Electric Vehicle Charging as an Enabling Technology

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Hawai‘i Distributed Energy Resource Technologies for Energy Security

Subtask 7.2 Deliverables 1 and 2

Report on Oahu Grid Model

Prepared by

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Overview

The Hawaii Natural Energy Institute (HNEI) has been involved in the analysis of the impacts of renewable energy on island grids since 2009 by collaborating with the Hawaiian Electric Company (HECO) and GE Energy to develop and validate detailed models of the Oahu power grid for the Oahu Wind Integration Study (OWIS). The OWIS models are now being leveraged as starting points for this study which focuses on evaluating how enabling technologies can facilitate the delivery and utilization of renewable energy on the Oahu power grid. Four enabling technologies are being considered together in a larger State of Hawaii research project for the US Department of Energy (DOE). In this study, one of the four enabling technologies, electric vehicles and the appurtenant charging infrastructure, is explored in detail to determine the impact that various energy delivery and utilization strategies might have on minimizing the curtailed renewable energy that results from: a)the variability of renewable energy, b) the lack of perfect alignment between renewable energy supply and system loads in Hawaii, and c) the existence of minimum operating rules under which the utility must operate to maintain system stability.

Under this contract HNEI engaged GE Energy to modify the OWIS models which previously had evaluated the impact of 600 MW of renewable energy on operating characteristics of the Oahu grid. The current project extends the renewable energy delivery assumptions to 800 MW and 1,000 MW and varies modeling scenarios to test assumptions regarding system load profiles, vehicle charging strategies, electric vehicle adoption rates, and storage support. The results of the simulations show comparative impacts on curtailed renewable energy, power plant generation, emissions and fuel consumption.

Interim Technical Report

This report summary highlights the key findings of the analysis to date, notably the maximum achievable levels of curtailed energy reduction the system can be expected to see. Other findings include the impact of varying the time of day vehicles are charged, the expected benefit of smart grid technologies, the impact of increasing or decreasing the number of EVs on the grid, the impact of storage, and the effect of modifying the utilities available reserves. The mix of renewables comprising the 1,000 MW is also explored, changing the mix of wind, central plant solar and distributed solar resources.

This Interim Report will be followed up by a full report in the spring of 2013 resulting from a continuation of this work under the Hawaii Energy Sustainability Program, DOE Cooperative Agreement No. DE-EE-0003507. The full report will have a comprehensive discussion of the modeling, assumptions, variables and results.

Assumptions

Base Case

The 600 MW model from OWIS is the initial scenario. Three additional base-case scenarios compare rates of curtailed energy at increasing rates of renewable energy contribution to the grid. Table 1 compares the initial 600 MW base case with an 800 MW case and two 1,000 MW cases with differing mixes of wind and solar. In these base-case runs, the loads are existing loads, with no additional impact from vehicle charging.

Table 1: Curtailed Renewable Energy Under Varying Renewable Energy Contribution Scenarios

Scenario	Renewable Generation Capacity, MW	Solar MW	Wind MW	Renewable Energy Curtailed GWh/yr	Percent Curtailed of Renew. Gen. %
Base Case 1	600	100	500	210	9.96%
Base Case 2	1000	300	700	736	23.15%
Base Case 3	1000	500	500	401	14.22%
Base Case 4	800	300	500	264	10.62%

As the quantities of renewable energy increase on a fixed system load, the percent of curtailed energy increases. However, when a greater proportion of the renewable energy is generated during the day, for example comparing Base Case 1 (100 MW solar) with Base Case 4 (300 MW solar) and Base Case 3 (500 MW solar), less energy is curtailed utilized due to daytime peak loads than the Base Case 2, where wind is the primary renewable. When the mix of renewables is dominated by wind, renewable energy is generated indiscriminately on and off peak, and night generation will occur while system loads are at their lowest, resulting in a higher curtailment percentage.

For a major portion of this report, the focus of the discussion will be on the variables run using the Base Case 2 model. This is based on the assumption that it 300 MW of solar on Oahu is more realistic than 500 MW due to geographic and land use constraints that could limit the deployment of solar systems.

Modeling Assumptions

In order to determine the larger order impacts that changes in load have on the grid, the models make certain assumptions regarding the magnitude of the charging load relative to the magnitude of the renewable energy generated. The assumption throughout the analysis is that on any given simulation, the amount of renewable energy available for EV charging is equal to the amount of curtailed renewable energy from the base case. That is to say, our target is to utilize exactly the amount of energy that would be curtailed should no additional charging load be added. For daily

EV charging, preliminary results are modeled assuming that the daily charging energy is the same very day, and equal to the annual curtailed energy divided by 365.

Total Annual EV Fleet Charging Energy = Total Annual Curtailed Renewable Energy
and
Daily EV Charging Energy = Total Annual Curtailed Renewable Energy/365

Variables Studied

Seven load profiles scenarios were evaluated for Base Case 2 and 3:

Annual Uniform Charging	Daily charging is equally distributed all year
Annual Perfect Tracking	Daily charging tracks the annual average of any hour
Annual, Profile 1	70% night charging, 30% day, including 5:00-9:00 pm Peak
Annual, Profile 2	70% night charging, 30% day, excluding 5:00-9:00 pm Peak
Annual, 85%	85% of charging between 9:00 pm – 7:00 am
Monthly Perfect Tracking	Daily charging for each hour set at monthly average curtailed for that month
Daily Perfect Tracking	Charging is proportional to daily curtailed load shape.

Other variables

Several other non-load variables were evaluated across scenarios:

- Impact of storage on dispatch of renewable energy
- Impact of thermal plant spinning reserves
- Impact of increasing and decreasing the electric vehicle fleet
- Effects of seasonality of load and wind.

Boundary Scenarios

In an effort to determine relative impacts of key variables, consultant GE Energy ran a large number of scenarios. From these runs, the team identified variables whose impacts were significant. This discussion highlights the scenarios that best illustrate and define the range of impact on curtailed energy. Variations on these scenarios will be addressed later in the report.

To answer the question *"What is the maximum possible reduction of curtailed renewable energy that we can achieve?"* a series of runs were performed using the theoretical assumption described in the following paragraph.

The daily charging profile tracks perfectly the daily average curtailed energy profile (Daily Perfect Tracking). This implies that perfect smart grid technologies are in place to monitor the renewable energy contribution, utility power plant dispatch and status, and access to the entire EV fleet to provide a perfect match between renewable supply and load.

It is understood that this is an untenable assumption in the real world. This scenario represents an upper boundary that defines the maximum achievable potential to reduce curtailed energy. Table 2 summarizes the percentage reduction in curtailed energy by scenario. The highlighted scenario is the best possible case, Daily Perfect Tracking. In this scenario, a ceiling of 53.35% reduction over the base case is established, which represents the best that we can do given our research assumptions.

Table 2: Reduction in Curtailed Energy by Scenario

EV Charging Plan	Reduction in Curtailed Energy from Base 2
Annual Uniform Charging	40.71%
Annual Perfect Tracking	46.12%
Annual Profile 1	40.45%
Annual Profile 2	45.80%
Annual 85% Evening Case	44.75%
Monthly Perfect Tracking	46.61%
Daily Perfect Tracking	53.35%

The duration curve in Figure 1 illustrates how much of the annual curtailed energy can be captured in a best-case scenario. Three regions of the graph represent: a) Unused Curtailed Renewable Energy, b) Used Curtailed Renewable Energy, and c) Energy that must be generated to meet the charging demand of the EV fleet during the periods when renewable energy is not available.

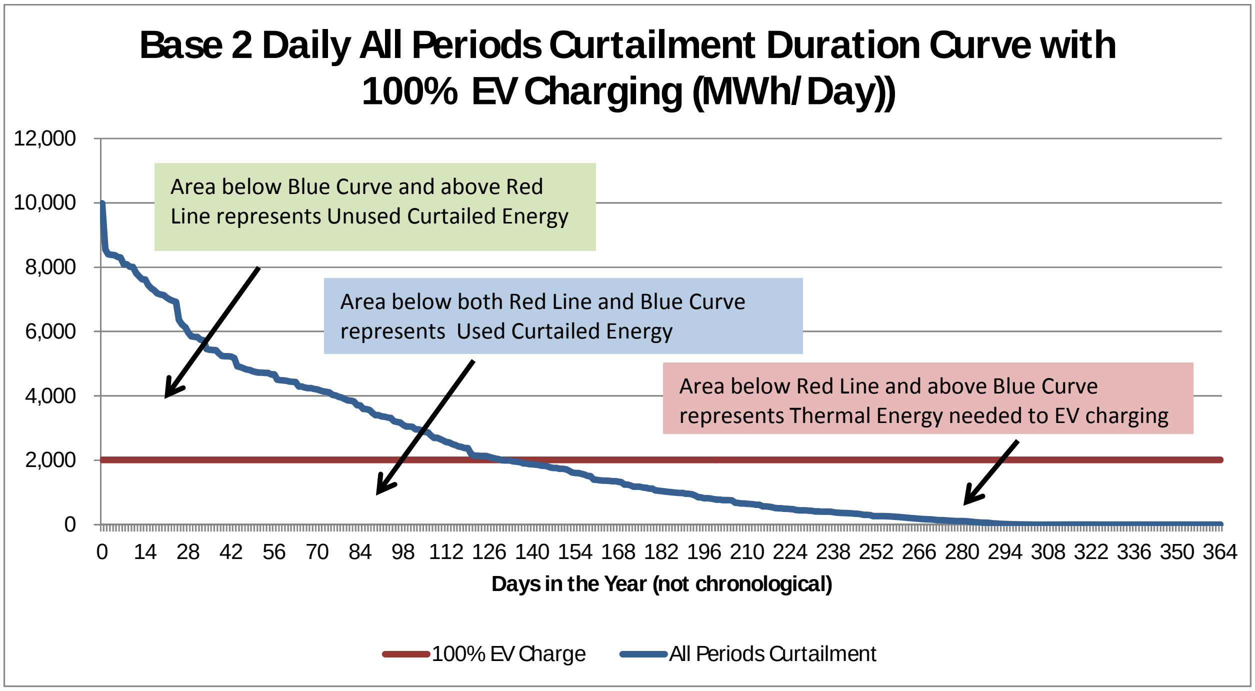
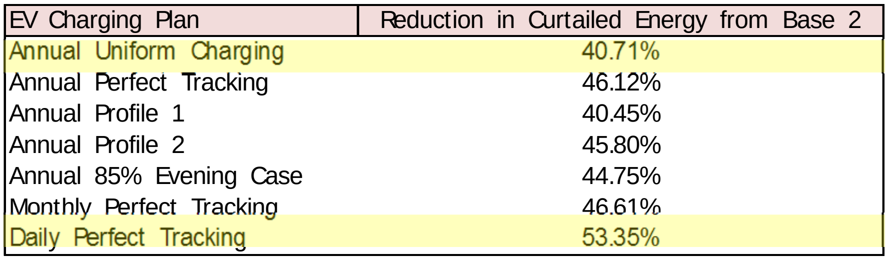


