

Feasibility of Using Smart Electric Vehicle Charging to Balance Intermittency in Renewable Energy

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Abstract

The intermittency that characterizes most renewable energy generation, specifically wind and solar power, must be balanced either through energy storage or variable “smart” loads that can adjust their energy demand based on available supply. This study examines the potential use of electric vehicle (EV) batteries as a smart load to balance out hourly wind energy fluctuations on a national scale in the United States in the year 2050. The findings are supportive of the idea that, given the projected magnitude of EV battery storage and the sustained length of time EVs will likely be plugged in, smart EV charging can effectively lower the variation in wind energy supply over the course of a year.

Introduction

The electric grid requires energy supply to exactly match demand at every moment. Excess generated electricity is wasted if sufficient storage is not present, and insufficient generated electricity causes more expensive peaking generation sources to be used, and in worst-case scenarios, blackouts. The constant balancing of supply and demand was a simpler process when the controllable, fossil fuel-driven supply sources of the past, namely coal and natural gas, could be ramped up or down to match the relatively predictable energy demand curve. However, the growing prominence of renewable energy sources whose energy output depends on variable and (obviously) uncontrollable weather patterns, such as wind and solar, means that utilities can no longer count on the ability to simply manipulate supply to match demand.

Without the ability to precisely control power supply, three options exist for matching demand. Power can be vastly over-generated, so that even when renewable output is low, it is still sufficient to meet demand. This option would require extremely significant financial and land resources, and would likely increase the cost of electricity greatly. Another option would be to build enough large-scale energy storage facilities to take advantage of all the time where generation exceeds demand. While likely cheaper than the first option, implementing storage at such a large scale would still be very costly, and of course would involve some losses in power due to efficiency limitations. The third option would be to expand the utilization of dynamic “smart” loads that strategically draw energy from the grid when it is most available (and therefore cheaper, assuming smart pricing is in effect). Instead of the expensive infrastructure upgrades to match supply to demand that characterize the first two options, the use of smart loads matches demand to supply. This option provides customers with the cheapest possible power both in the immediate context of smart energy pricing rates, and in the expanded context of cheaper rate structures overall due to fewer costly infrastructure demands on the utilities.

EV Batteries (as Smart Load) and Wind Power (as Intermittent Supply)

While the use of smart loads to match demand to supply is an economical and efficient strategy to incorporate increasing amounts of intermittent energy sources (as discussed in the previous section), not every load can be easily converted to a smart load. For example, most energy customers will likely not be willing to wait for the ideal energy supply/demand ratio to heat up leftovers in the microwave. An ideal smart load should not be a load that customers need to use for short and sporadic amounts of time, such as a microwave. Rather, ideal smart loads should be running or charging “in the background” for an extended period of time, so that their energy-use behavior can be modified without significant impact on the customer’s life. For example, smart home thermostats can shift their power usage to more optimally utilize cheaper electricity while still keeping the home within a certain temperature range.

Likewise, EV batteries that are connected to a charger overnight can selectively draw power from the grid when it is most affordable/abundant while still providing a certain level of charge by the morning. EV batteries also have the benefits of being prevalent (by 2050), geographically distributed roughly according to population, and featuring a relatively large energy capacity (enabling a significant impact on the overall demand curve). While other smart loads exist, such as smart home thermostats, EV batteries will be examined as the smart load in this simulation.

In the same way that EV batteries are not the only load, or even the only smart load, wind power is not the only source of energy, or even the only intermittent source of energy. However, wind and solar power are projected to be the largest two forms of intermittent energy by 2050 under a 100% renewable energy scenario⁷, and since solar obviously provides no power for about half of the 24-hour day, only wind power will be examined in this simulation. By examining the effects of smart EV battery charging (one type of smart load) on wind energy supply (one type of intermittent energy source), insights can be formed into the general relationship between smart loads and intermittent energy supplies.

Premise & Parameters of MATLAB Simulation

In order to determine whether smart EV charging could effectively reduce variation in intermittent wind power, a MATLAB simulation is carried out. In this simulation, two independent factors are explored, which are charging method and the proportion of customers who opt-in to being ok with an 80% battery charge. The five different charging methods examined consist of “ASAP,” meaning the batteries are charged as soon as possible once plugged in, and four thresholds (50/75% of the mean monthly/yearly wind power generation) where the batteries will only charge if the hourly wind power supply is greater than the given threshold. The two different proportions of customers who opt-in to being ok with 80% battery charge are 40% and 75%. These proportions are fairly arbitrary, but are meant to show the effect that differing amounts of needed charge will have on the simulation results.

The primary outcome examined by the simulation is the effect of the smart EV battery charging on the standard deviation of the resulting hourly wind power. The proportion of charging periods in which all EVs are adequately charged is also considered, although this proportion is only used to show the relative differences between different charging thresholds and not overall effectiveness of the smart charging technique, since other power sources and loads would be present in the real world, and the magnitude of charging EVs and available wind supply are based upon rough projections to 2050 (as will be discussed shortly).

The simulation occurs over the course of one year. The simulated year is the year 2050, which is chosen based on the presence of US wind energy capacity projections for the year 2050 based on a complete renewable energy scenario⁷, and the fact that EVs are expected to be the dominant type of vehicle by 2050.⁵ The wind capacity projections are necessary because the hourly wind energy supply curve (for the year 2050) in the simulation is based off of a capacity-scaled version of the 2019 hourly wind energy curve.^{4,6}

In order for the simulation to be run, several assumptions have to be made. The duration of the plugged-in charging period for the EVs is assumed to be 10 hours (the assumed context is that the EV is charging at the user's home). The average battery initial charge (when first plugged in) is set to be 50%. The average battery capacity is assumed to be 100 kilowatt-hours (kWh), which is on the higher-end of EV battery capacities today.⁵ The average home charging rate is assumed to be 11 kilowatts (kW), which is the average of a Tier II EV charger (fast EV home chargers) today.³ The total number of EVs equipped with smart chargers is assumed to be 161.6 million, which represents the vehicles of all homeownership households in 2050 based on 2050 projected US homeownership rate² and population¹ with a constant number of vehicles⁹ and people⁸ per household. The vehicles of non-homeowning households (such as apartment-dwellers) are not considered, since long-duration Tier II charging would likely be easier on one's own property compared to a street or parking lot (although it is certainly possible that by 2050, infrastructure for charging in these locations will exist). Finally, the proportion of actively charging EVs per 10-hour period is assumed to be half of all smart charger-equipped EVs (80.8 million).

Basic MATLAB Simulation Process

As mentioned in the previous section, a charging period consists of 10 hours. Charging periods in the simulation are offset by 1 hour (so 9 of their hours overlap), but each is considered with the same number of EVs independent of each other. This method was chosen to better simulate the real-world, in which EVs can be plugged in at any time (not exclusively at 10-hour intervals). The fundamental steps of the simulation process are described below.

1. Hourly wind energy is directed to batteries that need 100% charge (did not opt-in to being ok with 80%)
2. If the 80%-opted in batteries have more than 80% charge, they will transfer charge to batteries that need 100% charge (as needed)

3. Hourly wind energy is then directed to batteries that opted-in to 80% charge (will still charge to 100% if possible)
4. Iterates through 10-hour charging period, repeating steps #1-3 each hour
5. Moves on to next 10-hour charging period (1 hour offset) and repeat steps #1-4 until end hour of charging period is hour 8,760 (end of 1 year)

The resulting wind power after each 10-hour interval of EV charging is assigned to the midpoint of the period (for example, hour 5.5 for the first interval from hours 1-10) and divided by 10 hours (the length of the charging period) to represent the average post-charging power during that period. The plots and statistics of the resulting power will be shown and discussed in the following section.

