Simulating Grid Effects of Electric Vehicles, Batteries, and Solar in Vermont

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Executive Summary

This project uses computer simulation to examine the effects of distributed energy resources (DERs)—solar, electric vehicles (EVs), and home batteries—on the grid. As electric technologies continue to penetrate the market, grid loads will increase. Simulating the effects of DERs can provide quantitative data to inform grid management decisions and pinpoint the opportunities and challenges of solar, EV, battery, and other flexible load penetration.

Using a sample of actual meter data from 100 residences served by Green Mountain Power, the computer models in this paper demonstrate what various DER scenarios will mean for a sample residential neighborhood. Inputs can be adjusted to show varying levels of adoption and to simulate the behavior of individual households. The model also allows users to observe fleet level behavior (e.g., all the EVs collectively) as well as any combination of fleets (e.g., all home batteries and all EVs together).

Going forward, a review process could help identify and implement improvements for future iterations of the modeling tool. The tool is highly flexible and easily updated. Efficiency Vermont can use this tool in collaboration with the DUs to evaluate the impact of EV charging incentive programs, and with additional development, other flexible load management technologies on Vermont's grid in support of grid management and flattening Vermont's grid load shape.

Introduction

Electrification has become Vermont's low-carbon answer to every question. While electrification may be the most sensible path towards decarbonization, it brings its own set of challenges. Perhaps the biggest challenge is transmission and distribution of much larger total quantities of electricity. To accommodate the extra transmission and distribution without enormous infrastructure upgrades, Vermont will have to be very thoughtful about scheduling flexible loads like electric vehicles (EVs), water heating, and space heating.

Energy Action Network's Annual Progress Report for Vermont, 2022, attributes 40 percent of Vermont's greenhouse gas (GHG) emissions to transportation. Reducing emissions from this sector will play a central role in achieving the state's legally mandated GHG reduction targets. Given the state's low-carbon electricity supply, EVs provide an opportunity to significantly reduce transportation-related GHGs.

Vermont's electric transmission and distribution infrastructure will require upgrades to support the widespread adoption of electric vehicles. Many circuits on the grid currently cannot handle the additional load associated with vehicle charging. Effective grid management, however, can enable increased load and minimize the need for expensive infrastructure investments.

To support flexible load management program evaluation and grid management, the study team developed a simulation tool for coordinating grid assets and planning for grid liabilities. Managing behind-the-meter solar generation, home batteries, and EVs will facilitate the expansion of these technologies. The simulation tool enables Efficiency Vermont to model the impacts of customer incentive programs geared towards managing these loads in a home and across a community.

The simulation application developed for this report is not intended to provide a complete exploration of any specific grid problem or scenario. Rather, it is intended to show the simulation tool's current capabilities and shortcomings and suggest avenues for improving future iterations.

Background

Efficiency Vermont aims to increase adoption of EVs in Vermont by expanding the electric vehicle supply chain and increasing the awareness and support of EVs through outreach and education. Funding provided by Act No. 151 enables Efficiency Vermont to provide training and incentive programs to vehicle dealers across the state to increase electric vehicle adoption.

Efficiency Vermont works to establish flexible load management, including electric vehicle charging management, with commercial and residential customers in partnership with distribution utilities. Knowing the magnitude of reduced GHG emissions and increased reliability of the grid due to electric vehicle conversion can provide Efficiency Vermont better insight into the real value of EVs and opportunities to accelerate their adoption. Including home batteries and solar energy generation in the model alongside EVs provides a realistic view of residential energy load shapes. Lessons learned from modeling these systems can be applied to evaluating other flexible load technologies.

Methodology

The study team designed the simulation to use historical advanced metering infrastructure (AMI) data from Vermont residences to calculate grid load. Using the AMI data, the tool can show the actual grid load for a particular date. The tool is customizable, allowing the user to simulate the load for a unique configuration of solar energy production, home batteries, and EVs. The user can model varying penetration levels and use cases and can simulate the effects of utility incentive programs on grid load.

Data sources

The simulation relies on 15-minute interval data from the following sources .

Table 1: Simulation data sources

Name	Use case	Source
AMI	Neighborhood grid load	100 randomly selected unique Green Mountain Power residential accounts that didn't appear to be seasonal residences or own EVs and were active from at least December 2020 through August 2022; retrieved from VEIC's Snowflake AMI database in October 2022
Resource mix	Carbon footprint of New England's electricity generation and grid stress	ISO-New England
System demand	Total grid load and grid stress	ISO-New England
Insolation	Estimate solar generation in Vermont	Solcast
Weather	Grid stress	National Oceanic and Atmospheric Administration
Driving time distribution	Model when and how far each EV travels per day	Informed by statistics from the Bureau of Transportation Statistics

The resource mix and system demand load data from ISO-New England are combined with weather data in the simulation to assess grid stress at 15-minute intervals.