Figure 1: Maximum Achievable Potential

At the other end of the theoretical spectrum it is expected that random, uncontrolled charging would result in the smallest reduction of curtailed energy. As a proxy for this situation, the model assumes that all of the charging loads are evenly distributed throughout a 24-hour period. In Table 2a, the reduction in curtailed renewable energy for Annual Uniform Charging is 40.71%. This effectively represents the floor in our savings potential. Most of the variations of scenarios fall between the 40.71% floor and the 53.35% ceiling, with one exception, Profile 1. Further examination is required to explain this finding.

Table 2a: Reduction in Curtailed Energy by Scenario



EV Charging Plan	Reduction in Curtailed Energy from Base 2
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Annual 85% Evening Case	44.75%
Monthly Perfect Tracking	46.61%
Daily Perfect Tracking	53.35%

The scatterplot in Figure 2 illustrates why it is difficult to capture all of the renewable energy. The red line is the daily vehicle charging load, i.e., the average daily profile if all of the annual curtailed energy were distributed equally over 365 days. The data points below the line represent the actual amount of curtailed renewable energy available to the grid on a particular day. While the available curtailed energy can be used, the balance of the charging requirement must be generated at the power plant. The points above the line represent curtailed renewable energy that has been generated, but because it is greater than the daily required load, it cannot be utilized. Charging will not take place uniformly. This illustration simply indicates the wide variability there relative to a reference average charging day.

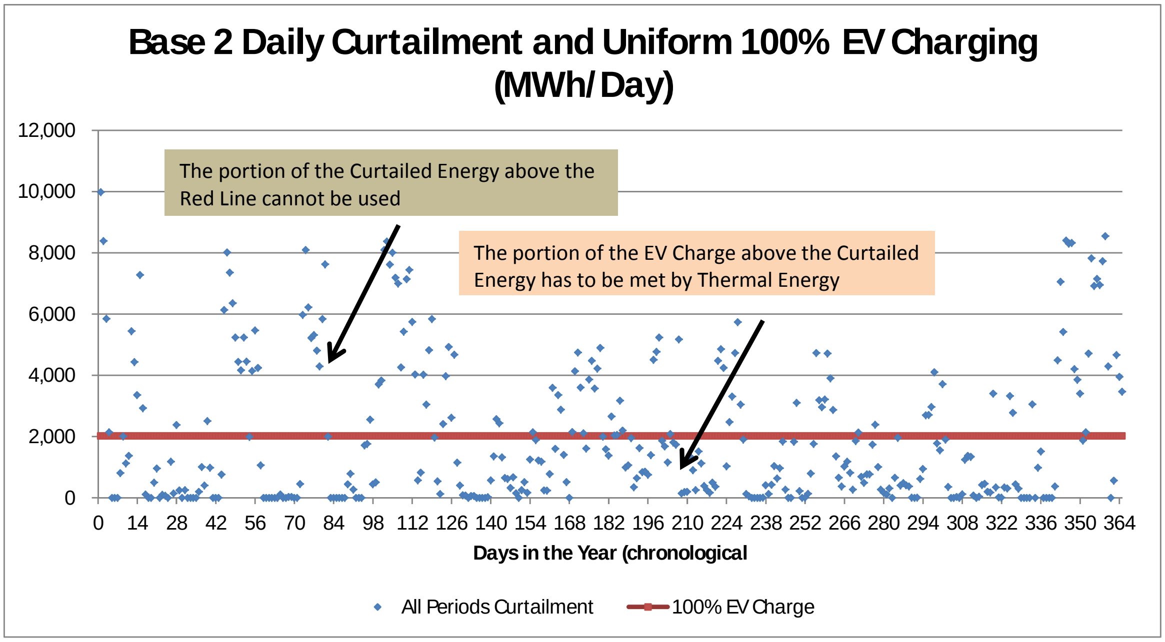


Figure 2: Availability of Renewable Energy

Impact of Load Shape Variables

Figures 3a-e offer graphic representations of the load profiles modeled, which combined reflect a full range of scenarios that allow discussion to be bracketed by worst- and best-case scenarios.

Figure 3a, Uniform Tracking, represents an indiscriminate charging profile where charging takes place anytime. This is an approximation of a worst-case scenario where peak utility load are not reflected in rates or operating patterns. Figure 3b, Perfect Tracking, represents a best-case scenario, where the EV charging perfectly tracks the utility system load. Figure 3c, Profile 1, represents a case where 70% of the charging is distributed during the night and 30% of the charging is assumed to take place during the day. Figure 3d, Profile 2, represents the same distribution, but charging during the priority peak, the utility's period of highest demand, is avoided. Figure 3e, 85% Evening, is similar to Profile 2; however, 85% of the daily charging takes place during the nighttime off-peak hours.

Figure 3a:

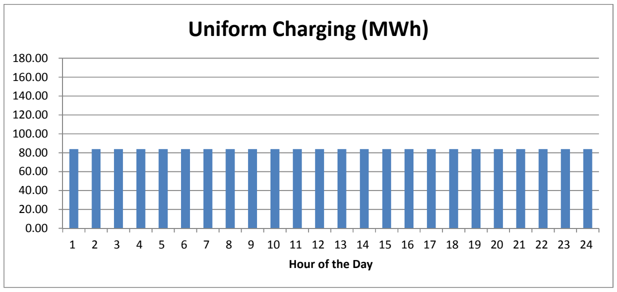


Figure 3b:

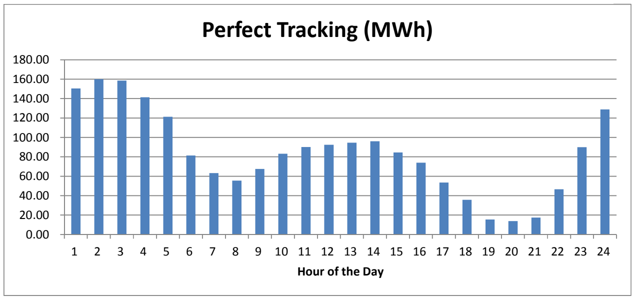


Figure 3c:

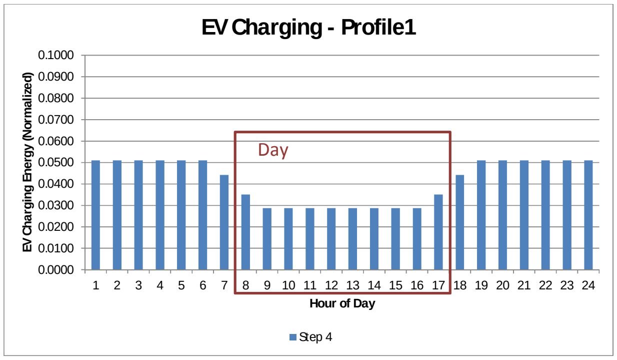


Figure 3d:

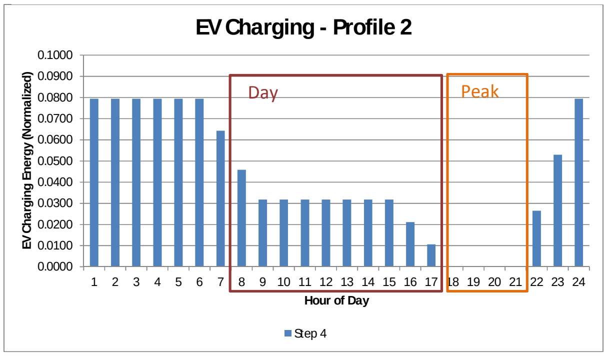


Figure 3e:

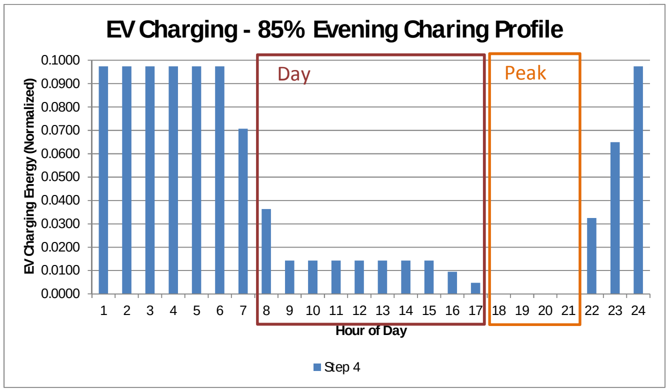


Figure 3: Load Profile Assumptions

Results

The potential reduction in renewable energy curtailment ranges from 40% to 53% when compared to the base case (100% curtailed energy). Figure 4 shows graphically the results of the seven load scenarios that were presented earlier in Tables 2 and 2a.