Results

The full numerical results from the simulation are displayed in Table 1 for reference, in which the first three columns represent the independent factors and the final two represent the outcomes. In order to graphically illustrate the data in Table 1, two examples of simulation outputs are included as Figures 1 and 2, which show examples of smart charging above static (proportion of yearly mean power) and dynamic (proportion of monthly mean power) thresholds respectively. From Figures 1 and 2, it is clear that the variation in the output wind power is greatly reduced after EV smart charging is employed, essentially converting wind power into a much more consistent (and less intermittent) power source.

Table 1. MATLAB simulation full numerical results.

| Charging Power Threshold | Monthly Dynamic Threshold? | % Customers Opted-In to 80% Charge | Std. Dev. of Remaining Power (MW) | % Periods Where Charge Adequate |
|--------------------------|----------------------------|------------------------------------|-----------------------------------|---------------------------------|
| Raw Wind Power | | N/A | 274,301 | N/A |
| 0 (ASAP) | No | 40% | 248,648 | 93.9% |
| 50% Mean | No | 40% | 154,068 | 49.9% |
| 50% Mean | Yes | 40% | 159,974 | 50.3% |
| 75% Mean | No | 40% | 119,913 | 25.1% |
| 75% Mean | Yes | 40% | 131,094 | 23.6% |
| 50% Mean | No | 75% | 155,261 | 56.6% |
| 50% Mean | Yes | 75% | 161,275 | 57.5% |
| 75% Mean | No | 75% | 119,501 | 30.5% |
| 75% Mean | Yes | 75% | 130,649 | 29.5% |

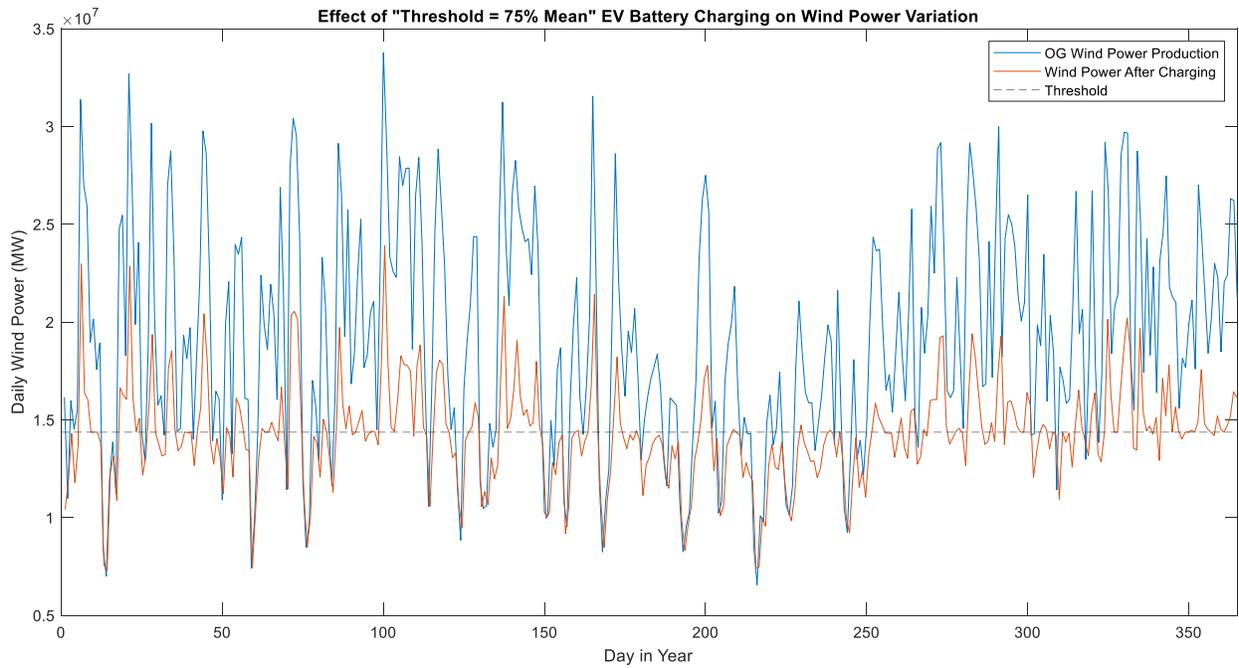


Figure 1. Output power curve before and after EV smart charging above 75% mean static threshold.

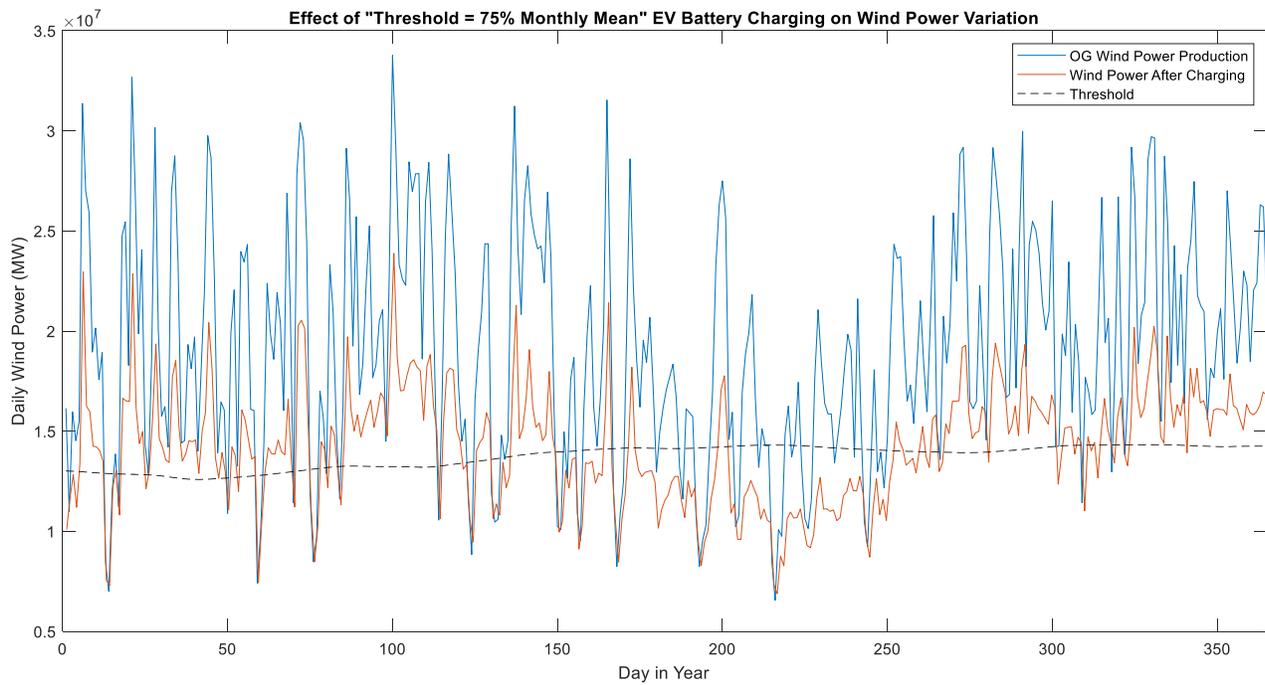


Figure 2. Output power curve before and after EV smart charging above 75% mean dynamic threshold.

