Integrated electricity supply and demand modelling to investigate renewable pathways at the city scale

Submitted to the Energy Modelling Initiative

Robert Xu, Lauren Stanislaw, Madeleine Seatle, Madeleine McPherson

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Abstract

In Canada, nearly 40% of national GHG emissions come from the transportation and building sectors. Electrification of the transportation and building sectors could contribute to decarbonization in jurisdictions with low-carbon electricity supply, though more electricity would be required. Other jurisdictions, which are powered by carbon intensive generation would need to decarbonize their electricity system, through integrating variable renewable energy (VRE) integration for example, prior to electrifying the demand side. These two trends – VRE integration and electrification – could in fact prove synergistic, with newly electrified loads providing the flexibility required to integrate variable sources of generation. Quantifying this synergy requires an operational perspective capable of representing the spatial and temporal fluctuations of both supply and demand. This report presents an integrated model platform consisting of three separate sector-specific models focused on transportation, buildings and the power system, at the city scale. The integrated model platform optimizes the operational aspects of a city with local VRE generation, as well as electrified private vehicles and residential building heating. By linking the outputs of the supply and demand sectors, the integrated model platform can be used to explore the effects that demand side electrification and management can have on system cost and GHG emissions. Once developed, the integrated platform is applied to Regina as a case study, which is seeking to be powered with 100% renewable energy sources by 2050.

Abstrait

Au Canada, près de 40 % des émissions nationales de GES proviennent des secteurs des transports et de la construction. Ces secteurs sont également responsables d'une grande partie des émissions à l'échelle de la ville. Dans certaines villes, l'électrification des secteurs des transports et du bâtiment peut contribuer à la décarbonisation en raison d'un approvisionnement en électricité à faibles émissions de carbone - bien qu'il faudrait plus d'électricité. Toutefois, d'autres villes, si elles tirent de l'électricité d'un réseau alimenté par la production à forte intensité de carbone - peuvent avoir besoin d'intégrer l'énergie renouvelable variable à l'échelle de la ville (ERV) comme l'énergie solaire et éolienne ainsi que l'électrification du côté de la demande pour décarboniser leur consommation d'énergie. En raison de la variabilité inhérente de ces types d'énergie renouvelable, la modélisation de l'électrification du côté de la demande exige une perspective opérationnelle capable de représenter les fluctuations spatiales et temporelles de l'offre et de la demande. Ce rapport présente une plate-forme modèle intégrée composée de trois modèles sectoriels distincts axés sur le transport, les bâtiments et le réseau électrique. La plate-forme modèle intégrée optimise les aspects opérationnels d'une ville hautement électrifiée avec la génération locale d'ERV. En particulier, la plate-forme met l'accent sur l'électrification des véhicules privés et les technologies thermiques des bâtiments résidentiels. En reliant les extrants des secteurs de l'offre et de la demande, la plate-forme modèle intégrée peut être utilisée pour explorer les effets de l'électrification du côté de la demande sur le coût du réseau électrique et les émissions de GES, ainsi que le rôle que les stratégies de gestion de la demande et le stockage de l'énergie peuvent avoir dans les futurs systèmes énergétiques. La plate-forme intégrée est ensuite appliquée à Regina dans le cadre d'une étude de cas, qui cherche à être alimentée à 100 % par des sources d'énergie renouvelables d'ici 2050.

Introduction

In Canada, the transportation and building sectors mainly rely on motor gasoline and natural gas as energy sources and are collectively responsible for approximately 40% of national greenhouse gas (GHG) emissions (Natural Resources Canada 2019). Within cities, these sectors make up the majority of GHG emissions (City of Vancouver 2015; Kennedy et al. 2009). Recognizing this, some cities in Canada and the United States have established targets to reduce their reliance on these carbon intensive energy sources and shift towards using renewable energy sources (Zuehlke 2017; Eaton and Enoch 2020).

Due to their inherent variability, large-scale integration of variable renewable energy (VRE) sources such as wind and solar require system flexibility to avoid high curtailment rates and maintain system reliability (McPherson et al. 2018). Electrification of demand could provide such flexibility (Mathiesen et al. 2015), as electrified technologies such as electric vehicles (EVs), electric space heating, and other electric appliances can be managed such that their electricity demand matches variable electricity generation (Dennis 2015). The practice of shifting or reducing consumer electricity demand in response to electricity generation characteristics is defined as demand response (DR) (FERC 2020).

Existing infrastructure in the current electricity system, such as smart meters, can support DR strategies via detailed metering of electricity use (O′Connell et al. 2014). Additionally, several jurisdictions in North America implement DR strategies, either directly through industrial scale, user-controlled electricity reduction in Saskatchewan, Quebec, and Alberta (SaskPower 2019, Hydro-Québec 2020, Alberta Electric System Operator 2019); utility control of appliances in Colorado (Holy Cross Energy 2016); or indirectly through incentives such as time-of-use electricity pricing in Ontario (Ontario Energy Board 2021). However, determining appropriate DR strategies requires balancing several conflicting needs. This includes minimizing adverse effects to electricity consumers, maximizing the amount of consumption that aligns with VRE production, and respecting the generation and transmission limits of the electricity grid (O′Connell et al. 2014). To ensure these conditions are met, it is necessary to characterize them explicitly. This requires models with spatial and temporal resolutions detailed enough to capture the operations of both electricity supply and demand (McPherson and Stoll 2020).

Some city scale energy models in Canada can represent the interactions between supply and demand for a city at high spatial resolution (Zuehlke 2017; Crockett et al. 2019). However, as these models focus on policy participation rates and planning instead of system operation, they lack the temporal resolution necessary to accurately model an electricity system with high VRE integration or DR strategies.

Alternatively, production-cost models (PCMs) of the electricity system have high temporal and spatial resolution to capture operational constraints. As a result, they are well-suited to explore the impacts of DR on the electric grid in real time (Jordehi 2019; Hummon et al. 2013). However, McPherson and Stoll (2020) document several issues with many DR formulations in PCMs:

- Model formulations are often not reported;
- Only a single sector or a few appliance types are included as potential sources of DR, rather than encompassing the entire demand seen by the grid;
- Representation of supply and demand dynamics as well as DR availability is frequently oversimplified, in part due to a lack of data; and
- Model constraints usually assume that shifted demand can be recovered at any point in time, ignoring that long delays in energy recovery will result in undesirable levels of consumer service disruption (Zerrahn and Schill 2015).

Finally, even for models with sound formulation, a significant challenge is ensuring that these results influence appropriate policy. Decision makers tend to rely as much on experience and other sources as they do on scientifically-validated evidence (Cvitanovic et al. 2015). As well, efforts for transparency in the modelling community tend to remain opaque to non-modellers, in part due to the high complexity of models (Bistline, Budolfson, and Francis 2021). It follows that decision makers may be unlikely to define policy scenarios in ways conducive to modelling work, even though they are better suited to do so than modellers.

In this report, an integrated model platform, created by linking a PCM, referred to going forward as the *electricity system model*, with detailed operational models of the transportation and building sectors, is described. Specifically, the transportation model can investigate the switch from conventional internal combustion vehicles to fully electrified vehicles, and the building model can incorporate any modifications to building envelopes and technologies. The flexible electricity system model can determine the effect of these changes on electricity cost and GHG emissions, and incorporate changes to the generation mix. With this integrated platform, the known shortcomings of PCMs are addressed in the following ways:

- The model formulation is clearly documented, serving as a guide for potential users on adapting the model to different cities.
- By linking models from different sectors, the platform is more comprehensive than existing formulations, and can be expanded to include more sectors or appliance types.
- The operational scope of each linked model allows for representation of individual actions in each sector and detailed simulation of how factors such as supply, demand, and DR availability might affect each other.
- The inclusion of sector-specific operational models ensures that there are temporal constraints on energy recovery, which ensures consumer comfort is considered.

In addition, to further aid the generation and communication of scenarios, a workflow that aims to streamline communication between decision makers and modellers is proposed.

In this report, the formulations of both the integrated model platform and the sector-specific models are described in detail. Next, the proposed workflow is described, which is augmented by data tables and a fillable form that walks potential users through the scenario specific independent variables. Policy scenarios and the types of insights that can be generated using the proposed integrated platform are then explored, while a case study of Regina, Saskatchewan exemplifies its application. Finally, the strengths and weaknesses of the platform are discussed.

