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Profitability of a Vehicle-to-Home system in different electricity tariff contexts

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Executive Summary

This study explores the economic benefits of a Vehicle-to-Home (V2H) system for residential consumers. Through a model minimizing the daily total cost of electricity by arbitraging from the price differential throughout the day, with a V2H system, we are able to analyze its value. Residential time-of-use tariffs from four different jurisdictions (Quebec, Vermont, Michigan and California) are used, under three different usage scenarios (Car away from 8am-6pm, Part-time at home and Full-time at home). Residential load profiles without and with electrical heating are analyzed. We find that, for the most common case in the United States where heating is not electricity-based, annual savings can be substantial in some cities. Savings are however highly dependent on the prevailing time-of-use (TOU) tariff and price differential between peak and off-peak periods. For the city of Burlington in Vermont, with one of most aggressive TOU tariffs, annual gains range from US$157 to US$379. For Detroit in Michigan, annual economic benefits go from US$24 to US$190. For San Diego in California, annual gains are high and go from US$620 to US$1,153 when choosing the appropriate tariff. For Santa Rosa in California, savings can be null or go up to US$100, depending on the car availability and the tariff applying. For Quebec, the consumer's bill reduction ranges from CAD$230 to CAD$475, when households use electric heating, as it is common.

Introduction

With the reduction of greenhouse emissions as an important objective in our society, and in the energy transition context currently underway in several countries, electric vehicles (EV) are likely to continue to gain in popularity in the future. However, due to the additional electricity demand that this clean transport option requires, it could cause many problems for grid operators if many of EV were to be charged simultaneously. Increasing demand at bad times, during peak hours, could result in economic and environmental costs, as the demand differential is most likely to be covered by non-clean energies. Therefore, the environmental and financial benefits they were supposed to bring in the first place would be cancelled out. As a solution to these problems inherent to electric vehicles, a vehicle-to-home (V2H) technology is worth our attention. The V2H concept offers an opportunity to turn the vehicle into a resource by allowing a bi-directional movement of electricity between the car and the house. The energy stored in the car can be used to smooth the grid consumption of households, resulting in potentially flatter load for electric suppliers and a reduced electricity bill to consumers. By storing excess renewable generation and using it when generation is low, vehicle-to-home have also the potential to improve the effectiveness of renewable energy sources. This study covers the profitability of *dcbel*, a new bi-directional charger soon offered by the firm Ossiaco (Ossiaco Inc., 2020). Their product (see Figures 1 and 2) allows integration with any solar panel setup, blackout power with their two-way power flow and is the world's only home electric vehicle supercharger. Furthermore, their complex system was built to optimize both the space it takes once installed at home and energy consumption, the latter being the opportunity that motivated our research.

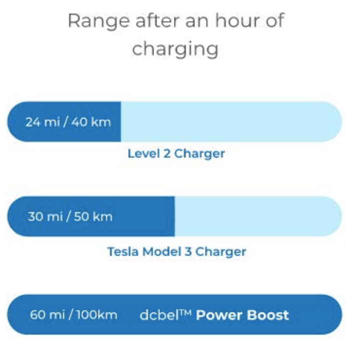


Figure 1 - Comparison of time-of-charge
Source :
https://dcbel.ossiaco.com/#whydc bel

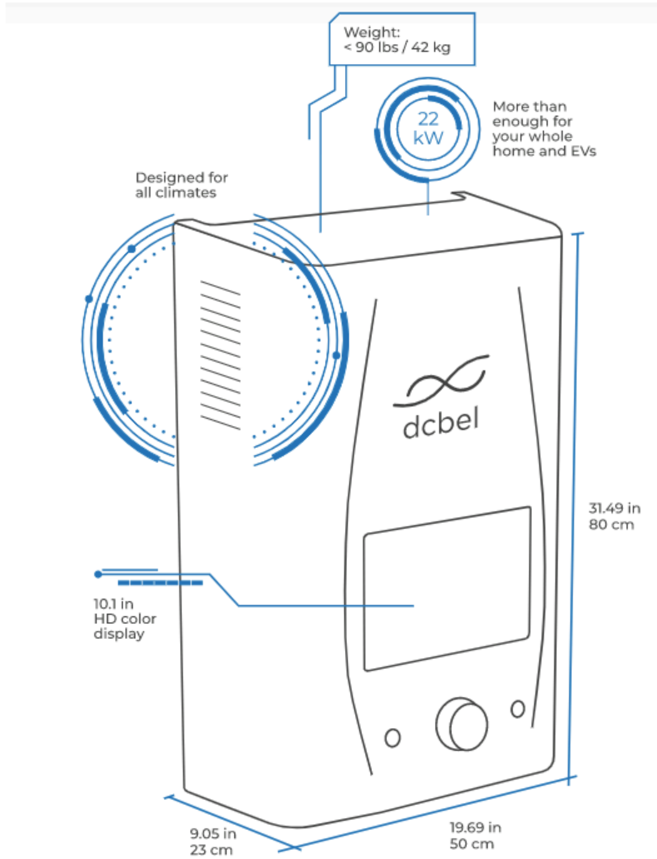


Figure 2 – Specifications of dcbel system
Source : https://dcbel.ossiaco.com/#whydcbel

Previous V2H studies

There are relevant studies that have examined the opportunity to use electric vehicles as a source of energy to power households when necessary. Haines, Gareth, Andrew McGordon, Paul Jenning and Neil Butcher (2009) have explored the feasibility of vehicle-to-home technology in reducing the peak power demand and increasing the load factor, a measure of how constant the electrical demand is. They found that when the vehicle was used for distances of 2 miles and 40 miles during the day, the V2H proved successful and the peak power demand of the electric grid was reduced from 10kW to 3kW using the car battery, with the load factor increasing by a factor of four. For distance of 80 miles, however, they found that the V2H was not useful, as the state of the battery was too low when the vehicle arrived at home. Even if our research is more consumer oriented, their findings remain a good argument for all electricity suppliers and their potential interest in promoting the use of such a system.

In another study, Kiaee, Mahdi, Andrew Cruden and Suleiman Sharkh (2015) estimated the cost savings from participation of electric vehicle in vehicle-to-grid (V2G) concept. Different from V2H system, V2G allows the energy stored in EV batteries to be fed back into the grid when prices are high to potentially make some profits for the EV owners if they are rewarded from the grid for this service. The results of their simulation show that the strategy using V2G system is able to reduce the charging cost of the vehicle by 13.6 %, while permitting the EV to have sufficient energy to complete the daily distance corresponding to only 8.3 kWh of energy consumption. Pushed a little further and looking at V2H, our work aims to find out whether there are not only savings to be made on the recharge of the EV, but also on the electricity bill as a whole.

Hence, somewhat different from these researches, this research investigates the direct economic benefits to be realized for customers from a smart V2H charger in four different jurisdictions: Quebec, Vermont, Michigan and California. We only consider the direct residential electricity bill gains, and not the additional benefits from a V2H system (ability to integrate solar generation, availability of backup supply, smart load-shifting).

Description of the model

The optimization model we developed is based on the arbitrage opportunity within a tariff structure and the possible storage provided by the EV battery. It minimizes the electricity bill of consumers equipped with the *dcbel* system. Given the daily pattern of electricity usage, the model runs on the MS Excel and uses its limited but convenient solver (maximum of 250 variables). To obtain yearly results, we use typical, representative days from the four seasons and use them to estimate annual benefits.

In the next pages, we present the methodology in four sections: Tariff structure, household load profile, vehicle characteristics and scenarios. The optimization model is explained in a fifth part.

Tariff structure

The four jurisdictions of interest have very different residential electricity tariff structures. The structure the most likely to be profitable is one of the type "Time-of-Use". When available, we also took the rates applicable to electric vehicle owners and still available to new customers. Table 1 below synthesizes the main components of the time-of-use tariff structures we use.

	Quebec		Vermont	Michigan		California		California		California		California	
	Hydro Quebec		Green Mountain Power	DTE Energy		SDG&E EV-TOU-5		SDG&E EV-TOU-2		Sonoma Clean Power		Pacific Gas & Electric	
	CAD		*USD*	*USD*		*USD*		*USD*		*USD*		*USD*	
Tariff structure - only variable charges	**Flex D**		**Rate 11 (Residential Time-of-Use)**	**Time-of-Day Electric Rate**		**EV-TOU-5** *(with monthly service fee of 16 $)*		**EV-TOU-2**		**EV2 Residential Rate for EV owners**		**E-6 (Residential Time-of-Use)**	
	Summer	Winter		Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
Date	Apr 1-Nov 30	Dec 1-Mar 31		Jun 1-Oct 31	Nov 1-May 31	Jun 1-Oct 31	Nov 1-May 31	Jun 1-Oct 31	Nov 1-May 31	Jun 1-Sept 30	Oct 1-May 31	May 1- Oct 31	Nov 1-Apr 30
Peak													
Price (cents/kWh)	n/a	50	26.114	16.929	14.301	50	26	55	31	26.66	21.227	39,696 first 8,8kWh/day 48,235 beyond	n/a
Time	n/a	Mon-Fri 6-9am & 4-8pm, 25-33 events max 100h	Mon-Fri 1-9pm	Mon-Fri 11am-7pm	Mon-Fri 11am-7pm	4-9pm all days	4-9pm all days	4-9pm all days	4-9pm all days	4-9pm all days	4-9pm all days	Mon-Fri 1-7pm	n/a
Super Off-Peak (San Diego) / Partial Peak (Santa Rosa) Price (cents/kWh)	n/a	n/a	n/a	n/a	n/a	9	9	19	19	22.41	20.012	27,853 first 8,8kWh/day 36,392 beyond	22,447 first 16,2kWh/day 30,986 beyond
Time	n/a	n/a	n/a	n/a	n/a	midnight-6am weekdays midnight-2pm weekends	midnight-6am weekdays midnight-2pm weekends	midnight-6am weekdays midnight-2pm weekends	midnight-6am weekdays midnight-2pm weekends	3-4pm & 9pm-12am	3-4pm & 9pm-12am	Mon-Fri 10am-1pm & 7-9pm Sat-Sun 5-8pm	Mon-Fri 5-8pm
Off-peak Price (cents/kWh)	6,08 first 40kWh 9,38 beyond	4,28 first 40kWh 7,36 beyond	11.131	5.699	5.476	29	25	34	30	18.7	19.001	20,33 first 8,8kWh/day 28,869 beyond	20,764 first 16,2kWh/day 29,303 beyond
Time	Always	All other times	All other times	All other times	All other times	All other times	All other times	All other times	All other times	All other times	All other times	All other times	All other times

Table 1 – Tariff structure summary

As the table above suggests, we push the research a little further for the case of California, where four different tariffs have been explored. We did so because of the highly-differentiated tariff structure across this state that causes volatility in the savings. Given that California could be of high potential in the market entry of *dcbel*, we want to find if there are tariff's characteristics that help to increase financial benefits. We use two rates from San Diego in California, both being offered by San Diego Gas & Electric (SDG&E). Tariff EV-TOU-5 (San Diego Gas and Electric Company, 2019) offers lower electricity rates in exchange for a monthly fixed charge of $16, whereas tariff EV-TOU-2 has no fixed charge but higher rates. We also use two rates from Santa Rosa in California, one having PG&E (Pacific, Gas and Electric) as both the energy provider and distributor, tariff E-6 (Pacific Gas and Electric Company, 2020), and the second having SCP (Sonoma Clean Power) as the energy provider and PG&E as the distributor, tariff EV2 (Sonoma Clean Power Authority, 2020). Because PG&E has been in the middle of all the controversy regarding forest fires in California, we think it is relevant to extend our analysis to a different operator. Indeed, in the event that the rates offered by Sonoma Clean Power are more beneficial when combined with the *dcbel* system, it could encourage people to switch operator and therefore would relieve PG&E in their reorganization after filing for bankruptcy in January 2019 (California Public Utilities Commission, 2020). More details about the tariffs and the way they were found are given in Appendix 1.

Household load profile

Open Energy Information offers a data bank of commercial and residential hourly load profiles for all TMY3 locations in the United States (Office of Energy Efficiency & Renewable Energy, 2018). This dataset contains hourly load profile data for a house for a representative simulated year and gives three different scenarios: High case, base case and low case. We used the base case scenario's data for our analysis. Such data are not available for Canada, so we used the city of Burlington as an approximation for Quebec's load profile, given its geographical proximity and similar weather. The city of Burlington was also used for Vermont's tariff structure. For Michigan, the city of Detroit was used. For California, the cities of San Diego and Santa Rosa were used. Santa Rosa was chosen because it was the only one in the data set which was served by both PG&E and Sonoma Clean Power, which is essential for comparison purpose. Two scenarios were of interest for us: electric consumption without and with electric heating. For the first one, data were given as is. For the second one, we added the electric heating to the previous one. Because the only provided data regarding heating were that of gas heating, we took the energy (in kWh) of gas heating and assumed it was equivalent to the energy consumed with electric heating. Data were sorted appropriately by season to have descriptive statistics relevant to the continuation of the study. More details regarding data manipulations and relevant findings are available in Appendix 2. Below are graphs of the selected representative daily load profile consumption per season in Vermont, the first one representing only electric utilities, and the second one containing electric heating as well.