While Figures 1 and 2 provide examples of wind power “smoothing” via threshold-dictated smart charging compared to the raw wind power production, Figure 3 provides a comparison between the three threshold values examined (ASAP/no-threshold, 50% mean power, and 75% mean power).

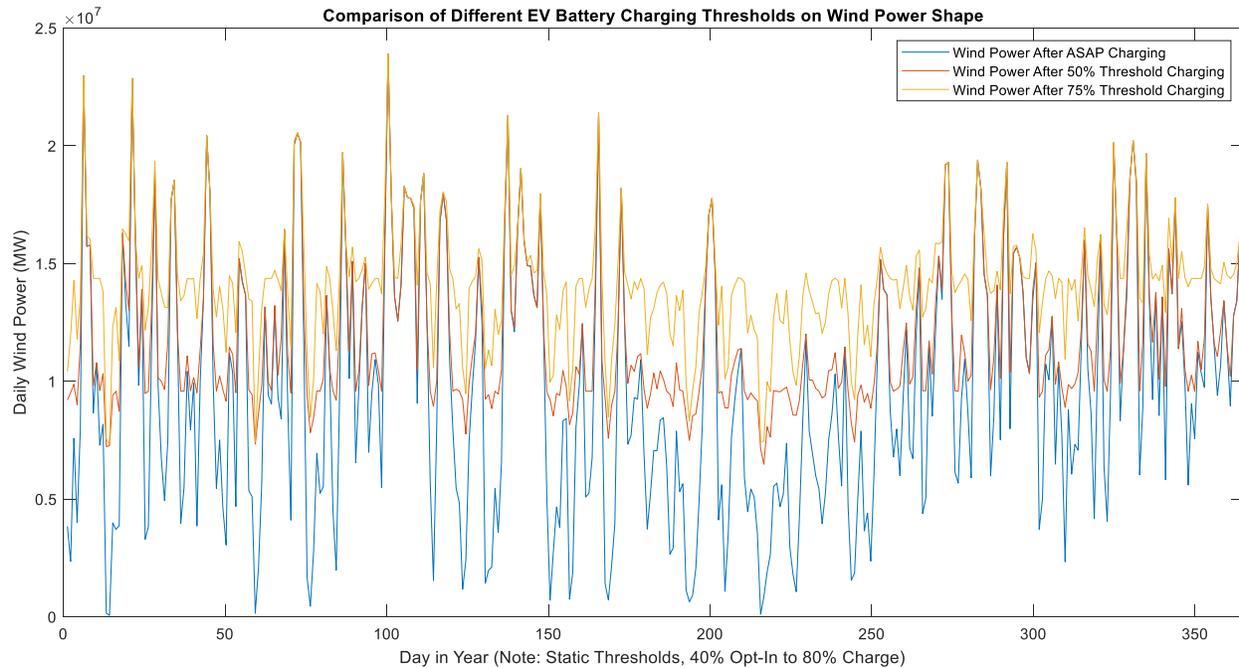


Figure 3. Comparison of output power curves after ASAP charging, 50% mean power threshold charging, and 75% mean power threshold charging.

Based on Figure 3, one can see that the variation in the ASAP-method charging (in blue) is much greater than the variation in the 50% and 75% mean power threshold smart charging (in red and yellow). Figure 4 provides a convenient visualization of the different standard deviations of the three examined charging types shown in Figure 3, as well as the raw power deviation. As indicated by the shape of the curves in Figure 3, Figure 4 confirms that the power variation is least under the highest threshold charging level and grows progressively greater with lower/no threshold levels.

The tradeoff associated with higher charging thresholds and smoother output power is the proportion of charging periods where all EVs receive adequate charge. As Figure 5 indicates, greater charging thresholds correspond to inferior charging outcomes. However, while lower values of charging status are used to illustrate the inherent tradeoff in employing greater charging thresholds, in practice greater power supply would be available since wind power represents only one of many power sources. Therefore, in theory, one could receive the benefits of smart charging power smoothing shown in Figure 4 without suffering the drawbacks illustrated by Figure 5.

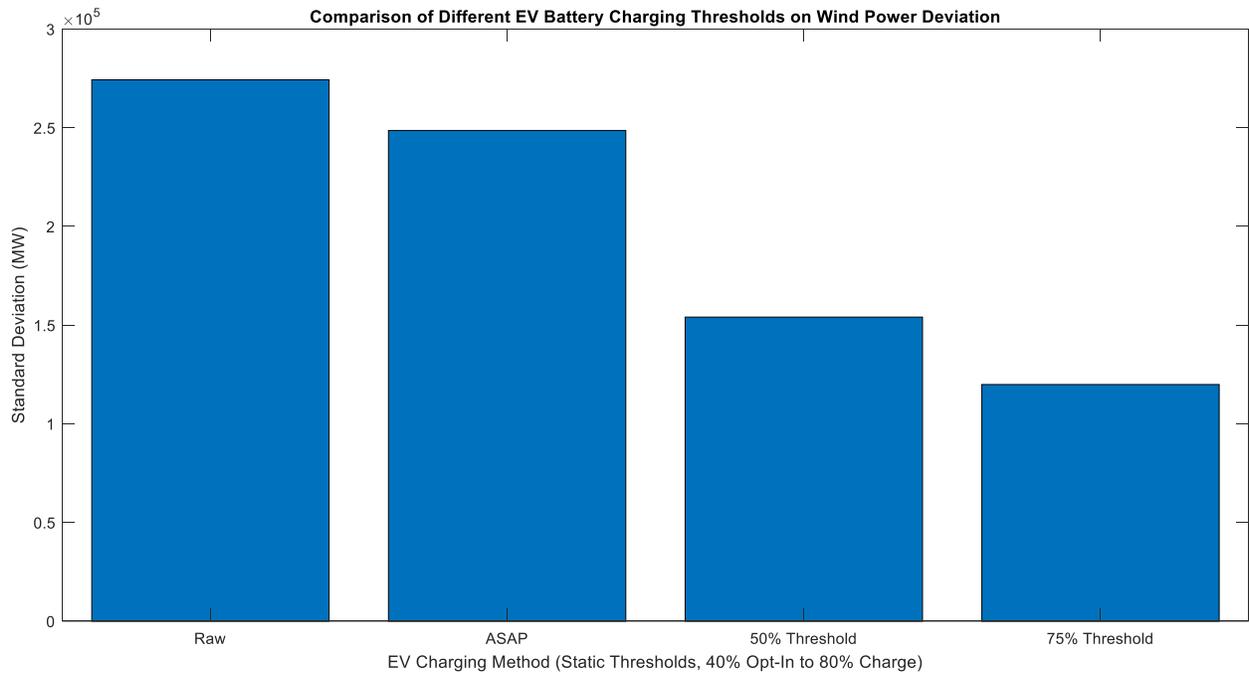


Figure 4. Comparison of output power standard deviation after various charging thresholds and raw power standard deviation.