User-adjustable inputs

Each application of the simulation includes several inputs that must be determined by the user.

- **Total service points:** The number of residential accounts, or service points, in a simulation. The collective group of accounts or service points is referred to as a 'neighborhood.'
- **Home batteries:** The number of home batteries in a particular simulation
- **Home battery mean size**: The mean capacity of the battery in the neighborhood (expressed in kWh).
- **Home battery standard deviation**: The standard deviation of home battery capacities in the neighborhood. This number helps determine the distribution of battery capacities in a given simulation.
- **Home battery maximum charge rate**: The maximum rate at which a home battery can charge (kWh/h or kW).
- **Home battery maximum discharge rate: T**he maximum rate at which a home battery can discharge to help alleviate a grid peak (kWh/h or kW).
- **Home battery minimum charge fraction**: The lowest charge fraction at which a home battery will still attempt to discharge to alleviate a grid peak.
- **Home battery charging stop fraction:** The threshold at which a battery will stop charging (fraction of total battery capacity).
- **Total EVs:** The number of EVs in a particular simulation.
- **EV battery mean size:** The mean capacity of an EV battery in the neighborhood (expressed in kWh).
- **EV battery capacity standard deviation**: The standard deviation of the capacity of the EV batteries in the neighborhood.
- **Electric vehicle connection incentive**: This variable simulates the propensity of the EV owner to participate in an incentive program to plug their EV into the grid even when they do not require charging so they can be used as a grid resource during peak periods.
- **Charge fraction urgency**: This variable simulates EV range anxiety by specifying electric vehicle battery levels which will feel too low by the EV driver and provoke vehicle charging.
- **Charging stop fraction:** The battery level at which EVs will stop charging.
- **EV mean driving mileage**: The mean distance an EV in the neighborhood will travel over a day (miles).
- **EV driving distance standard deviation:** The mean standard deviation among EV trips taken by neighborhood vehicles. This informs the distribution from which trips are selected and assigned to vehicles.
- **EV mean efficiency**: The mean driving efficiency among the neighborhood EVs (miles / kWh).
- **EV battery maximum charge rate**: The fastest rate at which an electric vehicle can charge.
- **EV battery maximum discharge rate**: The fastest rate at which an electric vehicle can discharge.

- **Driving probability distribution:** An irregular distribution informed by Bureau of Transportation Statistics study that helps determine when vehicles in the simulation are likely to be driving. Can be modified to suit other probability distributions.
- **Probability of distribution utility agreement:** The probability that a given resident has authorized the distribution utility to discharge their EV battery to help alleviate grid peaks. (All home batteries in the simulation are assumed to have a distribution agreement.)
- **Home battery / EV threshold for charging (separate input for each):** The maximum grid stress threshold during which charging of batteries / EVs is allowed. If grid stress exceeds this value, charging of home batteries or EVs ceases.
- **Home battery / EV threshold for discharging (separate input for each):** The minimum grid stress threshold required to trigger discharging of home batteries / EVs to alleviate grid peaks.
- **Grid stress thresholds:** The Vermont load thresholds indicating moderate, high, and very high loads (MW).
- **Carbon footprint thresholds**: The thresholds used to indicate whether carbon dioxide (CO_2) emission levels are low, moderate, high, or very high during a particular 15-minute period (gCO_2/kWh).
- **Grid build thresholds**: The Vermont load thresholds used to indicate when the grid would benefit from additional load to flatten the load shape (MW).

Process

For each simulation, the user performs the following steps:

1. Assemble a "neighborhood" based on real-world, historical, AMI consumption data
2. Merge the AMI data with other pertinent information such as weather, grid statistics, carbon footprint, total Vermont load, insolation (exposure to the sun's rays)
3. Calculate additional statistics to be used in the simulation, e.g., grid stress[1], and/or New England production carbon footprint
4. Build a fleet of EVs
5. Build a fleet of home batteries
6. Produce a table of date and time-specific trips for each electric vehicle
7. Calculate solar production for neighborhood using weather data
8. For each EV:
    a. Determine how many miles it travels every day of the simulation
    b. Divide its mileage into discrete trips
    c. Determine what time of day the EV travels

[1] Grid stress is a value used as a criterion in the simulation to decide whether to charge or discharge EVs or home batteries. Though it is user-configurable, the simulation results shown in this report use a combination of Vermont load and New England production carbon footprint to define degrees of 'grid stress' on a scale from 0-6. If both Vermont load and New England carbon footprint are below their 60th percentile from 2021 historical data, the grid stress is "0". As the percentile scores for carbon footprint and load increase, the grid stress increases to a maximum of "6". A grid stress score of "6" requires both the carbon footprint and load to surpass the 95th percentile of the historical 2021 data.