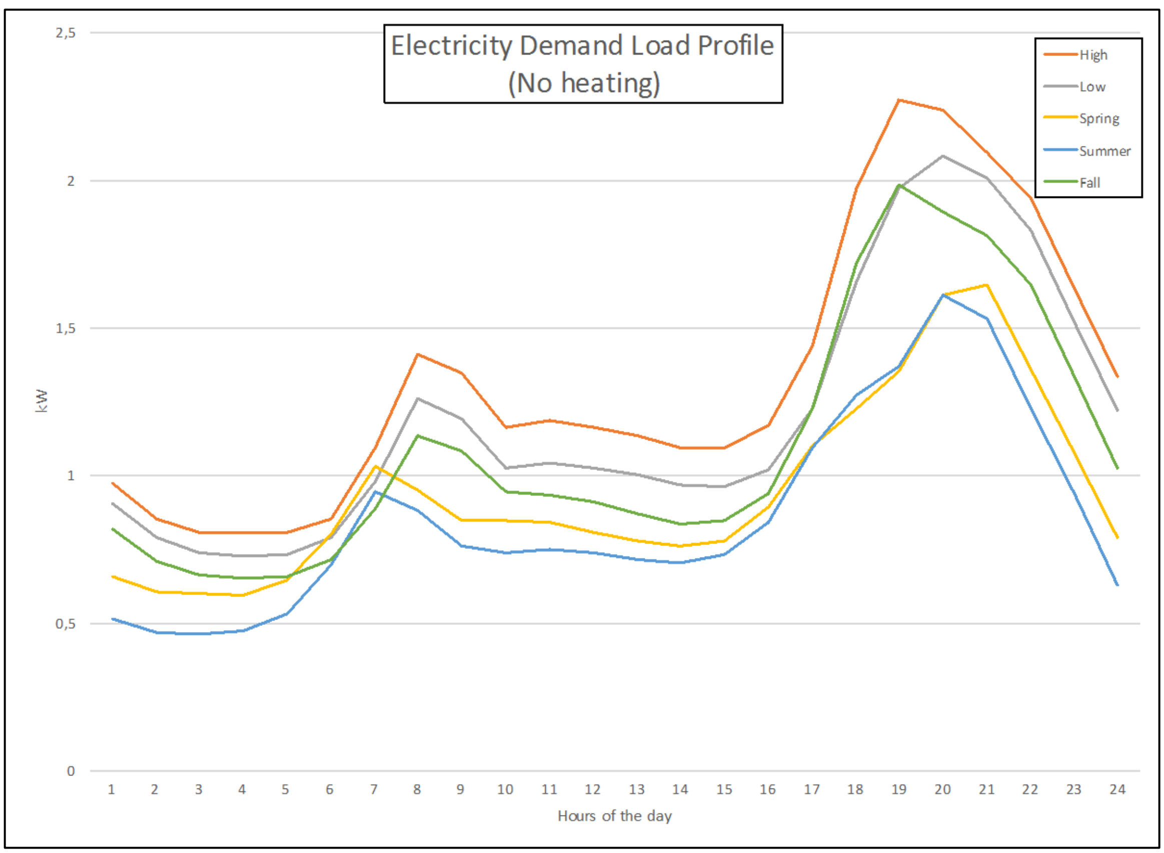


Figure 3 – Electricity load profile by season for Vermont, no electric heating

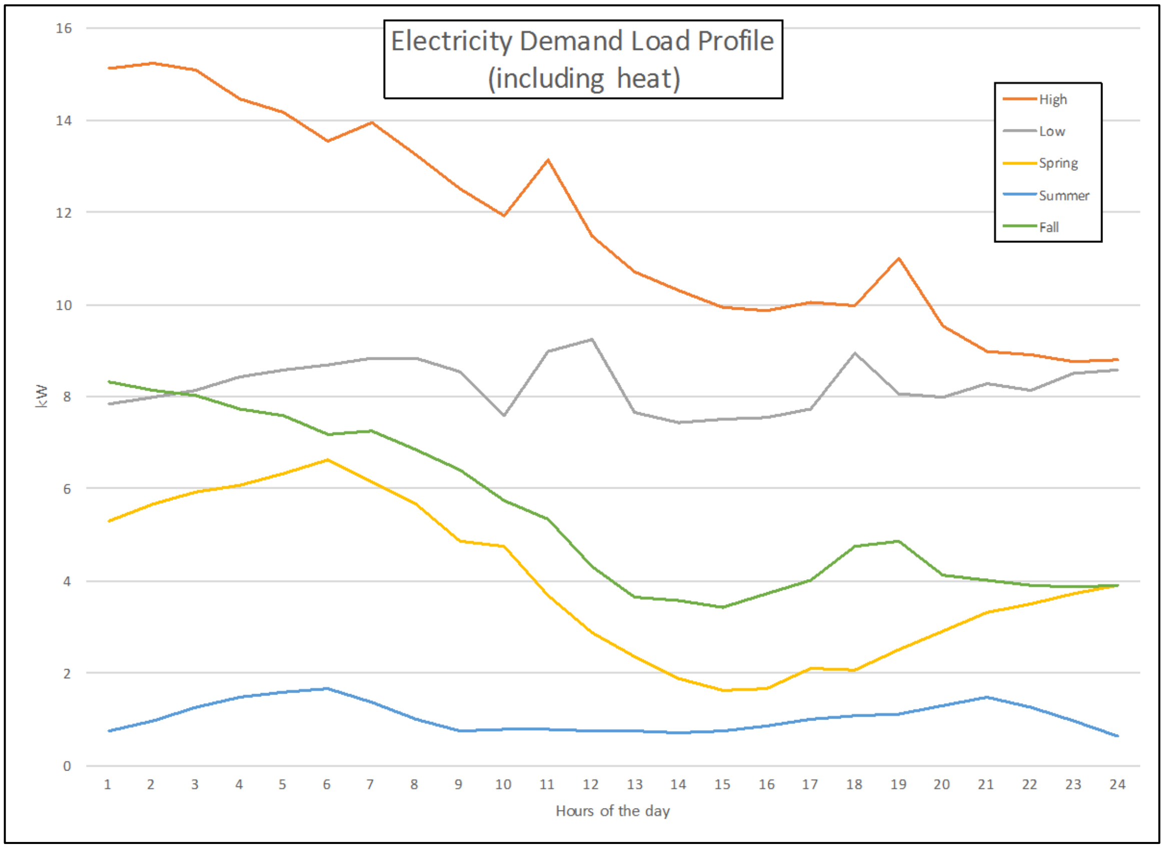


Figure 4 – Electricity load profile by season for Vermont, with electric heating

As it was expected, the graphs show the peak demand for electricity in the morning and in the evening, as well as the gap in electricity need between seasons.

Vehicle characteristics

To conduct our analysis, we used the parameters corresponding to a Nissan Leaf vehicle. Therefore, the battery availability to meet the user's travel need and avoid peak prices in household consumption is 60 kWh. However, manufacturer's warranty makes mention of a minimum state of charge of 40 % of maximum capacity, meaning that the actual energy available in the car is 36 kWh. Also, chargers are limited to a 10-kW charge and discharge. To account for the energy loss that occurs when charging and discharging a device, we built our model to take into account a battery roundtrip efficiency of 90 %.

Scenarios

The economic benefits to be realized with a V2H system depend on the lifestyle of the vehicle owner. Indeed, as the electricity tariffs that we studied varied depending on the hour of the day, the moment and amount of time the vehicle is parked at home and therefore available to *participate* in the system is an important consideration. To account for the different types of customers, we conducted our study for 3 scenarios:

- Car away from 8am to 6pm;
- Part-time at home and
- Full-time at home.

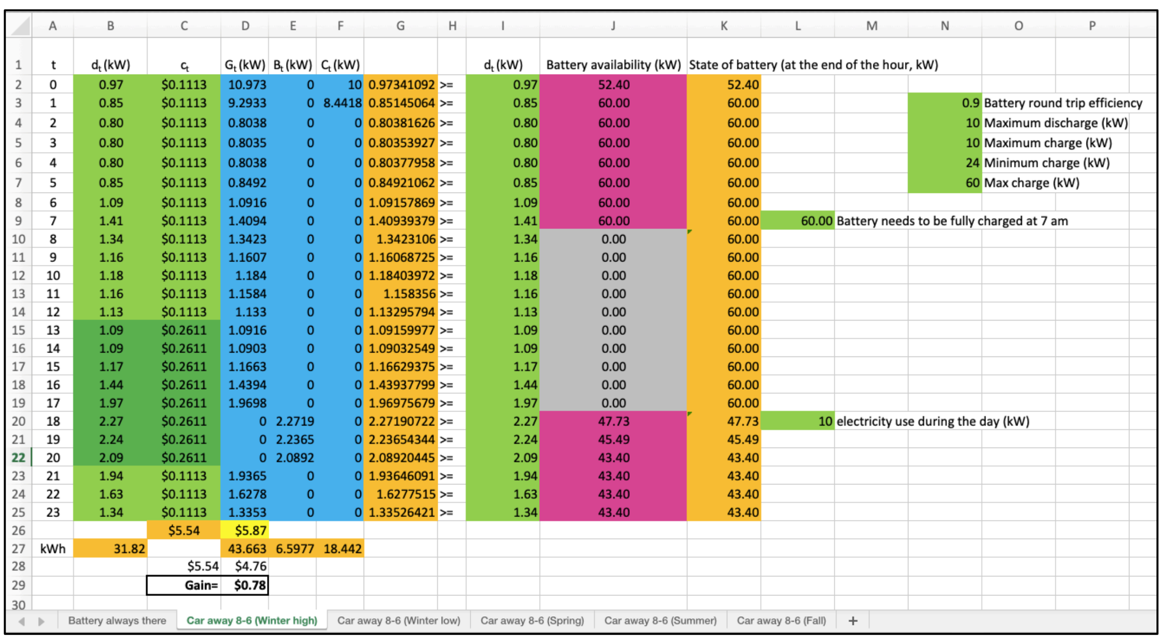
When the car is away during the day, we implemented a constraint into our model that requires the battery to be fully charged at 7am, so the worker could go to work with a fully charged battery. Also, we made the hypothesis that the worker would drive a total distance of 50 kilometers during the day, which represent an energy consumption of 10 kWh for the vehicle chosen for the study, based on its fuel efficiency (Natural Resources Canada, 2020). Therefore, when the car is connected back to the system at 6pm, the state of its battery is reduced to 50 kWh, so the available energy, when taking into account the minimum state of charge of 40 %, is 26 kWh.

For the "full-time at home" scenario, the EV is available to participate in the system all day long. Therefore, the chance of realizing savings here are higher, given that part of the peak hour times happens in the 8am - 6pm window.

For the "part-time at home" scenario, we simply assume that the worker would work at home and outside in exactly the same proportion. Therefore, the economic benefits for this type of worker would be exactly 50% of the "car away from 8am to 6pm" scenario and 50% of the "full-time at home" scenario.

Final model

All preceding steps led us to an optimization model implemented and solved with MS Excel. Every constraint mentioned is included in mathematical forms and is explained in appendix 3 as well as the objective function and variable cells. The model is used for every jurisdiction, but because the tariffs and peak times are different, those parameters are changed. Therefore, because there are four jurisdictions of interest and one of them (California) has four different tariffs at study, we ended up with seven instances of the model. In every instance, we reproduced the tab as many times as there were typical days (see Appendix 2), or events in the case of Quebec, plus one for the "full-time at home" scenario. So, for example, Quebec's model has six tabs representing its five event types for "car away from 8am-6pm" scenario and one more for "full-time at home" scenario, and Vermont would have the same number of tabs, but representing its own five typical days in a year. Below is a screenshot of this Excel's spreadsheet for Vermont's case.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	t	d_t (kW)	c_t	G_t (kW)	B_t (kW)	C_t (kW)			d_t (kW)	Battery availability (kW)	State of battery (at the end of the hour, kW)					
2	0	0.97	$0.1113	10.973	0	10	0.97341092	>=	0.97	52.40	52.40					
3	1	0.85	$0.1113	9.2933	0	8.4418	0.85145064	>=	0.85	60.00	60.00			0.9	Battery round trip efficiency	
4	2	0.80	$0.1113	0.8038	0	0	0.80381626	>=	0.80	60.00	60.00			10	Maximum discharge (kW)	
5	3	0.80	$0.1113	0.8035	0	0	0.80353927	>=	0.80	60.00	60.00			10	Maximum charge (kW)	
6	4	0.80	$0.1113	0.8038	0	0	0.80377958	>=	0.80	60.00	60.00			24	Minimum charge (kW)	
7	5	0.85	$0.1113	0.8492	0	0	0.84921062	>=	0.85	60.00	60.00			60	Max charge (kW)	
8	6	1.09	$0.1113	1.0916	0	0	1.09157869	>=	1.09	60.00	60.00					
9	7	1.41	$0.1113	1.4094	0	0	1.40939379	>=	1.41	60.00	60.00	60.00	Battery needs to be fully charged at 7 am			
10	8	1.34	$0.1113	1.3423	0	0	1.3423106	>=	1.34	0.00	60.00					
11	9	1.16	$0.1113	1.1607	0	0	1.16068725	>=	1.16	0.00	60.00					
12	10	1.18	$0.1113	1.184	0	0	1.18403972	>=	1.18	0.00	60.00					
13	11	1.16	$0.1113	1.1584	0	0	1.158356	>=	1.16	0.00	60.00					
14	12	1.13	$0.1113	1.133	0	0	1.13295794	>=	1.13	0.00	60.00					
15	13	1.09	$0.2611	1.0916	0	0	1.09159977	>=	1.09	0.00	60.00					
16	14	1.09	$0.2611	1.0903	0	0	1.09032549	>=	1.09	0.00	60.00					
17	15	1.17	$0.2611	1.1663	0	0	1.16629375	>=	1.17	0.00	60.00					
18	16	1.44	$0.2611	1.4394	0	0	1.43937799	>=	1.44	0.00	60.00					
19	17	1.97	$0.2611	1.9698	0	0	1.96975679	>=	1.97	0.00	60.00					
20	18	2.27	$0.2611	0	2.2719	0	2.27190722	>=	2.27	47.73	47.73	10	electricity use during the day (kW)			
21	19	2.24	$0.2611	0	2.2365	0	2.23654344	>=	2.24	45.49	45.49					
22	20	2.09	$0.2611	0	2.0892	0	2.08920445	>=	2.09	43.40	43.40					
23	21	1.94	$0.1113	1.9365	0	0	1.93646091	>=	1.94	43.40	43.40					
24	22	1.63	$0.1113	1.6278	0	0	1.6277515	>=	1.63	43.40	43.40					
25	23	1.34	$0.1113	1.3353	0	0	1.33526421	>=	1.34	43.40	43.40					
26			$5.54	$5.87												
27	kWh	31.82		43.663	6.5977	18.442										
28			$5.54	$4.76												
29			Gain=	$0.78												
30																