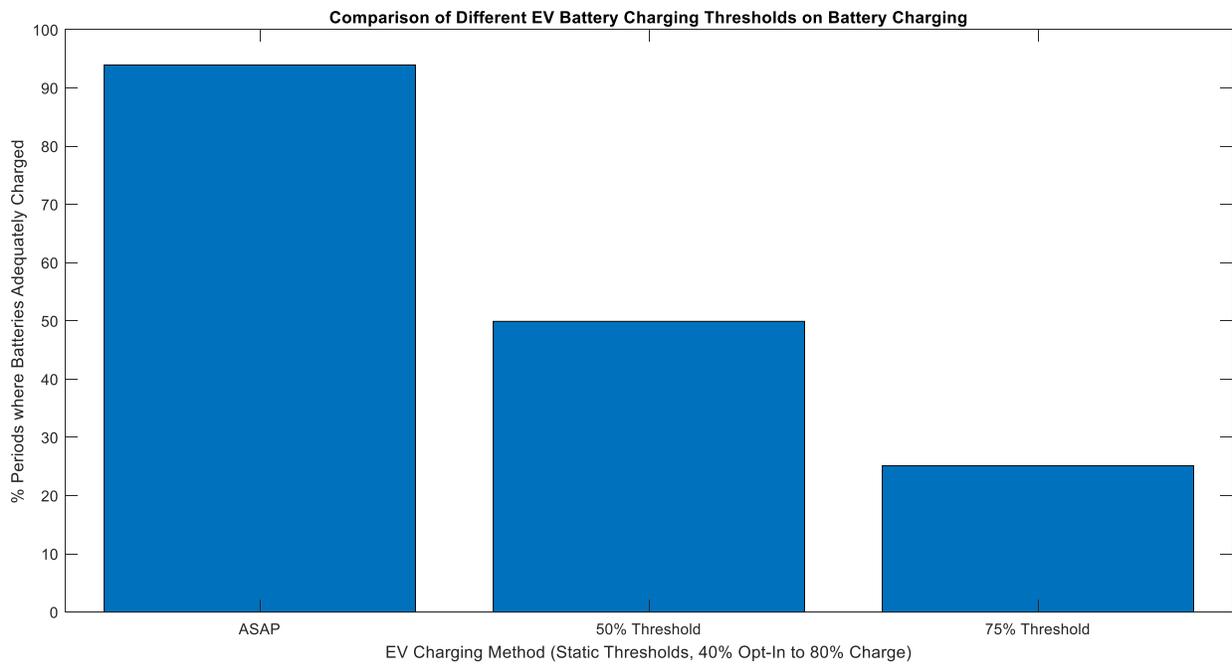


Figure 5. Comparison of adequate charging status after various charging thresholds.

The most significant trends from the simulation results – namely that greater smart charging thresholds correspond to lesser variation in (and hence smoother) output wind power but also lesser achievable charging (with caveats discussed in previous paragraph) – have been illustrated by Figures 1-5 and discussed above. The other two independent factors – proportion of customers who opted-in to being ok with 80% battery charge and dynamic versus static thresholds – both produced less relevant but still significant trends. The proportion of 80% battery charge opt-ins made no significant impact on power variation, but did increase the proportion of adequate charging (as one would expect, given that less charge is required). The dynamic thresholds made no significant impact on achievable charging, but did correspond to slightly greater power variation (it was expected that more localized thresholds would lower variation, but it is possible the monthly window was too large to achieve this desired reduction).

Conclusion

The smart EV charging simulation demonstrates the feasibility of using smart loads to reduce fluctuation in intermittent power supplies. The present advancement of the “smart grid” in the United States is enabling a rising number of utilities to offer real-time dynamic electricity pricing, which incentivizes the development of smart loads, such as smart home thermostats and smart EV charging. The increasing prevalence of these and other smart loads comes at a time when the nation is shifting to an ever-increasing magnitude of intermittent renewable energy sources. Given the delicate supply-load energy balance that must be maintained for the grid to operate, demand-side intermittent power smoothing solutions, such as the smart EV charging examined in this simulation, may be the key to unlocking the era of renewable energy.

References

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- [2] Acolin, Arthur, et al. “A Renter or Homeowner Nation?” 2016.
- [3] “Charging Station Levels.” *Plug-in NC*, 20 Nov. 2020, pluginnc.com/charging-levels/.
- [4] “Existing Capacity by Energy Source, 2019.” *Energy Information Administration*, 2020, www.eia.gov/electricity/annual/html/epa_04_03.html.
- [5] “Global EV Outlook 2020 – Analysis.” *International Energy Agency*, June 2020, www.iea.org/reports/global-ev-outlook-2020.
- [6] “Hourly Electric Grid Monitor.” *U.S. Energy Information Administration (EIA)*, www.eia.gov/beta/electricity/gridmonitor/dashboard/electric_overview/US48/US48.
- [7] Jacobson, Mark Z, et al. “100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for the 50 United States.” *Energy and Environmental Science*, vol. 8, 27 May 2015, pp. 2093–2117., doi:10.1039/c5ee01283j.
- [8] “QuickFacts - United States.” *United States Census Bureau*, 2020, www.census.gov/quickfacts/fact/table/US/HSD410219.
- [9] Wagner, I. “Number Cars per Household in the U.S.” *Statista*, 4 Mar. 2021, www.statista.com/statistics/551403/number-of-vehicles-per-household-in-the-united-states/#:~:text=On%20average%2C%20there%20are%201.88%20vehicles%20per%20U.S.%20household.

Appendix (MATLAB Simulation Code)

```

%% Energy Storage Project: Balancing Variation in Wind Power with Smart EV Battery
Charging
clear
clc

%% Import Hourly Wind Power
Wind = csvread('498_Proj_Data.csv',1,7,[1 7 8760 7]); %(filename,R1,C1,[R1 C1 R2 C2])
% MWh

AvgWind = mean(Wind); % Used for 2nd part to set "baseline"

DailyWind = zeros(365,1);
for Day = 1:365
    for Hour = 1:24
        DailyWind(Day) = DailyWind(Day) + Wind((Day-1)*24 + Hour);
    end
end

% Avg Battery capacity: 100 kWh (BUT assuming avg 50% charged when plugged in - 50
kWh)
% Avg Charging Rate: 3-19 kW (start w 11 kW)
% Buy in from 161.6E6 vehicles [BUT 50% of bought-in vehicles charging at
% given time so (161.6E6)*0.5]
BattCap100 = 0.6*(0.05*(161.6E6)*0.5); % MWh - 60% of batteries that need 100%
capacity - battery capacity for given 10-hr period
BattCap80 = 0.4*(0.05*(161.6E6)*0.5); % MWh - 40% of batteries that need 80% capacity
- battery capacity for given 10-hr period
BattCap80OG = 0.4*(0.05*(161.6E6)*0.5); % Unchanging val to check if energy donation
conditions met

MaxChargeRateTot = .011*(161.6E6)*0.5; % MW - max charge rate for given 10-hr period
MaxChargeRate100 = .6*MaxChargeRateTot;
MaxChargeRate80 = .4*MaxChargeRateTot;

ASAPArray = zeros(8751, 3); % Initialize array for ASAP battery filling method data
Threshold50Array = zeros(8751, 3); % Initialize array for 50% mean Threshold battery
filling method data
Threshold50MonthArray = zeros(8751, 3);

% Examine every 10-hour period in year (1-10,2-11,3-12,...,8751-8760)
for StartHr = 1:8751
    BattCap100 = 0.6*(0.05*(161.6E6)*0.5); % MWh - 60% of batteries that need 100%
capacity - battery capacity for given 10-hr period
    BattCap80 = 0.4*(0.05*(161.6E6)*0.5); % MWh - 40% of batteries that need 80%
capacity - battery capacity for given 10-hr period
    PeriodExcessHourlyWind = 0; % Reset at start of every new 10-hr period

%% 1. ASAP CHARGING
for PeriodHr = StartHr:(StartHr + 9)
    HourlyWind = Wind(PeriodHr); % MW in hour

    % Discard (but save for plot) any hourly wind power exceeding max power
    % charging level [useless for battery charging]
    if HourlyWind > MaxChargeRateTot
        HourlyWindExtra = HourlyWind - MaxChargeRateTot; % Unusable wind energy
        HourlyWind = MaxChargeRateTot;
    else
        HourlyWindExtra = 0;
    end

    % Transfer of power from wind supply to batteries
    % ^Dist energy to all batteries and then draw from 40% category if necessary
    % - 2 GROUPS- 60% that need full and 40% that need 80%

