1 Supplementary Information

1.1 Transportation model formulation

1.1.1 TASHA

Because TASHA simulates travel schedules for individuals, it requires a population of individuals to run. The Regina 2009 Household Travel Survey (Winram and Lui 2010) provides the geographic outline of Regina's traffic analysis zone (TAZ) system, as well as a record of households and household members who completed the survey. Each person that completed the survey recorded the trips they made in a single day. By sampling households from the travel survey to match population counts observed in the Canadian Census (Statistics Canada 2015), a synthetic population of Regina was generated using PopGen2 software, documented by Bar-Gera et al. (2009), Ye et al. (2009), Mobility Analytics Research Group (2016) and Konduri et al. (2016).

To predict the travel behavior of an individual in Regina, TASHA was calibrated to reflect local tendencies such as preference for certain zones for shopping and the importance of travel cost on mode choice. This required travel time and travel cost data in addition to the household and trip records from the travel survey. For travel times by public transit, the ArcGIS network analyst tool was used in combination with shapefile data for Regina's road network from Open Street Maps (GEOFABRIK 2020) and General Transit Feed Specification data from the City of Regina's online data portal (City of Regina 2017a). Travel times and distances by private vehicle were obtained using the Google Maps Distance Matrix API (Google Maps Platform 2021). Several TASHA sub models were calibrated using this data, including mode choice and location choice models.

After calibration, TASHA was run with a synthetic population. An example of a person-level schedule output of TASHA is shown in A.1. Four categories of Origin/Destination activity were modelled: Home, Other, Shopping, and Work. 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 processed further, as these trips are assumed to be EV trips, and therefore the source of electricity demand. Validation of TASHA outputs as compared to the Regina travel survey will be included in a forthcoming paper by Xu et. al (2022).

1.1.2 Charging model

Simulation of EV charging behavior – a key source of grid flexibility – is enabled through the disaggregated and detailed schedules that the TASHA model produces. Predicting charging for EVs requires vehicle schedules - the charging model first converts the person-level travel schedules shown in Table 1 to vehicle-level schedules to account for vehicle sharing in households. Along with battery capacity, charging rate, and depletion rate, different charging strategies can be defined for EVs. For example, one vehicle can be set to charge upon arrival, and another set to charge at the last minute before departure. To explore the potential for DR to reduce curtailment, different charging strategies are implemented depending on whether a DR scenario is investigated.

If an EV owner does not participate in a DR program, they may not be incentivized to charge a specific way. In this case, the simplest strategy for an EV owner is to charge as soon as they arrive at their destination, and this strategy is modelled for scenarios without DR. Charging is modelled by processing each vehicle's trip schedule in temporal order: when a vehicle departs from an activity, its battery level is updated based on the trip distance and depletion rate

$$SOC_a = SOC_d - D(temperature) * d \tag{1}$$

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 origin-destination distance between the zonal centroids in which the arrival and departure activities are located, and D is the depletion rate, which is a function of external temperature.

Once it arrives at its next activity, the EV is charged immediately until either the battery is fully charged, or the vehicle departs for its next activity.

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

where t_d is the departure time from the present activity, t_a is the arrival time of the current activity, R is the externally defined charging power, and $SOC_{max}$is the battery capacity. When the vehicle departs from its present activity, the cycle is repeated until all the vehicle's trips have been processed. To reduce computational time, a TASHA run of 5% of a simulated population was used, and its energy demand scaled up depending on the adoption scenario.

1.1.3 Modifications for DR

In scenarios involving DR, the flexibility of charging behaviour becomes a key concern, motivating a search for alternative charging strategies. Charging according to the non-DR scenarios described previously is ideal for consumers but offers no flexibility to the utility. To explore how EV charging can take advantage of VRE generation, a "last-minute" charging strategy is proposed for DR scenarios. With this strategy, vehicles initiate charging at the latest possible time such that the battery is charged to the desired level before departing for the next activity.

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

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

where t_c is the time at which charging must start.

Because of the last-minute nature of this strategy, a plugged in EV has a window during which any time t in the window,

$$t \in [t_a, t_c] \tag{5}$$

the vehicle will be plugged in, but not charging. During this window, any excess VRE generation can be used to charge this vehicle, shifting back the t_c for the vehicle. By maintaining a list of vehicles which are currently plugged in, but not charging, the utility is able to charge multiple vehicles this way, reducing curtailment as a result.