Methods

To illustrate the formulation of the integrated platform, the high level linkage architecture is described, followed by sector-specific model details. On the demand side, the transportation model considers individual EV travel schedules and charging patterns, while the building model considers individual building temperature setpoints. On the supply side, inputting demand model outputs allows detailed scenario-specific results to be explored in the electricity model.

Model linkage

To accurately model DR, electricity demand and supply must be represented simultaneously, allowing both demand patterns and VRE availability to be considered. To do so, the linkage of demand side and supply side models must pass information to each other. Electricity load curves from the demand side can be used as an input for the electricity system model, which can determine the least-cost operation for the electricity system. Following, the amount of VRE curtailment calculated on the supply side is used as an indicator to trigger changes in EV charging demand and building electricity load. For a given generation mix, lowering VRE curtailment is equivalent to increasing the demand met by VRE generation, lowering electricity system emissions as a result.

This novel linkage process is shown in Figure 1; the solid arrows represent the transfer of load curves from the transportation and building sector models to the electricity system model, while the dashed arrows represent the transfer of curtailment data from the electricity system model to the demand side models.

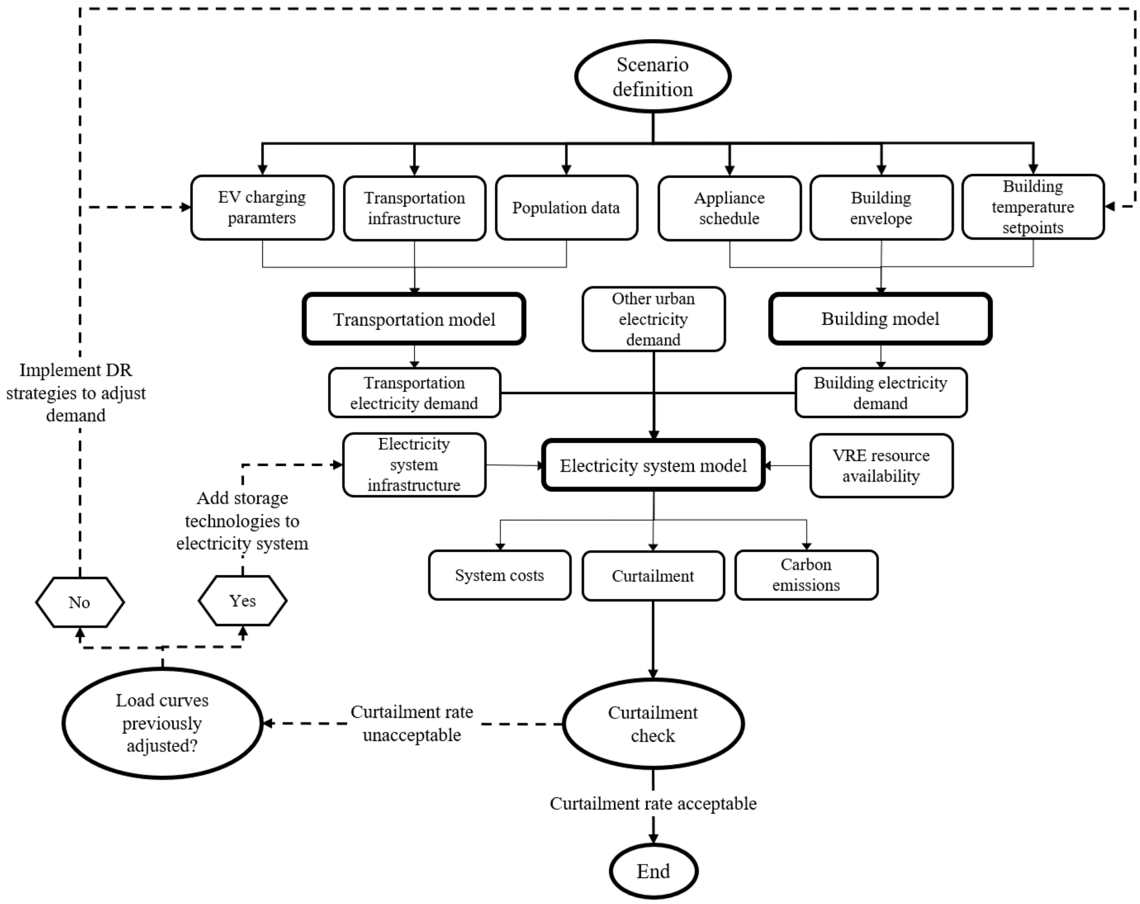

Figure 1: Bidirectional model framework with key inputs and outputs. Reproduced with permission from Seatle et al. (2021)

The scenario definition step in Figure 1 defines the electrification level within the transportation and building sector, and the VRE integration level of the local electricity supply. In the electricity system model, the generation mix can be specified, with special attention paid to VRE sources such as rooftop solar, utility scale solar, wind and storage. More detail on parameters and formulation within each sector-specific model can be found in their respective sections. A fillable scenario template, designed to facilitate the scenario definition step, is part of the proposed workflow and can be found in the appendix.

Each scenario is evaluated in up to three stages:

- Stage A combines the initial demand curve output from the transportation and building models with other urban electricity demand to create an initial load curve.

The level of curtailment from this electrified demand is then determined in the electricity system model.

- If curtailment from Stage A is too high, Stage B implements DR strategies to utilize the excess VRE generation forecasted. DR occurs through utility control of EV charging and building temperature setpoints, shifting as much demand load as possible to times when curtailment occurs. DR processes within each sector are elaborated further in their respective sections. The adjusted load curves are then re-evaluated in the electricity system model to determine if VRE curtailment has been reduced to an acceptable level.
- Stage C uses the load curves generated within Stage B, while adding storage technology to the grid before the curtailment is revaluated. Stage C may be repeated multiple times until the curtailment level is reduced to an acceptable value.

Transportation model

To predict EV charging, the transportation model simulates the travel and charging behavior of individual EVs. Electricity demand curves from EV charging are estimated by aggregating the demand from individual vehicles. The transportation model used in the integrated model platform has two main components: TASHA, an activity scheduling model (Miller and Roorda 2003), and an EV charging simulation model developed for the integrated platform.

TASHA is a central component of a transportation model for the Greater Toronto Area (Miller et al. 2015), which is used to forecast travel patterns and test policy decisions. TASHA's ability to consider spatiotemporal and resource constraints, such as vehicle availability, are necessary considerations for predicting EV demand within the integrated model platform. TASHA outputs a complete daily travel schedule for each household resident in a synthetic population; however, it does not consider commercial and freight transportation.

The travel schedules output by TASHA serve as the basis for modelling EV charging. As TASHA is calibrated using past travel surveys, in which EVs are not well represented, using the TASHA output schedules for EV charging modelling assumes that the travel behaviour of EVs is like that of non-EVs. The EV charging model simulates and aggregates the travel and charging behaviour of EVs using TASHA's output. Both TASHA and the EV charging model require key inputs and processing steps, shown in Figure 2 and further described in the following sections. For clarity, TASHA and the EV charging model are discussed separately.