```

```

    %% 1st supplies power to 100% batteries
    if HourlyWind >= MaxChargeRate100 % If hourly wind GREATER than max charge
rate for 100% batteries
        if BattCap100 >= MaxChargeRate100 % If needed 100% battery charge GREATER
than max charge rate for 100% batteries
            BattCap100 = BattCap100 - MaxChargeRate100; % Use max charge rate to
charge 100% batteries
            HourlyWind = HourlyWind - MaxChargeRate100; % Max charge rate deducted
from HourlyWind

            elseif BattCap100 < MaxChargeRate100 % If needed 100% battery charge LESS
than max charge rate for 100% batteries
                HourlyWind = HourlyWind - BattCap100; % Rest of 100% needed battery
charge deducted from HourlyWind
                BattCap100 = 0; % BattCap100 fully charged
            end

            elseif HourlyWind < MaxChargeRate100 % If hourly wind LESS than max charge
rate for 100% batteries
                if BattCap100 >= HourlyWind % If needed 100% battery charge GREATER than
available wind supply
                    BattCap100 = BattCap100 - HourlyWind; % 100% batteries charged by all
available wind supply
                    % Note: HourlyWind reduced to 0 below (val needed for
                    % donation rate below so not yet set to 0)

                    %% Charge 100% batteries from 80% if 80% has surplus (up to
MaxChargeRate100 rate)
                    if BattCap80 < 0.2*BattCap80OG % If needed 80% battery charge is less
than 20% (if above 80% charged)
                        MaxDonationChargeRate = MaxChargeRate100 - HourlyWind; % Max
hourly energy that can be transferred from 80% to 100% batteries
                        DonationSupply = 0.2*BattCap80OG - BattCap80; % Energy available
to donate from 80% batteries

                        if DonationSupply >= MaxDonationChargeRate % If donation supply
GREATER than max charge rate for 100% batteries
                            if BattCap100 >= MaxDonationChargeRate % If needed 100%
battery charge GREATER than max charge rate for 100% batteries
                                BattCap100 = BattCap100 - MaxDonationChargeRate; % Use max
charge rate to charge 100% batteries
                                BattCap80 = BattCap80 + MaxDonationChargeRate; % Max
charge rate deducted from 80% batteries

                                elseif BattCap100 < MaxDonationChargeRate % If needed 100%
battery charge LESS than max charge rate
                                    BattCap80 = BattCap80 + BattCap100; % Rest of 100% needed
battery charge deducted from 80% battery charge
                                    BattCap100 = 0; % BattCap100 fully charged
                                end

                                elseif DonationSupply < MaxDonationChargeRate % If donation supply
LESS than max charge rate for 100% batteries
                                    if BattCap100 >= DonationSupply % If needed 100% battery
charge GREATER than available DonationSupply
                                        BattCap100 = BattCap100 - DonationSupply; % 100% batteries
charged by entire DonationSupply
                                        BattCap80 = BattCap80 + DonationSupply; % DonationSupply
completely used and deducted from 80% batteries

                                        elseif BattCap100 < DonationSupply % If needed 100% battery
charge LESS than available DonationSupply
                                            BattCap80 = BattCap80 + BattCap100; % Rest of 100% battery
needed charge deducted from 80% batteries

```



```

else
    BatteriesCharged = 0; % Not all batteries charged :(
end

ASAPArray(StartHr,2) = BatteriesCharged; % Whether all batteries successfully
charged (1= yes, 0 = no)

ASAPArray(StartHr,3) = PeriodExcessHourlyWind; % Wind energy left over after
charging
end

%% ASAP Plotting
StartHours = linspace(1,8751,8751);
MidHoursASAP = ASAPArray(StartHours,1);
ChargedStatusASAP = ASAPArray(StartHours,2);
ExcessWindASAP = ASAPArray(StartHours,3)/10; % Excess wind per 10-hr period (must
divide by 10 to get excess wind hourly avg)

DailyExcessWindASAP = zeros(364,1);
for Day = 1:364
    for Hour = 1:24
        DailyExcessWindASAP(Day) = DailyExcessWindASAP(Day) + ExcessWindASAP((Day-
1)*24 + Hour);
    end
end

figure(1)
plot(MidHoursASAP,ChargedStatusASAP)
xlabel('Hour in Year (mid-period)')
ylabel('Charged Status (1 = All Batteries Adequately Charged)')
title('Complete/Incomplete Battery Charging - ASAP')

ChargedPercentASAP = (sum(ChargedStatusASAP)/8751)*100;

disp(['Annual proportion of 10-hour periods where all batteries adequately charged
(ASAP method): ',num2str(ChargedPercentASAP),'%'])

AllHours = linspace(1,8760,8760);
AllDays = linspace(1,365,365);
MidDays = linspace(1.229, 364.896,364); % Starts on hour 5.5 - Day 1 avg hour is 17.5
(not 12) - shifted by .229

figure(2)
plot(AllDays,DailyWind,MidDays,DailyExcessWindASAP)
legend('OG Wind Daily Power Production','Wind Power After ASAP Charging')
xlabel('Day in Year')
ylabel('Daily Wind Power (MW)')
title('Effect of ASAP EV Battery Charging on Wind Power')
xlim([0 365]);

% ^Plot annual raw hourly wind energy vs wind energy left after #1 and after #2
% (taking sum of wind energy left after each 10-hour period [inc
% discarded energy], dividing it by 10 [for hourly avg], and assigning it
% to middle hour of period [5.5, 6.5, 7.5, etc])

StdDevOG = std(Wind); % Standard deviation of OG wind power
StdDevASAP = std(ExcessWindASAP); % Standard deviation of ASAP battery wind power
disp(['Annual standard deviation of OG wind power: ',num2str(round(StdDevOG),6), '
MW'])
disp(['Annual standard deviation of ASAP-method wind power: ',
num2str(round(StdDevASAP),6), ' MW'])
disp(' ')

