregion analysis in this project focuses on the middle-of-the-road scenario (SSP2). The demands are adjusted for each sector by first fitting econometric models to historical data on energy use, population, and GDP at the national scale and then applying the fitted models with the SSP2 projections. The demand modeling framework also assumes long-term convergence of demand intensities (measured as a unit of GDP) across countries. Historical data comes from the IEA national energy balance sheets and is calibrated for 2015. The population and GDP projections for Canada across different Shared Socioeconomic Pathways (SSPs) are shown in **Error! Reference source not found.** below.

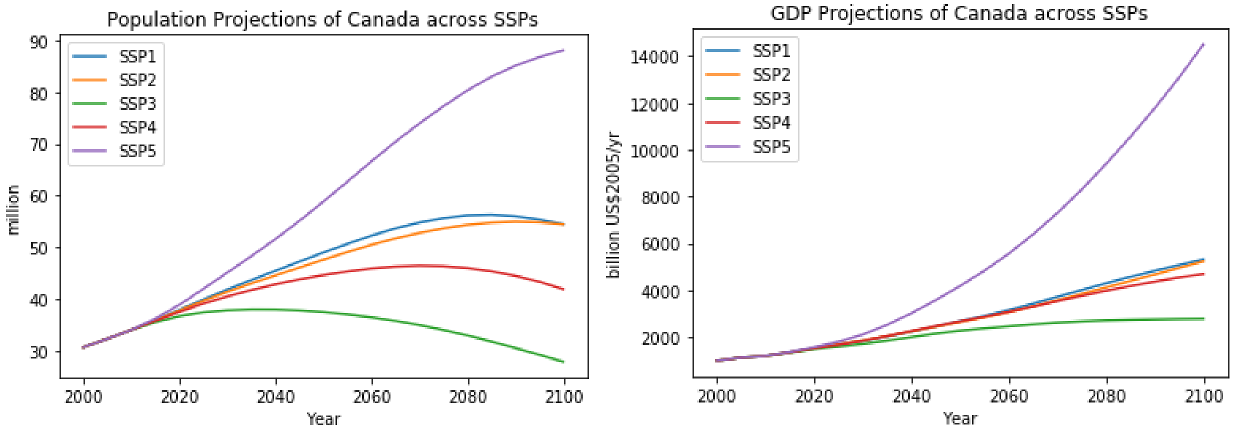


Figure 1 Population & GDP projections of Canada across SSP scenarios

MESSAGEix Canada is prototyped from MESSAGE-GLOBIOM using downscaling algorithms. Previously, this approach has been developed. for other countries as well, such as MESSAGEix-South Africa [20]. As a first step, the globally available databases are used to produce a preliminary baseline scenario for the model. The model is improved based on iterations to represent the Canadian energy system in IAM better. A baseline scenario has been accessed in this study using Canadian mitigation targets. Figure 7 shows the prototyping approach of a national scale IAM from the global IAM.

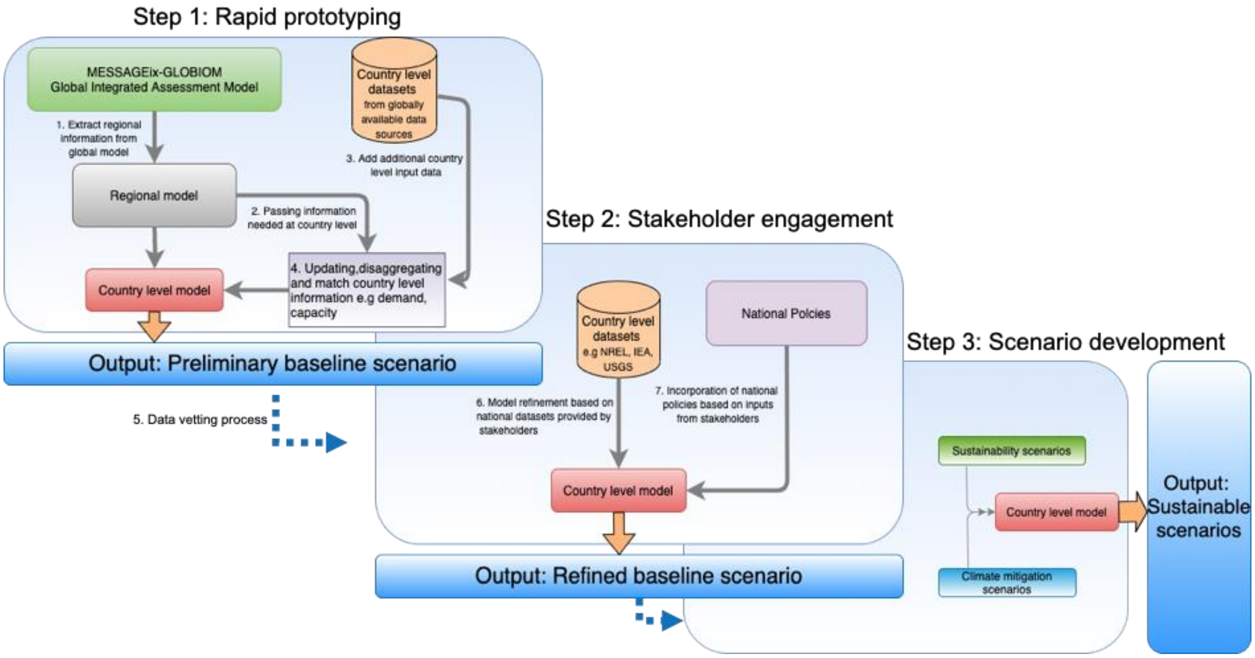


Figure 2 Rapid Prototyping approach to build a country model

2.2 Capacity Expansion Models

Capacity expansion models simulate generation and transmission investments and identify the optimized mix of generators to meet the future load. Data for fuel prices, capital, operation and maintenance costs, technical performance factors, demand, and policies are all given as inputs to these models. The planning tools are primarily used to address questions about environmental policies' impact on electricity generation and capacities. They can also analyze the costs of the electricity system in their pathway toward decarbonization. Furthermore, these platforms can calculate the emissions with respect to the electricity system of their modeled domain.

Different models explore various scales with different temporal and spatial resolutions based on their designed purpose; they can formulate the national scale with limited or aggregated representative network nodes, up to utility-scale models with high resolution.

They can also differ in the manner of managing respective operational constraints and characteristics based on the computational resources required. The method to model the renewable energies (hydro, wind, and solar) is another aspect for causing differences in representation. Moreover, some of the capacity expansion models can do calculations for the demand growth endogenously, but others make assumptions based on exogenous statistical data.

The capacity expansion models are a perfect candidate for the visualization platform because of their ability to address and assess policies and their relevant scenarios. Numerous models are developed and implemented in the Canadian domain, while the key models in this area include but are not limited to COPPER, CREST[21], ReEDS[22], IESD5, and SWITCH[9].