Battery always there | Car away 8-6 (Winter high) | Car away 8-6 (Winter low) | Car away 8-6 (Spring) | Car away 8-6 (Summer) | Car away 8-6 (Fall) | +

Figure 5 – Screenshot of Vermont's model

In every tab, column B contains the hourly consumption for a typical day of a season. In Figure 3, it is a high load (cold) Winter day ("Winter high") in Vermont. Column C reflects the precise hourly tariff that applies for this jurisdiction and this season, if applicable. Note that for the “full-time at home” scenario, we would change manually the hourly consumption and tariff, if applicable, for every representative day. From there, we run the model for every type of day and both for the “full-time at home” and “car away from 8 am-6 pm” scenarios, for all jurisdictions. The gain that appears in cell D29 in the figure above was then multiplied by the appropriate number of days corresponding to this particular day type in a year. Therefore, the sum of gains from types of representative days in a given scenario gives the annual gain of this scenario. As previously mentioned, for the “part-time at home” scenario, we assume that it represents half the savings of both calculated scenarios. Note that for some tariff’s structure, variable rates only apply during weekdays, meaning that the optimization was performed on 260 days (excluding weekends) rather than 365. The graphs below demonstrate the work accomplish by the V2H system in moving the energy consumption and arbitraging between rates throughout one fall day in Vermont.

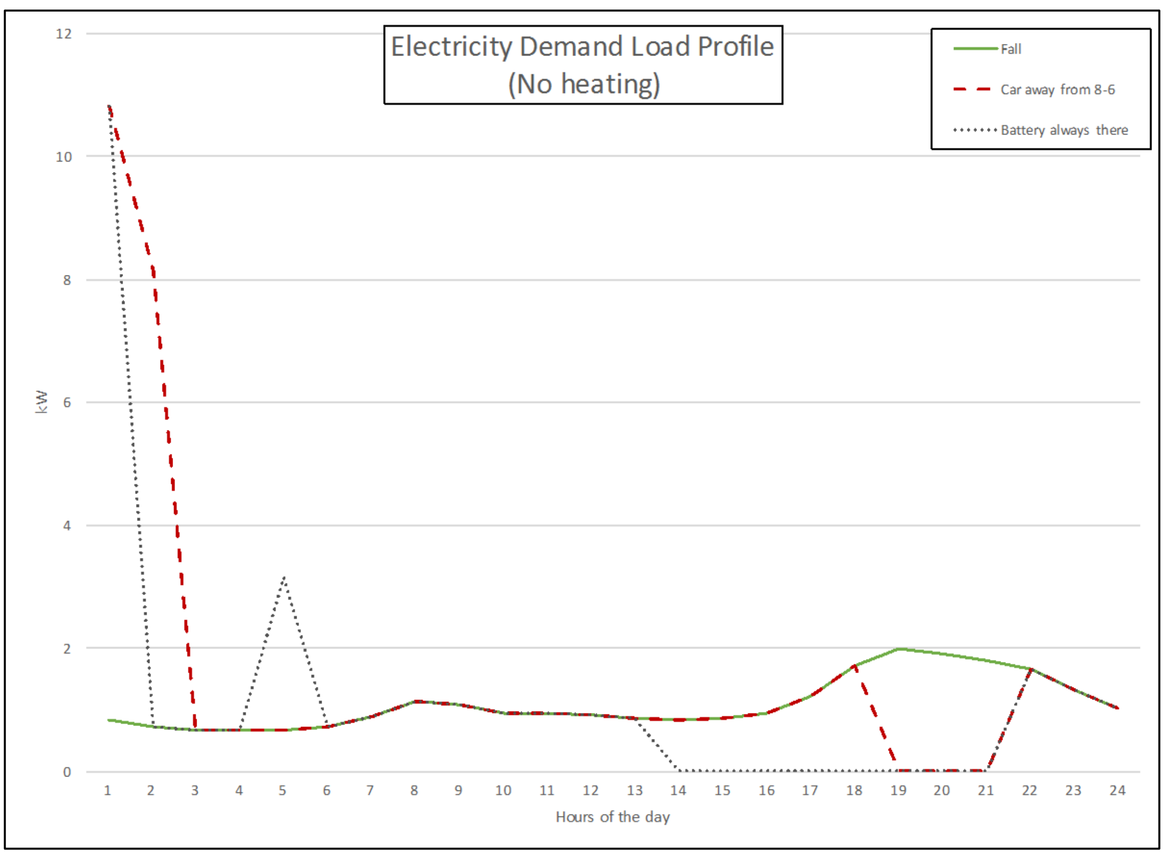


Figure 6 – Electricity load profile with V2H system in Vermont, no electric heating

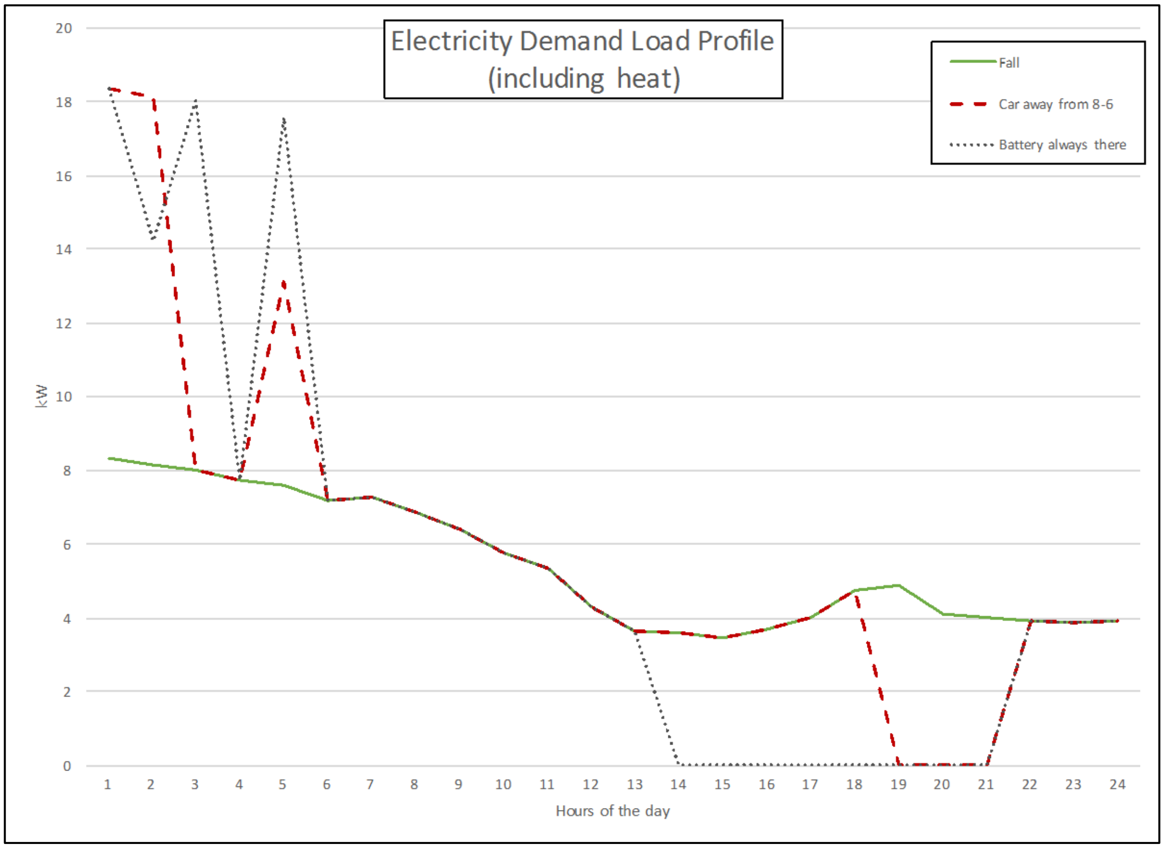


Figure 7 – Electricity load profile with V2H system in Vermont, with electric heating

In the special case of Vermont's tariff, where the peak rate occurs between 1 and 9 pm, it is interesting to see that the electricity need is completely fulfilled by the EV battery instead of the grid during those hours when the car is parked at home the entire day. For the scenario where a person would leave from 8 am to 6 pm, the electricity consumption switch from the grid to the battery as soon as the car comes back at 6 pm, and until the end of the peak rate at 9 pm. The recharge of the battery occurs at night or early in the morning, when the rates are the lowest.

Results

In this section, we review and interpret the final results of every jurisdictions. Note that all results are summarized in a table at the end of the section and are presented in the respective currency of the regions under study. Hence, results of United States' cities are expressed in USD and results of Quebec in CAD.

For tariff Flex D in Quebec, below are the tables showing the reconstitution of daily gain to annual gain for two scenarios: Car away from 8am to 6pm and Full-time at home. The third scenario's result was simply found by taking 50% of each. Recall that there is no *without electric heating* case for Quebec (Appendix 2).

Events type	1 (AM)	2 (PM)	3 (AM)	4 (PM)	5 (PM)
Gain (/day)	$8.28	$8.28	$8.28	$7.53	$8.28
Occurrence	$6.66	$5.00	$6.66	$5.00	$5.00
Total	$55.14	$41.40	$55.14	$37.65	$41.40
Gain (/year)	$230.74				

Table 2 – Daily and annual gain for Quebec, car away from 8-6 scenario, electric heating

Events type	1 (AM)	2 (PM)	3 (AM)	4 (PM)	5 (PM)
Gain (/day)	$15.44	$18.00	$15.44	$18.00	$18.00
Occurrence	$6.66	$5.00	$6.66	$5.00	$5.00
Total	$102.83	$90.00	$102.83	$90.00	$90.00
Gain (/year)	$475.66				

Table 3 –Daily and annual gain for Quebec, full-time at home scenario, electric heating

Given the five event types (Appendix 2) that can happen either in the morning (6am-9am) or in the afternoon (4pm-8pm), we simply multiply them by their occurrence in a year so we could find the annual gain. The case of Quebec is particular in that the peak periods only happen for certain events instead of certain hours every day. Therefore, we found that the maximum gain to be realized when the car is away during the day is when the event occurs in the afternoon. However, it is so because of the constraint to have a full battery at 7am before going to work, which disallow the system to use the EV battery to furnish the house during a possible event in the morning. We realized that if we modified this constraint and were more flexible, we could obtain the same maximum gain in the morning. One way to allow flexibility would be to change this constraint to a 40-kWh availability before leaving for work, which would still be enough to do the traveling. It makes sense, because there are exactly 2 hours of possible arbitrage either in the morning (from 6am until the car needs to leave at 8am) or in the afternoon (from 6pm, when the car comes back, to 8pm). The result given in table 2 is the annual gain to be realized under the assumptions that there are 28,32 peak events occurring in the morning (2) and afternoon (3) during the year. In order to choose when the event would occur in our model, we simply looked at the hourly load profile of every typical days and chose the event moment that corresponded to the highest consumption's moment of the day, which is likely to be the case in real life. The maximum gain per event is therefore capped at $8.28, but could be slightly lower depending on the hourly consumption of that particular day, as we can see for type 4 event in table 2. We chose the occurrence of every scenario in order to achieve 100 hours of peak event in a year, which corresponds to the maximum amount of time Hydro-Quebec can charge at peak price. For the "*Full-time at home*" scenario (Table 3), we kept the same assumptions of peak event moments as in the first one and found that the gain to be realized in the morning and afternoon events would be $15.44 and $18.00 respectively. Given that the car is always there to profit from the price differential, it was intuitive that the savings would be higher during the afternoon, as the peak period last 4 hours instead of only 3 during the morning. Finally, for the "*Part-time at home*" scenario, we found an annual saving corresponding to $353.20.