```

```

%% 2. STATIC THRESHOLD (50% of yearly avg)
for StartHr = 1:8751
    BattCap100 = 0.6*(0.05*(161.6E6)*0.5); % MWh - 60% of batteries that need 100%
capacity - battery capacity for given 10-hr period
    BattCap80 = 0.4*(0.05*(161.6E6)*0.5); % MWh - 40% of batteries that need 80%
capacity - battery capacity for given 10-hr period
    PeriodExcessHourlyWind = 0; % Reset at start of every new 10-hr period

    Threshold = .5*AvgWind; % Set energy threshold for battery charging

%% Loop thru 10-hour period (Use ONLY energy above preset THRESHOLD)
for PeriodHr = StartHr:(StartHr + 9)
    HourlyWind = Wind(PeriodHr); % MW in hour

    % NOTE: This loop subtracts threshold energy from HourlyWind
    % Discard (but save for plot) any hourly wind power exceeding max power
    % charging level OR UNDER THRESHOLD [useless for battery charging]
    if HourlyWind > (MaxChargeRateTot + Threshold)
        HourlyWindExtra = HourlyWind - MaxChargeRateTot; % Unusable wind energy
(incl THRESHOLD ENERGY)
        HourlyWind = MaxChargeRateTot;

    elseif HourlyWind <= (MaxChargeRateTot + Threshold) && HourlyWind > Threshold
        HourlyWindExtra = Threshold;
        HourlyWind = HourlyWind - Threshold;

    elseif HourlyWind <= Threshold
        HourlyWindExtra = HourlyWind;
        HourlyWind = 0;
    end

    % Transfer of power from wind supply to batteries
    % ^Dist energy to all batteries and then draw from 40% category if necessary
    % - 2 GROUPS- 60% that need full and 40% that need 80%

    %% 1st supplies power to 100% batteries
    if HourlyWind >= MaxChargeRate100 % If hourly wind GREATER than max charge
rate for 100% batteries
        if BattCap100 >= MaxChargeRate100 % If needed 100% battery charge GREATER
than max charge rate for 100% batteries
            BattCap100 = BattCap100 - MaxChargeRate100; % Use max charge rate to
charge 100% batteries
            HourlyWind = HourlyWind - MaxChargeRate100; % Max charge rate deducted
from HourlyWind

            elseif BattCap100 < MaxChargeRate100 % If needed 100% battery charge LESS
than max charge rate for 100% batteries
                HourlyWind = HourlyWind - BattCap100; % Rest of 100% needed battery
charge deducted from HourlyWind
                BattCap100 = 0; % BattCap100 fully charged
            end

            elseif HourlyWind < MaxChargeRate100 % If hourly wind LESS than max charge
rate for 100% batteries
                if BattCap100 >= HourlyWind % If needed 100% battery charge GREATER than
available wind supply
                    BattCap100 = BattCap100 - HourlyWind; % 100% batteries charged by all
available wind supply
                    % Note: HourlyWind reduced to 0 below (val needed for
                    % donation rate below so not yet set to 0)

                    %% Charge 100% batteries from 80% if 80% has surplus (up to
MaxChargeRate100 rate)
                    if BattCap80 < 0.2*BattCap800G % If needed 80% battery charge is less
than 20% (if above 80% charged)

```

```

        MaxDonationChargeRate = MaxChargeRate100 - HourlyWind; % Max
hourly energy that can be transferred from 80% to 100% batteries
        DonationSupply = 0.2*BattCap80OG - BattCap80; % Energy available
to donate from 80% batteries

        if DonationSupply >= MaxDonationChargeRate % If donation supply
GREATER than max charge rate for 100% batteries
            if BattCap100 >= MaxDonationChargeRate % If needed 100%
battery charge GREATER than max charge rate for 100% batteries
                BattCap100 = BattCap100 - MaxDonationChargeRate; % Use max
charge rate to charge 100% batteries
                BattCap80 = BattCap80 + MaxDonationChargeRate; % Max
charge rate deducted from 80% batteries

            elseif BattCap100 < MaxDonationChargeRate % If needed 100%
battery charge LESS than max charge rate
                BattCap80 = BattCap80 + BattCap100; % Rest of 100% needed
battery charge deducted from 80% battery charge
                BattCap100 = 0; % BattCap100 fully charged
            end

        elseif DonationSupply < MaxDonationChargeRate % If donation supply
LESS than max charge rate for 100% batteries
            if BattCap100 >= DonationSupply % If needed 100% battery
charge GREATER than available DonationSupply
                BattCap100 = BattCap100 - DonationSupply; % 100% batteries
charged by entire DonationSupply
                BattCap80 = BattCap80 + DonationSupply; % DonationSupply
completely used and deducted from 80% batteries

            elseif BattCap100 < DonationSupply % If needed 100% battery
charge LESS than available DonationSupply
                BattCap80 = BattCap80 + BattCap100; % Rest of 100% battery
needed charge deducted from 80% batteries
                BattCap100 = 0; % BattCap100 fully charged
            end
        end
    end

    HourlyWind = 0; % Wind supply reduced to 0 (all used on 100%
batteries)

    elseif BattCap100 < HourlyWind % If needed 100% battery charge LESS than
available wind supply
        HourlyWind = HourlyWind - BattCap100; % Rest of 100% battery needed
charge deducted from HourlyWind
        BattCap100 = 0; % BattCap100 fully charged
    end
end

%% 2nd supplies power to 80% batteries
% (Note: will never happen at same time as 80% batteries giving
% power to 100% batteries bc THAT only happens if all hourly wind
% charge going to 100% batteries and still not full [no HourlyWind
% left over])
if HourlyWind >= MaxChargeRate80 % If hourly wind GREATER than max charge rate
for 80% batteries
    if BattCap80 >= MaxChargeRate80 % If needed 80% battery charge GREATER
than max charge rate for 80% batteries
        BattCap80 = BattCap80 - MaxChargeRate80; % Use max charge rate to
charge 80% batteries
        HourlyWind = HourlyWind - MaxChargeRate80; % Max charge rate deducted
from HourlyWind
    end
end

```

```

        elseif BattCap80 < MaxChargeRate80 % If needed 80% battery charge LESS
than max charge rate for 80% batteries
            HourlyWind = HourlyWind - BattCap80; % Rest of 80% needed battery
charge deducted from HourlyWind
            BattCap80 = 0; % BattCap80 fully charged
        end

        elseif HourlyWind < MaxChargeRate80 % If hourly wind LESS than max charge rate
for 80% batteries
            if BattCap80 >= HourlyWind % If needed 80% battery charge GREATER than
available wind supply
                BattCap80 = BattCap80 - HourlyWind; % 80% batteries charged by all
available wind supply

                HourlyWind = 0; % Wind supply reduced to 0 (all used up to partially
charge 80% batteries)

            elseif BattCap80 < HourlyWind % If needed 80% battery charge LESS than
available wind supply
                HourlyWind = HourlyWind - BattCap80; % Rest of 80% battery needed
charge deducted from HourlyWind
                BattCap80 = 0; % BattCap80 fully charged
            end
        end

        PeriodExcessHourlyWind = PeriodExcessHourlyWind + HourlyWind +
HourlyWindExtra;

    end

    %% Record array w 10-hr period info - middle hour (5.5, 6.5, etc), whether battery
% power needs fulfilled (0 or 1), wind energy left
    Threshold50Array(StartHr,1) = StartHr + 4.5; % Middle Hour of that 10-hr period

    if BattCap100 == 0 && BattCap80 <= 0.2*BattCap800G
        BatteriesCharged = 1; % All batteries successfully charged
    else
        BatteriesCharged = 0; % Not all batteries charged :(
    end

    Threshold50Array(StartHr,2) = BatteriesCharged; % Whether all batteries
successfully charged (1= yes, 0 = no)

    Threshold50Array(StartHr,3) = PeriodExcessHourlyWind; % Wind energy left over
after charging

end

%% 50% Mean Threshold Plotting
StartHours = linspace(1,8751,8751);
MidHoursThreshold50 = Threshold50Array(StartHours,1);
ChargedStatusThreshold50 = Threshold50Array(StartHours,2);
ExcessWindThreshold50 = Threshold50Array(StartHours,3)/10; % Excess wind per 10-hr
period (must divide by 10 to get excess wind hourly avg)

DailyExcessWindThreshold50 = zeros(364,1);
for Day = 1:364
    for Hour = 1:24
        DailyExcessWindThreshold50(Day) = DailyExcessWindThreshold50(Day) +
ExcessWindThreshold50((Day-1)*24 + Hour);
    end
end

figure(3)
plot(MidHoursThreshold50,ChargedStatusThreshold50)
xlabel('Hour in Year (mid-period)')

