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APPENDIX D – STATUS OF MODELING BATTERIES FOR CALIFORNIA SINGLE-FAMILY AND MULTIFAMILY RESIDENTIAL CODE COMPLIANCE

D1 Modeling of Residential Battery/PV Systems for Self-Utilization Compliance Credit

Overview

The California Energy Commission added a self-utilization credit for residential battery systems to its residential building energy efficiency standards for 2019. Under these standards, a residential battery paired with an on-site photovoltaic (PV) system would receive fair credit toward the building's Energy Design Rating (EDR) score. Starting with the 2022 standards, multifamily residential buildings are treated differently than single-family residential buildings and use a different approach to determining compliance. Instead of EDR, compliance for multifamily residential buildings is based on Time Dependent Valuation and source energy. This document defines how the CBECC-Res compliance software will produce the battery EDR credit for single-family residential buildings, and how the CBECC compliance software will produce the battery calculations withing the compliance framework for multifamily residential buildings.

Whereas most energy upgrades reduce energy use in a house or multifamily building, battery systems actually increase electricity consumption in exchange for some shaping of the load. A 14-kWh battery, with a 90% round-trip efficiency, that cycles 13 of those kWh 300 times a year, will consume 4.1 MWh of electricity and discharge 3.7 MWh of electricity per annum. But by charging when there is excess PV production and discharging when PV production is low and electricity is expensive, the battery both saves money for the residence and provides value to the electricity system overall. Thus, the single-family EDR self-utilization credit and multifamily compliance credit must account not for energy savings, but for savings in value-of-energy.

Distributed electric storage can provide value to the electricity system overall through load shaping and other behaviors. Bolstering demand during low periods helps to leave efficient power plants running full time and reduces ramping requirements. Reducing peak demand helps in a number of ways, including by allowing expensive peaker plants to remain idle more days of the year. In recent years, a growing electricity contribution from solar generation has resulted in what many in California have termed the duck curve (see Figure 1): a dip in net electric load between the morning and evening peaks. Batteries, by filling in the midday trough and shaving the evening peak, can be part of the remedy for a worsening duck curve.

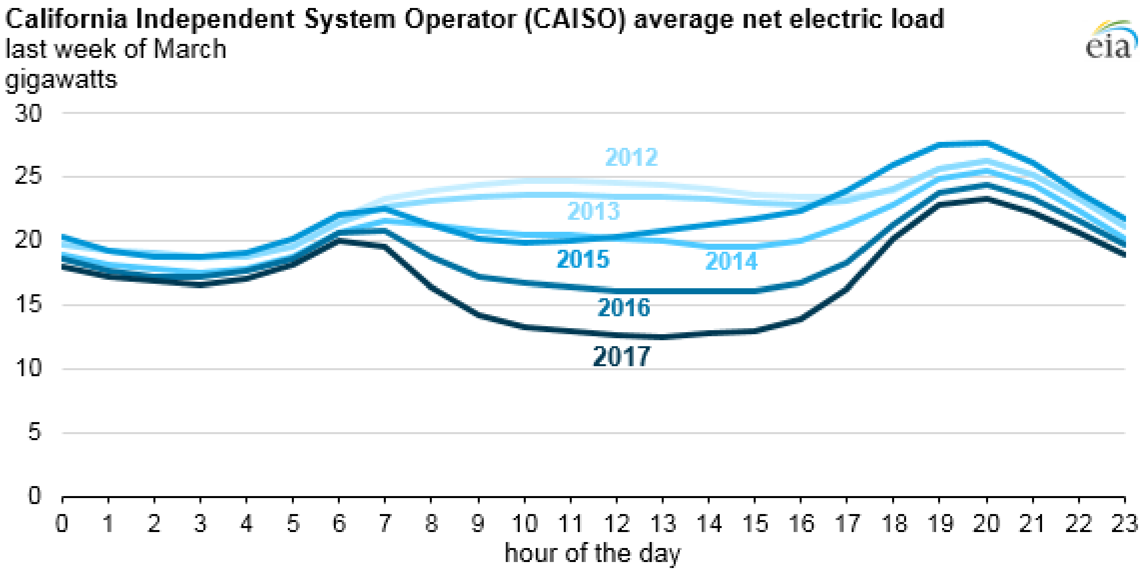

Figure 1: *An illustration of how increasing solar production in recent years has created a trough in net electric load between the morning and evening peaks. (Source: https://www.eia.gov/todayinenergy/detail.php?id=32172.)*

Using building energy code compliance incentives to encourage the adoption of residential batteries can mitigate the impact of the duck curve at the source: more batteries to soak up plentiful midday solar production, more batteries to serve the evening peak and to mitigate the steep ramp in early evening hours when solar production is going down and demand is rising as people turn on appliances in their homes. In addition, having the batteries on-site can help reduce wear-and-tear on distribution systems.