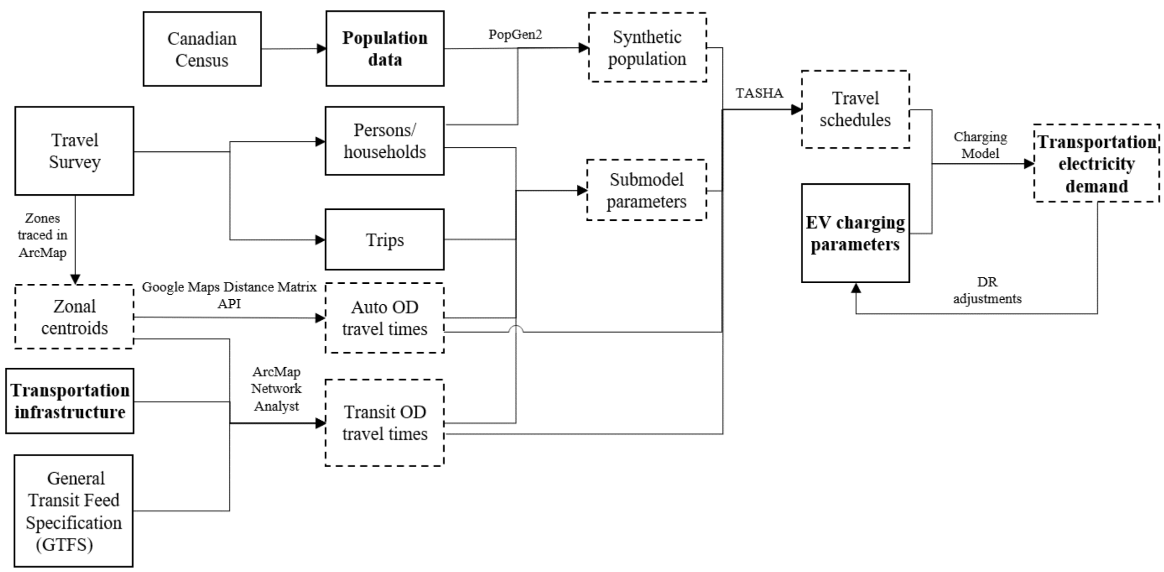

Figure 2: Transportation model processes, with solid boxes representing raw data inputs and dashes boxes representing a processed output. Note that bold text represents a direct tie-in to Figure 1. Reproduced with permission from Seatle et al. (2021)

TASHA

Running TASHA requires calibration of various submodels, including mode choice and location choice. The framework of TASHA is described by Miller and Roorda (2003) and Roorda, Miller, and Kruchten (2006). Additionally, the University of Toronto Travel Modelling Group website (Travel Modelling Group 2020) provides an in-depth overview of the calibration process. Major data sources required by TASHA include travel survey data, origin-destination (OD) data, and census data.

City-level travel surveys provide a record of households and household members that completed the survey, as well as a system of traffic analysis zones (TAZs), which serve as the endpoints of trips. Travel survey respondents record information on the trips they made over the course of a day: the trip origin/destination zones, the mode used, the start and end times of the trip, and the purpose of the trip. This data is crucial for calibrating TASHA to reflect local travel tendencies, such as the preference for driving versus public transit, or the preference of certain zones for shopping activities.

Calibrating TASHA also requires OD data including travel times, distances, and costs between zones, for different modes. Preferably, this data would be available for all modelled modes, including auto, public transit, walk, and bike. OD data can come from local travel models or other tools. The integrated model platform utilizes the Google Maps Distance Matrix API to obtain OD data for the vehicle mode, and ArcMap for the public transit mode. For public transit OD data, General Transit Feed Specification (GTFS), which is a collection of public transit schedules, and local road network shapefiles are required as well. For bike and walk modes, OD data are estimated using OD distance for the vehicle mode. Local travel models are likely the best source of OD data if available, as there are cost and computational issues associated with the tools described. These issues are further described in the discussion section.

Because TASHA simulates travel schedules for individuals, it also requires a synthetic population of individuals. PopGen2 software, which is documented by Bar-Gera et al. (2009), Ye et al. (2009), Mobility Analytics Research Group (2016), and Konduri et al. (2016), is used as the population synthesis software for TASHA. PopGen2 requires two data types: aggregate population characteristics for each TAZ, and a sample of households and the persons in those households. The population synthesis procedure draws individual households from the sample to best match the aggregate population characteristics. Person and household records from the travel survey can be used as the sample in the population generation procedure, and census data can provide the aggregate population characteristics.

After calibration, TASHA is run with the synthetic population and calibrated parameters. An example of a person-level schedule output of TASHA is shown in Table 1. Four categories of origin/destination activity are modelled: home, shopping, work, and other. Modes modelled include auto (as driver), passenger, public transit, walk, bike, and taxi. After travel schedules are generated for each person, the auto driver trips are filtered and processed further, as these trips are assumed to be EV trips, and therefore the source of electricity demand.

Table 1: Example schedule of Person 1 in Household 20004, making a trip to work and returning home

Household #	Person #	Trip #	Origin activity	Origin zone	Destination Activity	Destination Zone	Mode	Depart time	Arrive time
20004	1	1	Home	2	Work	7	Auto	535	540
20004	1	2	Work	7	Home	2	Auto	660	664

Charging model

Predicting charging for EVs requires vehicle schedules; thus, a preliminary step is to convert the person-level travel schedules shown in Table 1 to vehicle-level schedules by accounting for within-household vehicle sharing. An example of a vehicle travel schedule is shown in Table 2. The distance travelled on each trip is added as well.

Table 2: Example schedule of Vehicle 1 in Household 20034

Household #	Vehicle #	Origin activity	Origin zone	Destination activity	Destination zone	Depart time	Arrive time	Distance (m)
20034	1	Home	2	Other	35	401	420	19360
20034	1	Other	35	Home	2	480	499	19809
20034	1	Home	2	Work	46	521	540	15438
20034	1	Work	46	Home	2	1020	1037	15234

Besides the level of vehicle electrification, additional parameters can be set in the EV charging model, such as vehicle battery capacity, charging rate, and depletion rate, and a set of valid charging activity types (e.g. home charging only, or charging at all activity types permitted). These parameters can be set on a vehicle to vehicle basis, or for the vehicle population as a whole. In addition, EVs within the charging model can have different charging strategies, defined by when and where charging occurs. The charging model implements one of two different charging strategies depending on whether DR is investigated.

EV owners who do not participate in a DR program are assumed to charge immediately upon arrival at their destination if the destination activity type is valid for charging. Charging is simulated one vehicle at a time by processing the travel schedule after sorting the trips in temporal order. Each time an EV departs from an activity, its battery level is updated based on the trip distance to the next activity location, and the depletion rate.

$$SOC_a = SOC_d - D * d \qquad (1)$$

where SOC_a is the battery state of charge upon arrival to the current activity, SOC_d is the battery state of charge upon departure from the previous activity, d is the distance between the zonal centroids in which the arrival and departure activities are located, and D is the battery depletion rate.

Once the EV arrives at its next destination, the EV is immediately charged until either the battery is at full capacity, or the vehicle must depart for its next activity.

$$SOC_d = (SOC_a + (t_d - t_a) * R, SOC_{max}) \qquad (2)$$

where t_d is the departure time from the present activity, t_a is the arrival time of the current activity, R is the user defined charging power, and SOC_{max} is the battery capacity. The cycle represented by equation 1 and 2 is repeated until the entire daily schedule of the vehicle is completed, at which point the daily schedule is cycled through until the time horizon of the simulation period is reached. By keeping track of the activity and zone in which charging occurs, EV load curves can be disaggregated by activity type and zone. To reduce computational time, a subset of the vehicle schedules can be simulated, with the electricity demand scaled up based on the adoption scenario investigated.

The previously described formulation is simple for consumers but provides no flexibility to the utility, as a fully charged battery cannot receive excess renewable energy. To model flexibility, when DR is implemented, vehicles employ a "last-minute" charging strategy, wherein vehicles delay charging as long as possible while still being able to attain the desired level of charge before departure.

$$SOC_d = (SOC_a + (t_d - t_c) * R, SOC_{max}) \quad (3)$$

$$t_c = \begin{cases} t_a, & if\ SOC_a + (t_d - t_c) * R \leq SOC_{max} \\ t_d - \dfrac{SOC_{max} - SOC_a}{R}, & else \end{cases} \quad (4)$$

where $t_c$is the time at which charging commences. In DR scenarios, battery depletion still occurs according to Equation 1.

Due to last-minute charging, a plugged in EV has a window during which at any time t in the window,

$$t \in [t_a, t_c] \quad (5)$$

the vehicle will be plugged in, but not charging, and the vehicle's battery will not be at capacity. At this time, the utility can utilize excess VRE generation to charge the EV, shifting the vehicle's charging times while reducing excess VRE generation.

Modifications for DR

DR for EVs occurs through utility-controlled charging (UCC), in which the utility controls the charging of individual vehicles. If DR is implemented, all simulated EVs participate, and must communicate the following with the utility: charging status of the vehicle (e.g. plugged in and not charging, plugged in and charging), departure time of the next trip, and the desired battery level at departure time. The utility must also be able to predict the amount of curtailment at fifteen-minute intervals. Although the resolution of the curtailment predictions can be user-defined, fifteen minutes is the default assumption. The resolution determines how far in the future the utility can predict curtailment, as well as the duration that a vehicle's charging is shifted.