```

```

ylabel('Charged Status (1 = All Batteries Adequately Charged)')
title('Complete/Incomplete Battery Charging - Threshold=50% Mean')

ChargedPercentThreshold50 = (sum(ChargedStatusThreshold50)/8751)*100;

disp(['Annual proportion of 10-hour periods where all batteries adequately charged
("Threshold=50% Mean" method): ',num2str(ChargedPercentThreshold50),'%'])

AllHours = linspace(1,8760,8760);

figure(4) %% PLOTS DAILY VALS
plot(AllDays,DailyWind,MidDays,DailyExcessWindThreshold50)
yline(Threshold*24,'--'); % Note: Power under threshold ONLY when raw wind supply
under threshold
%
%
%           ^Other times it appears to dip under due to
%           taking daily sum (in hourly plot, would never be lower
than threshold except for when supply is)
legend('OG Wind Power Production','Wind Power After Charging','Threshold')
xlabel('Day in Year')
ylabel('Daily Wind Power (MW)')
title('Effect of "Threshold = 50% Mean" EV Battery Charging on Wind Power Variation')
xlim([0 365]);
% ^Plot annual raw hourly wind energy vs wind energy left after #1 and after #2
% (taking sum of wind energy left after each 10-hour period [inc
% discarded energy], dividing it by 10 [for hourly avg], and assigning it
% to middle hour of period [5.5, 6.5, 7.5, etc])

StdDevOG = std(Wind); % Standard deviation of OG wind power
StdDevThreshold50 = std(ExcessWindThreshold50); % Standard deviation of Threshold50
battery wind power
disp(['Annual standard deviation of OG wind power: ',num2str(round(StdDevOG),6),'
MW'])
disp(['Annual standard deviation of "Threshold = 50% Mean"-method wind power: ',
num2str(round(StdDevThreshold50),6),' MW'])
disp(' ')

%% #3: DYNAMIC THRESHOLD (monthly) - 50% of avg of 730 hr around [365 on either side]
- use IF statement- IF start hr = X, Threshold = Y)
% (Except for that, same code as Threshold 50 code above)
for StartHr = 1:8751
    BattCap100 = 0.6*(0.05*(161.6E6)*0.5); % MWh - 60% of batteries that need 100%
capacity - battery capacity for given 10-hr period
    BattCap80 = 0.4*(0.05*(161.6E6)*0.5); % MWh - 40% of batteries that need 80%
capacity - battery capacity for given 10-hr period
    PeriodExcessHourlyWind = 0; % Reset at start of every new 10-hr period

    if StartHr <= 365 % If not late enough for 365 on early side, take avg of 365
ahead plus whatever available on behind-side
        Threshold = .5*mean(Wind(1:(StartHr + 365))); % Set energy threshold for
battery charging

    elseif StartHr > 365 && StartHr <= (8760 - 365) % Takes avg of 365 hr on either
side
        Threshold = .5*mean(Wind((StartHr-365):(StartHr+365)));

    elseif StartHr > (8760 - 365) % If not early enough for 365 on late side, takes
avg of 365 behind plus whatever available in front
        Threshold = .5*mean(Wind((StartHr-365):8760));

    end

%% Loop thru 10-hour period (Use ONLY energy above preset THRESHOLD)

```

```

for PeriodHr = StartHr:(StartHr + 9)
    HourlyWind = Wind(PeriodHr); % MW in hour

    % NOTE: This loop subtracts threshold energy from HourlyWind
    % Discard (but save for plot) any hourly wind power exceeding max power
    % charging level OR UNDER THRESHOLD [useless for battery charging]
    if HourlyWind > (MaxChargeRateTot + Threshold)
        HourlyWindExtra = HourlyWind - MaxChargeRateTot; % Unusable wind energy
        (inc THRESHOLD ENERGY)
        HourlyWind = MaxChargeRateTot;

    elseif HourlyWind <= (MaxChargeRateTot + Threshold) && HourlyWind > Threshold
        HourlyWindExtra = Threshold;
        HourlyWind = HourlyWind - Threshold;

    elseif HourlyWind <= Threshold
        HourlyWindExtra = HourlyWind;
        HourlyWind = 0;
    end

    % Transfer of power from wind supply to batteries
    % ^Dist energy to all batteries and then draw from 40% category if necessary
    % - 2 GROUPS- 60% that need full and 40% that need 80%

    %% 1st supplies power to 100% batteries
    if HourlyWind >= MaxChargeRate100 % If hourly wind GREATER than max charge
rate for 100% batteries
        if BattCap100 >= MaxChargeRate100 % If needed 100% battery charge GREATER
than max charge rate for 100% batteries
            BattCap100 = BattCap100 - MaxChargeRate100; % Use max charge rate to
charge 100% batteries
            HourlyWind = HourlyWind - MaxChargeRate100; % Max charge rate deducted
from HourlyWind

            elseif BattCap100 < MaxChargeRate100 % If needed 100% battery charge LESS
than max charge rate for 100% batteries
                HourlyWind = HourlyWind - BattCap100; % Rest of 100% needed battery
charge deducted from HourlyWind
                BattCap100 = 0; % BattCap100 fully charged
            end

        elseif HourlyWind < MaxChargeRate100 % If hourly wind LESS than max charge
rate for 100% batteries
            if BattCap100 >= HourlyWind % If needed 100% battery charge GREATER than
available wind supply
                BattCap100 = BattCap100 - HourlyWind; % 100% batteries charged by all
available wind supply
                % Note: HourlyWind reduced to 0 below (val needed for
                % donation rate below so not yet set to 0)

                %% Charge 100% batteries from 80% if 80% has surplus (up to
MaxChargeRate100 rate)
                if BattCap80 < 0.2*BattCap80OG % If needed 80% battery charge is less
than 20% (if above 80% charged)
                    MaxDonationChargeRate = MaxChargeRate100 - HourlyWind; % Max
hourly energy that can be transferred from 80% to 100% batteries
                    DonationSupply = 0.2*BattCap80OG - BattCap80; % Energy available
to donate from 80% batteries

                    if DonationSupply >= MaxDonationChargeRate % If donation supply
GREATER than max charge rate for 100% batteries
                        if BattCap100 >= MaxDonationChargeRate % If needed 100%
battery charge GREATER than max charge rate for 100% batteries
                            BattCap100 = BattCap100 - MaxDonationChargeRate; % Use max
charge rate to charge 100% batteries