The Daily Perfect Tracking, a theoretical construct that establishes the upper limit, is not achievable since it assumes perfect information flow and perfect mechanical and operational response. Annual Uniform Charging and Annual Profile 1 set the lower boundary of the range. The Annual Profile 2 represents a reasonable operating assumption for comparing other variables. It assumes that 70% of the EV charging will take place at night, 30% during the day, and that no charging will take place during the HECO “Priority Peak” period of 5:00 PM to 9:00 PM (Figure 3d). This scenario is the basis for many of the comparisons. For some comparisons, it may be more appropriate to use another scenario as a basis of comparison. These will be noted.

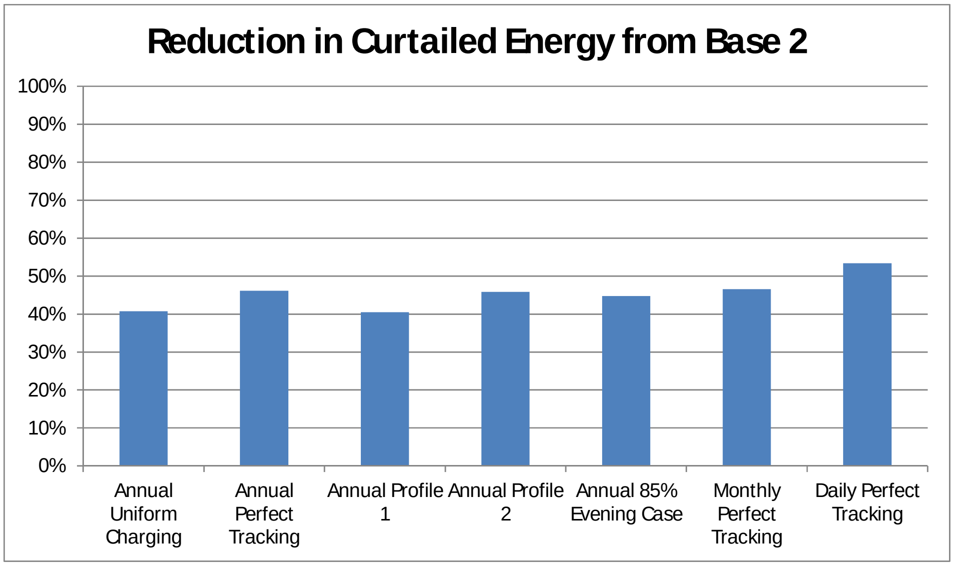


Figure 4: Reduction in Curtailed Energy Compared to Base Case

Detailed results are presented initially as a research question, supported by data from the study.

Question: When is curtailment typically taking place and which charging scenarios best mitigate?

The data in Table 3 shows that in absence of EV charging loads, 56.6% of the curtailment takes place at night, 39.3% during the day, and 4% during the peak for Base Case 2.

By comparison, Figure 5 compares the reduced curtailment scenarios against the base case. Profile 2 consistently shows the greatest potential, utilizing evening-generated renewable energy. The stacked area chart in Figure 6 shows the contribution of each utility generating asset, along with the additional EV load and the relative quantities of curtailed energy. This graph highlights the typical evening “valleys” where the amount of renewable energy far exceeds the demand, even when accounting for an additional EV load.

Table 3: Base Case 2 Average Daily Curtailment by Time Period

Base 2 Average Daily Curtailment	(MWh)	Percent of Total
Day Curtailment (7am - 5pm)	792	39.3%
Peak Curtailment (5pm - 9pm)	83	4.1%
Evening Curtailment (9pm - 7am)	1,141	56.6%
Total Daily Curtailment	2,016	100.0%

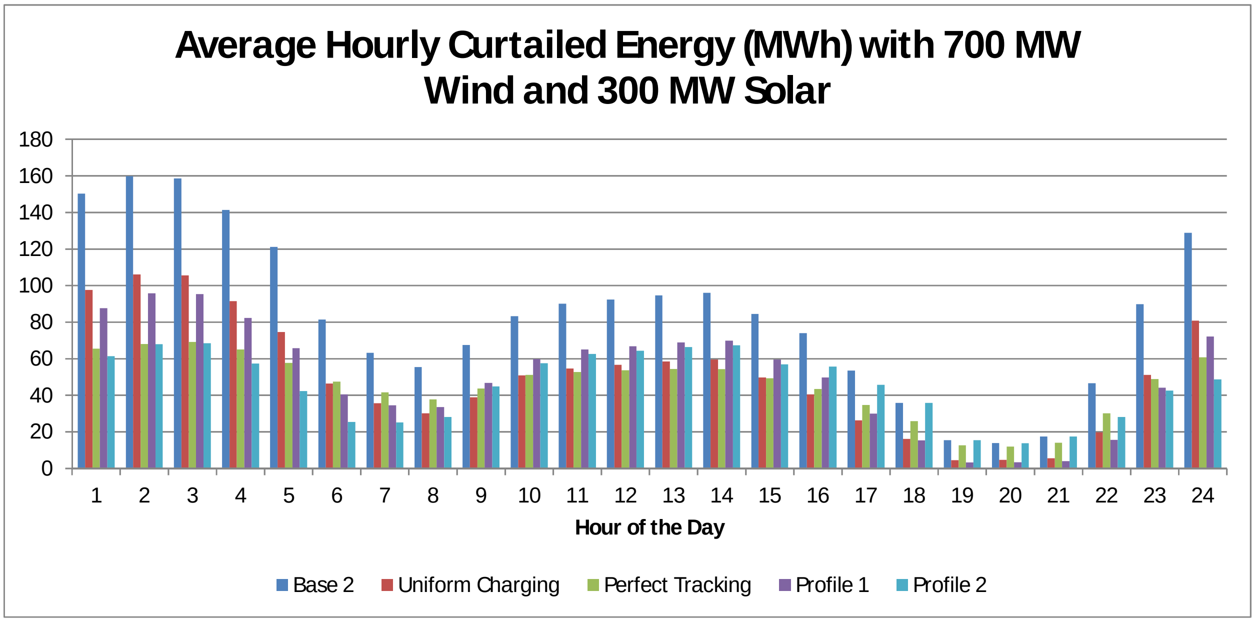


Figure 5: Impacts on Curtailment Over Average 24 Hour Day

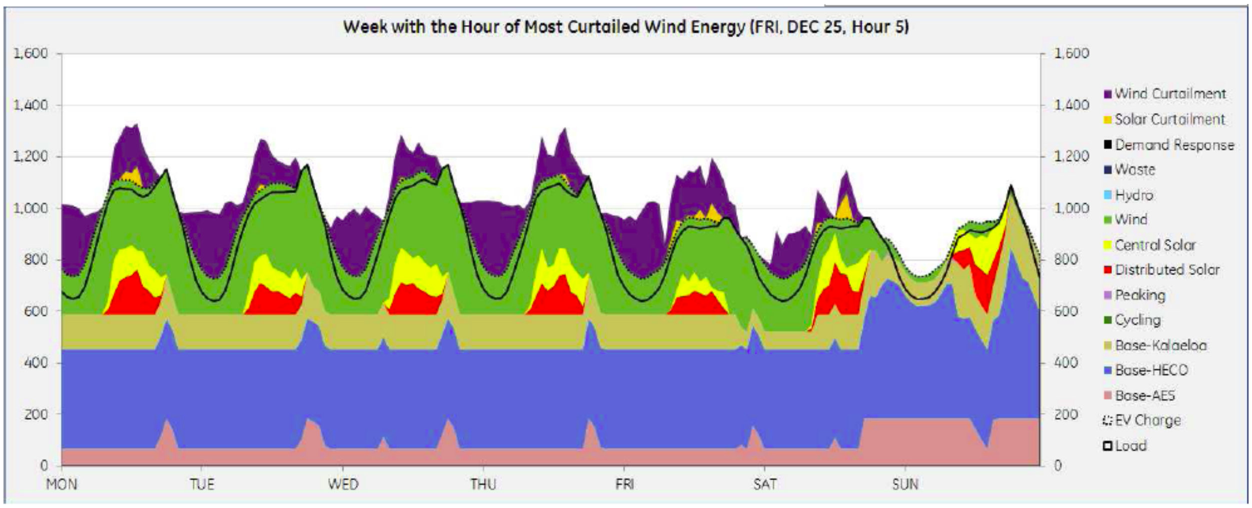


Figure 6: Week with Most Wind Curtailment

Question: What would be the impact of increasing or reducing the number of EVs charging on the grid?

Figures 7 through 9 and Table 4 compare energy utilization when the EV charging is cut in half, and when it is doubled. Figure 7 indicates that if the EV load is cut in half, the account of curtailed energy significantly increases. Figure 8 shows that if the number of EVs were to double, the annual curtailed energy would reduce. The result of increasing the number of vehicles is an increase in thermal generation that would be required to charge the EV fleet in absence of a renewable energy source.

For Profile 2, 144,117 MWh (36.0%) are provided by renewable energy with 256,536 MWh (64%) generated at the power plant using 36% of the curtailed energy, If the EV-charging requirement were cut in half (50% fleet size) a greater proportion of renewables would be used for charging, 39.4% of the charging source is renewable and 60.6% from the power plant. The amount of curtailed renewable energy drops to 19.7%. If the fleet is doubled, 59% of the curtailed energy is used; however, the thermal power plants must generate more than double the kWh than in the base case, 563,365 MWh compared to 256,536 MWh for the initial fleet size.