Vehicles follow their daily travel schedule and charge as previously described. As they travel and charge the utility maintains a list of vehicles which are eligible for DR; these are vehicles that are plugged in, but not charging as described in equation 5. Every fifteen minutes, the utility estimates the quantity of VRE that would be curtailed within the next fifteen-minute interval. While the estimated curtailment remains above zero, the utility will select a vehicle at random from the DR eligible vehicles, charge it for the next fifteen minutes or until the battery is full, and reduce the estimated curtailment by the amount charged. If the vehicle is not fully charged, the original start time of the vehicle's charging is then shifted back by fifteen minutes. The fifteen-minute time window is a user-defined figure, representing the granularity with which the utility forecasts curtailment and shifts vehicle charging. A pseudocode for the UCC procedure is provided below.

1.2 Building model formulation

1.2.1 Archetype definition

Effective archetype-based modeling requires that the properties of all the archetypes are representative of the target building stock. Archetype-defining characteristics had to be both major determinants of building energy use and measured from existing data. Since 60% of residential building energy use in Canada is consumed by climate control systems such as heating, ventilation, and air conditioning (HVAC) (Statistics Canada 2017), the archetypes are primarily based on a building's ability to exchange thermal energy with the outside environment. It has been found that a building's thermal properties are based on its vintage (Tooke, van der Laan, and Coops 2014), floor area, and building type (Swan and Ugursal 2009). Accordingly, six archetypes are defined using building type and vintage data from the Canadian Census (Table A.2) (Statistics Canada 2017). For each archetype, the solar heat gain coefficient of the windows and the rates of heat transfer (R-value) for the windows, walls, and ceiling are calculated from the equations defined by Tooke, van der Laan, and Coops (2014). Building floor areas are estimated such that newer homes are bigger than older ones, each building type's average floor area is similar to the average floor area stated in the Regina census, and the total area for all archetypes is equivalent to the total residential floor area in Regina. House shapes were assumed to be rectangular based on a visual inspection of Regina on Google Maps. Windows were placed symmetrically around the exterior of each archetype such that their total area satisfied the window-to-wall ration calculated from the equations defined by Tooke, van der Laan, and Coops (2014).

Heat exchange parameters for each archetype were calculated from the equations defined by Tooke, van der Laan, and Coops (2014). Building floor areas were estimated by modifying values from the census data to match the total floor area of residential buildings in Regina. House shapes were assumed to be rectangular based on a visual inspection of Regina on Google Maps. Windows were placed symmetrically around the exterior of each archetype such that their total area satisfied the equation described by Tooke, van der Laan, and Coops (2014).

1.2.2 EnergyPlus simulation

As stated above, thermal demands are a large portion of total building energy use. The commercially available building thermodynamics simulator EnergyPlus (Crawley et al. 2001; United States Department of Energy 2020) and associated GUI OpenStudio (Guglielmetti, Macumber, and Long 2011) were selected to model building thermal energy loads. The main inputs to this software are:

- Building envelope characteristics, which follow the archetype definitions described above;
- Outside air conditions, which follow a typical meteorological year in Regina as defined by the CWEEDS database (Environment and Climate Change Canada 2015);
- Occupant temperature preferences, which were based on industry standard recommendations (ENERGY STAR 2009; Manning et al. 2007) and assumed a constant setpoint of 19°C for heating and 27°C for cooling; and
- Usage of a forced-air furnace in any homes that were heated electrically before the introduction of any building upgrades for simulation purposes (Statistics Canada 2011). The operating specifications of this furnace are based on a template from OpenStudio 9.2.1.

1.2.3 Electricity load for one building

The EnergyPlus simulation outputs an electric thermal load curve for each modelled building, but thermal demands are only responsible for about 60% of each building's electric load (Government of Canada 2017a). A complete electric load for each archetype was therefore constructed by adding the average Canadian appliance, lighting, and plug load from a simulation by Armstrong et al. (2009).