```

```

        BattCap80 = BattCap80 + MaxDonationChargeRate; % Max
charge rate deducted from 80% batteries

        elseif BattCap100 < MaxDonationChargeRate % If needed 100%
battery charge LESS than max charge rate
            BattCap80 = BattCap80 + BattCap100; % Rest of 100% needed
battery charge deducted from 80% battery charge
            BattCap100 = 0; % BattCap100 fully charged
        end

        elseif DonationSupply < MaxDonationChargeRate % If donation supply
LESS than max charge rate for 100% batteries
            if BattCap100 >= DonationSupply % If needed 100% battery
charge GREATER than available DonationSupply
                BattCap100 = BattCap100 - DonationSupply; % 100% batteries
charged by entire DonationSupply
                BattCap80 = BattCap80 + DonationSupply; % DonationSupply
completely used and deducted from 80% batteries

                elseif BattCap100 < DonationSupply % If needed 100% battery
charge LESS than available DonationSupply
                    BattCap80 = BattCap80 + BattCap100; % Rest of 100% battery
needed charge deducted from 80% batteries
                    BattCap100 = 0; % BattCap100 fully charged
                end
            end
        end

        HourlyWind = 0; % Wind supply reduced to 0 (all used on 100%
batteries)

        elseif BattCap100 < HourlyWind % If needed 100% battery charge LESS than
available wind supply
            HourlyWind = HourlyWind - BattCap100; % Rest of 100% battery needed
charge deducted from HourlyWind
            BattCap100 = 0; % BattCap100 fully charged
        end
    end

    %% 2nd supplies power to 80% batteries
    % (Note: will never happen at same time as 80% batteries giving
    % power to 100% batteries bc THAT only happens if all hourly wind
    % charge going to 100% batteries and still not full [no HourlyWind
    % left over])
    if HourlyWind >= MaxChargeRate80 % If hourly wind GREATER than max charge rate
for 80% batteries
        if BattCap80 >= MaxChargeRate80 % If needed 80% battery charge GREATER
than max charge rate for 80% batteries
            BattCap80 = BattCap80 - MaxChargeRate80; % Use max charge rate to
charge 80% batteries
            HourlyWind = HourlyWind - MaxChargeRate80; % Max charge rate deducted
from HourlyWind

            elseif BattCap80 < MaxChargeRate80 % If needed 80% battery charge LESS
than max charge rate for 80% batteries
                HourlyWind = HourlyWind - BattCap80; % Rest of 80% needed battery
charge deducted from HourlyWind
                BattCap80 = 0; % BattCap80 fully charged
            end

            elseif HourlyWind < MaxChargeRate80 % If hourly wind LESS than max charge rate
for 80% batteries
                if BattCap80 >= HourlyWind % If needed 80% battery charge GREATER than
available wind supply

```

```

        BattCap80 = BattCap80 - HourlyWind; % 80% batteries charged by all
available wind supply

        HourlyWind = 0; % Wind supply reduced to 0 (all used up to partially
charge 80% batteries)

        elseif BattCap80 < HourlyWind % If needed 80% battery charge LESS than
available wind supply
            HourlyWind = HourlyWind - BattCap80; % Rest of 80% battery needed
charge deducted from HourlyWind
            BattCap80 = 0; % BattCap80 fully charged
        end
    end

    PeriodExcessHourlyWind = PeriodExcessHourlyWind + HourlyWind +
HourlyWindExtra;

    end

    %% Record array w 10-hr period info - middle hour (5.5, 6.5, etc), whether battery
% power needs fulfilled (0 or 1), wind energy left
    Threshold50MonthArray(StartHr,1) = StartHr + 4.5; % Middle Hour of that 10-hr
period

    if BattCap100 == 0 && BattCap80 <= 0.2*BattCap800G
        BatteriesCharged = 1; % All batteries successfully charged
    else
        BatteriesCharged = 0; % Not all batteries charged :(
    end

    Threshold50MonthArray(StartHr,2) = BatteriesCharged; % Whether all batteries
successfully charged (1= yes, 0 = no)

    Threshold50MonthArray(StartHr,3) = PeriodExcessHourlyWind; % Wind energy left over
after charging

    DynamicThresholdArray(StartHr) = Threshold; % Creates array for (changing)
threshold so can plot

end

%% 50% Monthly Mean Threshold Plotting
StartHours = linspace(1,8751,8751);
MidHoursThreshold50Month = Threshold50MonthArray(StartHours,1);
ChargedStatusThreshold50Month = Threshold50MonthArray(StartHours,2);
ExcessWindThreshold50Month = Threshold50MonthArray(StartHours,3)/10; % Excess wind per
10-hr period (must divide by 10 to get excess wind hourly avg)

DailyExcessWindThreshold50Month = zeros(364,1);
for Day = 1:364
    for Hour = 1:24
        DailyExcessWindThreshold50Month(Day) = DailyExcessWindThreshold50Month(Day) +
ExcessWindThreshold50Month((Day-1)*24 + Hour);
    end
end

figure(5)
plot(MidHoursThreshold50Month,ChargedStatusThreshold50Month)
xlabel('Hour in Year (mid-period)')
ylabel('Charged Status (1 = All Batteries Adequately Charged)')
title('Complete/Incomplete Battery Charging - Threshold=50% Monthly Mean')

ChargedPercentThreshold50Month = (sum(ChargedStatusThreshold50Month)/8751)*100;

disp(['Annual proportion of 10-hour periods where all batteries adequately charged
("Threshold=50% Monthly Mean" method): ',num2str(ChargedPercentThreshold50Month),'%'])

```

```

AllHours = linspace(1,8760,8760);
PeriodHours = linspace(1,8751,8751);

figure(6) %% PLOTS DAILY VALS
plot(AllDays,DailyWind,MidDays,DailyExcessWindThreshold50Month,PeriodHours,DynamicThresholdArray*24,'k--')
% Note: Power under threshold ONLY when raw wind supply under threshold
%           ^Other times it appears to dip under due to
%           taking daily sum (in hourly plot, would never be lower
than threshold except for when supply is)
legend('OG Wind Power Production','Wind Power After Charging','Threshold')
xlabel('Day in Year')
ylabel('Daily Wind Power (MW)')
title('Effect of "Threshold = 50% Monthly Mean" EV Battery Charging on Wind Power
Variation')
xlim([0 365]);
% ^Plot annual raw hourly wind energy vs wind energy left after #1 and after #2
% (taking sum of wind energy left after each 10-hour period [inc
% discarded energy], dividing it by 10 [for hourly avg], and assigning it
% to middle hour of period [5.5, 6.5, 7.5, etc])

StdDevOG = std(Wind); % Standard deviation of OG wind power
StdDevThreshold50Month = std(ExcessWindThreshold50Month); % Standard deviation of
Threshold50Month battery wind power
disp(['Annual standard deviation of OG wind power: ',num2str(round(StdDevOG),6), '
MW'])
disp(['Annual standard deviation of "Threshold = 50% Monthly Mean"-method wind power:
', num2str(round(StdDevThreshold50Month),6), ' MW'])

```