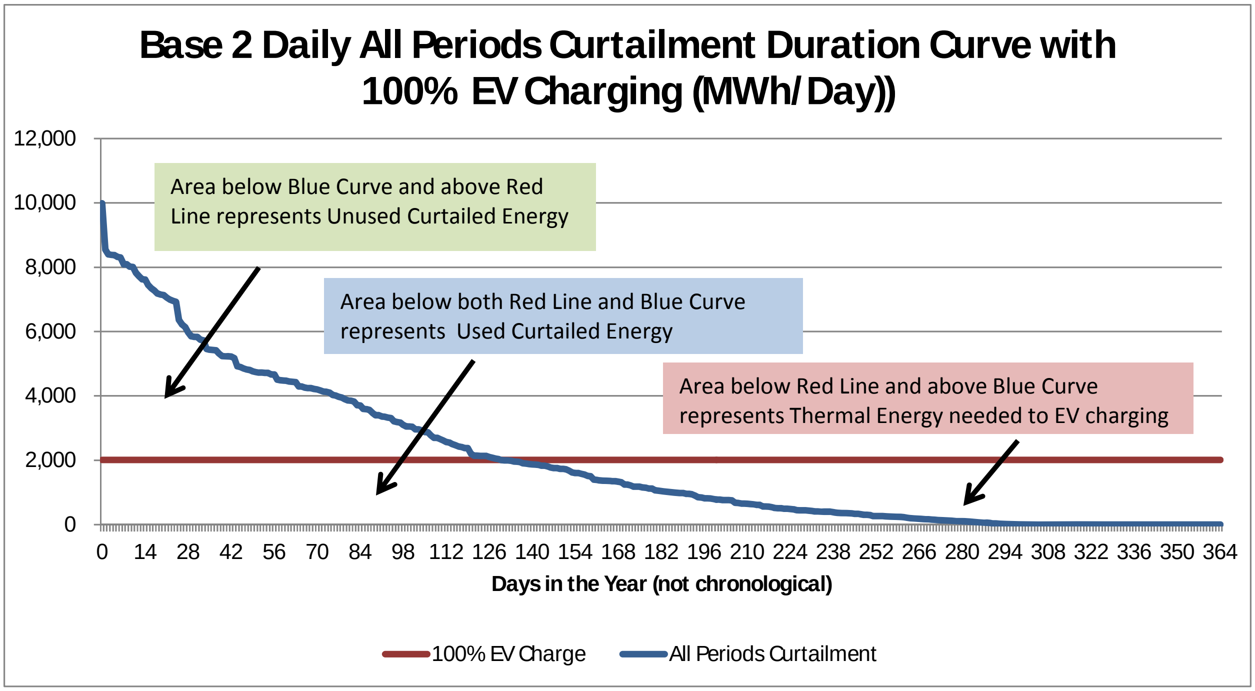


Figure 7: Base 2 Duration Curve 100% EV Charging

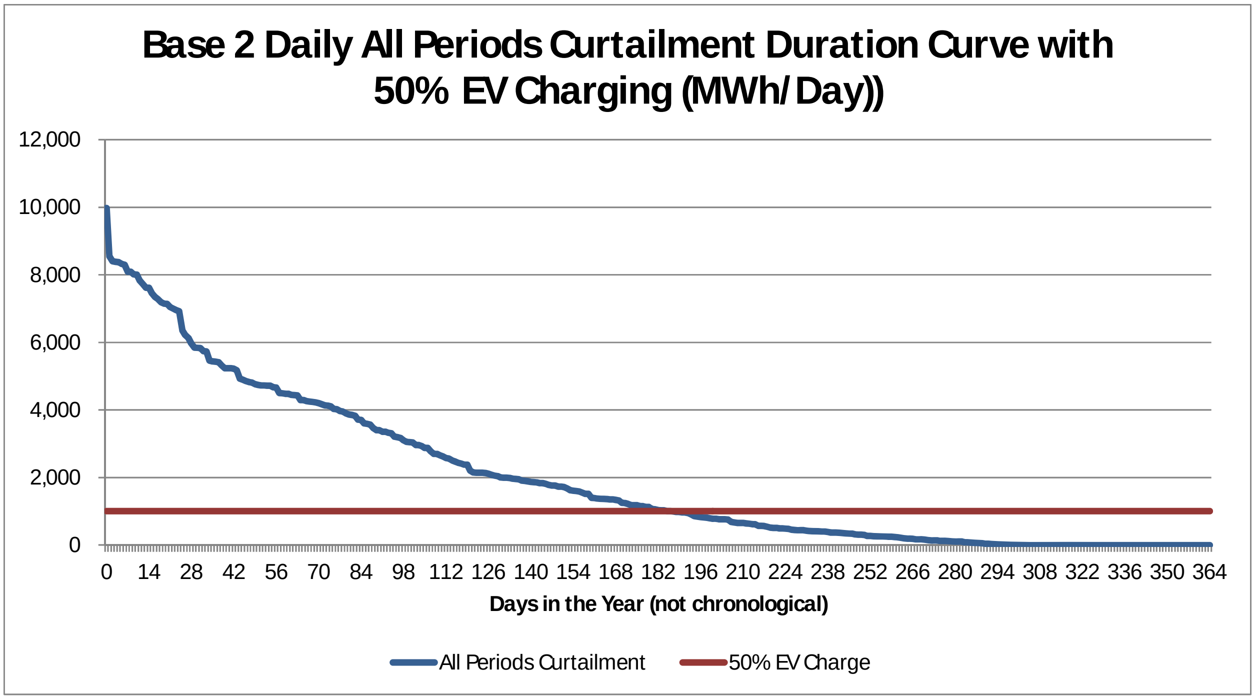


Figure 8: Duration Curve for 50% EV Charging

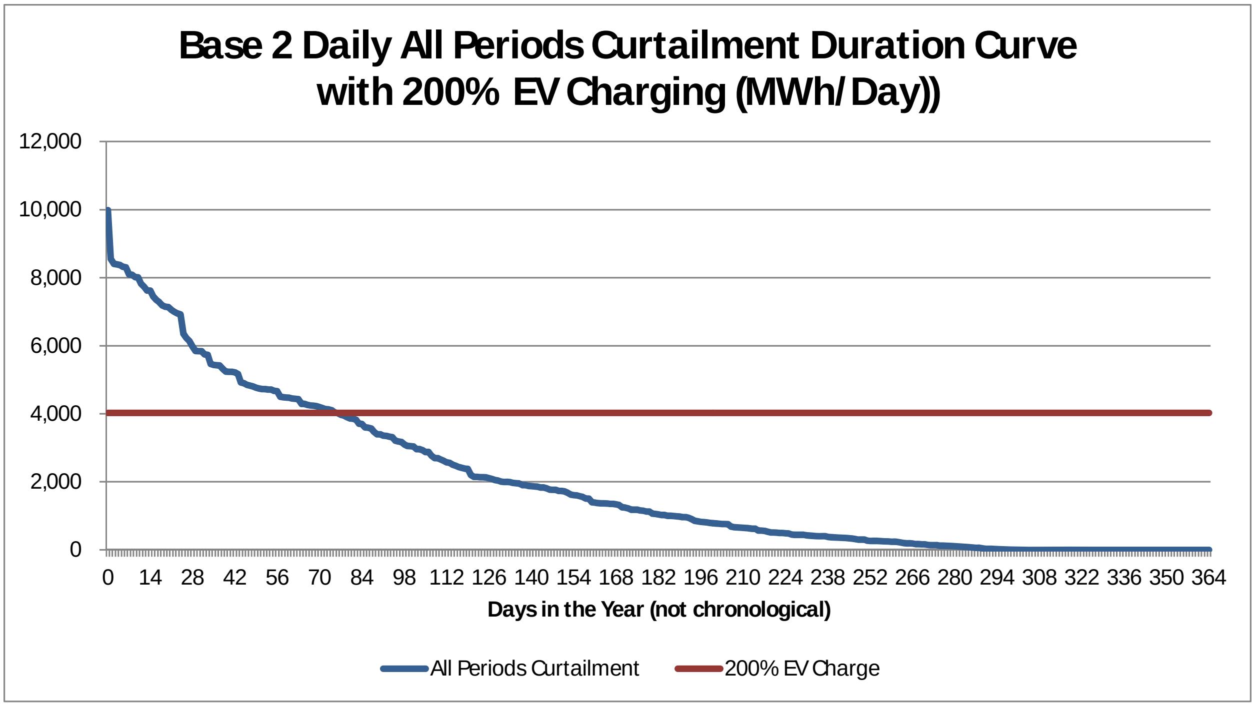


Figure 9: Duration Curve for 200% EV Charging

Table 4: Impact of varying EV Charging Amounts - Profile 2 / 50% - 100% - 200%

EV Charing Profile 2 70% Evening, 30% Day, 0% Peak	Units	EV Charging From Renewable Energy	EV Charging From Thermal Energy	Total EV Charging Energy	Unused Curtailed Energy	Used Curtailed Energy	Total Curtailed Energy
50% EV Charging	(MWh)	78,872	121,455	200,327	321,782	78,872	400,653
100% EV Charging	(MWh)	144,117	256,536	400,653	256,536	144,117	400,653
200% EV Charging	(MWh)	237,942	563,365	801,307	162,711	237,942	400,653
50% EV Charging	% of Total	39.4%	60.6%	100.0%	80.3%	19.7%	100.0%
100% EV Charging	% of Total	36.0%	64.0%	100.0%	64.0%	36.0%	100.0%
200% EV Charging	% of Total	29.7%	70.3%	100.0%	40.6%	59.4%	100.0%

Other Observations

Figures 10 through 14 examine the resultant metrics when two scenarios, Daily Perfect (best case) and Profile 2 (reasonable case) are compared to the Base Case, in terms of thermal generation (MWh), renewable generation (MWh), curtailed energy (MWh), CO_2 emissions (T,CO_2), and variable cost of operation ($,000). These figures have combined the results from Base Case 2 (700 MW wind / 300 MW solar) and Base Case 3 (500 MW wind / 500 MW solar).