d. Assess charge depletions to the EV based on its trips
e. Determine when EV is available to charge
f. Decide when to plug the EV into the grid (a plugged-in EV, even if it is not charging, can be used as a grid resource by the distribution utility)
g. Decide when to charge and discharge the EV from/to the grid

9. Decide based on grid stress when to charge/discharge the home battery fleet
10. Calculate fleet-level load statistics for all EVs and home batteries in the neighborhood
11. Calculate a new overall load incurred by the neighborhood
12. Write all results to a file readable by Microsoft Excel or other spreadsheet application

Assumptions in the simulation

The following assumptions were built into the model to fill in data gaps and to accommodate the scope limitations of the project.

The study team modeled the electric vehicle driving patterns from a normal (Gaussian) distribution of driving trips and times that were specified in a single 20-year-old study. This is the best data available, but certainly fails accurately to describe when and how Vermonters use their EVs today. Similarly, the best available data for estimating solar production accounts for temperature and sun exposure but does not account for snow cover which regularly reduces solar production in Vermont.

The study team modeled vehicle battery capacities and driving efficiencies with random selections from a normal distribution. While this sort of distribution is a good descriptor of driving efficiencies, it is less accurate for describing vehicle battery capacities. Vehicle battery capacities would be better described as a summation of many normal distributions (with each individual normal distribution representing a specific EV's battery size). Unfortunately, it was beyond the scope of this project to determine these distributions.

For all results in the current simulation, the study team modeled home battery and EV battery charge and discharge rates as constants. Thoroughly investigating how age and charge state affect battery charge and discharge rates, and incorporating that understanding into the simulation was beyond this project's scope.

Results

The results below demonstrate the capabilities of the simulation tool and show how models can facilitate management of distributed energy resources. Because this simulation sought to investigate the effects of widespread electric vehicle and home battery penetration on grid peaks, the study team targeted the two weeks in 2021 during which the grid exhibited the most intense stress. Figure 1 shows average grid stress by week as measured by Vermont grid load and ISO-New England carbon footprint status on a scale from 0 to 6. Figures and results labelled "cold week" or "cold weather," refer to the 4th week of 2021, January 25-January 31.

Figures and results labelled "hot week" or "hot weather," refer to the 32nd week of the year, August 9-August 15, 2021.

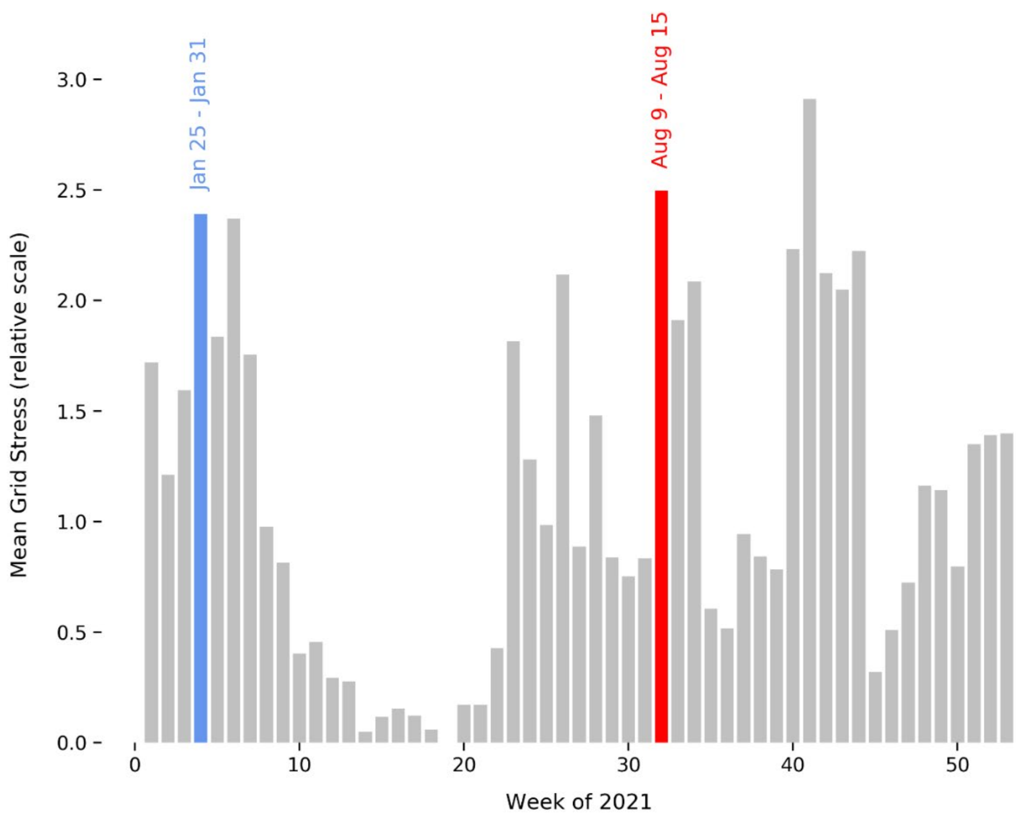


Figure 1: Average weekly grid stress as measured by a combination of ISO-New England electricity generation carbon footprint and Vermont load.