2.2.1 Case Study: COPPER

COPPER (Canadian Opportunities for Planning and Production of Electricity Resources) is a capacity expansion model that plans for the least cost solution representing the national Canadian electricity system with given demand, policy, and constraint—covering the horizon from the year 2020 to 2050. With recent development, the model is introduced with new features and further improvements in comparison to other models and its own predecessor – CREST [21]. Moreover, Dynamic modeling, the introduction of hydro development in the model, and recontacting availability are essential attributes that make COPPER distinguishable. Other than these new features, it also has a very fine spatial resolution representing VRE (Variable Renewable Energy) within the model. However, thermal generators are all aggregated over each province as a single node connected to the neighbor provinces with the inter-provincial transmission lines. Mathematically, COPPER solves a cost minimization problem. Its total cost function includes capital costs, fixed and variable operation and maintenance costs, fuel costs, and carbon pricing costs.

2.3 Electricity system operational models

Electricity system operational models also called grid operation models, simulate a specified electricity system's operation over a short period compared to the capacity expansion models but with a higher temporal resolution (e.g., hourly or even sub-hourly time steps). These models identify the minimized cost state of a complex system of connected generators which meets the users' demand at hourly or sub-hourly intervals on each location. Due to their short simulation period, the operational cost models can capture technical details of the electricity system.

Models in this category can vary in several pivotal factors: technical details and uncertainties representation, temporal resolution, generators characterization, spatial landscape, and reliability specification. They can vary in terms of operational state analysis and can be distinguished into three broad categories: Unit commitment, optimal dispatch, and optimal power flow. Several models were either developed or applied in the Canadian domain addressing different research questions, i.e., SILVER [23], HERMES [24], and WDCAS [25].

Operational cost models can assess resource adequacy and other reliability aspects, e.g., load shedding and curtailment. They can also analyze the impact of changes in the system, such as the effect of plant retirements and additions on system operation. Additionally, they can determine transmission congestions and local marginal prices. Lastly, Their high temporal resolution can achieve more accurate emission results at an hourly or sub-hourly basis.

The operational models can answer questions on a given generation fleet's adequacy and reliability in the electricity system of a selected region. How the retirement of pollution-intensive resources and the introduction of intermittent renewable energy generators impact a system's operation is the central question that an operational model can address. As discussed, capacity expansion models have a coarse temporal resolution. Thus, Answering the problems mentioned above is crucial in analyzing the functional aspects of a given system that underwent planning with a specific policy. As a result, the electricity system operational models have a unique role in exploring different policy choices by providing a detailed insight into the way system operates.

2.3.1 Case Study: SILVER

SILVER [26] includes optimal economic dispatch, day-ahead unit commitment, and optimal power flow modeling with network constraints as separate modules, working together to create the most realistic representation of a province's electricity network. It has several new features and improvements compared to other models in the domain. The model includes transmission expansion, storage, electric vehicles, and demand response. It can be inferred that SILVER can effectively assess different scenarios on renewable energy resources integration and retirement of pollution-intensive capacities.

2.4 Transport Model

Literature highlights several types of transportation models, all directing to one main goal of simulating and predicting the transportation load in various energy types. They vary from agent-based modeling concepts to travel demand models and integrated land use plus transportation models. The IAM models, as mentioned earlier, also include the transportation sector energy utilization and related emissions.

Electrification of the transportation system is a crucial step in achieving a decarbonized energy system of Canada, as it forms part of the targeted policy measures [27], it is targeted for the transportation sector to reduce 23 Mt of Carbon emissions plus 77 Mt of Carbon equivalent by 2030 relative to 2015 rates.

Several models are developed and used in the Canadian domain to simulate and assess routes toward the targeted goals, while these include but are not limited to TASHA [28], Residential and Transportation Stock-Rollover Model [29], Optimal Charging and Discharging Of Large Scale Electric Vehicle Systems [30],

2.4.1 Case Study: SESIT's transportation framework

The transportation model of the SESIT team is based on TASHA [28], a maintained and developed framework at the University of Toronto. The fundamental goal for TASHA is to model the Greater Toronto Area's transportation system. The model can gauge demand in the selected geographical domain by enabling EV Usage and behavioral aspects as key factors. An additional model is integrated within this framework to simulate the EV charging schedule, which translates each person's travel activities to the EV's usage in a household. The battery capacity, charging, and depletion rates are other aspects formulated in the charging model.

2.5 Building Model

Building models are usually designed to study a given building's energy usage with the given physical characteristics as inputs. The scale of a building simulation model can be varied from a single building to archetypes to a whole neighborhood or even city-scale.

In Canada, house retrofitting, new HVAC systems installation, and demand response actions are the main policies to achieve greenhouse gas reduction. Canada's building sector has a target to contribute 47 Mt of CO2 emissions by 2030 relative to 2015 levels[27]. Thus, assessing the pathways toward this and future goals is crucial and needed.

There are several building modeling frameworks developed or applied in the Canadian domain, including but not limited to BESOS[31], NZEH[32], and archetypal[33]. These models can answer various research questions based on their designed structure and purpose.

2.5.1 Case Study: SESIT's building modeling tool

The model developed by the SESIT team [2] is designed to simulate the archetypes energy use in a given building, based on the physical characteristics and their dwellers' rational behavior. Several archetypes are introduced in this model, then scaled up to represent the building sector of the whole city. The framework uses the EnergyPlus simulation tool to assess the energy consumption, then scales and calibrates the results based on the evaluated formulation for the archetype concepts.

3 Methodology

This section gives an overview of the workflows of converting different model results into standard and flexible data templates and discusses the software tools and methods applied in the visualization platform.

3.1 Overview of workflows

An appropriate data format is a key feature of hosting the visualization plots on the dashboard. This study uses two standard formats across five different model types; MESSAGE & COPPER reporting their output into Integrated Assessment Modeling Consortium (IAMC) data template, whereas SILVER, Transport & Buildings models are reported onto a different data format. The data was collected from various modelers within the SESIT Group [2], who are developing and applying energy system modeling frameworks for different sectors and various scales. The data was then post-processed to standardize their data formats. The case studies for the specific models are discussed in the previous secitons. Figure 3 visualizes the overall workflow from using the raw model output to hosting it on a visualization board.