In general, the results from Profile 2 are similar to those of Annual Perfect Tracking, which is another indicator that the model is reasonable as a best case.

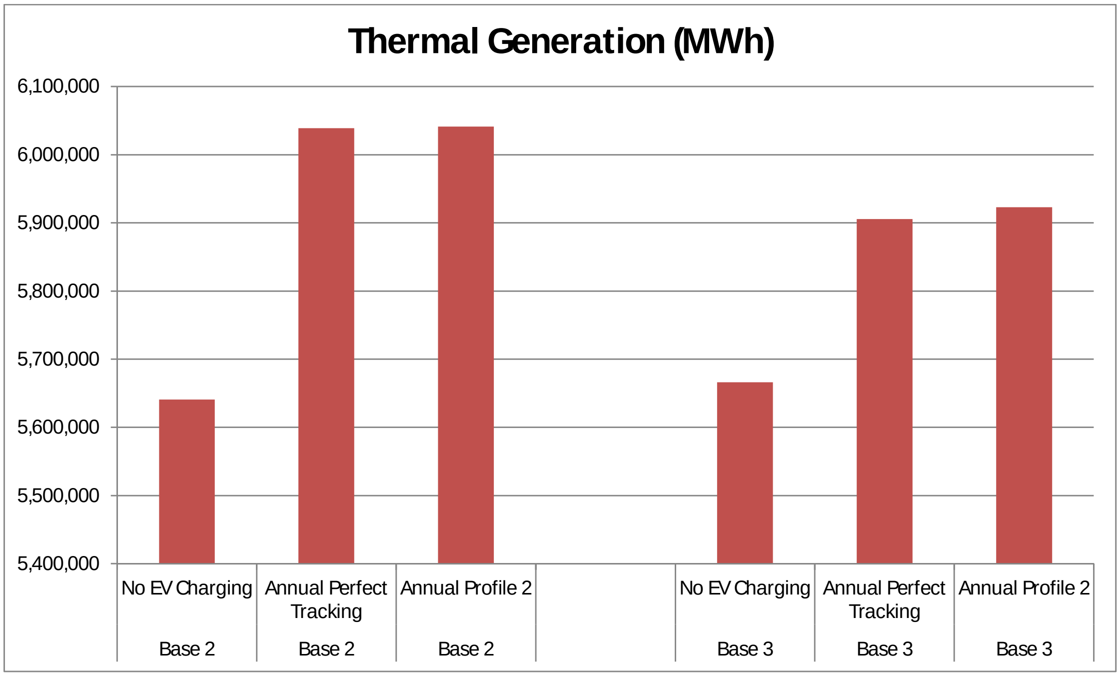


Figure 10

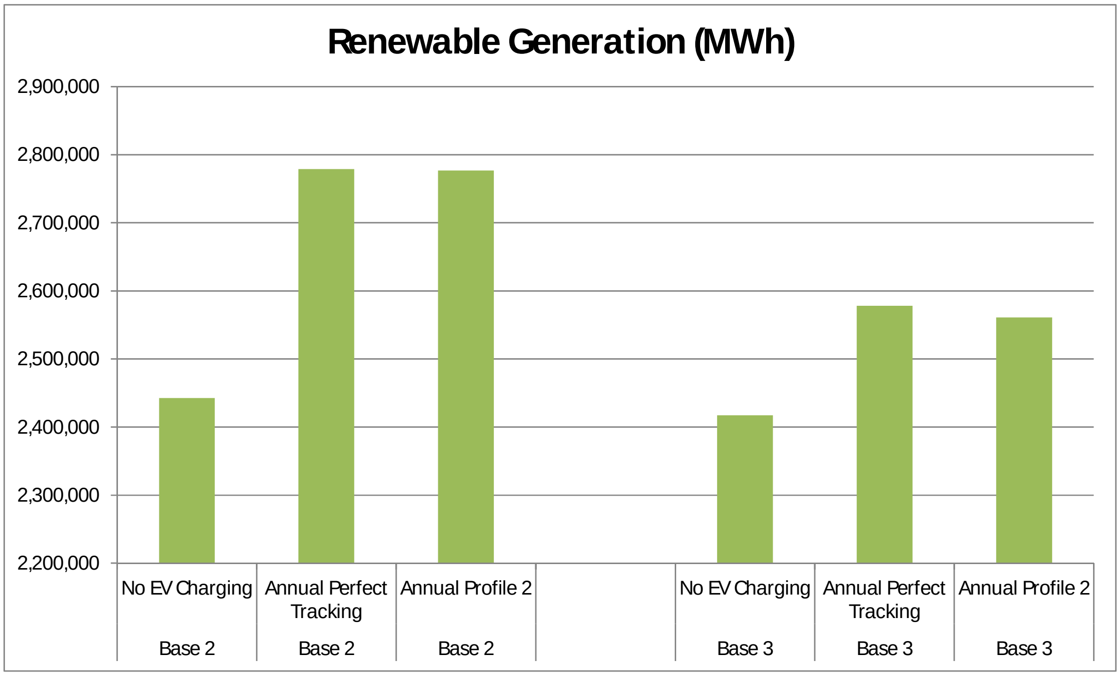


Figure 11

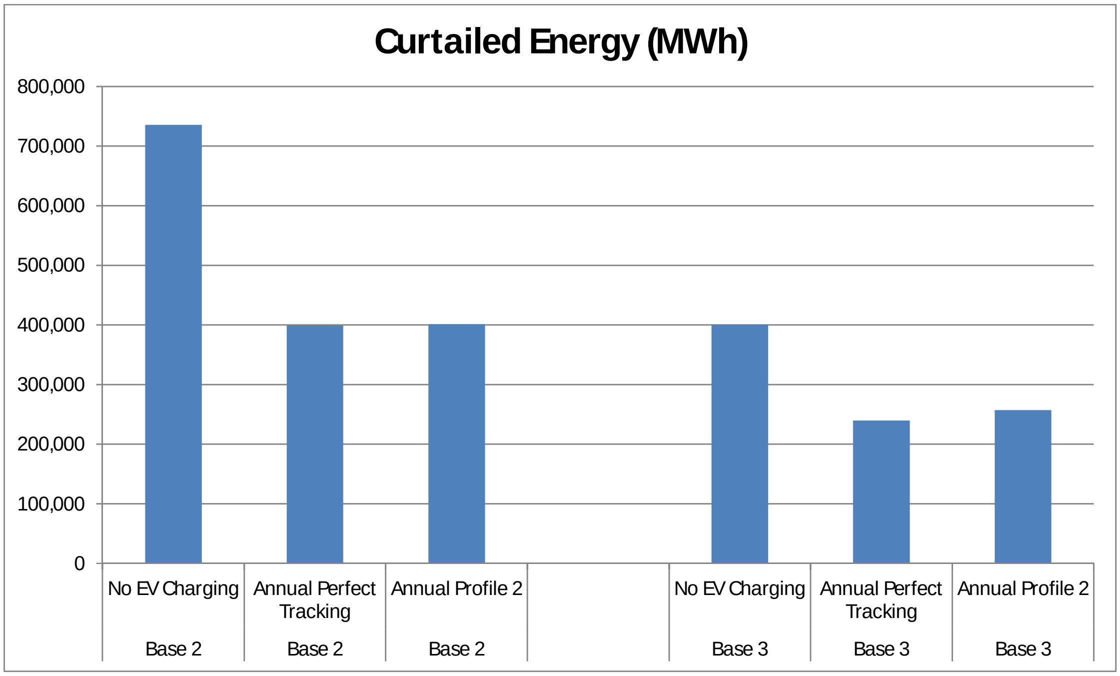


Figure 12

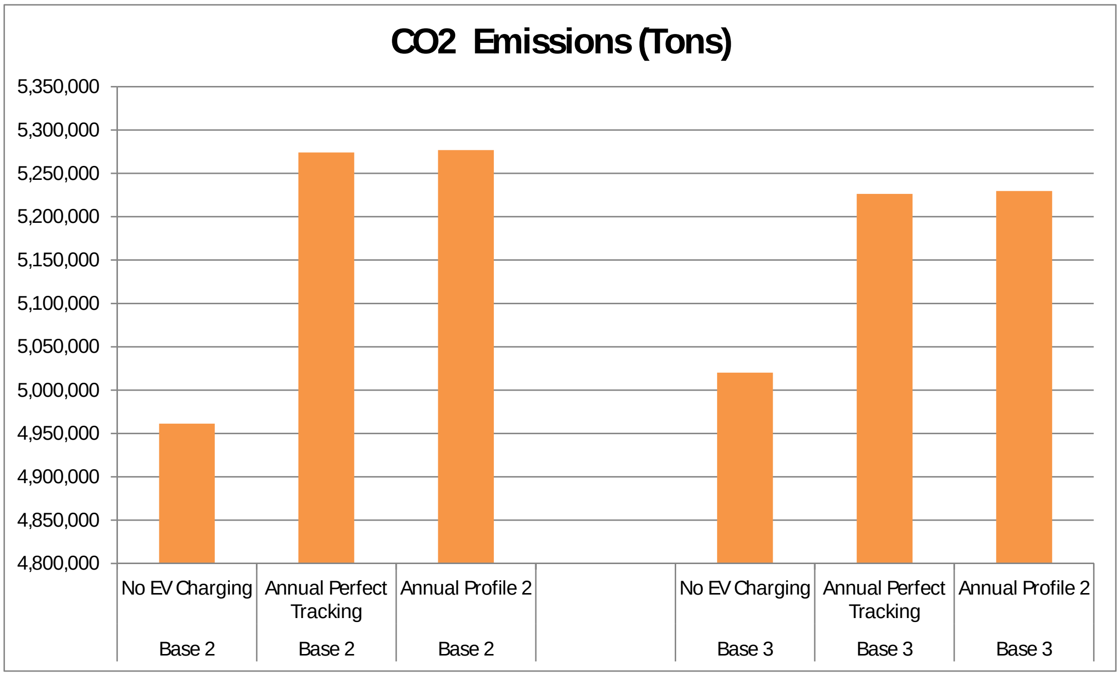


Figure 13

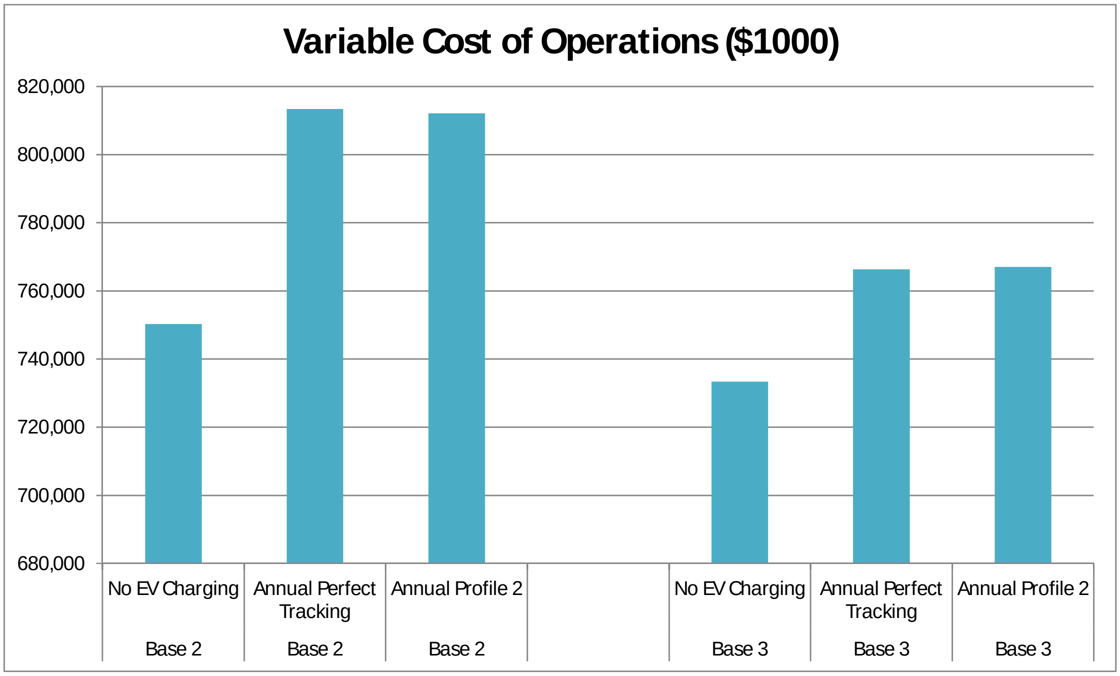

Variable Cost of Operations ($1000)
820,000
800,000
780,000
760,000
740,000
720,000
700,000
680,000
No EV Charging
Annual Perfect Tracking
Annual Profile 2
Base 2
Base 2
Base 2
No EV Charging
Annual Perfect Tracking
Annual Profile 2
Base 3
Base 3
Base 3

Figure 14

Impact from a Change in Utility Operations: Spinning Reserves

Question: *What is the impact of reducing the utilities spinning reserve requirements by using a combination of storage, demand response , smart grid technologies to utilize renewable energy that might otherwise be curtailed?*

Table 5: Impact of Reduced Spinning Reserve Requirements

	Total Available Renewable Energy (MWh)	Total Renewable Generation (MWh)	Total Curtailed Renewable Energy (MWh)	Curtailed Energy as Percent of Available Energy	Curtailed Energy as Percent of Base with Half Spin	Curtailed Energy as Percent of Base with Full Spin
Base 2 with No EV Charging	3,178,114	2,442,510	735,662	23.1%		100.0%
Base 2 with Annual Perfect Tracking	3,178,114	2,778,802	399,364	12.6%		54.3%
Base 2 with Profile 2	3,178,114	2,776,758	401,409	12.6%		54.6%