Behavior of an individual EV

Each EV in the simulation has a unique profile of driving trips, driving efficiency, battery capacity, agreement for discharge with the distribution utility, and other variables as explained in the user-adjustable inputs. The results for each individual vehicle can be observed in isolation. Figure 2 shows the simulated effects of a single vehicle, EV #17, on the grid during 2021's highest-stress cold week.

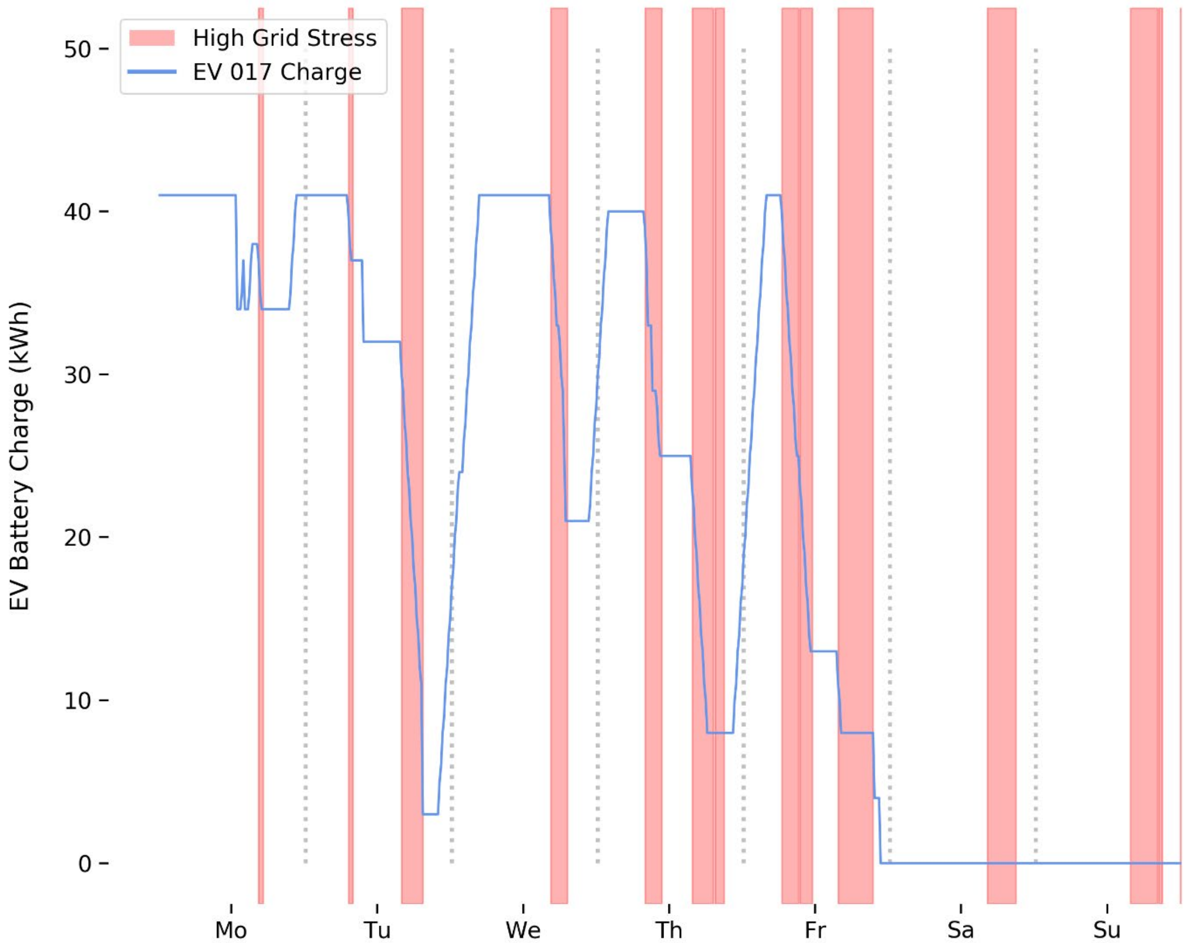


Figure 2. Simulated charging for electric vehicle #17 during the highest-stress, cold week of 2021.