The four tables below show the daily and annual gains in Vermont for both "*Car away from 8am-6pm*" and "*Full-time at home*" scenarios, first without electric heating, and second with electric heating.

	Winter (High)	Winter (Low)	Spring	Summer	Fall
Gain (per day)	0.78 $	0.71 $	0.51 $	0.50 $	0.66 $
Occurrence	32.14	32.14	65.71	65.71	65.00
Total	25.07 $	22.82 $	33.51 $	32.86 $	42.90 $
Gain (per year)	157.16 $				

Table 4 – Daily and annual gain for Vermont, car away from 8-6 scenario, no electric heating

	Winter (High)	Winter (Low)	Spring	Summer	Fall
Gain (per day)	1.84 $	1.63 $	1.29 $	1.26 $	1.54 $
Occurrence	32.14	32.14	65.71	65.71	65.00
Total	59.14 $	52.39 $	84.77 $	82.80 $	100.10 $
Gain (per year)	379.21 $				

Table 5 –Daily and annual gain for Vermont, full-time at home scenario, no electric heating

	Winter (High)	Winter (Low)	Spring	Summer	Fall
Gain (per day)	3.45 $	3.22 $	1.08 $	0.41 $	1.66 $
Occurrence	32.14	32.14	65.71	65.71	65.00
Total	110.89 $	103.50 $	70.97 $	26.94 $	107.90 $
Gain (per year)	420.21 $				

Table 6 – Daily and annual gain for Vermont, car away from 8-6 scenario, electric heating

	Winter (High)	Winter (Low)	Spring	Summer	Fall
Gain (per day)	4.95 $	4.95 $	2.48 $	1.14 $	4.46 $
Occurrence	32.14	32.14	65.71	65.71	65.00
Total	159.11 $	159.11 $	162.97 $	74.91 $	289.90 $
Gain (per year)	846.00 $				

Table 7 – Daily and annual gain for Vermont, full-time at home scenario, electric heating

We attributed to each type of days the occurrence that corresponds to the number of days contained in this particular season (according to GMP's tariff) adjusted for the weekend. Indeed, peak hours only happen from Monday to Friday, so there are no benefits to be realized during the weekends. For the two different types of day during winter (high and low), we simply attributed half of the days during winter (90) to both, as the median was used to distinguish them. From the results of those two scenarios, we also found an annual saving of $268.19 for the "*part-time at home, no electric heating*" scenario, as well as $633.10 for the "*part-time at home, electric heating*" scenario.

Below are the results for Michigan, and more precisely for the city of Detroit.

	Winter (High)	Winter (Low)	Summer (High)	Summer (Low)
Gain (per day)	0.13 $	0.06 $	0.12 $	0.07 $
Occurrence	75.71	75.71	54.64	54.64
Total	9.84 $	4.54 $	6.56 $	3.83 $
Gain (per year)	24.77 $			

Table 8 – Daily and annual gain in Michigan, car away from 8-6 scenario, no electric heating

	Winter (High)	Winter (Low)	Summer (High)	Summer (Low)
Gain (per day)	0.91 $	0.69 $	0.70 $	0.57 $
Occurrence	75.71	75.71	54.64	54.64
Total	68.90 $	52.24 $	38.25 $	31.15 $
Gain (per year)	190.54 $			

Table 9 – Daily and annual gain in Michigan, full-time at home, no electric heating

	Winter (High)	Winter (Low)	Summer (High)	Summer (Low)
Gain (per day)	0.74 $	0.18 $	0.08 $	0.10 $
Occurrence	75.71	75.71	54.64	54.64
Total	56.03 $	13.63 $	4.37 $	5.46 $
Gain (per year)	79.49 $			

Table 10 – Daily and annual gain in Michigan, car away from 8-6 scenario, electric heating

	Winter (High)	Winter (Low)	Summer (High)	Summer (Low)
Gain (per day)	2.96 $	2.15 $	0.83 $	0.64 $
Occurrence	75.71	75.71	54.64	54.64
Total	224.11 $	162.79 $	45.35 $	34.97 $
Gain (per year)	467.23 $			

Table 11 – Daily and annual gain in Michigan, full-time at home, electric heating

Again, the annual gain was calculated by multiplying the daily gain of every typical days by their occurrence in a year. For this DTE Energy's tariff, variable rate occurs only during weekdays, therefore an adjustment to remove potential gains during weekends was necessary. For the third scenario where the EV is available part of the time, annual savings were $107.66 when no electric heating was used and $273.36 when heating with electricity.

For the state of California, and more precisely for the city of San Diego, let’s first look at the results for the EV-TOU-5 tariff.

	Winter (High)	Winter (Low)	Summer (High)	Summer (Low)
Gain (per day)	1.24 $	0.98 $	2.82 $	2.21 $
Occurrence	106	106	76.5	76.5
Total	131.59 $	103.88 $	215.73 $	169.07 $
Gain (per year)	620.27 $			

Table 12 – Daily and annual gain for San Diego, California, car away from 8-6 scenario, no electric heating, SDG&E EV-TOU 5

	Winter (High)	Winter (Low)	Summer (High)	Summer (Low)
Gain (per day)	2.32 $	1.97 $	5.15 $	3.99 $
Occurrence	106	106	76.5	76.5
Total	245.92 $	208.37 $	393.87 $	305.13 $
Gain (per year)	1 153.28 $			

Table 13 – Daily and annual gain for San Diego, California, full-time at home scenario, no electric heating, SDG&E EV-TOU-5

	Winter (High)	Winter (Low)	Summer (High)	Summer (Low)
Gain (per day)	1.31 $	0.94 $	2.82 $	2.21 $
Occurrence	106	106	76.5	76.5
Total	139.16 $	99.64 $	215.73 $	169.07 $
Gain (per year)	623.60 $			

Table 14 – Daily and annual gain for San Diego, California, car away from 8-6 scenario, electric heating, SDG&E EV-TOU-5

	Winter (High)	Winter (Low)	Summer (High)	Summer (Low)
Gain (per day)	2.46 $	1.89 $	5.15 $	3.99 $
Occurrence	106	106	76.5	76.5
Total	260.31 $	200.34 $	393.87 $	305.13 $
Gain (per year)	1 159.64 $			

Table 15 – Daily and annual gain for San Diego, California, full-time at home scenario, electric heating, SDG&E EV-TOU-5

For the two tariffs offered by SDG&E, a different rate applies during the weekend. Therefore, the gain per day is calculated as a weighted average of the gain during weekdays and the gain during weekends. For the realistic Californian scenario of "*part-time at home*" worker, we find savings of $887 and $892 <u>without</u> electric heating and <u>with</u> electric heating, respectively. Now, let's look at the results for the EV-TOU-2 tariff.

	Winter (High)	Winter (Low)	Summer (High)	Summer (Low)
Gain (per day)	0.52 $	0.38 $	2.07 $	1.59 $
Occurrence	106	106	76.5	76.5
Total	55.42 $	40.28 $	158.57 $	121.64 $
Gain (per year)	375.91 $			

Table 16 – Daily and annual gain for San Diego, California, car away from 8-6 scenario, no electric heating, SDG&E EV-TOU-2

	Winter (High)	Winter (Low)	Summer (High)	Summer (Low)
Gain (per day)	1.22 $	1.03 $	3.86 $	2.98 $
Occurrence	106	106	76.5	76.5
Total	129.62 $	109.18 $	295.18 $	228.19 $
Gain (per year)	762.17 $			

Table 17 – Daily and annual gain for San Diego, California, full-time at home scenario, no electric heating, SDG&E EV-TOU-2

	Winter (High)	Winter (Low)	Summer (High)	Summer (Low)
Gain (per day)	0.56 $	0.35 $	2.07 $	1.59 $
Occurrence	106	106	76.5	76.5
Total	59.21 $	37.10 $	158.57 $	121.64 $
Gain (per year)	376.52 $			

Table 18 – Daily and annual gain for San Diego, California, car away from 8-6 scenario, electric heating, SDG&E EV-TOU-2

	Winter (High)	Winter (Low)	Summer (High)	Summer (Low)
Gain (per day)	1.32 $	0.99 $	3.86 $	2.98 $
Occurrence	106	106	76.5	76.5
Total	139.47 $	104.49 $	295.18 $	228.19 $
Gain (per year)	767.32 $			

Table 19 – Daily and annual gain for San Diego, California, full-time at home scenario, electric heating, SDG&E EV-TOU-2

For the "*part-time at home*" scenario, we find annual savings of $569 when there is no electric heating, and $571 when there is. There are two important observations for the city of San Diego. First, the fact that there is, or not, electric heating has only a negligible impact on the annual savings, which makes sense given the weather in southern California. Second, at first glance, it looks like the EV-TOU-5 tariff brings significantly more economic value to the V2H system. However, let's not forget that the EV-TOU-5 tariff requires a fixed charge of $16 per month. In the discussion, we will come back to this specification and compare, in absolute term, both tariffs.

Finally, for the city of Santa Rosa, let's start with the EV2 tariff offered by Sonoma Clean Power.

	Winter (High)	Winter (Low)	Summer (High)	Summer (Low)
Gain (per day)	(0.14) $	(0.15) $	0.05 $	0.03 $
Occurrence	121.5	121.5	61.0	61.0
Total	(17.01) $	(18.23) $	3.05 $	1.83 $
Gain (per year)	(30.36) $			

Table 20 – Daily and annual gain for California, car away from 8-6 scenario, no electric heating, SCP

	Winter (High)	Winter (Low)	Summer (High)	Summer (Low)
Gain (per day)	0.09 $	0.08 $	0.40 $	0.37 $
Occurrence	121.5	121.5	61.0	61.0
Total	10.94 $	9.72 $	24.40 $	22.57 $
Gain (per year)	67.63 $			

Table 21 – Daily and annual gain for California, full-time at home scenario, no electric heating, SCP

	Winter (High)	Winter (Low)	Summer (High)	Summer (Low)
Gain (per day)	(0.13) $	(0.15) $	0.07 $	0.05 $
Occurrence	121.5	121.5	61.0	61.0
Total	(15.80) $	(18.23) $	4.27 $	3.05 $
Gain (per year)	(26.70) $			

Table 22 – Daily and annual gain for California, car away from 8-6 scenario, electric heating, SCP

	Winter (High)	Winter (Low)	Summer (High)	Summer (Low)
Gain (per day)	0.11 $	0.09 $	0.41 $	0.38 $
Occurrence	121.5	121.5	61.0	61.0
Total	13.37 $	10.94 $	25.01 $	23.18 $
Gain (per year)	72.49 $			

Table 23 – Daily and annual gain for California, full-time at home scenario, electric heating, SCP

Following the same procedures, we calculated the annual gains by multiplying the daily gain for a typical day by the occurrence of that typical day. Here, we simply divided by two the number of days in each season in order to reconstitute a full year, as the flexible tariff of SCP also applies during weekends. The results are less appealing than for the two previous tariffs in San Diego, and are even sometimes negative. It is not intuitive to interpret a negative gain when our model was supposed to minimize the daily cost of electricity using V2H in the first place. However, this negative gain, therefore a loss, comes from the energy loss occurring when charging and discharging the battery, which was taken into account in our model as the 90% roundtrip efficiency. In fact, if this constraint was removed, the gain would be null instead of negative. Hence, one who is living in Santa Rosa, subscribed to this exact tariff with this exact load profile consumption and working from 8am to 6pm would be better off buying all of its electricity from the grid when necessary, regardless of the price, than using a V2H system. However, the more the car becomes available, the more there are economic benefits to be realized, as showed by the "*full-time at home*" scenario. The annual savings for the "*part-time at home*" scenarios represent an amount of $18.64 and $22.90 respectively for the case without and with electric heating.

Now let's turn to the results using E-6's rate of PG&E in the same city of California.