Base 2 (Half Spin) with No EV Charging	3,178,114	2,536,448	641,724	20.2%	100.0%	87.2%
Base2 (Half Spin) with Annual Perfect Tracking	3,178,114	2,850,290	327,890	10.3%	51.1%	44.6%
Base 2 (Half Spin) with Profile 2	3,178,114	2,855,426	322,753	10.2%	50.3%	43.9%

Table 5 shows the results of this impact. When compared to the curtailed renewable energy from the base case, 2,735,662 MWh per year, substituting renewable reserves for power plant-generated spinning reserves reduces the curtailed energy by 93,938 MWh. In the Annual Perfect Tracking scenario, 71,474 MWh of curtailed energy can be achieved by reducing spinning reserve requirements. With Profile 2, 78,656 MWh can be saved by reducing spinning reserve.

The decision to utilize other technologies to reduce spinning reserve will be made by the utility and must be compatible with other operational protocols.

Storage

Question: How can energy storage impact the amount of curtailed renewable energy captured on the grid?

Figure 15 illustrates that the 250-MWh-Charge rate captures much of the curtailed energy. Charge rates above 500 MWh/hr will contribute very little.

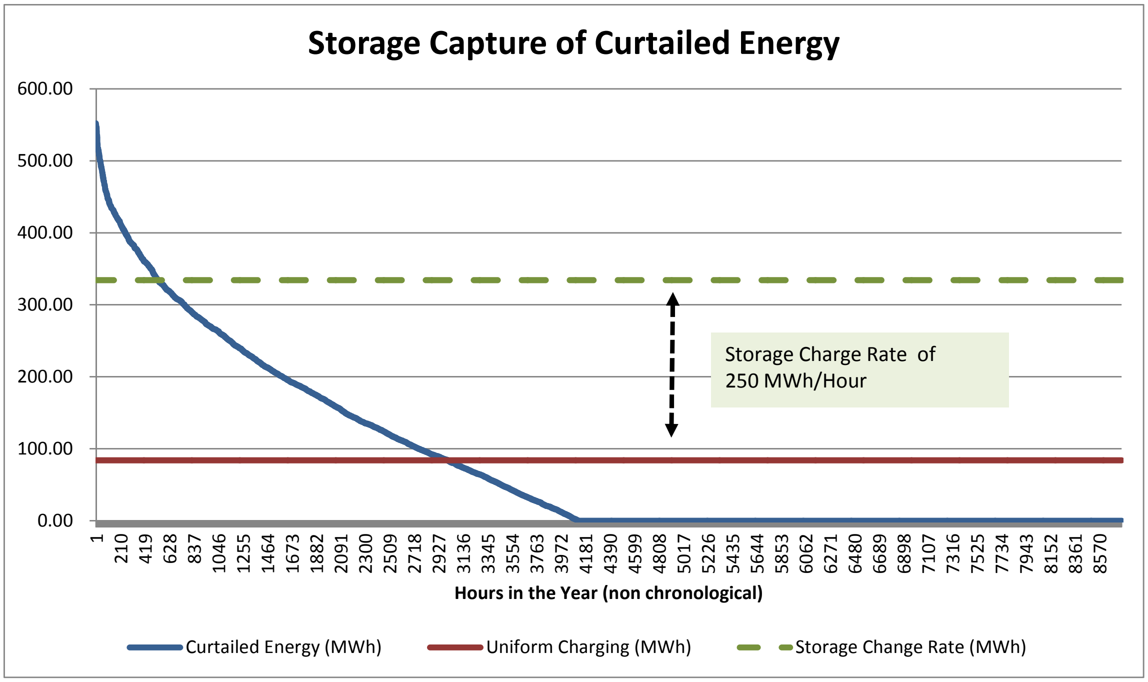


Figure 15

Results of analysis of numerous scenarios are summarized in Tables 6 through 8. Observations include:

- Larger storage size enables higher utilization of otherwise curtailed energy;
- Larger storage size reduces amount of additional thermal energy required for EV charging; and
- Even larger storage (10,000 MWh) will be exhausted several times during the year (see Figure 16).