To simulate DR, EVs charge according to the DR formulation previously described. As they do so, the utility maintains a list of EVs that are currently plugged in, but not charging as described in equation 5, indicating that they are eligible for DR. At the beginning of every fifteen-minute interval, the utility estimates the quantity of VRE curtailment during the next fifteen minutes. This data is taken from the output of the electricity system model in stage A. If curtailment is forecast to occur, the utility selects a random vehicle from eligible pool and charges it for the next fifteen minutes, or until the battery reaches capacity. The estimated curtailment is then reduced by the amount charged. If the vehicle is fully charged at this point, it is removed from the list of DR eligible vehicles. Otherwise, the original start time of the vehicle's charging is then shifted back by fifteen minutes and the vehicle remains in the list of DR eligible vehicles, allowing it to be charged again in the next fifteen-minute interval. The process of charging vehicles from the pool of eligible vehicles is repeated until either the estimated curtailment reaches zero, or the eligible pool of vehicles is empty. Once either point is reached, the simulation continues - with vehicles arriving, departing, and charging - until the next fifteen-minute interval is reached.

Building model

The building model is an archetype-based engineering model, in which the thermal demands of a small number of representative buildings, called archetypes, are modelled in detail using a physics-based simulation software (Ballarini et al. 2014; Swan and Ugursal 2009). While the high level of detail allows accurate simulation of changes to buildings, the relatively small number of buildings modelled keeps data and computational requirements manageable.

The building model is run as a multi-step process including the following major steps:

- Archetype or representative building definition;
- Scenario setup, which includes the specification of parameters specific to the policy scenarios being explored;
- Electric load simulation using the building physics software EnergyPlus;
- Scaling and calibration of archetype outputs up to represent the entire modelled region; and
- When applicable, enacting DR strategies and re-running the simulation.

These steps are summarized in Figure 3 and are described in more detail in the following sections.

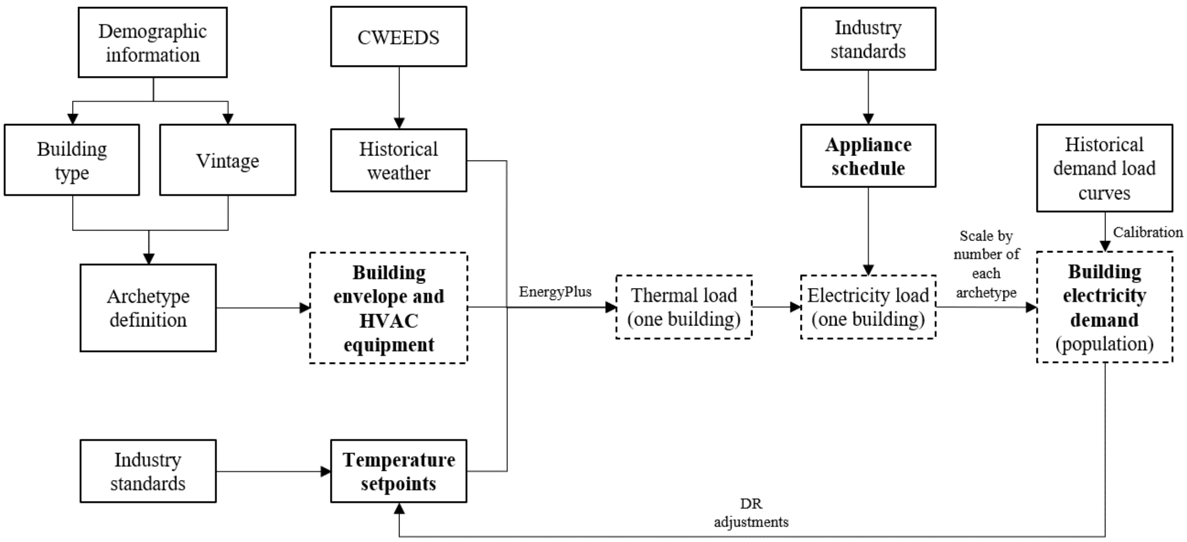

Figure 3: Building model processes, with solid boxes representing raw data inputs and dashes boxes representing a processed output. Note that bold text represents a direct tie-in to Figure 1. Reproduced with permission from Seatle et al. (2021)

Archetype definition

The first step in the building energy model is to select or determine the set of representative buildings, or archetypes, that will be modelled in detail. The goal of selection is to accurately represent the building stock before any policy changes are made, giving the modeler a realistic starting point from which different options can be explored. To accomplish this, the target population must be characterized in terms of the shape, size, construction materials, climate-control equipment, and other physical properties of existing buildings; this information can come from census data, tax data, GIS analysis of satellite imagery, or even a sufficiently large number of detailed appraisals of existing buildings. Archetypes can be selected either by averaging the characteristics seen in the building stock, or by simply identifying the most common building types.

Scenario setup

After a set of archetypes is defined, some additional input information is specified. Indoor and outdoor air conditions are needed to calculate the energy exchanged between the building and the environment. Outdoor conditions can be taken from historical weather data, which can be downloaded in the appropriate format from the EnergyPlus website (United States Department of Energy 2020c). Indoor conditions are input in the form of temperature setpoints and can be assumed based on industry standards or measured data.

In addition, to explore any policy scenario, the appropriate inputs (building envelope, HVAC specifications, or temperature settings) can be manipulated within the appropriate archetypes to reflect the policy under investigation. For example, to represent increasing insulation values in half of the population, the walls of half of the archetypes could be replaced with high-insulation materials.

Electricity load simulation

Once the building parameters have been specified for each archetype, all of the information is input into EnergyPlus, a building thermodynamics software that then calculates an hourly thermal load curve for one year of building operation (Crawley et al. 2001; United States Department of Energy 2020a). OpenStudio, a graphical user interface, can be used in conjunction with EnergyPlus as it contains various templates that can be used to make changes to each archetype (Guglielmetti, Macumber, and Long 2011; United States Department of Energy 2020b).

To form a complete hourly electric load curve for each archetype, energy uses not included within the thermal load - such as appliances, lighting, and other devices that use wall outlets - are added to the EnergyPlus output. Hourly values for these energy uses can be taken from nationally representative simulated data as seen in Armstrong et al. (2009), measured from an existing population, or simulated externally using a model such as that described by Richardson et al. (2010).

Output scaling and calibration

After the previous steps are repeated for all archetypes in the study, the electric load curves for each archetype are scaled by the number of buildings each represents, and then summed across all the archetypes. If the existing building stock with no modifications was modelled, the resulting building stock-level output can be validated and/or calibrated by further scaling to match measured data. The resulting building stock-level electric load curve is passed to the electricity system model in order to evaluate curtailment.

Modification for DR

If curtailment occurs at any point during the modelled timeframe, DR is simulated in the building model by manipulating its thermal controls within EnergyPlus. In practice, this occurs by changing temperature setpoints. After DR is implemented, the simulation is run again by repeating the thermal load simulation, appliance load incorporation, and output scaling steps.

Electricity system model

To allow for the analysis of the outputs from the transportation and building models, a PCM is used at the centre of the integrated platform. The SILVER model (McPherson and Karney 2017) was chosen because it can be applied at a city-scale, as seen in a recent study of Lusaka, Zambia (McPherson et al. 2018). As well, its flexibility allows the user to modify almost any part of the modelled electricity system. The key inputs, processes, and outputs, as seen in Figure 4, are described in more detail in this section.

Further information on the formulation of the SILVER model is detailed by McPherson and Karney (2017).