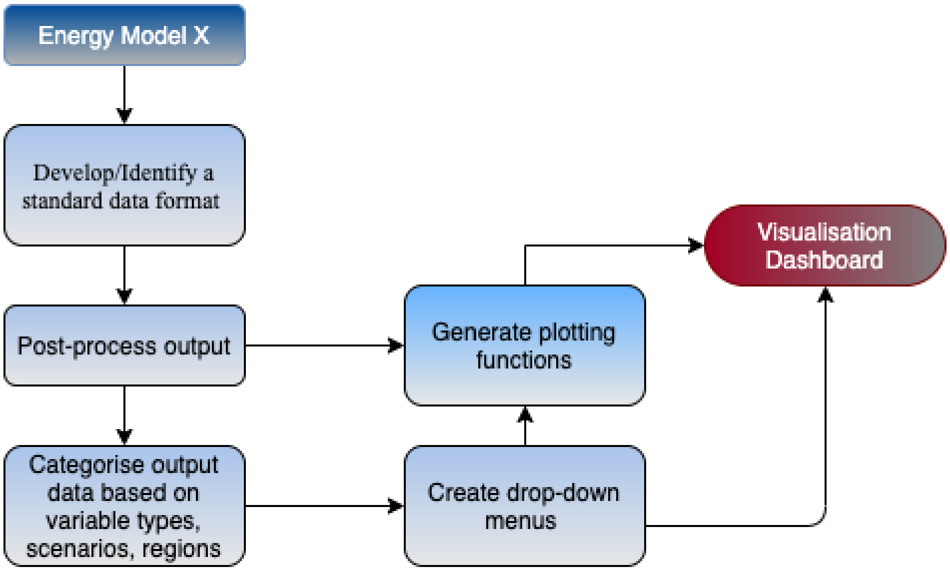
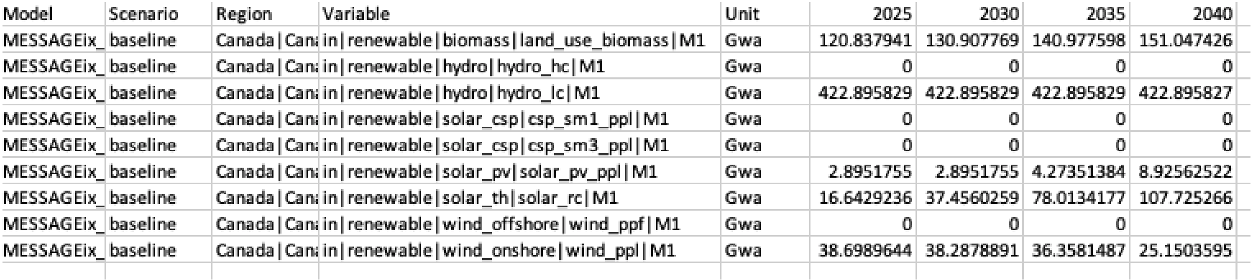


Figure 3 Workflow diagram for reporting a model output on a visualization dashboard

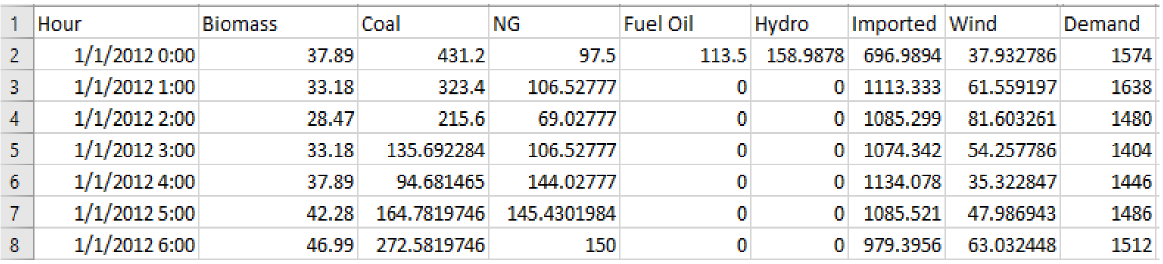
The standard data format is chosen based on the model type, and the data is post-processed and categorized into different variable types and scenarios. Followed by data structuring, plotting function is performed on resulting data structures and then hosted on the visualization dashboard (Panel Python package). The software-specific details are mentioned in Sec\ction 3.2. The platform uses a data template from IAMC for MESSAGE & COPPER models. The IAMC data template allows the user to navigate model name, scenario, region and variable names in a time-series format. Any model that can be reported using the format shown in Figure 2 can be integrated into the dashboard.



Model	Scenario	Region	Variable	Unit	2025	2030	2035	2040
MESSAGEix_	baseline	Canada|Can	in|renewable|biomass|land_use_biomass|M1	Gwa	120.837941	130.907769	140.977598	151.047426
MESSAGEix_	baseline	Canada|Can	in|renewable|hydro|hydro_hc|M1	Gwa	0	0	0	0
MESSAGEix_	baseline	Canada|Can	in|renewable|hydro|hydro_lc|M1	Gwa	422.895829	422.895829	422.895829	422.895827
MESSAGEix_	baseline	Canada|Can	in|renewable|solar_csp|csp_sm1_ppl|M1	Gwa	0	0	0	0
MESSAGEix_	baseline	Canada|Can	in|renewable|solar_csp|csp_sm3_ppl|M1	Gwa	0	0	0	0
MESSAGEix_	baseline	Canada|Can	in|renewable|solar_pv|solar_pv_ppl|M1	Gwa	2.8951755	2.8951755	4.27351384	8.92562522
MESSAGEix_	baseline	Canada|Can	in|renewable|solar_th|solar_rc|M1	Gwa	16.6429236	37.4560259	78.0134177	107.725266
MESSAGEix_	baseline	Canada|Can	in|renewable|wind_offshore|wind_ppf|M1	Gwa	0	0	0	0
MESSAGEix_	baseline	Canada|Can	in|renewable|wind_onshore|wind_ppl|M1	Gwa	38.6989644	38.2878891	36.3581487	25.1503595

Figure 4 IAMC data template sample used for MESSAGE & COPPER

The data template used for the other three types of operational models SILVER, transport & buildings is hourly, and thus includes a date time-indexed column. The column names are variable types with respect to type of model (Figure 3).



1	Hour	Biomass	Coal	NG	Fuel Oil	Hydro	Imported	Wind	Demand
2	1/1/2012 0:00	37.89	431.2	97.5	113.5	158.9878	696.9894	37.932786	1574
3	1/1/2012 1:00	33.18	323.4	106.52777	0	0	1113.333	61.559197	1638
4	1/1/2012 2:00	28.47	215.6	69.02777	0	0	1085.299	81.603261	1480
5	1/1/2012 3:00	33.18	135.692284	106.52777	0	0	1074.342	54.257786	1404
6	1/1/2012 4:00	37.89	94.681465	144.02777	0	0	1134.078	35.322847	1446
7	1/1/2012 5:00	42.28	164.7819746	145.4301984	0	0	1085.521	47.986943	1486
8	1/1/2012 6:00	46.99	272.5819746	150	0	0	979.3956	63.032448	1512

Figure 5 Hourly Template sample used for SILVER, Transport & Buildings Models

3.2 Software development

3.2.1 Python

Python is chosen as the programming language of choice to develop the visualization dashboard because of the perceived familiarity and accessibility of Python for researchers.Python is extensively used in energy system modellinga and popular among the community due to its flexibility and usability. One does not need to be an expert in semantics; they can focus more on getting the logic out for programming and reading code easier than a Java program.

3.2.2 Panel package

The Panel Python package is applied here to develop the visualization board. Panel is an open-source Python library that allow users to create custom interactive web apps and dashboards by connecting widgets, such as drop-down boxes, sliders, and buttons, to plots. The decision to use Panel was based on what it provides: a stable platform for hosting apps for the models described [34]. Panel hosts its own tutorial, showcasing common operations most developers would want on their application, making the learning curve simple. Ease of user interactivity is a priority for this application; the variability and selection options make Panel. Furthermore, the models become reactive and immediately reflect changes to the state of the plot, making the process efficient and seamless[1]. Various types of graphs can be plotted, such as stack plots or pie charts. Helpful legends, labels, and titles can be simply added to plots. Data can also be quickly processed and plucked from various models to give the user the information they want to view, and that can lead to making rich multi-platform comparisons.