In this case, the simulation modeled a scenario in which EV #17 had an agreement with the distribution utility that allowed it to be discharged during high stress periods with no recharging until grid stress had dropped. The model demonstrates that during this cold week, grid stress did not drop low enough under the configured thresholds from Friday to Sunday to enable recharging. In the case of a real EV charging program, either the user needs to be able to override this flexible charging program or the boundaries of charging times need to be loosened in times of extended grid stress such as those experienced in the test week.

Load of entire EV fleet

The simulation also makes it possible to analyze the behavior of all EVs in the neighborhood at one time. The color map in Figure 3 shows when cars are a) connected to the grid and charging, b) connected to the grid and discharging, c) connected to the grid and not charging or discharging, and d) not connected to the grid.

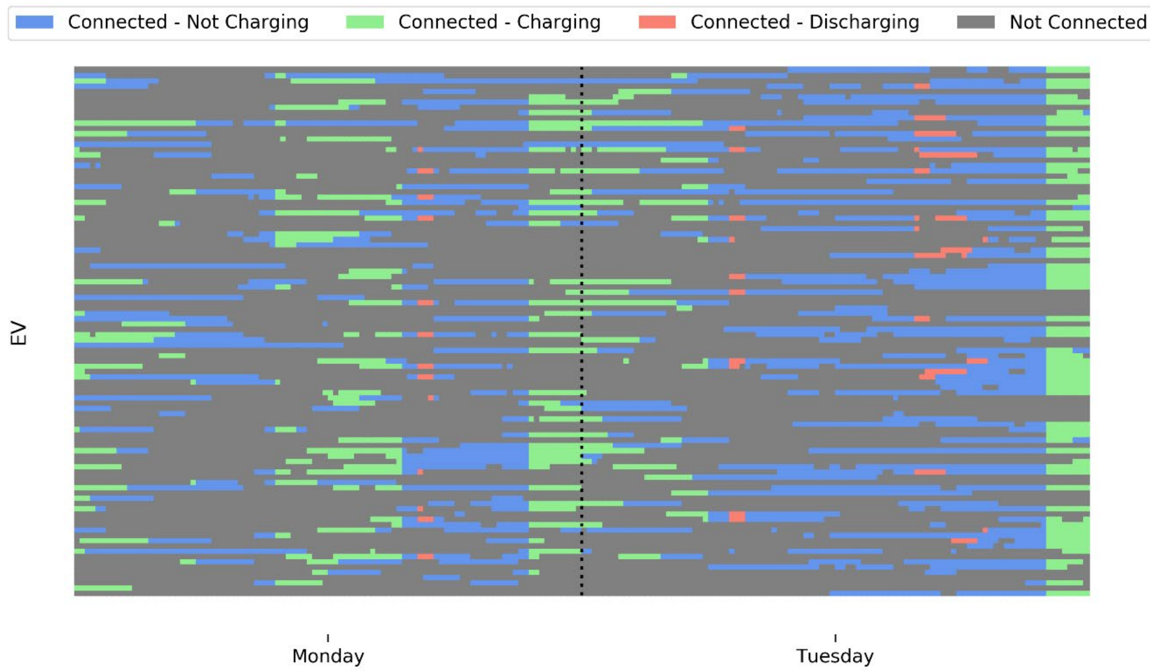


Figure 3. A color map showing the behavior of 100 simulated EVs over two particularly cold, high-stress days on the grid.

All of the EVs simulated in Figure 3 agreed not to charge during high-stress periods, but only about 40% allowed themselves to be discharged to help alleviate stress during the highest stress periods. The pink colored blocks in Figure 3 make these vehicles easy to identify. This scenario includes a modest incentive for EV users to connect to the grid even if their vehicle does not require charging.

Load + solar + EVs + home batteries

For grid planners, one of the great challenges of the coming decades is predicting how load shape and total load will change and designing infrastructure to meet new demand. This simulator can help anticipate and plan for changing loads by modeling both normal load and fleet-level load for EVs, home batteries, and behind-the-meter solar.

Figure 4 shows load for 20 home batteries, 20 behind-the-meter solar installations, and 100 EVs over two days of the high-stress, hot week of 2021. Positive values show increased electricity demand while negative values indicate periods when solar and storage resources removed load from the grid.