Table 6: Impact of Storage Size with 100% Charging Level

Storage Size (MWh)	Max Charge/ Discharge (MW)	Units	EV Charging From Renewable Energy (MWh)	EV Charging From Thermal Energy (MWh)	Total EV Charging Energy (MWh)	Used Curtailed Energy (MWh)	Unused Curtailed Energy (MWh)	Total Curtailed Energy (MWh)
0	0	(MWh)	339,298	396,364	735,662	339,298	396,364	735,662
1,000	250	(MWh)	402,203	333,459	735,662	403,203	332,459	735,662
2,000	500	(MWh)	422,474	313,188	735,662	424,474	311,188	735,662
4,000	1,000	(MWh)	450,575	285,086	735,662	454,575	281,086	735,662
6,000	1,500	(MWh)	471,803	263,859	735,662	477,803	257,859	735,662
8,000	2,000	(MWh)	489,803	245,859	735,662	497,803	237,859	735,662
10,000	2,500	(MWh)	507,803	227,859	735,662	517,803	217,859	735,662
0	0	% of Total	46.1%	53.9%	100.0%	46.1%	53.9%	100.0%
1,000	250	% of Total	54.7%	45.3%	100.0%	54.8%	45.2%	100.0%
2,000	500	% of Total	57.4%	42.6%	100.0%	57.7%	42.3%	100.0%
4,000	1,000	% of Total	61.2%	38.8%	100.0%	61.8%	38.2%	100.0%
6,000	1,500	% of Total	64.1%	35.9%	100.0%	64.9%	35.1%	100.0%
8,000	2,000	% of Total	66.6%	33.4%	100.0%	67.7%	32.3%	100.0%
10,000	2,500	% of Total	69.0%	31.0%	100.0%	70.4%	29.6%	100.0%

Table 7: Impact of Storage Size with 50% Charging Level

Storage Size (MWh)	Max Charge/ Discharge (MW)	Units	EV Charging From Renewable Energy (MWh)	EV Charging From Thermal Energy (MWh)	Total EV Charging Energy (MWh)	Used Curtailed Energy (MWh)	Unused Curtailed Energy (MWh)	Total Curtailed Energy (MWh)
0	0	(MWh)	185,559	182,272	367,831	185,559	550,103	735,662
1,000	250	(MWh)	247,583	120,248	367,831	248,583	487,079	735,662
2,000	500	(MWh)	272,336	95,495	367,831	274,336	461,326	735,662
4,000	1,000	(MWh)	296,829	71,002	367,831	300,829	434,832	735,662
6,000	1,500	(MWh)	313,380	54,451	367,831	319,380	416,281	735,662
8,000	2,000	(MWh)	327,380	40,451	367,831	335,380	400,281	735,662
10,000	2,500	(MWh)	341,380	26,451	367,831	351,380	384,281	735,662
0	0	% of Total	50.4%	49.6%	100.0%	25.2%	74.8%	100.0%
1,000	250	% of Total	67.3%	32.7%	100.0%	33.8%	66.2%	100.0%
2,000	500	% of Total	74.0%	26.0%	100.0%	37.3%	62.7%	100.0%
4,000	1,000	% of Total	80.7%	19.3%	100.0%	40.9%	59.1%	100.0%
6,000	1,500	% of Total	85.2%	14.8%	100.0%	43.4%	56.6%	100.0%
8,000	2,000	% of Total	89.0%	11.0%	100.0%	45.6%	54.4%	100.0%
10,000	2,500	% of Total	92.8%	7.2%	100.0%	47.8%	52.2%	100.0%

Table 8: Impact of Storage Size with 200% Charging Level

Storage Size (MWh)	Max Charge/ Discharge (MW)	Units	EV Charging From Renewable Energy (MWh)	EV Charging From Thermal Energy (MWh)	Total EV Charging Energy (MWh)	Used Curtailed Energy (MWh)	Unused Curtailed Energy (MWh)	Total Curtailed Energy (MWh)
0	0	(MWh)	553,929	917,394	1,471,323	553,929	181,733	735,662
1,000	250	(MWh)	604,459	866,864	1,471,323	604,459	131,203	735,662
2,000	500	(MWh)	619,628	851,695	1,471,323	619,673	115,989	735,662
4,000	1,000	(MWh)	637,363	833,961	1,471,323	637,407	98,254	735,662
6,000	1,500	(MWh)	650,740	820,583	1,471,323	650,785	84,877	735,662
8,000	2,000	(MWh)	660,740	810,583	1,471,323	660,785	74,877	735,662
10,000	2,500	(MWh)	669,308	802,015	1,471,323	670,785	64,877	735,662
0	0	% of Total	37.6%	62.4%	100.0%	75.3%	24.7%	100.0%
1,000	250	% of Total	41.1%	58.9%	100.0%	82.2%	17.8%	100.0%
2,000	500	% of Total	42.1%	57.9%	100.0%	84.2%	15.8%	100.0%
4,000	1,000	% of Total	43.3%	56.7%	100.0%	86.6%	13.4%	100.0%
6,000	1,500	% of Total	44.2%	55.8%	100.0%	88.5%	11.5%	100.0%
8,000	2,000	% of Total	44.9%	55.1%	100.0%	89.8%	10.2%	100.0%
10,000	2,500	% of Total	45.5%	54.5%	100.0%	91.2%	8.8%	100.0%

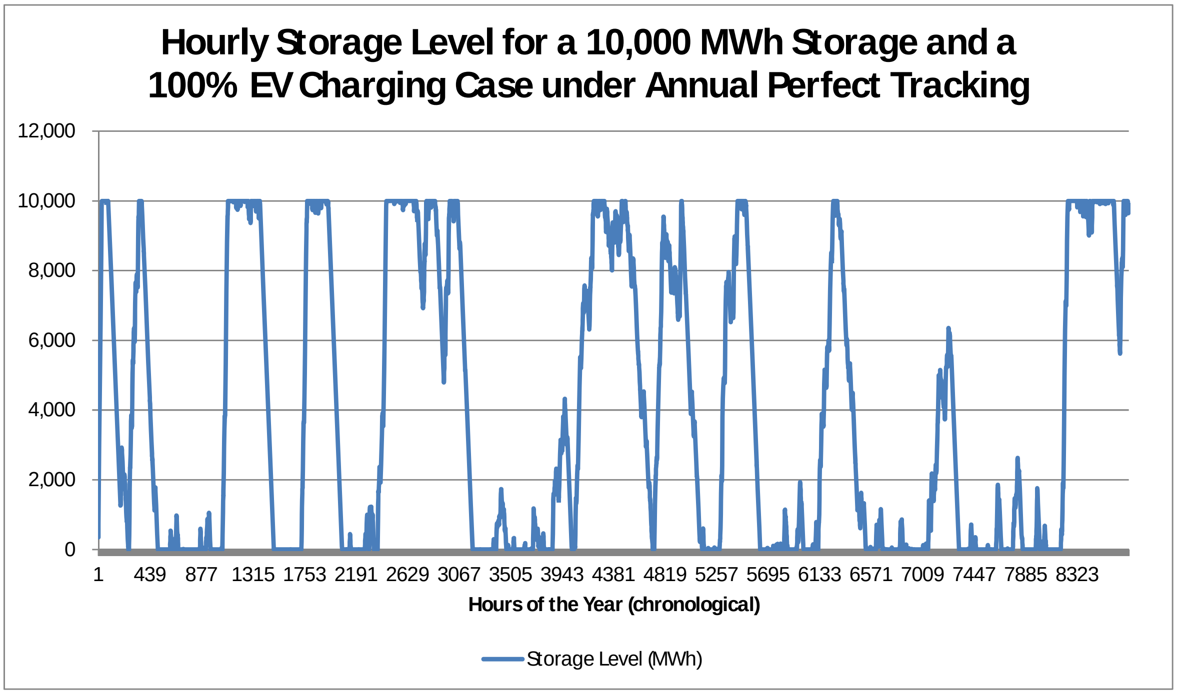


Figure 16

Question: But why we still not able to capture all of the Curtailed Energy in the Storage?

Figure 17 shows the primary reason appears to be the fact that some days have clustering of many hours of high curtailed energy, resulting in filling up of storage to the limit. There are also days with very little Curtailed Energy.

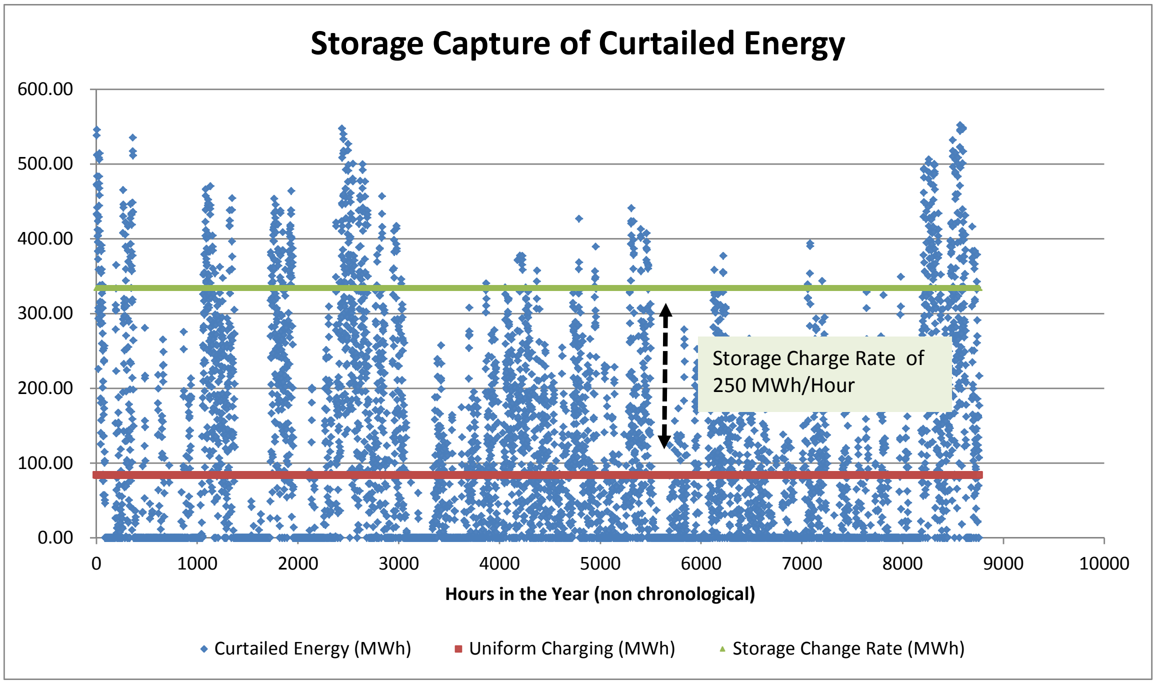


Figure 17

Seasonality

The following charts demonstrate the seasonality of load and wind patterns.