	Winter (High)	Winter (Low)	Summer (High)	Summer (Low)
Gain (per day)	(0.26) $	(0.25) $	0.03 $	0.01 $
Occurrence	86.8	86.8	43.6	43.6
Total	(22.92) $	(22.10) $	1.22 $	0.46 $
Gain (per year)	(36.73) $			

Table 24 – Daily and annual gain for California, car away from 8-6 scenario, no electric heating, PG&E

	Winter (High)	Winter (Low)	Summer (High)	Summer (Low)
Gain (per day)	- $	- $	1.11 $	1.04 $
Occurrence	86.8	86.8	43.6	43.6
Total	- $	- $	48.37 $	45.11 $
Gain (per year)	100.10 $			

Table 25 – Daily and annual gain for California, full-time at home scenario, no electric heating, PG&E

	Winter (High)	Winter (Low)	Summer (High)	Summer (Low)
Gain (per day)	(0.31) $	(0.30) $	0.03 $	0.02 $
Occurrence	86.8	86.8	43.6	43.6
Total	(27.04) $	(26.22) $	1.49 $	0.83 $
Gain (per year)	(44.84) $			

Table 26 – Daily and annual gain in California, car away from 8-6 scenario, electric heating, PG&E

	Winter (High)	Winter (Low)	Summer (High)	Summer (Low)
Gain (per day)	- $	- $	1.12 $	1.07 $
Occurrence	86.8	86.8	43.6	43.6
Total	- $	- $	48.64 $	46.42 $
Gain (per year)	101.16 $			

Table 27 – Daily and annual gain in California, full-time at home scenario, electric heating, PG&E

As PG&E's tariff depends not only on the moment of the day but also on the total quantity of electricity used during the day, the calculation of annual gain was slightly more complex. Indeed, the first 8.8 kWh and 16.2 kWh during summer and winter respectively are charged at the first price's bloc, whereas all the energy consumed beyond that level is charged at a second price's bloc, which is higher. Because we couldn't implement this somewhat complicated constraint into our model, we chose to run the model and find the optimized cost at both price's bloc for all typical days and to calculate the adjusted gain as the weighted average of savings at both prices. Below is an example of the adjustments made in order to calculate the actual gain given two prices' bloc.

Winter				Summer			
High		Low		High		Low	
First bloc	Second bloc	First bloc	Second bloc	First bloc	Second bloc	First bloc	Second bloc
18.40%	**81.60%**	**27.87%**	**72.13%**	**26.25%**	**73.75%**	**45.44%**	**54.56%**
-0.23	-0.33	-0.23	-0.33	0.13	0	0.09	-0.04
Adjusted =	-0.312	Adjusted =	-0.302	Adjusted =	0.034	Adjusted =	0.019

Table 28 – Calculation of the adjusted gain from two different prices' bloc, car away from 8-6 scenario, electric heating

Those daily gains were then multiplied by their occurrence in a year, and a final adjustment was made to the annual gain in order to take into consideration the benefits that can be realized during weekends as well with PG&E's tariff. Indeed, partial peak prices are also charged from 5pm to 8pm on Saturday and Sunday, only during summer. Therefore, we ran the model given this particular weekends' tariff and for summer's typical days only, and we added those extra possible savings to the final annual gain. Same as with SCP, there are no financial incentives to use the V2H system when working during the day in Santa Rosa under this specific PG&E's tariff. For the "*part-time at home*" scenario, annual gains are $31.69 and $28.16 respectively without and with electric heating.

The next page provides a summary table containing all results that are further discussed in the next section.

	Quebec	Vermont	Michigan	California	California	California	California
	Hydro Quebec	Green Mountain Power	DTE Energy	SDG&E EV-TOU-5	SDG&E EV-TOU-2	Sonoma Clean Power	Pacific Gas & Electric
	CAD	*USD*	*USD*	*USD*	*USD*	*USD*	*USD*
Annual estimated savings							
No electric heating							
Scenario 1: Car away from 8-6	n/a	157 $	25 $	620 $	376 $	(30) $	(37) $
Scenario 2: Part-time at home	n/a	268 $	108 $	887 $	569 $	19 $	32 $
Scenario 3: Full-time at home	n/a	379 $	191 $	1 153 $	762 $	68 $	100 $
Electric heating							
Scenario 1: Car away from 8-6	203 $	420 $	79 $	624 $	376 $	(27) $	(45) $
Scenario 2: Part-time at home	353 $	633 $	273 $	892 $	572 $	23 $	28 $
Scenario 3: Full-time at home	476 $	846 $	467 $	1 160 $	767 $	72 $	101 $
Annual estimated consumed energy (kWh)							
No electric heating		9 071	9 037	8 145	8 145	7 594	7 594
Electric heating	44 483	44 483	42 352	9 376	9 376	18 113	18 113
City of reference	Burlington	Burlington	Detroit	San Diego	San Diego	Santa Rosa	Santa Rosa
Reference Data	https://openei.org/doe-opendata/dataset/commercial-and-residential-hourly-load-profiles-for-all-tmy3-locations-in-the-united-states						
Annual average energy cost (no V2H) *Variable charges only (except for EV-TOU-5)*[1]							
No electric heating		1 588 $	818 $	2 479 $	2 738 $	1 554 $	2 031 $
Electric heating	5 725 $	6 721 $	3 434 $	2 694 $	3 048 $	3 573 $	5 109 $
Annual average energy cost (with V2H) *Variable charges only*							
No electric heating (except for Quebec)							
Scenario 1: Car away from 8-6	*-3.6%* 5 522 $	*-9.9%* 1 430 $	*-3.0%* 794 $	*-25.0%* 1 859 $	*-13.7%* 2 362 $	*2.0%* 1 584 $	*1.8%* 2 068 $
Scenario 2: Part-time at home	*-6.2%* 5 372 $	*-16.9%* 1 319 $	*-13.2%* 711 $	*-35.8%* 1 592 $	*-20.8%* 2 169 $	*-1.2%* 1 535 $	*-1.6%* 1 999 $
Scenario 3: Full-time at home	*-8.3%* 5 249 $	*-23.9%* 1 208 $	*-23.3%* 628 $	*-46.5%* 1 326 $	*-27.8%* 1 976 $	*-4.4%* 1 486 $	*-4.9%* 1 931 $
Hours of backup during outage[2] *depending on the season*	2.85	28-41	31-40	36-40	36-40	38-48	37-46
Payback time of V2H (in years)[3]	14.16	18.64	46.45	5.64	8.79	268.24	157.78

[1] Fixed charge of 16$/month have been added for comparison purpose with tariff EV-TOU-2 in San Diego

[2] Battery fully charged, 36kWh available, no electric heating

[3] Based on price difference between a level 2 charger (1500 USD, installation + hardware) and dcbel (6500 USD, installation + hardware), no electric heating and part-time at home scenario

Table 29 –Tariff Analysis summary

Discussion

The table above summarizes the results of our study. As we can see, annual savings differ drastically between jurisdiction, but also between tariffs in one jurisdiction, as it is the case in California. The tariffs in San Diego allow great economic benefits, whereas the same system has no significant value in Santa Rosa. The main factor that contributes to this is the price differential in the tariff itself. Indeed, there has to be a large gap between rates throughout the day in order for the system to truly benefits in storing the energy. The rates under study for the city of San Diego show this characteristic, and that is even more true for the EV-TOU-5 tariff. As mentioned previously, a monthly fixed charge of $16 has to be paid to be eligible to this tariff, in exchange of what the consumers have access to lower rates. Therefore, to compare both tariffs (EV-TOU-5 and EV-TOU-2) in absolute, we added these monthly charges to the estimated annual energy cost without V2H for the EV-TOU-5 tariff. When subtracting the annual estimated savings, we can compare the annual energy cost with V2H for both tariffs. Results are given in the table above and show that, even when taking the fixed charge into account, EV-TOU-5 tariff results in the lowest annual energy cost with V2H, compared to EV-TOU-2. This confirms the fact that one essential tariff's characteristic to maximize the economic value of a system like *dcbel* is a large price differential.

Because a vehicle-to-home system like *dcbel* is more expensive than a regular charger would be, the savings realized due to the utilization of this technology constitutes one of the key arguments to justify its purchase. According to Ossiaco, the price of $6,500 for their system should be compared to a regular level 2 charger that sells for $1,500, both including installation and hardware. Therefore, we calculated the payback time of *dcbel* by dividing the price differential of both chargers ($5,000) by the annual gain of the "part-time at home, no electric heating" scenario. The resulting amount of time is given at the bottom of the table above.

If financial benefits are one important factor in justifying the purchase of a technology like *dcbel*, there are a lot more arguments that were not covered in this study. First, the fact that it permits a backup in case of outages. To account rapidly for this in the previous summary table, we simply divided the 36-kWh available in the EV battery by the hourly consumption's (no electric heating) average of every season in order to obtain a duration backup interval (in hours). Evidently, in Quebec's case the duration is low because it represents the backup time one would have during the coldest days in winter while heating its house with electricity. For the other jurisdictions, however, household could be self-sufficient for periods ranging from 28 to 48 hours, depending on the season.

Second, something that does not appear in this study but could be interesting in regard to pushing further the investigation on *dcbel* technology is the possibility to allow photovoltaic panels to participate in the system as well. Indeed, household consumption could be provided in part by solar energy, thus extending the time frame and possibility of arbitrage between rates. For customers who work during the day and therefore do not have their electric vehicle available to store and supply electricity, this added energy source might recover some of this loss in savings. Therefore, a sunny place like California could potentially improve the situation and allow real economic benefits for Santa Rosa's city where there was initially, according to our results, a loss using only the EV battery as a second energy source.

Third, if the purchase of an EV is the expression of some environmental values, then we should certainly mention that such a system amplifies the positive impact by flattening the load curve, reducing the peak demand and therefore diminishing the non-clean energy utilization when the grid has difficulty to supply. The calculation of greenhouse gas emission's reduction could open the door to another research.

Finally, as some other studies have shown, the vehicle-to-grid system offers a real congestion relief to electricity distributors during peak demand. Because suppliers sometimes supply electricity at a loss throughout this period of time, managing the demand so that it is more spread out could result in economic benefits at the suppliers' level as well. If this paper only paid attention to the consumers, another research could be realized on behalf of the distributors' gains and could potentially encourage them to incite or even subsidize the use of *dcbel*.

The fact that the peak demand could simply be moved to another time frame if the system commercialization were to be successful constitutes one limitation of our study. In fact, our model does not impose restrictions on the number of vehicles that can be charged simultaneously at any given time but could require such a consideration eventually. Furthermore, our model imposes strict constraints that certainly restrain the possible savings. Indeed, to have a full battery when leaving the house in the morning requires to charge at a higher price or disallow the discharge of the EV battery to furnish the household before going to work, resulting in a loss in savings. If a worker were to be comfortable in leaving the house with a less than full battery, or if he has access to a charger at work, then annual economic benefits could be slightly higher. Moreover, the true battery roundtrip efficiency of the vehicle under consideration (Nissan Leaf) is unknown, but it is argued that a loss in energy of 10 % (90 % efficiency) is very conservative. It is also important to mention that the results we obtained are subject to a lot of hypothesis, going from the exact city where one lives to its exact life habits. Therefore, even though we tried to approximate an analysis for entire jurisdictions, our findings are only accurate for the specific city under study in every region. This is particularly true for California, where there are a lot of different territories covered by different distributors, and each distributor offering multiple tariffs. Furthermore, household load profiles vary drastically between territories because of the air conditioner's consumption habit of the population. Then, it is not possible to generalize our results to the entire region under study. Lack of data availability certainly constrained our research, but expanding this methodology to different tariffs and different cities could help to assess the true economic value of *dcbel* system for multiple North American consumers.

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Appendix

Appendix 1: Tariff structure

Information about the Flex D tariff in Quebec was found directly on the Hydro-Quebec website (Hydro-Québec, 2020). This tariff is somewhat different from those in the other jurisdictions as it is based on peak events. Therefore, customers who choose this tariff have access to an annual lower cost of electricity, except for 25 to 33 events where the rate goes from 4.28 cents/kWh for the first 40kWh to 50 cents/kWh. These events would only occur during winter (December 1st to March 31st) and on weekdays (Monday to Friday), from 6 to 9 am or 4 to 8 pm, for a maximum of 100 hours per year.

For the Rate 11 tariff in Vermont (Green Mountain Power, 2020), the pricing is straightforward and does not depend on the season.

For the Time-of-Day Electric Rate in Michigan, offered by DTE Energy (DTE Energy, 2020), the prices were always divided in two components: Capacity fees and non-capacity fees. Capacity fees refer to fixed fees, whereas Non-capacity fees refer to variable fees. The sum of the two gave us the final tariff.

For both tariffs offered by San Diego Gas and Electric (EV-TOU-5 and EV-TOU-2), there is a distinction between summer and winter, as well as between weekdays and weekends. One distinction in California's tariff is that there is one more tariff level than the two always observed (Peak and Off-Peak). In the particular case of San Diego, the third period is called Super Off-Peak and results in the lowest rate of the day.

For the EV2 Rate offered by Sonoma Clean Power, we took the generation prices from PG&E and added the distribution prices of Sonoma Clean Power. The third level of rate in Santa Rosa is called Partial Peak and is, as his name suggests, an intermediary between peak rate and off-peak rate.

For the E-6 PG&E's rate, information was found on their website but was much more complicated to summarize given their multiple codes and territories. The codes and territories refer only to the baseline quantities, in kWh per day, that a household is allowed to consume at the first price bloc. Everything in excess of the baseline quantity is therefore subject to the second price bloc. Between Code B – Basic Quantities and Code H – All Electric Quantities, we chose Code H. Between the 10 territories, we chose territory X because, as the PG&E territories' map below illustrates, the city of Santa Rosa is part of this one.