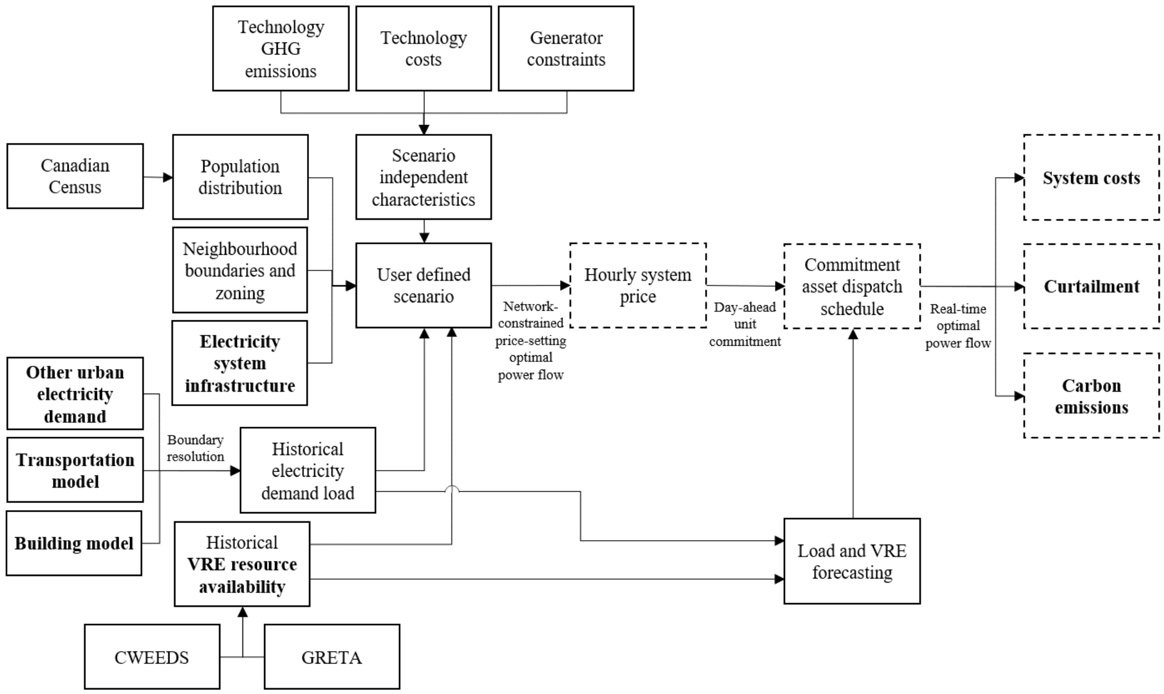

Figure 4: Electricity model processes, with solid boxes representing raw data inputs and dashes boxes representing a processed output. Note that bold text represents a direct tie-in to Figure 1. Reproduced with permission from Seatle et al. (2021)

User defined scenario

SILVER is a scenario-based model, which allows it to explore a wide-range of system configurations, but also requires detailed inputs. One such input that must be specified for each scenario is the electricity system infrastructure. This includes generation type and capacity, along with related transmission infrastructure. Any storage infrastructure within the system can also be modelled.

Another input required on the supply side of the electricity system is historical VRE resource availability, which is input as hourly capacity factors based on the location of the VRE generators within the scenarios. Solar capacity factors can be found using the procedure outlined by Masters (2004). Historical weather station data required for the calculations can be found in the Canadian Weather Energy and Engineering Datasets (CWEEDS) (Environment and Climate Change Canada 2015). In the specific case of rooftop solar, QGIS software[1] can be used in conjunction with the procedure outlined by

[1] Other GIS software can be used as long as it has the required capabilities for the outlined procedure

Latif et al. (2012). The required surface cover data can be found in the High Resolution Digital Elevation Model (HRDEM) (Natural Resources Canada 2020), and can be used with building footprints found in most major Canadian cities' open data portal. Location-specific wind capacity factors can be found through the Global Renewable Energy Timeseries and Analysis (GRETA) online tool (McPherson et al. 2017).

On the demand side of the electricity system, historical electricity demand data must be provided. Demand data can be measured, such as that provided by an electricity system distributor, or modelled, such as that taken from the transportation and building models. This demand can be broken up by regions, which are assumed to be substations within city-scale modelling. Further regions, such as neighbourhoods, can be used to further disaggregate demand. It should be noted that neighbourhood boundaries must be defined so that they are consistent with electricity demand regions; otherwise, the disaggregation of demand will be inaccurate. Census tract population data can be considered alongside municipal zoning to determine where residential buildings are located, so as to find neighbourhood population distribution. This allows for the specific electricity demand from each neighbourhood to be estimated. Neighbourhoods are considered both demand centres and buses (i.e. nodes) within the city-scale application of SILVER.

Finally, scenario independent characteristics must be considered. These include various electricity generation characteristics (i.e. capital costs, operational costs, and GHG emissions), as well as the generator constraints (i.e. ramping constraints, minimum down-time, efficiency, etc.).

Hourly system price

After a scenario is defined, SILVER produces a day-ahead hourly system price based on historical electricity demand data. At this point, power flow is optimized to meet demand at each node, while being constrained by system physical features, such as generator constraints, transmission capacity, etc. The resulting price is the system marginal price, which is set by the highest cost generator dispatched by the system to meet its demand at any given hour. If the electricity demand for an hour is met completely by VRE generation, then the marginal price for that hour will be zero due to the negligible operational costs of VRE generation.

Commitment asset dispatch schedule

Using the hourly system prices previously determined to ensure electricity demand could be met, the generator dispatch is optimized to reduce overall system costs. This takes into account additional constraints, such as start-up and shutdown costs, while also optimizing the usage of storage.

Like the hourly system price, the initial asset dispatch schedule is created based on historical electricity demand data and historical VRE resource availability. The system then creates a final schedule based on user-inputted forecasting. Generators that are inflexible within a 24-hour period retain the same schedule, while flexible generation and storage assets are used to meet any remaining demand.

Outputs

The outputs from SILVER that are of relevance to the integrated model platform are overall system costs, curtailment, and carbon emissions. The system costs can be represented as the system marginal price (i.e. variable operational and fuel costs), or the levelized cost of electricity (LCOE). Curtailment can be represented by either the hourly energy curtailed or the percentage of total VRE generation curtailed. Carbon emissions are calculated based on national average emissions per unit electricity produced for each generation type. Hourly system emissions, or overall system emissions per unit electricity produced, can also be found. Further, these emissions can then be used to determine the impact of a carbon tax on the cost of specific grid configurations.

Model workflow

This section overviews the decision maker - modeller workflow for the integrated model platform. This includes key data sources for each sector-specific model, the parameters that define a scenario, and a summary of key results and the target audience for each result. Figure 5 shows the proposed workflow with reference to applicable forms and tables at the relevant step. See case study section for more details on Tables A2 and A3.