3.2.3 Pyam package

The Pyam [35] open-source Python package includes a suite of tools and functions for analyzing and visualizing input data and results of integrated-assessment model scenarios, energy system analysis, and sectoral studies. In this project, we have extended

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[1] For further documentation and technical details of the Python package, refer to documentation, https://panel.holoviz.org/.

the use of Pyam beyond IAMs and used it for reporting COPPER, a capacity expansion model. The package gives the ability to filter different variables that are called by the plot. It also has the capability to interpolate the time series data and aggregate the variables for sectoral reporting of results. Pyam uses Matplotlib plotting functions at the backend. It is one of the most widely used tools in software for data visualizations. The results from the model were post-processed using the pyam package and visualized on the dashboard. The app can filter different variables, and scenarios are provided in a properly structured input file. Integrating the Panel and Pyam packages creates new functionalities for plots, such as selecting regions, scenarios, or variables for visualizing multiple plots.

3.2.4 Bokeh package

We also used the open-source Python package, Bokeh [36], for creating interactive visualizations. The Bokeh package builds high-quality graphics, ranging from simple plots to complex dashboards with streaming datasets. In this project, they are used to display and create drop-down boxes for the SILVER, Building, and Transport models. The remainder of the models shares the Bokeh package in the backend, which is implemented in the Panel app. The features introduced in this plot type as well as the operational models are as follows:

1. Zoom in and out feature: it enables the plot to be focused on a specific part of the plot. This feature is usable in both box zoom and wheel zoom types.
2. Saving: If a snapshot is needed for the user, there is a "save" button in the app that gives the desired image.
3. Hover: it gives the interactive ability to the user to read the exact data for a specified date/time
4. Drop-down lists: to switch between different scenarios and regions

5. Turing the variables on and off: the variables stacked in the plot can potentially be turned on and off if a specific selection of the variables needs to be assessed. In the case of the electricity operational models, the different generation types can be switched on and off.

4 Results

4.1 Integrating models on the dashboard

The five energy system models discussed in Section 2 are integrated on a single visualization dashboard. This section discusses the data structure and output of different models used and the types of plots were generated, along with sample screenshots. The data used to create plots are illustrative only; they should not be interpreted as final or representative in any way. Table 1 summarizes all the model data output types and templates used.

Table 1 Models' output and plots summary

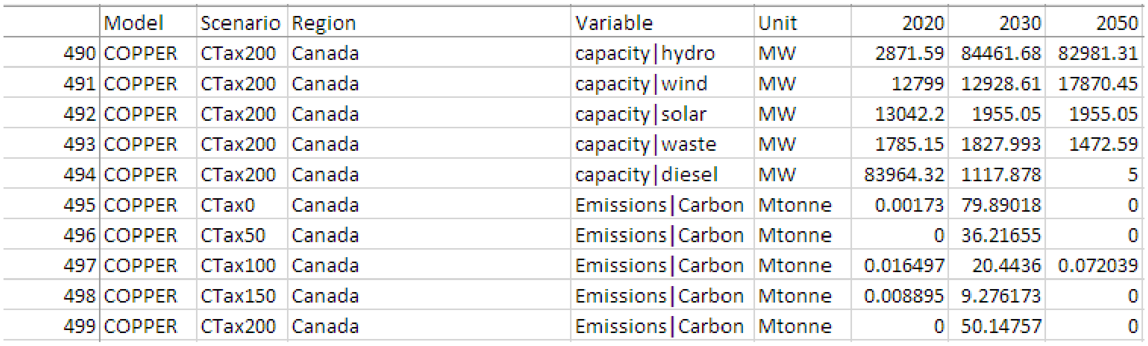
CASE MODEL	NATURE OF OUTPUT DATA	SPATIAL SCALE	TEMPORAL SCALE	DATA TEMPLATE	PLOT TYPES
COPPER	Energy System's total cost, wind, solar and thermal capacities, generation, and interprovincial transmission capacities and flows.	National	Yearly	IAMC template	Stack Plots

SILVER	Generation potential of power plants as output, power flow within the transmission lines & emissions from generations and generation types	Provincial	Hourly	Hourly time-series	Interactive Stack Plots
MESSAGE	Costs, capacities, activities and emissions of the whole energy system from different sectors	National	Five yearly	IAMC template	Stack Plots
TRANSPORT	Electricity load profiles	Municipal	Hourly	Hourly time-series	Interactive Stack Plots
BUILDING	Thermal load of the building on the electricity grid, demand response instruments using the thermostat preferences change over the 24-hr course of the day.	Municipal	Hourly	Hourly time-series	Interactive Stack Plots

In Sections 4.1.1 & 4.1.2, the data structure and results from the showcase models are presented. They are categorized by their applied package type and input data structure.

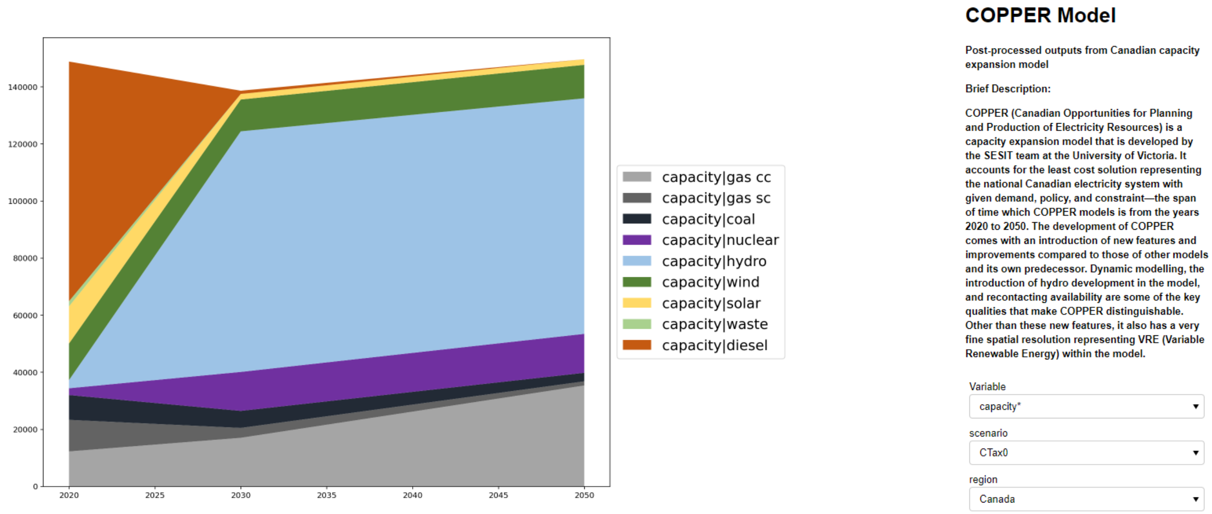
4.1.1 COPPER & MESSAGE Models

For COPPER & MESSAGE models, the IAMC data template is used to report the results. These results are post-processed with the powerful capabilities of pyam-iamc package [35]. Figure 8 shows a sample data structure reported from COPPER model onto IAMC data format. These data templates are used to plot stacked area charts using built-in functions. The user can interactively switch between different regions and output variables for different plots from COPPER model (Figure 9). While,for MESSAGE model, primary energy, secondary and system costs are reported on the platform (Figure 10).