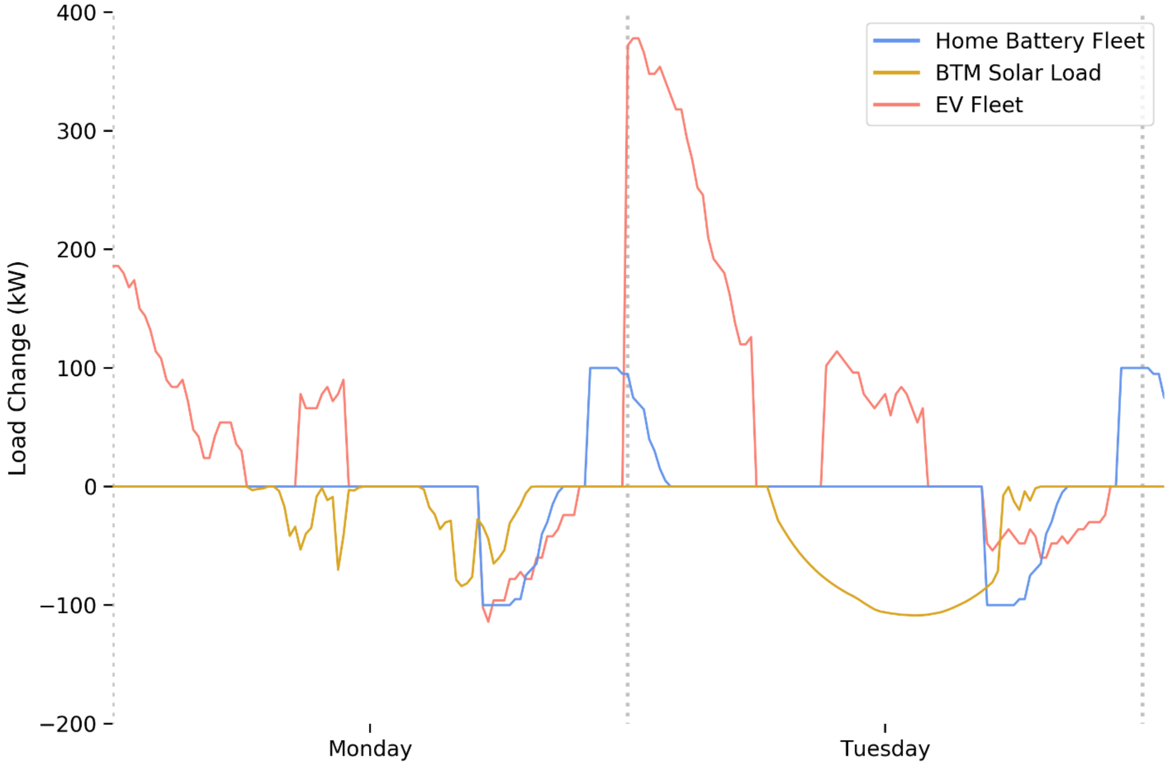


Figure 4. Load change incurred on the neighborhood grid by each group of resources. Positive values indicate increased demand from the neighborhood while negative values are loads removed from the grid. This scenario includes 100 EVs, 20 home batteries, and 20 solar installations during the Monday and Tuesday of the high stress 'hot' week of 2021.