D2 Time Dependent Valuation and Source Energy

The California Title 24 Building Energy Efficiency Standards have utilized a Time Dependent Valuation (TDV) methodology since 2005 to account for the time value of energy for load and for self-generation credit. TDV is a composite measure of the actual cost of energy (for each of electricity, natural gas, and propane) to the utility, customers, and society at large. It has been crafted for evaluating energy efficiency savings based on when those savings manifest. The TDV sources and methods have recently been updated for 2019 (Ming, et al., 2017).

The TDV concept allows even-footing comparison of a set of time-series simulations of how different building designs use energy. Accordingly, it is the mechanism by which the CBECC-Res (for single-family residential) and CBECC (for multifamily residential) compliance software converts a residential battery's load shaping patterns into a self-utilization credit. If a building charges a battery from on-site PV during midday, the simulation foregoes a small TDV credit for power it would have fed to the grid. When the battery discharges in the evening, it can earn a much larger credit for reducing load when TDV is high. That net-TDV reduction counts toward reducing the single-family residential building's design EDR or the multifamily residential building's performance with respect to the compliance margin.

Starting with the 2022 standards, hourly source energy factors are also used to determine compliance for multifamily residential buildings.

D3 Calculating Compliance

For single-family residential buildings, CBECC-Res calculate compliance for a proposed design based on its energy design ratings (EDRs). An EDR is generally calculated as the annual integrated time-dependent value (TDV) of energy (across fuels) of a building relative to a common reference design (based on the 2006 International Energy Conservation Code) (Wilcox, 2017). Accordingly, the EDR is a unitless score, generally between 0 and 100, with a lower score being better.

EDR scores are based on the total annual-TDV of a design relative to the total annual-TDV of the reference design. Annual-TDV is the sum across hours of the net energy used in that hour multiplied by that hour's TDV[1].

$$AnnualTDV = \sum_{hour=1}^{8760} TDV(hour) * load(hour)$$

The EDR for a specific design is (generally) calculated as the ratio of the design's annual-TDV and the reference building's annual-TDV:

$$EDR_{design} = \frac{AnnualTDV_{design}}{AnnualTDV_{reference}}$$

Compliance for a proposed design in CBECC-Res has two requirements:

1. The EDR of the building design, ignoring contributions from renewable generation and battery storage (except for the self-utilization credit described below), must be lower than the EDR of the code prescriptive standard design (also ignoring contributions from renewable generation and battery storage). These EDRs are called the "Efficiency EDR" for the respective proposed and standard designs. The intent of this requirement is to encourage designs that reduce loads in addition to generating energy.

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[1] TDV during hours when there is a net generation (i.e., the load is negative) is adjusted to account for net energy metering rules.

2. The EDR of the final design (including contributions from renewable generation and battery storage) must be lower than the EDR of the code prescriptive standard design (also including contributions from renewable generation and battery storage). These EDRs are called the "Final EDR" for the respective proposed and standard designs.

A minimum of five annual-TDV calculations are required to evaluate the compliance of a specific proposed design:

1. Proposed design "Efficiency" TDV
2. Proposed design "Final" TDV
3. Standard design "Efficiency" TDV
4. Standard design "Final" TDV
5. Reference design TDV (the common denominator in all EDR calculations)

The specific computations that produce the EDR from annual-TDV totals are described in the Single-Family Residential Alternative Compliance Method (ACM) Reference Manual. Because the reference design annual-TDV is used in the calculation of all EDRs, the compliance of a building design can generally be determined when the TDV of the proposed design is lower than the TDV of the standard design, for both the "Efficiency" and "Final" simulations (though this is not strictly the case due to some small adjustment factors used to determine EDR). The standard design is also described in the ACM.

Beginning with the 2022 Energy Code update, code compliance evaluates EDR using two metrics: TDV, and source energy. Similar to TDV, source energy also accounts for hourly variation in how energy is generated and delivered through the grid.

For multifamily residential buildings, CBECC calculates compliance for a proposed design based on its TDV and source energy performance. Two TDV values are calculated by the software for both the proposed and standard design: one value for Total TDV (which accounts for flexibility measures such as PV and battery storage) and one value for Efficiency TDV (which does not account for flexibility measures). Additionally, a total source energy value is calculated for the proposed and standard design (including flexibility measures).

Compliance for a proposed design in CBECC has three requirements:

1. The TDV, ignoring contributions from renewable generation and battery storage (except for the self-utilization credit described below), must be equal or lower than the TDV of the code prescriptive standard design (also ignoring contributions from renewable generation and battery storage). These values are called the "Efficiency TDV" for the respective proposed and standard designs. The intent of this

requirement is to encourage designs that reduce loads in addition to generating energy.