	Model	Scenario	Region	Variable	Unit	2020	2030	2050
490	COPPER	CTax200	Canada	capacity|hydro	MW	2871.59	84461.68	82981.31
491	COPPER	CTax200	Canada	capacity|wind	MW	12799	12928.61	17870.45
492	COPPER	CTax200	Canada	capacity|solar	MW	13042.2	1955.05	1955.05
493	COPPER	CTax200	Canada	capacity|waste	MW	1785.15	1827.993	1472.59
494	COPPER	CTax200	Canada	capacity|diesel	MW	83964.32	1117.878	5
495	COPPER	CTax0	Canada	Emissions|Carbon	Mtonne	0.00173	79.89018	0
496	COPPER	CTax50	Canada	Emissions|Carbon	Mtonne	0	36.21655	0
497	COPPER	CTax100	Canada	Emissions|Carbon	Mtonne	0.016497	20.4436	0.072039
498	COPPER	CTax150	Canada	Emissions|Carbon	Mtonne	0.008895	9.276173	0
499	COPPER	CTax200	Canada	Emissions|Carbon	Mtonne	0	50.14757	0

Figure 6 App's sample input data structure – from COPPER's output



COPPER Model

Post-processed outputs from Canadian capacity expansion model

Brief Description:

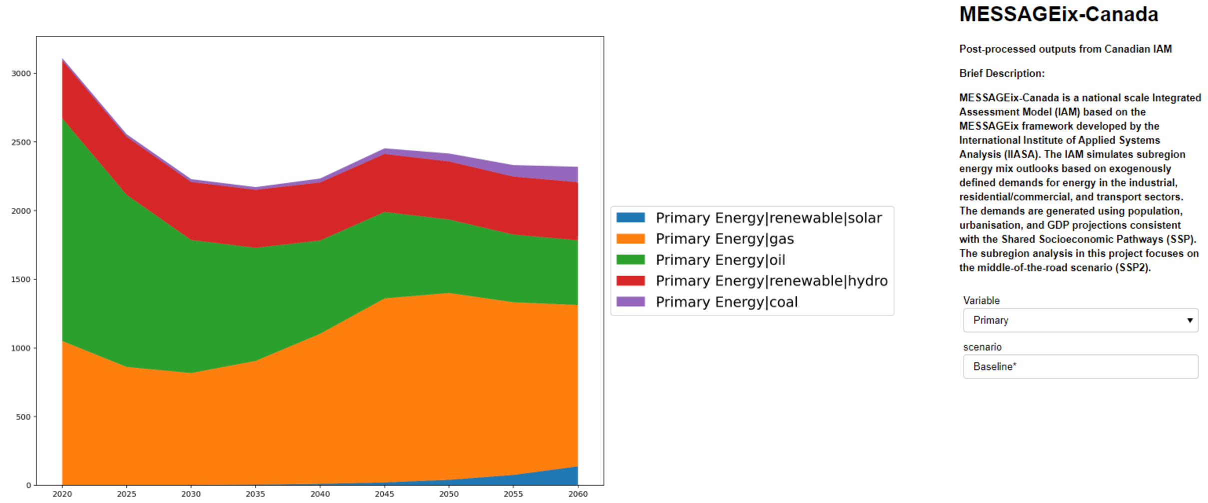
COPPER (Canadian Opportunities for Planning and Production of Electricity Resources) is a capacity expansion model that is developed by the SESIT team at the University of Victoria. It accounts for the least cost solution representing the national Canadian electricity system with given demand, policy, and constraint—the span of time which COPPER models is from the years 2020 to 2050. The development of COPPER comes with an introduction of new features and improvements compared to those of other models and its own predecessor. Dynamic modelling, the introduction of hydro development in the model, and recontacting availability are some of the key qualities that make COPPER distinguishable. Other than these new features, it also has a very fine spatial resolution representing VRE (Variable Renewable Energy) within the model.

Variable: capacity*

scenario: CTax0

region: Canada

Figure 7 Sample Screenshot of Panel App (COPPER)



MESSAGEix-Canada

Post-processed outputs from Canadian IAM

Brief Description:

MESSAGEix-Canada is a national scale Integrated Assessment Model (IAM) based on the MESSAGEix framework developed by the International Institute of Applied Systems Analysis (IIASA). The IAM simulates subregion energy mix outlooks based on exogenously defined demands for energy in the industrial, residential/commercial, and transport sectors. The demands are generated using population, urbanisation, and GDP projections consistent with the Shared Socioeconomic Pathways (SSP). The subregion analysis in this project focuses on the middle-of-the-road scenario (SSP2).

Variable: Primary ▾

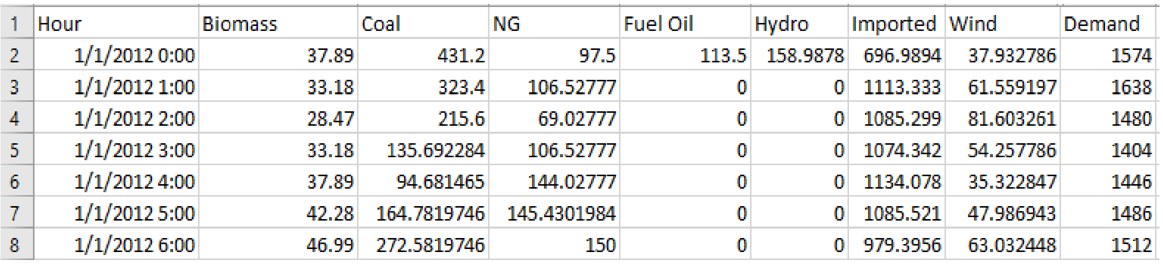
scenario: Baseline*

Figure 8 Sample Screenshot of Panel App (MESSAGE)

4.1.2 SILVER, Transport & Buildings Models

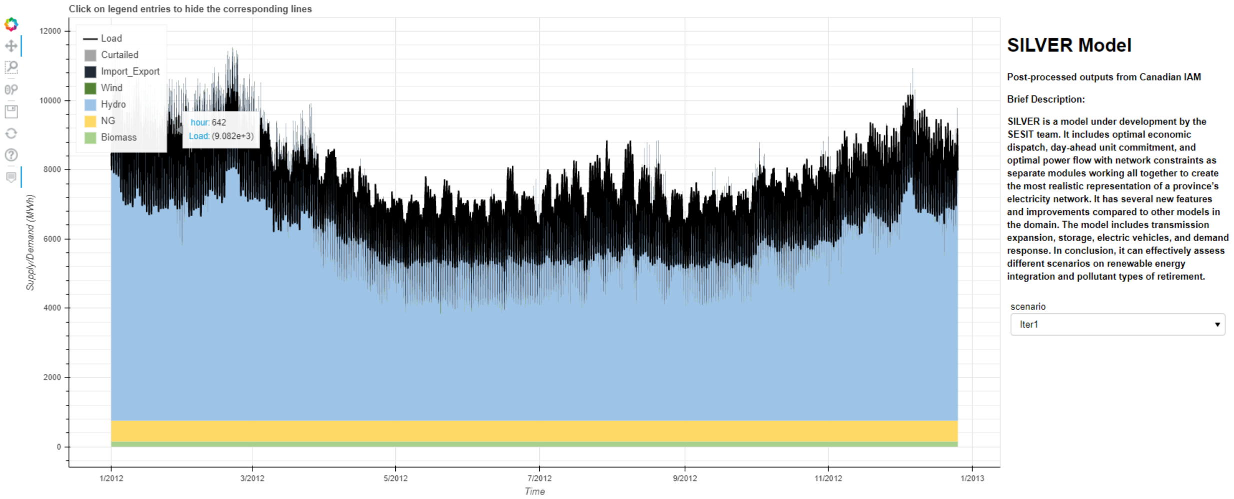
Results from SILVER, Transport & Building models are reported on a standard and flexible format. Figure 11 shows the standard data format sample used for post-processed results.