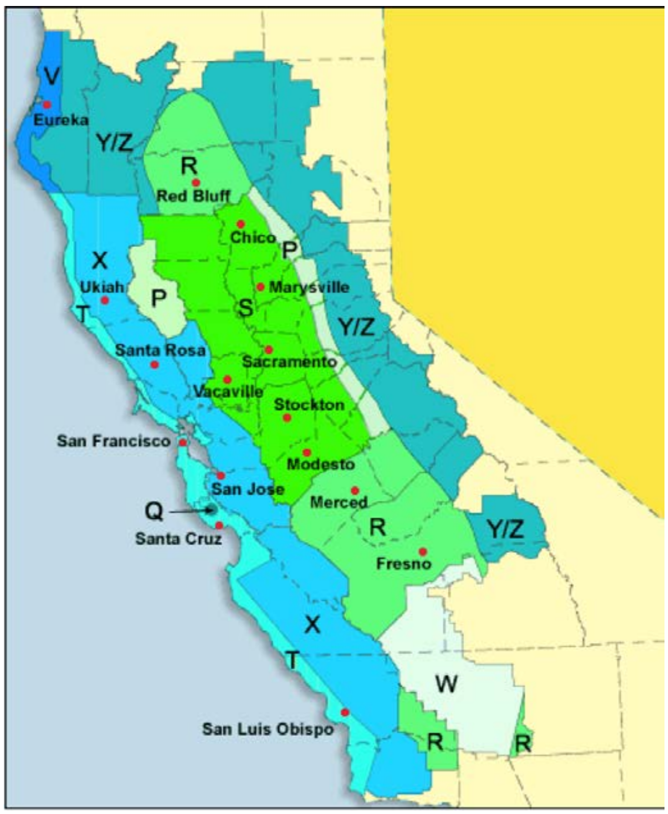

Figure 8 – PG&E baseline division's map
Source: California Public Utilities, 2020

As we can see, the PG&E's tariff depends not only on the moment of the day (off-peak, partial-peak or peak), but also on the overall daily energy consumption, with a first price's bloc lower than the second. Therefore, to reconstitute the annual cost of energy, the procedure was slightly different for this tariff, as it is explained in the *Results* section.

It is important to note that every one of the four jurisdictions add fixed charges on their consumer's bill (except tariff EV-TOU-5), but because our study focuses on the economic benefit there is to realize given a variable tariff, simply adding a constant to our results would not alter their meaning and is therefore irrelevant.

Appendix 2: Household load profile

As mentioned previously, the base case's load profile was used for our analysis. All building characteristics assumed for all scenarios can be found on OpenEI's website (openei.org), but below is the table summarizing the assumptions they made to build the base case's load profile.

	Selected Building Fuel Types				
	Very Cold/Cold	Mixed-Humid	Mixed-Dry/Hot-Dry	Hot-Humid	Marine
Space Heating	Natural Gas	Natural Gas	Natural Gas	Electric	Natural Gas
Air Conditioning	Yes	Yes	Yes	Yes	No
Water Heating	Natural Gas	Electric	Natural Gas	Electric	Natural Gas

	Selected Building Structure Types				
	Very Cold/Cold	Mixed-Humid	Mixed-Dry/Hot-Dry	Hot-Humid	Marine
Total Size (sq. ft.)	2696	2546	2000	2023	2090
Urban and Rural	Urban	Urban	Urban	Urban	Urban
Metropolitan and Micropolitan	Metro	Metro	Metro	Metro	Metro
Number of Stories / Levels	1 Story	1 Story	1 Story	1 Story	1 Story
Major Outside Wall Construction	Siding (Aluminum, Vinyl, Steel)	Siding (Aluminum, Vinyl, Steel)	Stucco	Brick	Wood
Major Roofing Material	Ceramic or Clay Tiles	Ceramic or Clay Tiles	Ceramic or Clay Tiles	Ceramic or Clay Tiles	Ceramic or Clay Tiles
Foundation/Basement of Single-Family	Basement	Concrete Slab	Concrete Slab	Concrete Slab	Crawlspace
Bedrooms	3	3	3	3	3
Full Bathrooms	1	1	2	2	1
Half Bathrooms	None	None	None	None	None
Basement Single-Family Homes	Yes	No	No	No	No
Finished Basement	No	No Basement	No Basement	No Basement	No Basement
Type of Glass in Windows	Double-pane Glass	Double-pane Glass	Single-pane Glass	Single-pane Glass	Double-pane Glass

Figure 9 – Building characteristics for Residential Hourly load data, Base case

Source: OpenEI, 2014

All four jurisdictions' load profile were analyzed separately to reflect their particular tariff structure. Indeed, in order to find appropriate typical days to optimize, we had to analyze and sort the data according to the season and find a daily load profile that was representative enough to be taken as the season itself. Therefore, the first step that was applied to every region was to transform the hourly data into daily data and to identify, using dates, which season each of the 365 days belonged to, depending on what was specified in the tariff structure. Below is an example of the first step's application for the particular case of Quebec, where the winter season for electricity prices goes from December 1st to March 31st.

	cumulative sum	kWh/day		
1	225.94	225.94	01/01/2019	Winter
2	459.30	233.36	02/01/2019	Winter
3	722.74	263.44	03/01/2019	Winter
4	989.89	267.15	04/01/2019	Winter
5	1 248.69	258.80	05/01/2019	Winter
6	1 468.61	219.91	06/01/2019	Winter
7	1 678.60	209.99	07/01/2019	Winter
8	1 925.32	246.72	08/01/2019	Winter
9	2 151.41	226.09	09/01/2019	Winter
10	2 355.39	203.98	10/01/2019	Winter
11	2 580.43	225.04	11/01/2019	Winter
12	2 797.60	217.17	12/01/2019	Winter
13	3 020.77	223.17	13/01/2019	Winter

Table 30 – Sample of the first step in ordering and sorting the data according to the season, Quebec's case.

From here, we will review the rest of the methodology region by region in order to show their relevant descriptive statistics and specific standard days.

For Quebec, we found the following parameters for winter and summer. Because the flexible rate is only possible during winter, no extra attention has been put on the summer season.

	Date		Mean	Max	Min	# of days	Median
Winter	01/12/2019	31/03/2019	226.99	365.87	117.44	121	224.77
Summer	01/04/2019	30/11/2019	69.75	215.65	16.19	244	

Table 31 – Relevant descriptive statistics for Quebec's tariff season

Then, in order to simulate the 100 peak events that are highly likely to happen, we found, in our daily consumption data bank, the 25 highest daily consumptions during winter. These 25 days are shown below.

	25 events of 4 hours each (highest consumption)	
	Consumption (/day)	Date
1	365.873	26/01/2019
2	362.998	27/01/2019
3	350.689	19/12/2019
4	344.896	05/02/2019
5	336.050	06/02/2019
6	332.957	07/02/2019
7	331.361	24/01/2019
8	327.785	18/12/2019
9	326.529	17/01/2019
10	321.041	07/03/2019
11	311.071	11/02/2019
12	308.813	25/01/2019
13	305.117	08/03/2019
14	294.357	20/01/2019
15	294.027	09/02/2019
16	293.273	06/03/2019
17	292.773	03/02/2019
18	290.094	28/01/2019
19	285.967	09/03/2019
20	282.721	20/12/2019
21	280.795	10/03/2019
22	280.525	18/01/2019
23	279.819	17/12/2019
24	276.549	21/02/2019
25	270.747	04/02/2019

Table 32 – 25 highest electricity consumption's days for Quebec

To make the optimization more time-efficient, we condensed the 25 days to create five event types. Therefore, the mean of the five highest consumptions was taken as the first event type, the mean of the 6^{th} to 10^{th} highest consumptions refers to the second event type, and so on until the fifth event. Then, we found the day in our sample that was the closest to the mean previously calculated so we could find back the consumption per hour of that day. Below is the five typical days' consumption per hour that we used in the model to do the optimization.

	5 events types				
	1	2	3	4	5
Mean	352.10	327.93	302.68	288.97	277.69
Closest	350.689244	327.785044	305.117491	290.094093	276.548989
Date	19/12/2019	18/12/2019	08/03/2019	28/01/2019	21/02/2019
1	15.03	12.40	13.44	13.84	7.75
2	15.36	12.48	13.74	13.83	8.70
3	15.57	12.51	14.09	13.66	9.03
4	15.76	12.61	14.34	13.66	9.54
5	15.87	12.89	14.61	12.89	10.10
6	16.18	12.93	14.87	12.25	10.63
7	16.24	14.03	14.79	12.50	11.77
8	17.23	14.38	14.42	11.87	11.42
9	16.00	13.80	13.90	11.37	12.72
10	15.21	13.48	13.32	10.28	13.18
11	16.60	15.42	14.73	10.87	13.00
12	13.41	13.71	12.87	9.47	12.52
13	12.71	13.14	11.85	9.05	11.75
14	11.77	12.72	11.01	8.04	10.99
15	11.28	12.42	10.43	7.96	10.63
16	11.73	12.80	10.20	7.74	10.91
17	12.30	13.33	10.57	8.00	11.36
18	15.16	15.92	12.27	9.90	13.77
19	14.00	14.61	11.21	9.21	12.92
20	13.85	14.33	11.16	8.98	12.78
21	14.14	14.16	11.50	9.14	12.49
22	14.30	14.36	11.68	9.29	12.70
23	15.71	14.56	11.84	9.88	12.80
24	15.31	14.80	12.29	10.12	13.08

Table 33 – Hourly consumption for five event types in Quebec

Note that for Quebec, because there is a large proportion of the population that is using electricity as the heating source, the "no electric heating" case was not relevant and therefore was not part of our study.

For Vermont, the same flexible tariff applies all year long. Therefore, we reproduced a full year using typical days for each season following the *regular* season's date of Vermont. The following parameters were found, first for the "no electric heating" case and second for the "with electric heating" case.

	Date		Mean	Max	Min	# of days	Median
Winter	21/12/2019	20/03/2019	30.22	34.56	25.01	90	30.56
Spring	21/03/2019	20/06/2019	22.54	27.28	18.46	92	
Summer	21/06/2019	20/09/2019	20.50	33.57	16.19	92	
Fall	21/09/2019	20/12/2019	26.28	34.41	20.54	91	

Table 34 – Relevant descriptive statistics for Vermont's tariff season, no electric heating

	Date		Mean	Max	Min	# of days	Median
Winter	21/12/2019	20/03/2019	239.06	365.87	130.57	90	232.77
Spring	21/03/2019	20/06/2019	95.00	215.65	18.73	92	
Summer	21/06/2019	20/09/2019	24.80	59.85	16.19	92	
Fall	21/09/2019	20/12/2019	131.28	350.69	30.56	91	

Table 35 – Relevant descriptive statistics for Vermont's tariff season, with electric heating

As winter in Burlington tends to be quite cold and volatile in terms of temperature, we judged it would be more precise to admit 2 typical days for the winter season: High and low. To account for that, we took the average of the daily consumption above the median of winter for the "High" case, and the average of the data below the median for the "Low" case. Then again, we searched for the days that had the closer consumption to the mean calculated, and we found back the hourly consumption of those particular days. Below are the final types of days that we used in our model, first for the "no electric heating" case and second for the "with electric heating" case.

	Winter		Spring	Summer	Fall
	High	Low			
Closest	31.819	28.61	22.548	20.579	26.183
Date	03/01/2019	20/02/2019	12/04/2019	13/09/2019	05/11/2019
1	0.97	0.90	0.66	0.51	0.82
2	0.85	0.79	0.61	0.46	0.71
3	0.80	0.74	0.60	0.46	0.66
4	0.80	0.73	0.59	0.47	0.65
5	0.80	0.73	0.65	0.53	0.65
6	0.85	0.79	0.80	0.70	0.71
7	1.09	0.98	1.03	0.94	0.88
8	1.41	1.26	0.95	0.88	1.13
9	1.34	1.19	0.84	0.76	1.08
10	1.16	1.02	0.85	0.74	0.94
11	1.18	1.04	0.84	0.75	0.93
12	1.16	1.02	0.81	0.73	0.91
13	1.13	1.00	0.77	0.71	0.87
14	1.09	0.96	0.76	0.70	0.83
15	1.09	0.96	0.78	0.73	0.84
16	1.17	1.02	0.89	0.84	0.93
17	1.44	1.22	1.10	1.09	1.23
18	1.97	1.66	1.22	1.27	1.72
19	2.27	1.97	1.35	1.37	1.98
20	2.24	2.08	1.61	1.61	1.89
21	2.09	2.00	1.65	1.53	1.81
22	1.94	1.83	1.35	1.23	1.65
23	1.63	1.51	1.07	0.93	1.33
24	1.34	1.22	0.78	0.63	1.03

Table 36 – Hourly consumption for five days' types in Vermont, no electric heating

	Winter		Spring	Summer	Fall
	High	Low			
Closest	280.525	197.93	95.406	24.900	130.621
Date	18/01/2019	19/03/2019	27/04/2019	09/07/2019	11/12/2019
1	15.12	7.85	5.31	0.72	8.32
2	15.21	8.00	5.66	0.97	8.13
3	15.09	8.12	5.94	1.27	8.02
4	14.46	8.43	6.06	1.49	7.74
5	14.17	8.57	6.32	1.59	7.58
6	13.53	8.69	6.63	1.64	7.17
7	13.95	8.81	6.16	1.37	7.25
8	13.24	8.83	5.65	0.98	6.85
9	12.49	8.52	4.87	0.74	6.39
10	11.93	7.57	4.74	0.76	5.74
11	13.13	8.98	3.69	0.77	5.35
12	11.46	9.25	2.85	0.75	4.29
13	10.72	7.65	2.35	0.73	3.66
14	10.29	7.44	1.88	0.71	3.59
15	9.94	7.49	1.62	0.73	3.43
16	9.87	7.55	1.67	0.84	3.70
17	10.05	7.71	2.11	1.01	4.00
18	9.98	8.95	2.05	1.08	4.76
19	11.00	8.07	2.50	1.12	4.87
20	9.52	7.98	2.92	1.31	4.11
21	8.98	8.28	3.30	1.48	4.00
22	8.89	8.13	3.48	1.25	3.91
23	8.75	8.50	3.73	0.94	3.86
24	8.78	8.57	3.90	0.64	3.89

Table 37 – Hourly consumption for five days' types in Vermont, with electric heating

For Michigan, we separated the data into two seasons (summer and winter) given by its tariff. Then, to seek more realism, we created two typical days for each season: high and low case. Indeed, we judged that having only one representative day per season would be a simplistic assumption and could lessened the strength of our results. Therefore, just like the case of Vermont, we took the mean of the data over the median in a given season as the high case and the mean of the data below the median as the low case. Then again, we were able to find the exact days in our data sample that were the closest, in terms of consumption, to the means calculated. So, we found back the hourly consumption of those days to use them in our model. Below are the parameters found for Detroit's load profile, followed by the hourly consumption of the four representative days used for modeling.