Key observations include:

- Daily load shapes appear similar though magnitude of load changes month to month (Figure 18);
- There is little variation from month to month with normalized results normalized to the daily average load of 84 MWh/day (Figure 19);
- There appears to be minimal seasonal or monthly variations in diurnal curtailed energy patterns; and
- By definition, the Annual Perfect Tracking scenario matches perfectly the annual curtailed energy profile. Profile 2, the more realistic scenario, tracks very well (Figure 20).

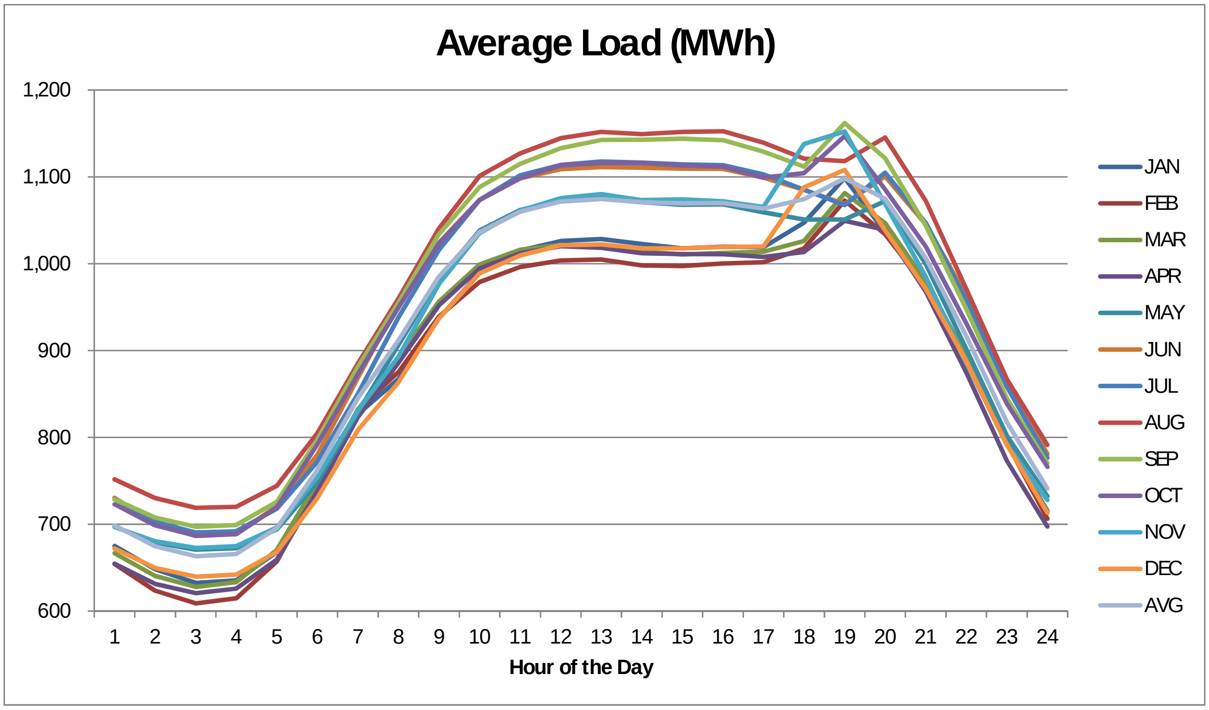


Figure 18

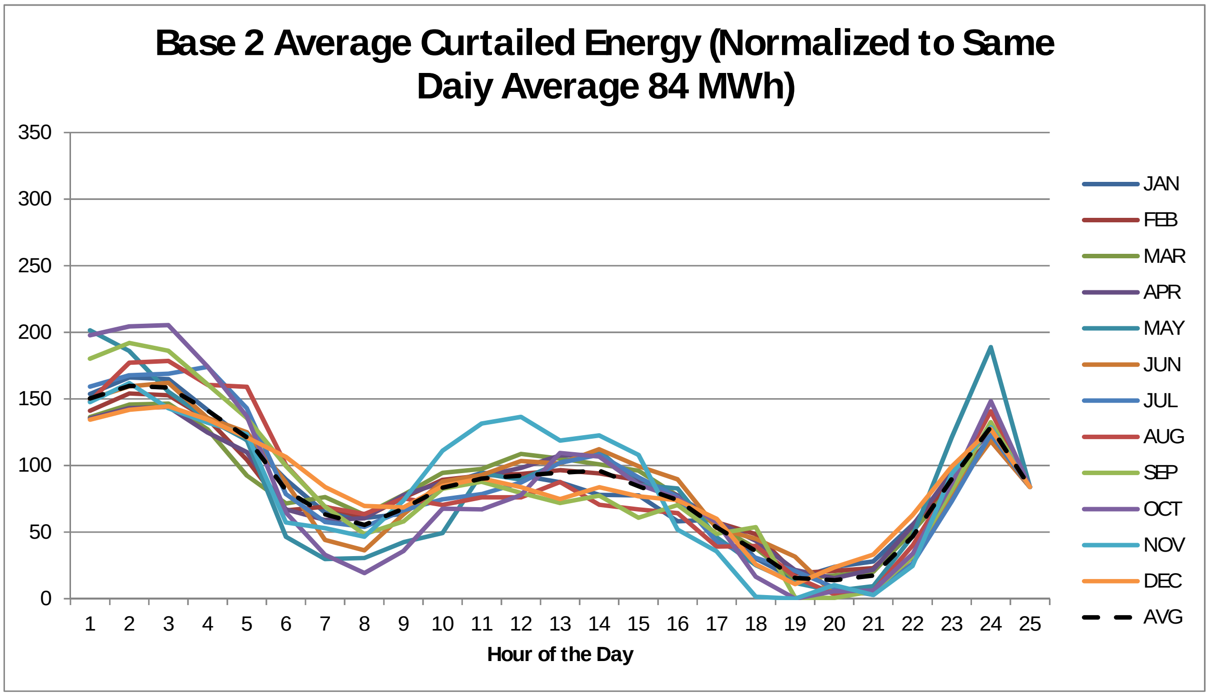
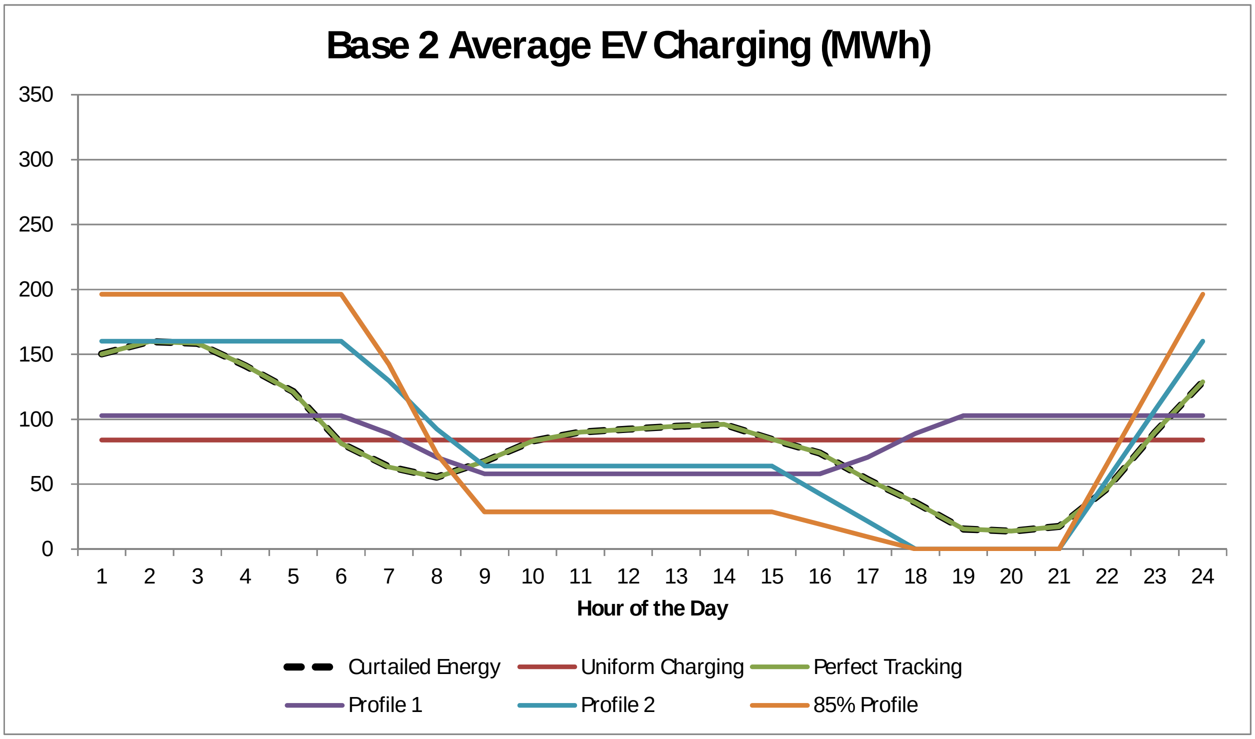


Figure 19



Base 2 Average EV Charging (MWh)
350
300
250
200
150
100
50
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
Hour of the Day
Curtailed Energy
Uniform Charging
Perfect Tracking
Profile 1
Profile 2
85% Profile

Figure 20