Data from SILVER is generally a time series in an hourly resolution. Different data are collected that are indexed by the date and time. The data can then be aggregated by the generators' type or region required for visualization or analysis purposes. For users to apply the platform to their model's output, the only requirement is to sort their data with properly categorized labels (e.g., generators or generator types) in a date-indexed table (Figure 12): The transportation model's output shares the same data structure as the output from SILVER. A sample data structure & plots from transportation model are shown below in Figure 11 and Figure 12 respectively. Similarly, for building modellling framework, load curves are integrated on the platform (Figure 15 and 16).



1	Hour	Biomass	Coal	NG	Fuel Oil	Hydro	Imported	Wind	Demand
2	1/1/2012 0:00	37.89	431.2	97.5	113.5	158.9878	696.9894	37.932786	1574
3	1/1/2012 1:00	33.18	323.4	106.52777	0	0	1113.333	61.559197	1638
4	1/1/2012 2:00	28.47	215.6	69.02777	0	0	1085.299	81.603261	1480
5	1/1/2012 3:00	33.18	135.692284	106.52777	0	0	1074.342	54.257786	1404
6	1/1/2012 4:00	37.89	94.681465	144.02777	0	0	1134.078	35.322847	1446
7	1/1/2012 5:00	42.28	164.7819746	145.4301984	0	0	1085.521	47.986943	1486
8	1/1/2012 6:00	46.99	272.5819746	150	0	0	979.3956	63.032448	1512

Figure 9 App's sample input data structure – from SILVER's output



SILVER Model

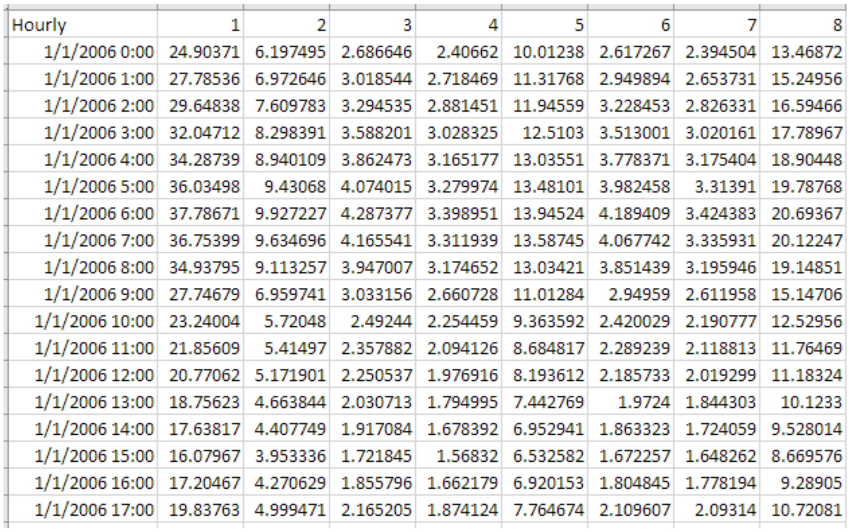
Post-processed outputs from Canadian IAM

Brief Description:

SILVER is a model under development by the SESIT team. It includes optimal economic dispatch, day-ahead unit commitment, and optimal power flow with network constraints as separate modules working all together to create the most realistic representation of a province's electricity network. It has several new features and improvements compared to other models in the domain. The model includes transmission expansion, storage, electric vehicles, and demand response. In conclusion, it can effectively assess different scenarios on renewable energy integration and pollutant types of retirement.

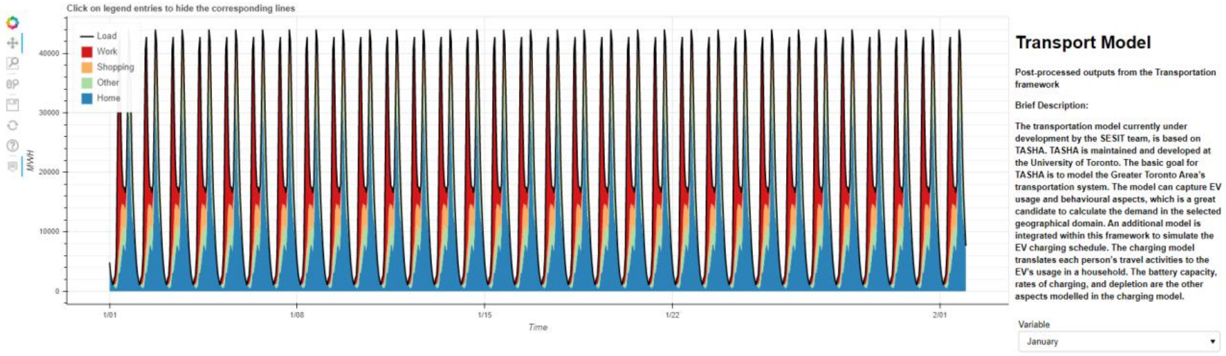
scenario: Iter1

Figure 10 Sample plot from SILVER



Hourly	1	2	3	4	5	6	7	8
1/1/2006 0:00	24.90371	6.197495	2.686646	2.40662	10.01238	2.617267	2.394504	13.46872
1/1/2006 1:00	27.78536	6.972646	3.018544	2.718469	11.31768	2.949894	2.653731	15.24956
1/1/2006 2:00	29.64838	7.609783	3.294535	2.881451	11.94559	3.228453	2.826331	16.59466
1/1/2006 3:00	32.04712	8.298391	3.588201	3.028325	12.5103	3.513001	3.020161	17.78967
1/1/2006 4:00	34.28739	8.940109	3.862473	3.165177	13.03551	3.778371	3.175404	18.90448
1/1/2006 5:00	36.03498	9.43068	4.074015	3.279974	13.48101	3.982458	3.31391	19.78768
1/1/2006 6:00	37.78671	9.927227	4.287377	3.398951	13.94524	4.189409	3.424383	20.69367
1/1/2006 7:00	36.75399	9.634696	4.165541	3.311939	13.58745	4.067742	3.335931	20.12247
1/1/2006 8:00	34.93795	9.113257	3.947007	3.174652	13.03421	3.851439	3.195946	19.14851
1/1/2006 9:00	27.74679	6.959741	3.033156	2.660728	11.01284	2.94959	2.611958	15.14706
1/1/2006 10:00	23.24004	5.72048	2.49244	2.254459	9.363592	2.420029	2.190777	12.52956
1/1/2006 11:00	21.85609	5.41497	2.357882	2.094126	8.684817	2.289239	2.118813	11.76469
1/1/2006 12:00	20.77062	5.171901	2.250537	1.976916	8.193612	2.185733	2.019299	11.18324
1/1/2006 13:00	18.75623	4.663844	2.030713	1.794995	7.442769	1.9724	1.844303	10.1233
1/1/2006 14:00	17.63817	4.407749	1.917084	1.678392	6.952941	1.863323	1.724059	9.528014
1/1/2006 15:00	16.07967	3.953336	1.721845	1.56832	6.532582	1.672257	1.648262	8.669576
1/1/2006 16:00	17.20467	4.270629	1.855796	1.662179	6.920153	1.804845	1.778194	9.28905
1/1/2006 17:00	19.83763	4.999471	2.165205	1.874124	7.764674	2.109607	2.09314	10.72081