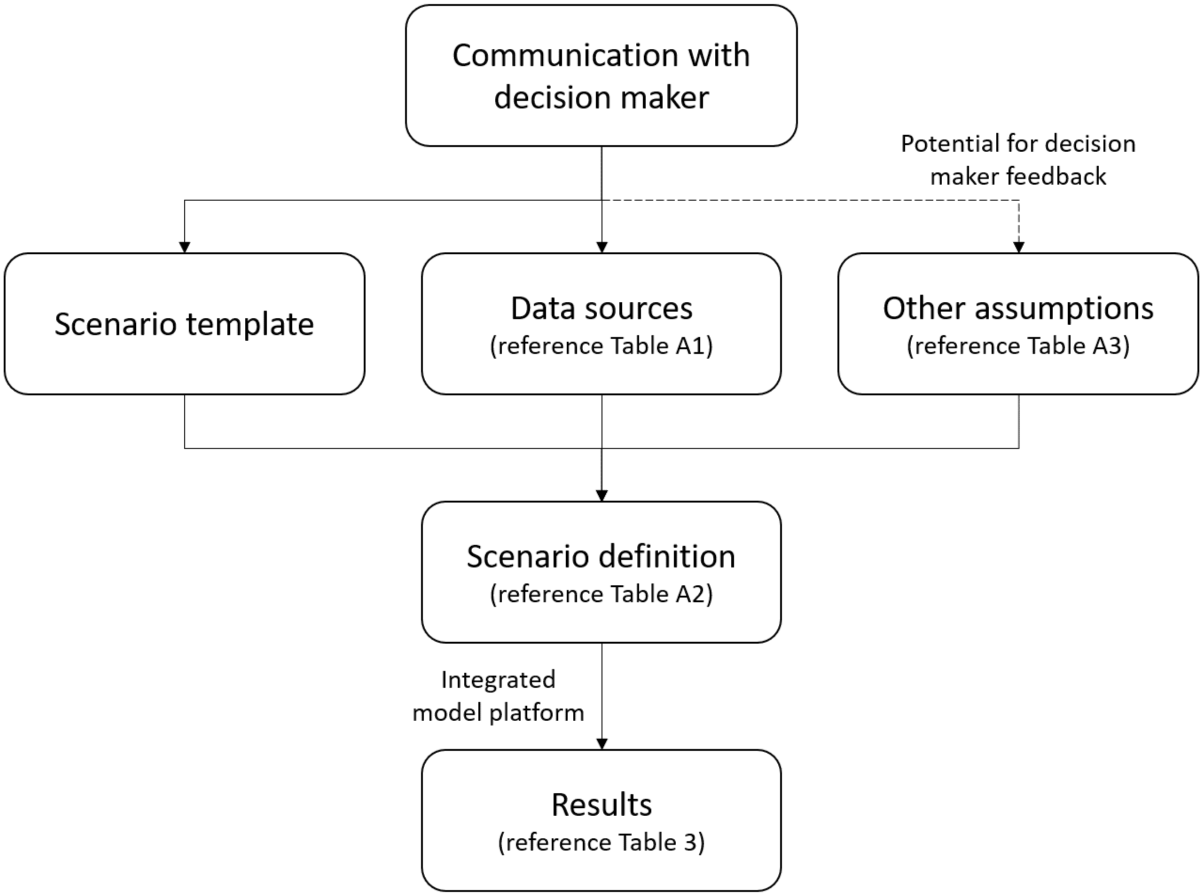

Figure 5: Proposed model workflow

Data sources

General data requirements for the integrated model platform are described in the Methods section and are summarized in Table A1 in the appendix. Table A1 can be used as a checklist of required data sources needed from a prospective city interested in using the integrated platform and includes: purpose of model input within the integrated platform, potential issues with acquiring data, and preferable sources.

Scenario definition

To leverage decision makers' knowledge on the exploration space of city-focused scenarios, a scenario template (found in the appendix) has been developed to communicate the range of scenarios capable of being modelled. The scenario template gives decision makers the space to reflect on what policies are important, and aids modellers in translating policy into quantifiable parameters (i.e. target EV charger penetration, building retrofit penetration, etc.), overall allowing for better communication.

Results

General results that can be obtained from the integrated model platform can be seen in Table 3, as well as the group for which the result is expected to be impactful. These results show the full capabilities of the integrated platform.

Table 3: General results of the integrated model platform

<table>
<tr><th>Result</th><th>Impact group</th><th>Purpose</th></tr>
<tr><td>Levelized cost of electricity (LCOE)</td><td>Decision makers</td><td>LCOE considers capital costs, as well as fixed and variable O&M costs based on the average electricity output over the infrastructure's lifetime. This result can be used to compare scenarios on the basis of cost.</td></tr>
<tr><td>GHG emissions</td><td>Decision makers</td><td>Calculated using average carbon intensity of non-electric end-use fuel sources or electricity generation type (National Energy Board, 2017). This can be used to assess feasibility of scenarios to meet various GHG reduction goals.</td></tr>
<tr><td>Ability to meet renewable electricity target</td><td>Decision makers</td><td>Based on the specific target set by the city, quantified by the percent of electric load met by renewable energy</td></tr>
<tr><td>Transportation electricity demand profile</td><td rowspan="2">Modellers</td><td rowspan="2">Sector specific spatiotemporal distribution of electricity demand that can be used to evaluate the effects of transport or building-sector electrification and/or energy efficiency policies (e.g. improved building insulation).</td></tr>
<tr><td>Building electricity demand profile</td></tr>
<tr><td>Generation asset dispatch schedule</td><td>Modellers</td><td>Demonstrates what the required capacity is for a scenario to meet a specific demand schedule. This can be used to assess the feasibility of scenarios that are being considered to meet this demand load.</td></tr>
</table>

Table 3 continued

Result	Impact group	Purpose
Electricity system operational cost	Modellers	This can be used to compare feasibility of scenarios if all generation infrastructure already exists, or if capital costs are similar.
Curtailment	Modellers	Used to estimate effectiveness of scenario generation mix in terms of how much potential VRE generation is “wasted”. This can be an indication that further system flexibility, in the form of DR or storage may benefit grid operations.
DR impact	Modellers	Measured based on the amount of curtailment reduced through DR programs. Can be used to determine if a DR program is beneficial when comparing savings from reducing curtailment to the compensation required for consumer participation.
Storage impact	Modellers	Measured based on the amount of curtailment reduced by means of adding storage capacity. Can be used to determine if a storage is beneficial when comparing savings from reducing curtailment to the cost of storage.

Case study - decarbonizing Regina

To demonstrate the potential usage of the integrated model platform, this section describes its application in the context of Regina, Saskatchewan. Regina made a commitment in 2018 to using 100% renewable energy by 2050 (Tink and Folk 2019). The city is a prime candidate for this target, as it draws electricity from one of the most carbon-intensive grids in Canada but is located in one of the highest solar and wind potential areas in Canada (Canada Energy Regulator 2020b). There is also significant potential for electrification in Regina, as most vehicles and building heaters are powered by non-electric sources (gasoline and natural gas, respectively) (Canada Energy Regulator 2020a).

A full summary of the scenario modelled (based off the scenario template) can be found in Table A2. In the case of Regina, the modelled parameters represent a boundary case for Regina, with an extreme shift towards both VRE integration and electrification: the transportation and buildings sectors are both fully electrified; rooftop solar is installed on every available rooftop; a wind farm is installed outside city limits; and storage capacity is added to the grid. Specific data sources for Regina are outlined in Table A1, while sector-specific modelling assumptions not previously addressed can be seen in Table A3. Further results from the Regina scenario can be seen in Figure 6.

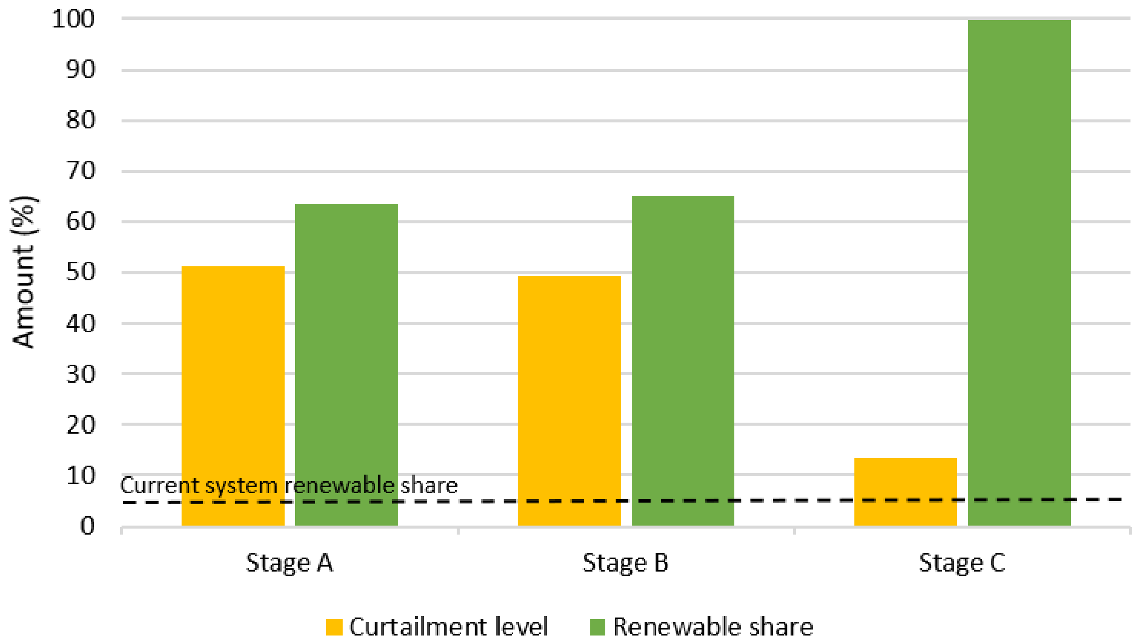

Figure 6: Annual average curtailment value across stages compared to ability to meet Regina's renewable target

Electrification of the building and transportation sector increases electricity demand, but the significant amount of VRE added to the grid still creates a large amount of curtailment in Stage A. The introduction of DR in Stage B lowers the level of curtailment compared to Stage A, but even greater reduction occurs when storage capacity is introduced in Stage C. Though the curtailment in Stage C is still well above zero, it is found to be an acceptable stopping point for the modelling in terms of Regina's ability to meet their target: Regina can meet over 99% of their electricity demand with renewables in Stage C, which is a significant improvement from both Stages A and B. For further analysis of Regina and their energy policy, refer to Seatle et al. (2021).