	Date		Mean	Max	Min	# of days	Median
Winter	01/11/2019	31/05/2019	27.27	34.17	17.99	212	27.34
Summer	01/06/2019	31/10/2019	21.28	30.24	16.19	153	20.77

Table 38 – Relevant descriptive statistics for Michigan's tariff season, no electric heating

	Date		Mean	Max	Min	# of days	Median
Winter	01/11/2019	31/05/2019	172.23	351.15	23.95	212	177.18
Summer	01/06/2019	31/10/2019	38.17	122.41	16.19	153	25.53

Table 39 – Relevant descriptive statistics for Michigan's tariff season, with electric heating

	Winter		Summer	
	High	Low	High	Low
Closest	30.21	24.27	23.27	19.32
Date	15/12/2019	29/04/2019	10/10/2019	23/08/2019
1	0.89	0.70	0.61	0.51
2	0.78	0.65	0.57	0.46
3	0.72	0.64	0.56	0.44
4	0.71	0.64	0.57	0.44
5	0.71	0.69	0.62	0.49
6	0.77	0.85	0.82	0.64
7	1.00	1.09	1.13	0.85
8	1.30	1.03	1.06	0.79
9	1.26	0.94	0.89	0.71
10	1.10	0.96	0.87	0.71
11	1.11	0.95	0.85	0.73
12	1.08	0.92	0.80	0.71
13	1.05	0.88	0.78	0.69
14	1.03	0.86	0.77	0.68
15	1.04	0.88	0.80	0.71
16	1.15	0.99	0.95	0.84
17	1.47	1.18	1.24	0.99
18	2.02	1.31	1.49	1.09
19	2.28	1.42	1.68	1.17
20	2.11	1.68	1.74	1.39
21	2.01	1.71	1.57	1.52
22	1.85	1.40	1.26	1.22
23	1.53	1.09	0.96	0.92
24	1.23	0.79	0.67	0.63

Table 40 – Hourly consumption for four days' types in Michigan, no electric heating

	Winter		Summer	
	High	Low	High	Low
Closest	223.556	119.47	56.750	20.876
Date	17/12/2019	11/05/2019	01/06/2019	12/09/2019
1	8.68	6.49	1.89	0.51
2	8.80	6.70	2.63	0.46
3	9.00	6.71	3.32	0.44
4	9.07	6.86	3.80	0.44
5	9.15	6.84	4.23	0.49
6	9.29	6.83	4.39	0.66
7	9.23	6.73	4.36	0.91
8	9.31	6.62	4.12	0.85
9	9.25	6.39	3.65	0.74
10	9.28	6.58	3.30	0.74
11	10.60	5.37	2.60	0.75
12	9.36	4.71	2.11	0.73
13	8.98	4.07	1.73	0.71
14	8.67	3.51	1.34	0.70
15	8.89	2.88	0.97	0.73
16	9.01	2.51	0.80	0.89
17	9.31	3.05	0.97	1.16
18	10.96	2.56	1.05	1.41
19	9.77	2.91	1.09	1.51
20	9.39	3.40	1.27	1.71
21	9.35	4.02	1.44	1.53
22	9.35	4.21	1.56	1.23
23	9.29	4.60	1.86	0.93
24	9.58	4.91	2.30	0.63

Table 41 – Hourly consumption for four days' types in Michigan, with electric heating

For San Diego's load profile, the exact same methodology as Detroit was used, resulting in four typical days, hence two per season. As both tariffs used in San Diego have the same load profile data as well as the same season's date, they also have the same descriptive statistics and typical representative days, which are shown below.

	Date		Mean	Max	Min	# of days	Median
Winter	01/11/2019	31/05/2019	21.15	24.22	15.48	212	20.99
Summer	01/06/2019	31/10/2019	23.94	33.97	17.14	153	23.74

Table 42 – Relevant descriptive statistics for California's tariff season, San Diego, no electric heating, SDG&E

	Date		Mean	Max	Min	# of days	Median
Winter	01/11/2019	31/05/2019	26.95	60.65	15.48	212	24.85
Summer	01/06/2019	31/10/2019	23.94	33.97	17.14	153	23.74

Table 43 – Relevant descriptive statistics for California's tariff season, San Diego, with electric heating, SDG&E

	Winter		Summer	
	High	Low	High	Low
Closest	22.76	19.69	27.22	20.59
Date	19/02/2019	10/04/2019	03/09/2019	17/08/2019
1	0.64	0.50	0.63	0.53
2	0.53	0.45	0.55	0.46
3	0.49	0.44	0.52	0.43
4	0.48	0.44	0.50	0.40
5	0.49	0.49	0.57	0.43
6	0.56	0.63	0.77	0.56
7	0.76	0.86	1.05	0.74
8	1.01	0.79	0.99	0.64
9	0.94	0.71	0.93	0.54
10	0.83	0.72	0.92	0.57
11	0.83	0.73	1.04	0.67
12	0.85	0.72	1.08	0.75
13	0.83	0.75	1.13	0.83
14	0.81	0.82	1.20	0.93
15	0.80	0.88	1.33	1.08
16	0.85	0.82	1.48	1.21
17	1.03	1.02	1.64	1.33
18	1.38	1.12	1.79	1.41
19	1.65	1.30	1.83	1.36
20	1.72	1.48	1.98	1.47
21	1.65	1.44	1.84	1.51
22	1.50	1.13	1.49	1.19
23	1.21	0.86	1.14	0.91
24	0.93	0.60	0.79	0.63

Table 44 – Hourly consumption for four days' types in San Diego, California, no electric heating, SDG&E

	Winter		Summer	
	High	Low	High	Low
Closest	33.323	20.88	27.215	20.593
Date	16/01/2019	25/04/2019	03/09/2019	17/08/2019
1	1.15	0.50	0.63	0.53
2	1.30	0.45	0.55	0.46
3	1.49	0.49	0.52	0.43
4	1.59	0.75	0.50	0.40
5	1.76	0.93	0.57	0.43
6	1.91	1.00	0.77	0.56
7	2.78	1.16	1.05	0.74
8	2.03	1.09	0.99	0.64
9	1.53	0.73	0.93	0.54
10	0.82	0.72	0.92	0.57
11	0.97	0.73	1.04	0.67
12	0.83	0.72	1.08	0.75
13	0.81	0.70	1.13	0.83
14	0.79	0.69	1.20	0.93
15	0.79	0.71	1.33	1.08
16	0.85	0.82	1.48	1.21
17	1.08	1.02	1.64	1.33
18	1.54	1.12	1.79	1.41
19	1.78	1.19	1.83	1.36
20	1.73	1.38	1.98	1.47
21	1.60	1.39	1.84	1.51
22	1.46	1.13	1.49	1.19
23	1.30	0.86	1.14	0.91
24	1.42	0.60	0.79	0.63

Table 45 – Hourly consumption for four days' types in San Diego, California, with electric heating, SDG&E

For Santa Rosa's load profile, we also separated the data into two seasons (summer and winter), but because the two distributors attribute different dates for both seasons, we had to make a separate analysis for them. Given the tariff EV2 of Sonoma Clean Power, the descriptive statistics found for Santa Rosa's consumption are as follow.

	Date		Mean	Max	Min	# of days	Median
Winter	01/10/2019	31/05/2019	22.28	26.26	15.95	243	22.14
Summer	01/06/2019	30/09/2019	17.87	19.59	14.69	122	17.81

Table 46 – Relevant descriptive statistics for California's tariff season, Santa Rosa, no electric heating, SCP

	Date		Mean	Max	Min	# of days	Median
Winter	01/10/2019	31/05/2019	63.85	136.81	21.54	243	64.01
Summer	01/06/2019	30/09/2019	21.29	33.79	14.69	122	19.55

Table 47 – Relevant descriptive statistics for California's tariff season, Santa Rosa, with electric heating, SCP

For the E-6's tariff offered by PG&E, we found the following parameters.

	Date		Mean	Max	Min	# of days	Median
Winter	01/11/2019	30/04/2019	23.05	26.26	19.71	181	23.20
Summer	01/05/2019	31/10/2019	18.59	21.89	14.69	184	18.45

Table 48 – Relevant descriptive statistics for California's tariff season, Santa Rosa, no electric heating, PG&E

	Date		Mean	Max	Min	# of days	Median
Winter	01/11/2019	30/04/2019	73.19	136.81	29.79	181	71.01
Summer	01/05/2019	31/10/2019	26.45	62.13	14.69	184	23.70

Table 49 – Relevant descriptive statistics for California's tariff season, Santa Rosa, with electric heating, PG&E

Below is the consumption per hour of the four types of day chosen, first for SCP's tariff, second for PG&E's tariff.

	Winter		Summer	
	High	Low	High	Low
Closest	24.05	20.50	18.47	17.34
Date	18/02/2019	18/04/2019	20/08/2019	02/06/2019
1	0.71	0.59	0.47	0.47
2	0.60	0.55	0.42	0.42
3	0.56	0.55	0.41	0.41
4	0.55	0.56	0.41	0.41
5	0.55	0.61	0.46	0.45
6	0.61	0.77	0.60	0.57
7	0.79	0.97	0.80	0.73
8	1.06	0.90	0.77	0.69
9	1.01	0.80	0.72	0.66
10	0.90	0.80	0.74	0.67
11	0.92	0.78	0.75	0.68
12	0.92	0.75	0.73	0.67
13	0.90	0.72	0.70	0.65
14	0.85	0.70	0.68	0.64
15	0.84	0.72	0.70	0.66
16	0.88	0.83	0.80	0.76
17	1.05	1.02	0.97	0.92
18	1.42	1.13	1.06	0.99
19	1.69	1.21	1.10	1.00
20	1.76	1.41	1.28	1.15
21	1.70	1.42	1.38	1.29
22	1.55	1.16	1.11	1.09
23	1.26	0.91	0.84	0.83
24	0.99	0.66	0.57	0.57

Table 50 – Hourly consumption for four days' types in Santa Rosa, California, no electric heating, SCP

	Winter		Summer	
	High	Low	High	Low
Closest	83.054	44.97	24.412	18.060
Date	04/02/2019	14/10/2019	08/09/2019	10/08/2019
1	3.75	1.66	0.47	0.46
2	4.33	2.25	0.42	0.42
3	4.78	2.82	0.54	0.41
4	5.27	3.21	0.93	0.41
5	5.61	3.60	1.37	0.45
6	5.91	3.71	2.13	0.85
7	6.83	4.06	2.06	0.78
8	7.16	3.69	1.74	0.73
9	5.98	2.75	1.25	0.67
10	4.75	2.07	0.70	0.68
11	4.26	0.96	0.71	0.69
12	2.67	0.80	0.70	0.68
13	1.66	0.77	0.67	0.66
14	1.21	0.76	0.66	0.65
15	1.09	0.79	0.69	0.67
16	0.94	0.92	0.79	0.77
17	1.04	1.18	0.98	0.94
18	2.03	1.39	1.12	1.02
19	1.86	1.53	1.23	1.07
20	1.90	1.57	1.43	1.24
21	2.16	1.43	1.36	1.35
22	2.28	1.15	1.09	1.08
23	2.58	0.87	0.83	0.83
24	2.98	1.02	0.57	0.57

Table 51 – Hourly consumption for four days' types in Santa Rosa, California, with electric heating, SCP