Figure 11 App's sample input data structure – from transportation model's output



Transport Model

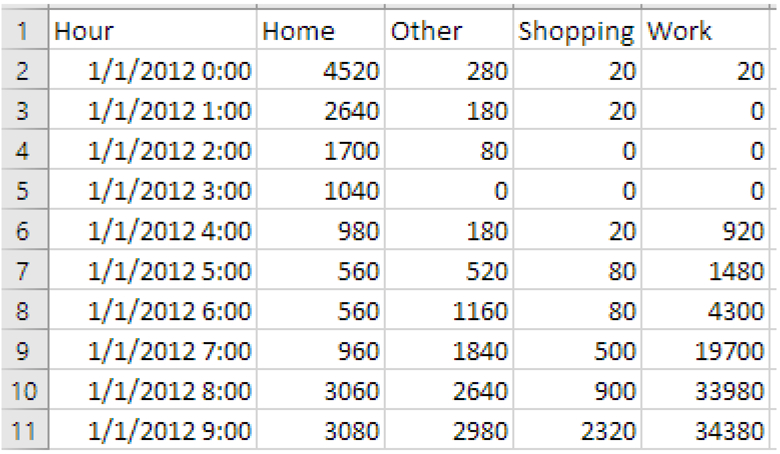
Post-processed outputs from the Transportation framework

Brief Description:

The transportation model currently under development by the SESIT team, is based on TASHA. TASHA is maintained and developed at the University of Toronto. The basic goal for TASHA is to model the Greater Toronto Area's transportation system. The model can capture EV usage and behavioural aspects, which is a great candidate to calculate the demand in the selected geographical domain. An additional model is integrated within this framework to simulate the EV charging schedule. The charging model translates each person's travel activities to the EV's usage in a household. The battery capacity, rates of charging, and depletion are the other aspects modelled in the charging model.

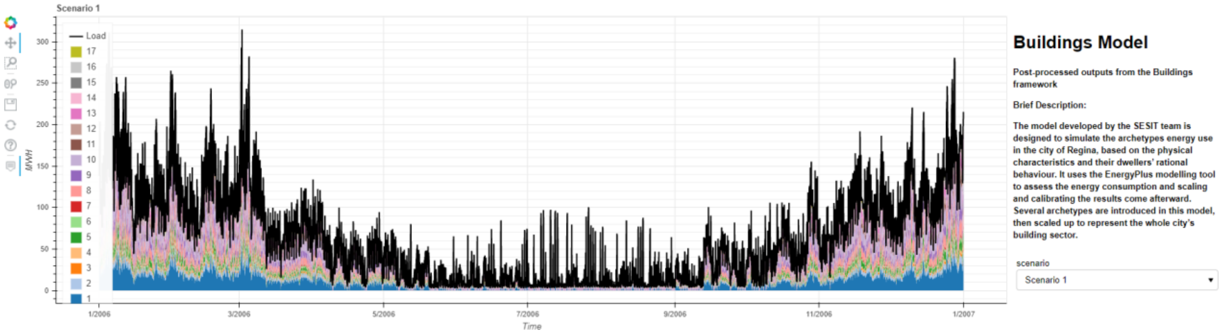
Variable: January

Figure 12 Sample plot from the SESIT’s transportation model



1	Hour	Home	Other	Shopping	Work
2	1/1/2012 0:00	4520	280	20	20
3	1/1/2012 1:00	2640	180	20	0
4	1/1/2012 2:00	1700	80	0	0
5	1/1/2012 3:00	1040	0	0	0
6	1/1/2012 4:00	980	180	20	920
7	1/1/2012 5:00	560	520	80	1480
8	1/1/2012 6:00	560	1160	80	4300
9	1/1/2012 7:00	960	1840	500	19700
10	1/1/2012 8:00	3060	2640	900	33980
11	1/1/2012 9:00	3080	2980	2320	34380

Figure 13 App’s sample input data structure – from building model’s output



Buildings Model

Post-processed outputs from the Buildings framework

Brief Description:

The model developed by the SESIT team is designed to simulate the archetypes energy use in the city of Regina, based on the physical characteristics and their dwellers' rational behaviour. It uses the EnergyPlus modelling tool to assess the energy consumption and scaling and calibrating the results come afterward. Several archetypes are introduced in this model, then scaled up to represent the whole city's building sector.

scenario: Scenario 1

Figure 14 Sample plot from SESIT’s building model

5 Discussion

This visualization platform has been designed according to state-of-the-art principles (accessibility, transparency, usability) to facilitate the integration of insights from different model types (discussed in Section 2). The plots generated as an output from the project allow exploration of energy transition scenarios across different models for respective use cases. On the other hand, using open-access tools to generate the overall visualization platform will enable future users to rapidly prototype a similar methodology for data processing and plotting of model results. The interactive plots on the platform with varying options allow for the exploration of energy transition scenarios. The platform is designed using open-source tools that are easily replicable for other modeling communities and facilitate stakeholders in decision-making. Moreover, this study develop standard & flexible data formats for reporting the output of five different model types, and sets an example for the research community to follow a standard format for the models' post-processed results.

5.1 Contribution of the project to electrification and decarbonization pathways

The project contributes to the decarbonization pathways of the energy system for Canada. The models used for developing the visualization project are state-of-the-art models that contribute to decarbonization pathways individually. However, having these models on a single platform enhances the ability to assess many energy transition scenarios with little effort and lesser time, allowing decision-makers to filter out consistent and practical pathways towards electrification and decarbonization. This helps local and national level policymakers and stakeholders to access regional and national energy transition pathways across time scales, regions, scenarios, and sector-specific models. The results from the various energy system models allows a comparison, enabling a fair assessment of their ability to simulate different Canadian system pathways. It can motivate other researchers and modeling communities to follow standard guidelines for reporting their modeling results for compelling model comparison studies. The model comparison studies can help the stakeholders better analyze the sensitivity of different scenarios and modeling frameworks. The platform's accessibility features enable a researcher or policy analyst to explore different scenarios of modeling platforms. The platform also allows modelers to better map the solution space for decarbonization pathways, which in turn gives policy makers a better idea of how flexible the system is and how to prioritize efforts to transition the system.

5.2 Accessibility, transparency, usability

The visualization platform is accessible via a GitLab repository at (https://gitlab.com/McPherson/visualizations). All the packages used in the platform have open-source/open-access licenses. This report's software documentation (refer to Appendix A) explains how new users can easily access, download, install, and apply the fully functional apps for different models. The user can interactively switch between different options for their desired output conditions.Moreover, all the included packages are well-docuemnted. In conclusion, the platform's transparency is maintained based on the documentation, implemented open-access codes and documentation in the repository, and the included open-source packages. Besides transparency, giving open-access abilities to the framework may enable developer or expert user to suggest features, plot types, and model types to within the framework.