Discussion

The following section discusses the applications to policy; limitations, including accessibility and transparency issues within the model framework; and future work.

Usability for policy design

To increase the usability of the integrated model platform for policy design and evaluation, this report presents a fillable form and several useful tables describing model inputs, scenarios, and outputs. These tables/forms are intended to facilitate the collaborative process between decision makers and modellers by presenting model requirements and capabilities in an easy to understand format.

The operational focus of the integrated platform offers a high degree of spatial, temporal, and sectoral resolution, allowing it to be used to analyse target-based policies in the city scale transportation, building, and electricity sectors. This is useful for evaluating sector-specific and system-wide targets such as:

- Canada's goal of 100% EV market share by 2040 (Clean Energy Canada 2019);
- Building codes such as the BC Energy Step Code (Government of British Columbia 2017);
- Technology improvements such as EV efficiency and building HVAC properties; and
- Target levels of renewable generation capacity such as Regina's 100% renewable energy target (Seatle et al. 2021).

The feasibility and costs of alternative pathways can be compared through model outputs. Furthermore, the model can be used to quantify the trade-offs between alternative strategies, such as the trade-off between cost and curtailment reduction when DR and storage are implemented.

Current limitations

Limitations of the current model framework include software and data accessibility issues; simplifying assumptions that were made during the model process; the framework's focus on residential buildings and private transportation; and the exclusion of non-electric energy prices, which limits the effectiveness of price comparisons.

Each of the three sector-specific models mainly uses free and open-source software: TASHA, PopGen2, OpenStudio, and EnergyPlus are currently freely available, and SILVER is in the process of becoming open source. This was done due to a desire to improve the accessibility and transparency of the integrated model platform, as well as to demonstrate that detailed operational models can be built using freely available tools. However, some software which these components rely on is not necessarily accessible. In the building model, scenario analyses require the use of EnergyPlus measures, which are OpenStudio/EnergyPlus add-ons, but are not always well-documented. As described in Table A1, data collection may rely on software which has cost restrictions as well. Finally, there remains a large portion of the model platform which is currently not publicly available - such as the charging simulation model, and scripts which perform the tasks of spatial boundary resolution and simulation of DR.

Further, an issue that occurs across all sector-specific models is a lack of consistency in data availability between jurisdictions. Due to inconsistencies in the type of data available, sector-specific models may need to be formulated differently for each region the integrated model is applied to, increasing the development time.

Another issue that occurs throughout the model framework is the usage of crucial simplifying assumptions. The transportation model lacks a traffic assignment step, which would ensure that travel schedules output by TASHA are consistent with the Origin/Destination data used as an input. It is also assumed that EV drivers follow the same travel patterns as non-EV drivers. Both assumptions may reduce the accuracy of activity scheduling and the associated travel patterns. Similarly, the archetype-based framework used in the building model and the inclusion of a data-based appliance, lighting, and plug load component without sufficient randomness may underrepresent the diversity of electricity use patterns, leading to higher peaks and lower lows in the building demand curve. Finally, load forecasting in the electricity system model is based on electricity distributors' current system assumptions (i.e. majority non-electrified) and may not take into account the electrification of the transportation and building sectors. This may result in temporal trends specific to these electrified sectors not being fully represented between day-ahead and real-time electricity system operation schedules.

As well, both demand-side models are currently limited in scope: the transportation model only includes private vehicles, and the inclusion of commercial vehicles would require significant modification to the model framework. Similarly, the building model is optimized for residential buildings. Inclusion of other building types could be done with relatively little effort, but requires additional data to characterize the building envelopes, equipment properties, and non-thermal load components, all of which may be more varied than in the residential sector. In contrast, the electricity system model includes both private and commercial/industrial energy consumption.

Finally, another limitation of the overall framework is that it does not include the prices of non-electric energy sources, such as gasoline or natural gas for non-electrified vehicles or buildings. As a result, the LCOE found by the integrated platform does not include the amount of energy offset by fuel switching, which may obscure any cost benefits of using renewables.

Future work

This report has improved the transparency of the integrated model; however, it is recognized that the usability and accessibility of the model could be improved. Currently, the information flow between the models - load curves from the demand sectors to the electricity system model, and curtailment data in the opposite direction - occurs manually. Automation of the data flow would streamline the use of the model and improve usability. Even with the information presented in the report, all of the sector specific models are opaque. Writing development guides or user manuals for each model and for the associated linkage processes would drastically improve the framework's transparency and accessibility.

Future work at the city-scale includes expanding the modelling capabilities by creating additional variables within the sector-specific models. For example, the current DR formulation includes only utility-controlled DR, but user-controlled DR and time-of-use pricing are both strategies that can be considered in the future. Similarly, in the transportation model, more complex charging strategies could be investigated; and in the building model, a more detailed simulation of non-thermal loads could increase model accuracy.

Another future extension is applying the city-scale model framework to different cities in Canada. Since electricity systems, VRE resource potential, and demand profiles vary significantly between cities, the model outcomes would reflect these differences. The benefit of modelling multiple cities across Canada is that the model recommendations can be tailored to specific cities: instead of making assumptions across large spatial areas, each city's unique characteristics could be considered.

Stepping back from the city-scale, the model framework can also be applied on a national scale. This may entail modifying the transportation model to include not only personal vehicles, but also interprovincial freight transportation. Similarly, the building model could be modified to include different building archetypes that may not be found within a city, and thus may not be included in a city-scale model. The benefits of a national scale model would be to better influence national policies regarding interprovincial transportation infrastructure, national building codes, and national generation capacity planning.

Finally, integration within a national modelling platform would increase the visibility of the model, which would come with benefits both from a policy and a model development standpoint. Increased familiarity with the model among policymakers might encourage them to better understand the model and ultimately use it for decision-making. Meanwhile, scrutiny from other modellers could lead to model improvements or to the development of similar models encompassing other sectors.

Conclusion

This report outlines a novel integrated model platform in which operational transportation and building models are linked with an electricity system model at the city scale. This allows for the exploration of cross-sectoral effects of specific technology changes in the building and transportation sectors and increased renewable generation within the electricity system. To help decision makers at the city scale, this report is presented as a user manual, with a focus on increasing the transparency of the modelling effort. Special attention has been paid to describing the various data sources required as inputs to the integrated model platform, why they are needed, and possible sources for data. To facilitate conversations between decision makers and modellers, a scenario template is included to translate city-level outcomes and policies into modelling parameters. A case study of Regina’s renewable energy target illustrates some of the capabilities of the model, including electrification impacts on cost, as well as the potential of DR and energy storage.

The wide range of results within the case study demonstrate how one city can achieve their energy targets given local energy system characteristics. Applying the integrated model platform to other cities across Canada may allow local decision makers to evaluate a range of energy policies in relation to their own cities. With the ability to determine effective ways forward, cities can collectively contribute to decarbonization at the national scale.

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Appendix

Table A1: General and case-study specific data sources for integrated model platform

	Generic data type	Input to model	Purpose of input	Possible issues	Preferable sources of data	Regina specific source
Transportation	Travel survey	Household and persons	Provide sample for population synthesis	NDA (restrictions on use possible if travel survey contains sensitive data)	Municipal government transportation branch	Regina 2009 Travel Survey (Winram and Lui 2010)
		Trip records	Calibration			
		Zone system	Centroids used to obtain OD data			
	OD data	Zone-to-zone travel times, distances, for different modes	Calibration and run data	Google Maps Distance Matrix API becomes expensive for large zone systems; ArcMap Network requires a license and may be expensive computationally	Local travel models operated by municipality can provide OD data	Google Maps Distance Matrix API (auto) (Google Maps Platform 2021)
						ArcMap Network analyst feature with GTFS and network shapefiles (public transit) (City of Regina 2017a)
						Based on OD data for auto mode (walk and bike)
	Canadian census	Total population	Scale sample in population synthesis	None	Statistics Canada	Canadian Census 2011 (Statistics Canada 2015)
	General transit feed specification	Public transit schedules	Obtain OD data for public transit	May not line up with travel survey year	Municipal government	Regina open data portal (City of Regina 2017a)
	Road network shapefile	Road network data		Open source data may contain inaccuracies	Open Street Maps	Open Street Maps (GEOFABRIK 2020)