	Winter		Summer	
	High	Low	High	Low
Closest	24.59	21.52	19.76	17.45
Date	16/01/2019	15/03/2019	07/05/2019	20/06/2019
1	0.70	0.70	0.52	0.47
2	0.60	0.61	0.48	0.42
3	0.56	0.57	0.47	0.41
4	0.55	0.57	0.48	0.42
5	0.55	0.57	0.53	0.47
6	0.60	0.63	0.67	0.59
7	0.80	0.77	0.85	0.75
8	1.08	0.96	0.80	0.70
9	1.04	0.88	0.77	0.66
10	0.90	0.79	0.79	0.68
11	0.91	0.79	0.80	0.68
12	0.91	0.77	0.78	0.67
13	0.89	0.74	0.74	0.65
14	0.86	0.70	0.72	0.64
15	0.86	0.69	0.75	0.66
16	0.92	0.73	0.86	0.76
17	1.15	0.88	1.04	0.92
18	1.59	1.16	1.12	0.99
19	1.85	1.40	1.15	1.00
20	1.80	1.53	1.32	1.15
21	1.67	1.57	1.43	1.29
22	1.53	1.43	1.17	1.09
23	1.26	1.17	0.90	0.83
24	0.99	0.92	0.63	0.57

Table 52 – Hourly consumption for four days' types in Santa Rosa, California, no electric heating, PG&E

	Winter		Summer	
	High	Low	High	Low
Closest	88.047	58.13	33.517	19.367
Date	08/02/2019	12/11/2019	12/05/2019	18/06/2019
1	3.97	3.04	0.74	0.47
2	4.30	3.35	1.28	0.42
3	4.57	3.67	2.05	0.41
4	4.73	3.96	2.51	0.50
5	4.84	4.27	2.96	0.65
6	4.95	4.53	3.09	0.68
7	4.92	4.59	2.84	0.85
8	5.61	4.34	2.39	0.93
9	4.91	3.60	1.64	0.94
10	4.05	2.70	1.15	1.17
11	4.50	2.37	0.73	0.74
12	3.58	1.09	0.71	0.72
13	2.98	0.81	0.69	0.69
14	2.73	0.78	0.68	0.67
15	2.56	0.78	0.71	0.70
16	2.28	0.85	0.82	0.79
17	2.10	1.10	1.00	0.96
18	3.05	1.77	1.09	1.02
19	2.66	1.75	1.12	1.04
20	2.58	1.65	1.29	1.18
21	2.82	1.57	1.39	1.32
22	3.01	1.70	1.15	1.11
23	3.05	1.86	0.88	0.84
24	3.31	2.01	0.61	0.57

Table 53 – Hourly consumption for four days' types in Santa Rosa, California, with electric heating, PG&E

Appendix 3: Final model

Here we will explore our thinking process in the construction of the model. In order to do so, let's look at the same screenshot previously shown that refers to the particular case of Vermont. We will first review the modelling process, and then we will analyze the meaning of every output.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	t	d_t (kW)	c_t	G_t (kW)	B_t (kW)	C_t (kW)			d_t (kW)	Battery availability (kW)	State of battery (at the end of the hour, kW)					
2	0	0.97	$0.1113	10.973	0	10	0.97341092	>=	0.97	52.40	52.40					
3	1	0.85	$0.1113	9.2933	0	8.4418	0.85145064	>=	0.85	60.00	60.00			0.9	Battery round trip efficiency	
4	2	0.80	$0.1113	0.8038	0	0	0.80381626	>=	0.80	60.00	60.00			10	Maximum discharge (kW)	
5	3	0.80	$0.1113	0.8035	0	0	0.80353927	>=	0.80	60.00	60.00			10	Maximum charge (kW)	
6	4	0.80	$0.1113	0.8038	0	0	0.80377958	>=	0.80	60.00	60.00			24	Minimum charge (kW)	
7	5	0.85	$0.1113	0.8492	0	0	0.84921062	>=	0.85	60.00	60.00			60	Max charge (kW)	
8	6	1.09	$0.1113	1.0916	0	0	1.09157869	>=	1.09	60.00	60.00					
9	7	1.41	$0.1113	1.4094	0	0	1.40939379	>=	1.41	60.00	60.00	60.00	Battery needs to be fully charged at 7 am			
10	8	1.34	$0.1113	1.3423	0	0	1.3423106	>=	1.34	0.00	60.00					
11	9	1.16	$0.1113	1.1607	0	0	1.16068725	>=	1.16	0.00	60.00					
12	10	1.18	$0.1113	1.184	0	0	1.18403972	>=	1.18	0.00	60.00					
13	11	1.16	$0.1113	1.1584	0	0	1.158356	>=	1.16	0.00	60.00					
14	12	1.13	$0.1113	1.133	0	0	1.13295794	>=	1.13	0.00	60.00					
15	13	1.09	$0.2611	1.0916	0	0	1.09159977	>=	1.09	0.00	60.00					
16	14	1.09	$0.2611	1.0903	0	0	1.09032549	>=	1.09	0.00	60.00					
17	15	1.17	$0.2611	1.1663	0	0	1.16629375	>=	1.17	0.00	60.00					
18	16	1.44	$0.2611	1.4394	0	0	1.43937799	>=	1.44	0.00	60.00					
19	17	1.97	$0.2611	1.9698	0	0	1.96975679	>=	1.97	0.00	60.00					
20	18	2.27	$0.2611	0	2.2719	0	2.27190722	>=	2.27	47.73	47.73	10	electricity use during the day (kW)			
21	19	2.24	$0.2611	0	2.2365	0	2.23654344	>=	2.24	45.49	45.49					
22	20	2.09	$0.2611	0	2.0892	0	2.08920445	>=	2.09	43.40	43.40					
23	21	1.94	$0.1113	1.9365	0	0	1.93646091	>=	1.94	43.40	43.40					
24	22	1.63	$0.1113	1.6278	0	0	1.6277515	>=	1.63	43.40	43.40					
25	23	1.34	$0.1113	1.3353	0	0	1.33526421	>=	1.34	43.40	43.40					
26			$5.54	$5.87												
27	kWh	31.82		43.663	6.5977	18.442										
28			$5.54	$4.76												
29			Gain=	$0.78												
30																

Battery always there | Car away 8-6 (Winter high) | Car away 8-6 (Winter low) | Car away 8-6 (Spring) | Car away 8-6 (Summer) | Car away 8-6 (Fall) | +

Figure 10 – Screenshot of Vermont's model

Column A contains numbers from 0 to 23, representing the 24 hours there are in a day. Let's first analyze every column in the range of those first 24 lines, and then we will concentrate on lines 26 to 29. Column B and C, as already mentioned previously, represent the daily electricity demand and the specific tariff applied. Column D, E and F constitute the variable cells of our optimization, in which the first one (D) corresponds to the amount of electricity (in kWh) that is bought on the grid, the second (F) represents the amount of electricity (in kWh) that is taken out of the battery to feed the household and the third (F) is the amount of electricity (in kWh) that is taken to charge the battery. Column G is the sum of D and E minus F (D+E-F), which demonstrates that the amount of energy coming from either the grid or the battery (net of its inflows and outflows) need to supply the hourly demand for electricity (constraint illustrated in column G to I). Column J refers to the battery availability, here in the scenario where the car is away from 8am to 6pm. This column takes the exact same values as column K (state of battery), except for when the car is not there, where the values are voluntarily set to 0. The state of the battery in a given hour is calculated as the state of the battery in the previous hour, minus the energy taken out of the battery (column E), plus the energy going in the battery (column F) times the battery roundtrip efficiency of 90% to take into account the energy loss that occurs when charging and discharging the battery. In column L, we can observe two constraints: one stating that the battery needs to be fully charged at 7am before the person goes to work, and the other one mentioning that the worker used 10kWh of energy during the day, meaning that the battery will have 10kWh less to supply the house. Finally, in column L, all other relevant constraints that were implemented in the excel solver are shown.

Now, line 26 will lead us to the final objective's cell. In cell C26, we calculated the daily cost of electricity if no V2H system was used, so it is simply the sum product of column B and C. Cell D26 refers to the daily cost of electricity if the V2H system is in place, thus it is the sum product of column C and D.

Below is a screenshot of all the parameters properly implemented into the excel solver before running the optimization.

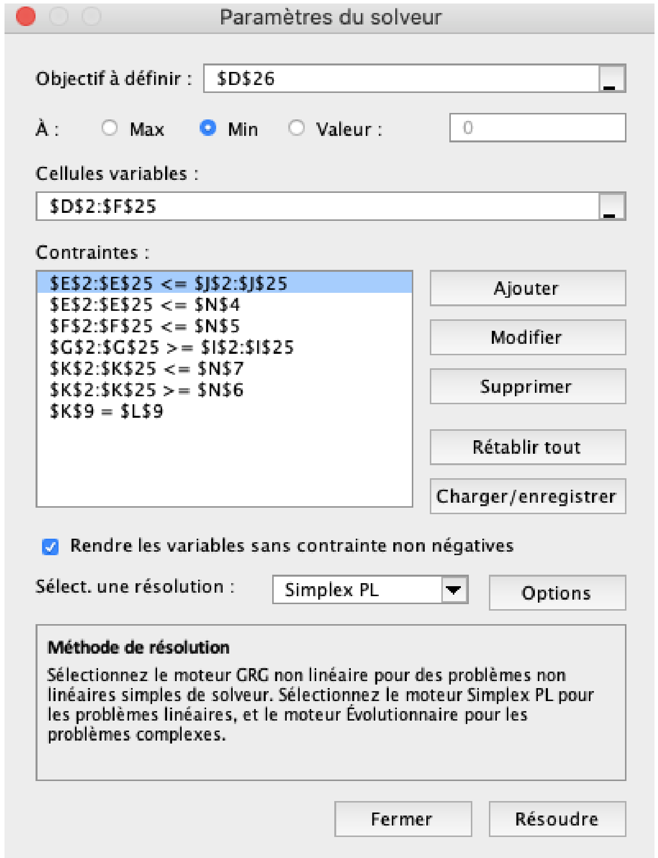

Figure 11 – Screenshot of Excel's solver parameters, case of Vermont

As one can see, the defined objective is to minimize the cell D26, and therefore to minimize the daily cost of electricity by using the V2H technology. Variable cells are in column D to F, thus allowing the model to assign adequately the energy in and out of the battery depending on the cost of electricity at every hour, just like the *dcbel* charger would. The first constraint refers to the energy going out of the EV battery being affected by the battery availability, therefore cancelling any possible arbitrage when the car is not available. The second and third constraints take into account the maximum possible charge and discharge of 10 kWh, as recommended by the car's manufacturer. The fourth constraint is there to make sure that the energy coming both from the grid and the battery is at least equal to the demand at every hour. It is important to make the distinction here that although all of the energy (to supply the house and to charge the EV battery) is bought from the grid, this constraint is especially present to allow the model to store energy into the battery when it sees fit. The fifth and sixth constraints are present to prevent the state of the battery to discharge below 24 kWh and to recharge to more than 60 kWh. Finally, the last constraint ensures that the state of the battery at 7am will be 60 kWh, therefore the worker is going to have a full battery when leaving the house.

Once the solver found a solution to the optimization problem, we were able to work with this minimized number to find the actual gain realized with V2H system. In order to do so, let's go through all other cells below line 26. Cell B27 represents the daily demand of electricity. Cell D27 shows the daily demand of electricity with the V2H system and is therefore the sum of column D. Cell E27 and F27 represents the sum of their respective column. Cell D28 is the calculation of daily costs of electricity with V2H system (cell D26) adjusted for the use of the EV during that day. Therefore, we subtract the amount of energy used (10kWh) times the cost of energy at which the vehicle was charged. Intuitively, if our model was calibrated well, the EV would charge itself at the off-peak hours, where the electricity rate is at its lowest. Finally, cell D29 represents the actual gain the V2H system realized on that particular day, and is calculated as the difference of daily cost without V2H minus daily cost with V2H adjusted for use.

Now we will interpret the optimization solution in order to better understand how the model works. We still refer to the figure 7 above. First, when looking at variable cells, it is interesting to see that as soon as the car comes back home, since it is during the peak hour and there is still energy left in the battery, the electricity demand is covered by the EV battery instead of the grid for 3 hours. Whenever the peak period ends, the household consumption goes back on the grid and we take advantage of those low tariffs to fully charge the battery. In this particular case, the battery discharges from 6pm to 9pm and charges from 12-2am. Therefore, the minimized cost obtained in cell D26 corresponds to $5.87. At first glance, one could say that this cost is higher than the daily cost of $5.54 without V2H system (cell C26), so that there are no economic benefits to be realized. However, the optimized cost takes into consideration the 10-kWh surplus that was used to go to work. Once adjusted for that, the daily cost is now $4.76 (cell D28), meaning that the real net gain is $0.78 for that particular day in Vermont (cell D29). Another important factor to demonstrate is the difference between the daily demand without V2H (cell B27;

31.82 kWh) and with V2H (cell D27; 43.66 kWh). First, there is a difference of 10 kWh due to the use of the EV during the day. The rest of the difference is due to the 90 % efficiency of the battery, so it represents a loss in energy.

We used the exact same model for every jurisdiction, so the only difference between the case of Vermont that we analyzed and all of the other regions would lie in the final output data, which are the variable cells as well as the defined objective's cell and the final net gain.