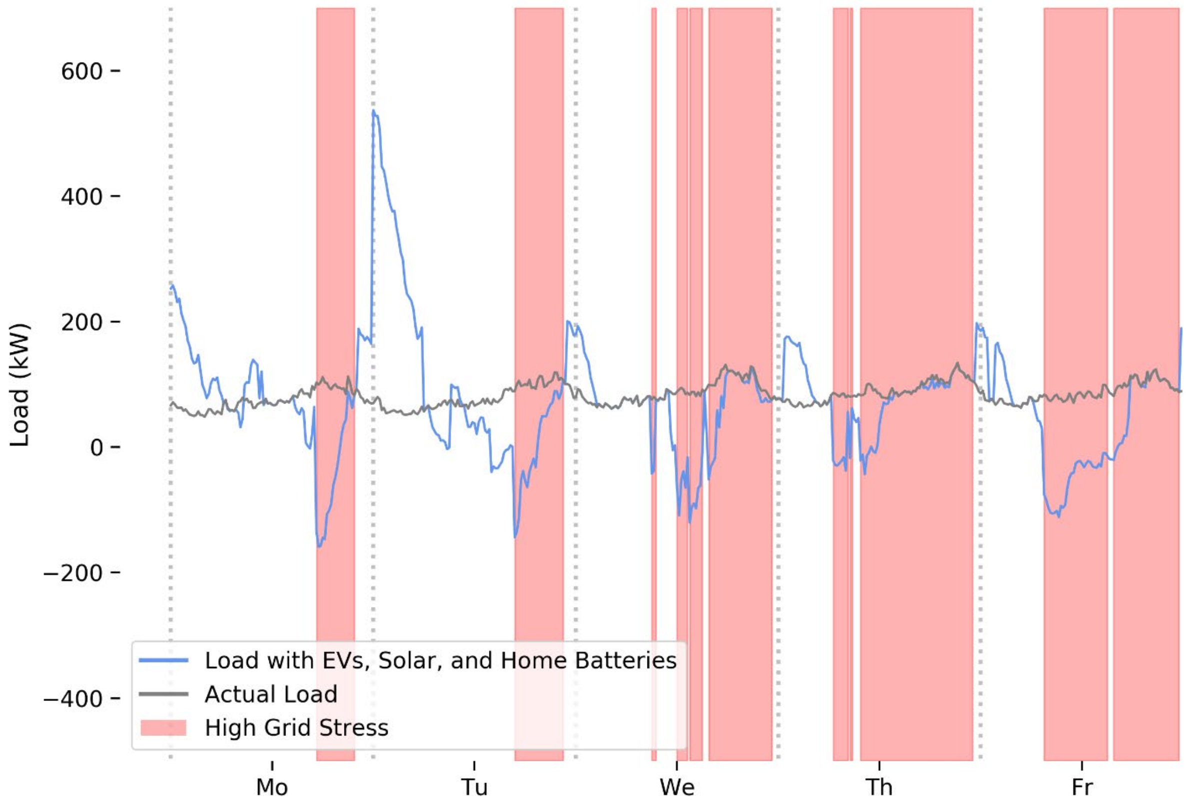


Figure 5. Comparison during 2021’s hot stress week of the actual neighborhood load (gray) and a simulated load with 100 EVs, 20 home batteries, and 20 home solar installations.

Comparing the neighborhood’s simulated load with EVs, solar, and home batteries, to the actual load without those resources during the hot, high-stress, peak week of 2021 reveals a mixed picture.

The wider grid will benefit from the new load shape because the neighborhood’s load during peak periods is reduced; the neighborhood has even become a producer of electricity during most periods of high stress. However, EVs and home batteries can only charge after grid stress drops to a reasonable level and without careful scheduling, they could all go online at once and overwhelm the local infrastructure. Just after midnight on Monday night, Figure 5 shows that when these resources go back on the grid, load spikes to nearly six times its normal peak magnitude. Though there would be more than sufficient electricity on the grid available just after midnight, the local substation may not be able to handle such demand. A possible solution would be to stagger start times among EVs that require charging.

Vermont load vs. neighborhood load

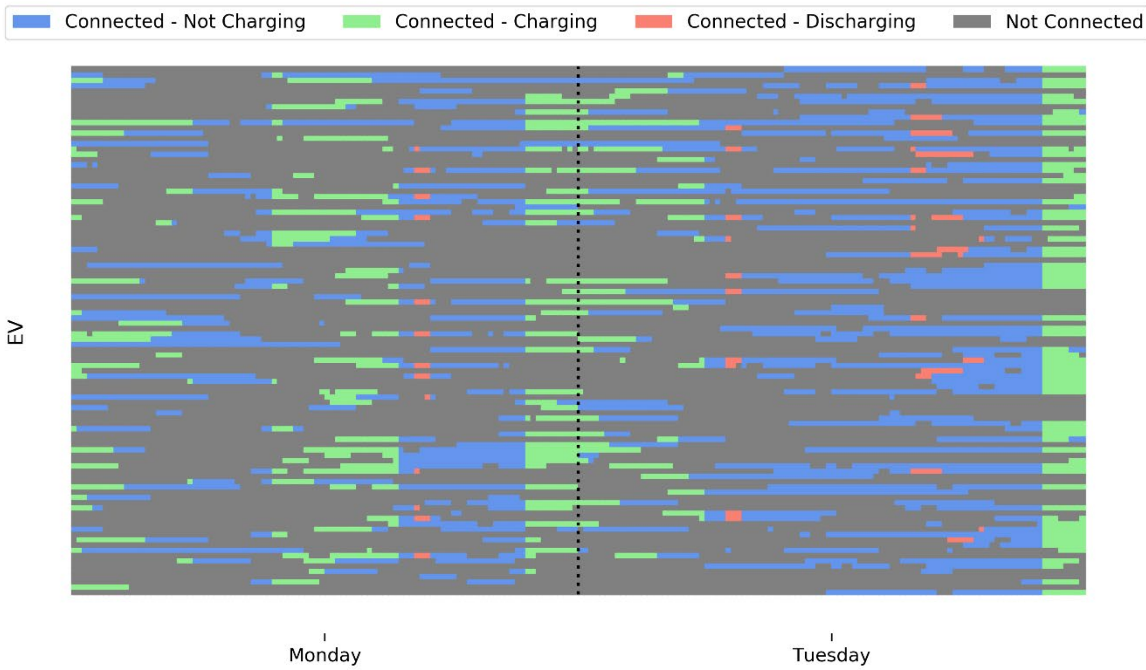
Figure 6 helps visualize the beneficial effects that distributed resources could have for the grid. In this simulation, every home in the neighborhood has one EV and there are also some solar and battery resources. In the scenario, residents have authorized the distribution utility to decide when to charge their vehicles overnight and when to discharge their EV batteries if it is deemed helpful to the grid. Ideally, during a high-stress cold week like this one, the distribution utility would be able to build the neighborhood's load when Vermont's load is low and minimize the neighborhood's demand when statewide load is high.