	Generic data type	Input to model	Purpose of input	Possible issues	Preferable sources of data	Regina specific source
Building	Building type and vintage	Archetype definition	Determine original electricity demand (pre-electrification)	Data for existing buildings is not sufficiently detailed, so some assumptions need to be made	Statistics Canada	Canadian Census 2016 (Statistics Canada 2017)
	HVAC properties					Households and the Environment Survey (existing technologies) (Statistics Canada 2011)
						OpenStudio template for ground source heat pumps (new technologies) (Parker 2020)
	Temperature setpoints	Temperature setpoints	Ensure compliance with industry standards	Limited data on consumer preferences	Nationally recognized standards	Energy Star (ENERGY STAR 2009)
	Insulation standards	Building insulation		Other step codes may be more stringent and preferable to use, but may not be locally recognized	Local building step codes	BC Step Code (Robinson 2018)
	Appliance properties	Appliance load	Generation of building electricity demand load	NDA (restrictions on use possible if required by the electricity distributor)	Smart meter data	Simulated data (Armstrong et al. 2009)
	Historical electricity demand load	None	Calibration	NDA (restrictions on use possible if required by the electricity distributor)	Local electricity distributor	SaskPower
Electricity system	Technology features	Technology GHG emissions	Create scenario independent characteristics	May be variation in values across Canada	Nationally recognized standards	Canada's Renewable Power Landscape 2017 – Energy Market Analysis report (Canada Energy Regulator 2020b)
		Technology costs				Levelized Cost of Energy and Levelized Cost of Storage 202 report (Lazard 2020; International Renewable Energy Agency 2020)
		Technology constraints				Previously defined SILVER values (McPherson and Karney 2017)

	Generic data type	Input to model	Purpose of input	Possible issues	Preferable sources of data	Regina specific source
Electricity system	Canadian census	Population distribution	Scale electricity demand to population centers	None	Statistics Canada	Canadian Census 2016 (Statistics Canada 2017)
	Neighbourhood boundaries and zoning	Population centers			Municipal government	Regina open data portal (City of Regina 2017b; 2017c; 2018)
	Electricity system infrastructure	Generation infrastructure and transmission	Determine system capabilities	NDA (restrictions on use possible if required by the electricity distributor)	Local electricity distributor	SaskPower
	Historical electricity demand load	Electricity demand load (actual)	Generate day-ahead schedules	None	Integrated model platform	Transportation model (transportation demand)
						Building model (building demand)
				NDA (restrictions on use possible if required by the electricity distributor)	Local electricity distributor	SaskPower (other urban electricity demand)
	Historical VRE resource availability	VRE capacity factor		None	Local weather station data	GRETA online tool (wind) (McPherson et al. 2017)
						CWEEDS (Environment and Climate Change Canada 2015)
	Rooftop solar shading and orientation	Rooftop solar generation capacity	Determine rooftop solar generation potential	None	Landcover GIS data	Regina open data portal (City of Regina 2017b)
						HRDEM (Natural Resources Canada 2020)
	Load forecasting	Electricity demand load (forecasted)	Generate real-time schedule	NDA (restrictions on use possible if required by the electricity distributor)	Local electricity distributor	SaskPower

Modelled scenario template

Notes:

- *Unless otherwise specified, penetration refers to percentage of population/buildings that the changes should apply to (ex. 100% personal EV penetration indicates that all vehicles on the road are EVs).*
- *If specific spatial distribution is required in any category, please indicate in additional notes.*
- *Unless otherwise requested, scenario will be modelled to include the federal carbon tax at the current increase rate.*

City:

Scenario name:

Target

What is the decarbonization target that your city is exploring?

☐ _____% renewable generation

☐ _____% carbon/GHG emission reduction from _____ levels

☐ Other:

Target deadline: 20____

Additional notes:

Residential buildings

Please indicate the level and type of residential building retrofits that you are interested in exploring.

Residential electric water heating penetration: _______%

Residential electric space heating (can select multiple)

☐ Forced air electric furnace penetration: _______%

☐ Ground source heat pump penetration: _______%

Residential insulation retrofit penetration: _______%

Additional notes:

Commercial buildings

Please indicate the level and type of commercial building retrofits that you are interested in exploring.

Commercial electric water heating penetration: _______%

Commercial electric space heating (can select multiple)

☐ Forced air electric furnace penetration: _______%

☐ Ground source heat pump penetration: _______%

Commercial insulation retrofit penetration: _______%

Additional notes:

Industrial buildings

Please indicate the level and type of industrial building retrofits that you are interested in exploring. Also include the predominant industries within the city and their approximate contribution to municipal GDP in the additional notes section.

Industrial electric water heating penetration: _______%

Industrial electric space heating (can select multiple)

- ☐ Forced air electric furnace penetration: _______%
- ☐ Ground source heat pump penetration: _______%

Industrial insulation retrofit penetration: _______%

Additional notes:

Electric vehicle (EV) penetration

Please indicate the level of EV penetration that you are interested in exploring.

- ☐ Personal EV penetration: _______%
- ☐ Electric public transit penetration: _______%
- ☐ Electric freight vehicle penetration: _______%

Additional notes:

EV charging infrastructure

Please indicate the type and level of EV charging infrastructure penetration that you are interested in exploring.

Business charging infrastructure

- ☐ Level 1 charger penetration: _______%
- ☐ Level 2 charger penetration: _______%
- ☐ Level 3 charger penetration: _______%

Home charging infrastructure

- ☐ Level 1 charger penetration: _______%
- ☐ Level 2 charger penetration: _______%
- ☐ Level 3 charger penetration: _______%

Alternative

- ☐ Assume there are chargers wherever they are needed

Additional notes:

Solar generation integration

Please indicate the type and level/amount of solar integration that you are interested in exploring. Rooftop solar penetration levels indicate the share of viable rooftops that would have rooftop solar installed.

Rooftop solar:

☐ Residential rooftop solar penetration: _______%

☐ Commercial/industrial rooftop solar penetration: _______%

Utility solar capacity added: _______MW

Additional notes:

Wind generation integration

Please indicate the amount of wind integration that you are interested in exploring.

Wind capacity added: _______MW

Additional notes:

Electricity storage technologies

Please indicate the amount of storage capacity that you are interested in exploring.

Storage capacity added: _______MW

Storage discharge duration: _______hours

Alternative

☐ Assume enough storage capacity to meet target

Additional notes:

Demand response (DR)

Please indicate the type and participation level of DR strategies that you are interested in exploring.

☐ Time-of-use pricing

Details:

☐ Utility controlled DR

Utility controlled charging (EVs) participation level: _______%

Building heating demand response participation level: _______%

☐ Voluntary demand curtailment (large-scale electricity consumers)

Details of participants (amount able to curtail and how many times annually as per contract):

Additional notes:

Table A2: Regina scenario template details

Variable	Details
Target	100% renewable energy
	Target deadline: 2050
Residential buildings	0% electric water heating penetration
	100% ground source heat pump penetration
	100% residential insulation retrofit penetration
Commercial buildings	Not considered
Industrial buildings	Not considered
EV penetration	100% personal EV penetration
	0% electric public transit penetration
	0% electric freight vehicle penetration
EV charging infrastructure	Assume there are chargers wherever they are needed
Solar generation integration	100% residential rooftop solar penetration (838 MW)
	100% commercial/industrial rooftop solar penetration (624 MW)
	0 MW utility solar capacity added
Wind generation infrastructure	200 MW wind capacity added
Electricity storage technologies	325 MW storage capacity added
	4-hour storage discharge duration

Table A3: Sector-specific assumptions made in modelling of Regina, Saskatchewan

Sector	Assumptions
Transportation	EV chargers have a constant power rating of 2 kW
	Battery capacity of EVs is 40 kWh
	EV battery depletion rate is a function of temperature, estimated using an online tool (Geotab 2021), assuming a 2019 Nissan Leaf with a 40 kWh battery; temperature is sampled monthly using Regina average monthly temperatures from (Environment Canada 2020)
	All modelled EVs participate in DR in stage B
Building	All modelled buildings participate in DR in stage B
Electricity	Available rooftops for solar installation are defined as those where the resource has a capacity factor of at least 10% and where the rooftop can fit a 5 kW PV array
	Wind farm is to the size of the largest wind farm planned in Saskatchewan at the time of writing
	Storage technology modelled as a lithium-ion battery; maximum capacity equal to the maximum curtailment found in Stage 2