6 Conclusions

The aim of this project is to initiate integration of energy modeling activities. The scope of our project delivers a preliminary platform by integrating multiple model outputs using standard data formats. We believe in strong potential of this project to perform well when applied on a larger scale where it can be integrated better and is adaptable to Canada's energy research community.

6.1 Limitations

The visualization platform developed in this project has some limitations that include the need for additional resources for software development which are beyond the scope of this project.

We developed the application using one model from each modeling framework categoty as a case study. Also the results visualized are the samples taken from different model outputs and doesn’t refelect all of the results on the platform. The functions generated during this project have not been tested yet for reporting other model outputs. The flexibility to adapt to other models may require some prerequisite knowledge and expertise at this stage. Access to the project is also limited to the open repository that has mentioned before and might need a basic knowledge for a user to implement.

6.2 Envisioned future work

Providing the platform’s flexibility to upload model output data on the platform, post-process it to a common data template using built-in functions and visualize the results is our immediate priority moving past the project deadline. The future work includes adding more results from the existing models to allow exploring the results under a variety of options.

As part of future directions, the project will move toward launching the framework in an online web-hosting platform. In that way, the usability increases tremendously. With an online user interface, the user does not need any software pre-requisites and can visualize and compare the results.

The visualization platform created in this research will be further developed to overcome the limitations outlined above. The toolkit will be adapted to take on new data formats to support visualization efforts for energy system modeling frameworks beyond those discussed in this report. Additionally, the platform will be developed to enhance the dashboarding features of the toolkit and allow users to have custom control over the setup of their dashboard window. Redeveloping the toolkit is pertinent for the next step with this platform which is to integrate it with several energy system models and a new database with Canadian energy system information via the Spine Toolbox; this toolbox is a suite of software that stores data in a structured, version-controlled manner, and connects modeling tools to that data via processing tools [37]. This integration aims to create a new comprehensive energy system workflow framework that will be used to compare different models of energy system. Applying the toolkit to more energy system models will identify the need for new dashboarding features and software development for application to new input formats.

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Appendices

Appendix A: Software Documentation – Users manual

Visualization Toolkit

User Manual

Table of Contents

Implementation of the Visualization Toolkit

Prerequisites

To be able to the Visualization Toolkit, a certain skillset and pre-requisites are required. The user should be able to understand basicenergy system concepts in order to understand the visualizations. is important that the user have the knowledge of Python on a beginner level. Specifically, a user should have basic understanding of python notebooks to be able to navigate through the platform.

Python dependency packages

The toolkit is developed using certain open-source python packages. Following are the version and details of those dependency packages;

- `bokeh==2.2.3`
- `matplotlib==3.3.2`
- `pandas==1.1.3`
- `panel==0.10.3`
- `pyam-iamc==0.10.0`
- `numpy==1.19.2`
- `packaging>=16.8`
- `tornado>=5.1`
- `PyYAML>=3.10`
- `pillow>=7.1.0`

- `typing-extensions>=3.7.4`
- `python-dateutil>=2.1`
- `Jinja2>=2.7`
- `certifi>=2020.06.20`
- `kiwisolver>=1.0.1`
- `pyparsing!=2.0.4`
- `cycler>=0.10`
- `pytz>=2017.2`
- `param>=1.10.0`
- `pyviz_comms>=0.7.4`
- `markdown==3.3.3`
- `requests==2.24.0`
- `tqdm==4.50.2`
- `pyct>=0.4.4`
- `plotly==4.14.3`
- `pint==0.16.1`
- `iam-units>=2020.4.12`
- `six==1.15.0`
- `seaborn==0.11.0`
- `xlrd<2.0`
- `argparse==1.4.0`
- `MarkupSafe>=0.23`
- `chardet<4,>=3.0.2`
- `idna<3,>=2.5`
- `urllib3!=1.25.0,!=1.25.1,<1.26,>=1.21.1`
- `retrying>=1.3.3`
- `setuptools>=41`
- `scipy>=1.0`

Benefits of Writing in Notebooks

The benefits of writing in notebooks are that they are effective at demonstrating works. The code and the end result are both visible simultaneously, so one may showcase each portion of the code and link that to a visual result at the output. You can also run individual snippets of code called cells one by one to understand exactly what each portion of the code is responsible for so that time spent understanding the code itself is done so efficiently.

Generic functions

change_plot()

change_plot() takes in the variable we want to display, the function ex_fig_general and the scenario as well as placeholder text and is the method that gets called when you use to interact in order to load in the updated values and pass them into ex_fig_general through view_fn.

ex_fig_general()

This method takes the name of the plot (the variable name) and the scenario we wish to display; its purpose is to take the data returned from produce_list() and transform that alongside the axis names and convert it into a figure object and is then returned.

produce_list()

This method takes the title of the plot, variable, and scenario and returns a container that holds all the values we wish to plot for a given plot.

str_value()

The purpose of str_value() is to take a column from your data frame, and return the numeric value associated with that column, adds it to a list, and returns it so that it may be plotted within ex_fig_general()

create_df()

The purpose of create_df() is to take in the variable (capacity or emissions in this case), the carbon tax scenario, and the region one wishes to display and to create a filtered data frame out of those variables and return it so that it may be plotted. This method is only used in the notebook for the COPPER framework case study.

Each model has slightly different options, but the principles are the same. For example, the MESSAGE app, as seen in Fig. 1 below, has a drop-down box called variable, which has the options Primary, Secondary, Emissions, and Useful all showing different data. The COPPER plot, as seen in Fig. 2 below, has drop-downs for variable, scenario, and region. However, the principle remains, any combination of variables, scenarios, or regions are all independent of each other and will not cause errors.

Interactive Notebooks

The Visualization Toolkit has been developed into a series of Jupyter notebooks. One notebook has been created for each of five case studies that the toolkit has been applied for. For each case study, the toolkit is applied to output from a different energy system modeling framework, which is all described in a later section. The use of multiple case studies and notebooks helps to illustrate how to adapt this toolkit for application to models with different output data formats. There are two data frame standards used for toolkit input among the different case studies described here, but it is possible to develop the toolkit for new standards of input.

- `Message_Canada.ipynb`

This notebook is designed for the MESSAGEix model outputs. The notebook takes a CSV file and converts essential data into data frames, and through manipulating those data frames the result is a figure which displays the model along with drop-down boxes to select between variables on a stacked area graph.

- `BUILDINGS_Bokeh.ipynb`

This notebook is designed for the Buildings model outputs. This notebooks takes in ten different scenarios from ten different CSV files and organizes them into their own data frames, which can be filtered by using a drop-down box to display exactly which scenario is desired on a stacked area graph.

- `SILVER_Bokeh.ipynb`

This notebook is designed for the SILVER model outputs. Similar to the Buildings model outputs there are multiple scenarios that can be filtered through as well. There are future plans to introduce a slider that would allow for manipulating the start and end dates of the figure on a stacked area graph.

- `TRANSPORT_Bokeh.ipynb`

This notebook is designed for the Transport model outputs. On a stacked area graph, one can view how many MWh of energy are expended through traveling for various reasons on a monthly basis. This is done by reading a CSV for each month and making them an option on a drop-down list.