Figure 6. Simulated normalized neighborhood load with widespread EV adoption vs. Vermont actual 2021 load during the cold weather high grid stress week.

Figure 6 shows that these results were possible. Collectively, the neighborhood built load late at night when the grid was least stressed and minimized load or even provided electricity during peak periods.

Load with and without an EV connection incentive

The two colormaps in Figure 7 simulate the effect of increasing incentives to encourage people to plug-in their EVs and authorize utilities to access them to alleviate grid peaks. In these scenarios any time an EV is not in use, it is assigned a probability of being plugged into the grid, depending on how badly it needs to be charged and whether the resident is incentivized to plug-in.



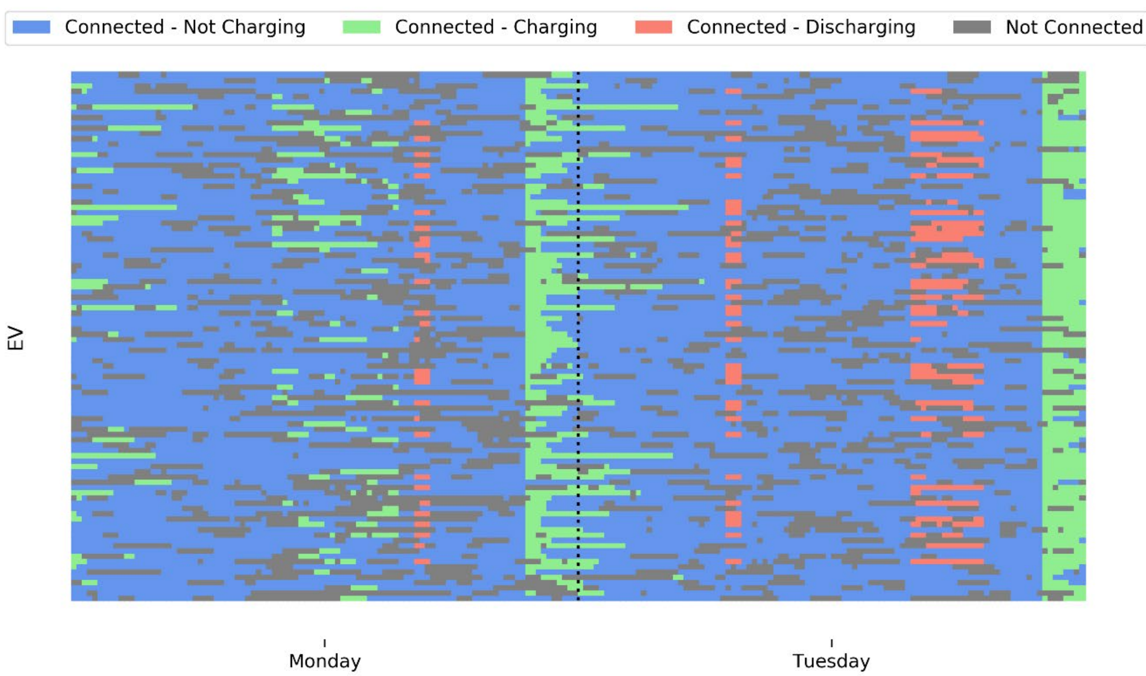


Figure 7. Comparison of two simulated fleets of 100 EVs in a cold weather, high grid stress scenario.

The top colormap shows a scenario with a very modest incentive for users to connect to the grid. Only about 40% of the residents have authorized the utility to discharge their battery to help the grid. The lower colormap, by contrast, depicts a scenario with a very high incentive to connect to the electric grid. About 80% of residents have authorized the utility to access their EV batteries to help alleviate grid peaks and the time, shown in blue, when the vehicles are plugged in is much greater.

While it is beyond the scope of this study to quantify the size of incentive that would cause this shift in behavior, this simulation tool provides a way to create an ideal grid scenario and model the estimated effects of real-life incentives.

Future Work

In its current form, this computer simulation has great promise, but is not yet sophisticated enough for planning purposes. A review process could help identify and implement improvements for future iterations of the tool. The existing simulation has the flexibility to add or change parameters, and nearly any part of the simulation can be modified with minimal difficulty. Going forward, Efficiency Vermont can use this tool in collaboration with the DUs to evaluate the impact of EV charging incentive programs, and with additional development, other flexible load management technologies on Vermont’s grid.