1.2.4 Scaling and calibration

To produce a load curve for the entire building stock of Regina, a non-electrified load curve was developed for calibration purposes. This involved scaling the archetype load curves via two post-processing steps. First, to scale up the load curves to the size of the population, each archetype was multiplied by the number of houses of that type existing in Regina. It was assumed that 10% of central heating systems in Regina were electric, based on provincial data (Statistics Canada 2011), and all buildings were assumed to have electric air conditioning, based on historical demand trends.

Secondly, it was important that the modelled non-electrified load curves were consistent with measured data. The final load curves were therefore compared visually and in terms of yearly totals to historical load curves from SaskPower. These appeared to be roughly equivalent, so the model was considered to be an accurate representation of reality. However, to correct for situations in which the actual distribution of buildings in one region was slightly different from the assumed distribution, the modelled data for some regions was multiplied by a scaling factor.

1.3 Electricity system model formulation

1.3.1 Boundary resolution assumptions

The service area for each electrical substation defines one immutable spatial boundary. The analysis uses boundaries that are recognized by the City of Regina, so that the ensuing results are meaningful. Slight spatial modifications were made to neighbourhood boundaries to keep them consistent with the substation service areas, including splitting neighbourhoods into their subsidiary subdivisions and joining neighbourhoods that were serviced together. Land that was not part of a neighbourhood recognized by the city was grouped into “outskirts” neighbourhoods. Census tract data was attributed to each neighbourhood through proportional overlap with residential buildings. As Regina is considered as a whole within the integrated model platform, none of these boundary manipulations have any effect on the results; if the electricity system were considered at a community-scale, these boundaries would need to be further verified to ensure that they are consistent between all data sources.

Based on the granularity of the electricity demand data, each substation service area is modelled as a region within SILVER, each with their own hourly demand load. The same substation service areas are also modelled as buses, or nodes, to preserve the granularity of the transmission infrastructure data. An additional bus for the connection to the provincial electricity grid is included to allow for electricity from provincial generation infrastructure to still be utilized when necessary. Neighbourhoods are modelled as demand centers within Regina, with the spatially resolved population data being used to estimate the demand within each substation attributed to each neighbourhood.

Demand loads from the transportation and building models also involve boundary resolution. The transportation model zones vary significantly from neighbourhood boundaries used within SILVER. These boundaries are spatially resolved by dividing the transportation electricity demand by the preceding trip purpose and land use zoning to determine which neighbourhood the EV charging occurs in.

For example, assume transport zone (TAZ) A overlaps with two SILVER zones (zone 1 and zone 2). SILVER zone 1 has 80% commercial buildings and 20% residential buildings, based on building footprint, while SILVER zone 2 has 90% residential buildings and 10% commercial buildings (Table A.3). We can then assume that a trip is going to TAZ A with the purpose of work or shopping, it has an 89% chance of going to SILVER zone 1 and an 11% chance of going to SILVER zone 2 (resolved so that the total likelihood is 100%). Similarly, if there is a trip to TAZ A with the purpose of going home, it has an 18% chance of going to SILVER zone 1 and an 82% chance of going to SILVER zone 2 (Table A.4). This means that any charging occurring in TAZ A when the trip purpose was work would have 89% of the load attributed to SILVER zone 1 and 11% of the load attributed to SILVER zone 2.

Building electricity demand loads are spatially resolved through building type distribution. The process for attributing the load to different neighbourhoods within SILVER is done by multiplying the output for each archetype modelled by the number of that type of building within each neighbourhood.

Table A.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

Table A.2. Building archetype definitions

Building Type	Vintage	Dimensions	Height
House (freestanding)	1960	12.2 x 9 m	3 m
	1975	12.5 x 10 m	
	1987	13 x 10 m	
	2014	14 x 10.5 m	
Apartment (2 walls adiabatic)	1960	9 x 11.5 m	
	1975	10 x 12 m	

Table A.3. SILVER zone composition within TAZ A

	Residential	Commercial
SILVER zone 1	20%	80%
SILVER zone 2	90%	10%

Table A.4. Share of load attributed to SILVER zone by trip purpose

	SILVER zone 1	SILVER zone 2	Total load
Work	89%	11%	100%
Shopping	89%	11%	100%
Home	18%	82%	100%