2. The TDV of the final design (including contributions from renewable generation and battery storage) must be equal or lower than the TDV of the code prescriptive standard design (also including contributions from renewable generation and battery storage). These values are called the "Total TDV" for the respective proposed and standard designs.
3. The source energy of the proposed design must be equal or lower than the source energy of the standard design.

A minimum of six annual calculations are required to evaluate the compliance of a specific proposed design:

1. Proposed design "Efficiency" TDV
2. Proposed design "Total" TDV
3. Proposed design source energy
4. Standard design "Efficiency" TDV
5. Standard design "Total" TDV
6. Standard design source energy

The specific computations that produce these values are described in the Nonresidential and Multifamily Alternative Compliance Method (ACM) Reference Manual. The standard design is also described in the ACM.

Self-Utilization Credit

Initially implemented in the 2019 energy code, the self-utilization credit for a residential battery system allows proposed designs with PV systems and batteries (5 kWh or larger) to subtract additional TDV from the "Efficiency" TDV of the proposed design. The self-utilization credit is capped at a fraction of the PV-related TDV of the standard design. The cap varies by climate zone and is between 7% and 14% for a single-family residence and between 2% and 9% for a multi-family building (see Table 1 in Section 2.1.5.5).

The actual credit applied to the "Efficiency" TDV of the proposed design is the lesser of the battery related TDV in the "Final" proposed design and the cap defined above. Effectively, the self-utilization credit allows the proposed "Efficiency" design to also get credit for a portion of the TDV savings that would otherwise be seen only in the "Final" design.

D4 The CBECC-Res, CBECC and CSE Software Packages

Annual building loads used in the annual TDV calculation for single-family buildings in CBECC-Res and for multifamily buildings in CBECC are simulated using the underlying California Simulation Engine (CSE). CSE models the thermal and electrical interactions within a building. CBECC-Res and CBECC generates CSE input files based on the Title 24 rulesets. Separate CSE inputs files are created to simulate the standard design, and proposed design. For single-family buildings the reference design is also created. CBECC-Res then processes the CSE simulation results to determine the Efficiency and Final EDR values as described in the previous section and CBECC processes the CSE simulation results to determine the Efficiency and Final TDV, and source energy values described in the previous section.

While the capability of CBECC-Res and CBECC are intentionally constrained by ruleset definitions, CSE has much greater flexibility to simulate a wide range of building components. CSE has the unique capability to define dynamic battery system control strategy using its built-in expression language. CSE predicts the building load and PV generation and operates the battery according to expressions pre-defined by CBECC-Res and CBECC rules.

D5 Battery Representation in CSE

In each simulated timestep, the control strategy sends a charge/discharge request to the battery module. The control strategies themselves are described in the next section. For now, it will suffice to say that the input to the battery module is a charge request (in kW) that can be either positive or negative.

```
charge_request > 0   // charge
charge_request < 0   // discharge
charge_request = 0   // do nothing
```

The battery has maximum charge and discharge rates (kW) with default values set based on the battery’s size. CBECC-Res and CBECC define both defaults as the same fixed fraction (kW/kWh) of the battery’s user-defined maximum capacity (kWh). These default values may be overridden with custom values by the user.

```
max_charge_power = 0.42 * max_capacity
max_discharge_power = 0.42 * max_capacity
```

And both a charge and discharge efficiency (fraction), which are user-defined:

```
η_charge
η_discharge
```

The user has the option to input a round-trip efficiency (fraction) as an alternative to inputting both the charge and discharge efficiencies. In this case, the charge and discharge efficiency would be equal to:

```
η_charge = sqrt(η_rte)
η_discharge = sqrt(η_rte)
```

At each timestep, there are also maximum charge and discharge limits (kW) defined by the state of charge on the battery. Charge and discharge power levels are measured at the battery's edge: before efficiency losses in the case of charging and after efficiency losses in the case of discharging. The battery's state-of-charge is metered between the two efficiency multipliers.

```
max_charge_available = (max_capacity - charge_level) /
                        η_charge * (timestep_minutes / 60)
max_discharge_available = charge_level * η_discharge *
                        (timestep_minutes / 60)
```

Altogether, that enables the module to determine the amount the battery should charge or discharge in the hour:

```
if charge_request > 0:
    charge_power = min(charge_request, max_charge_rate,
    max_charge_available)
else if charge_request < 0:
    charge_power = max(charge_request, max_discharge_rate,
    max_discharge_available)
else:
    charge_power = 0
```

At the conclusion of that timestep, the battery's charge level will have been updated:

```
if charge_power > 0:  // charging
    charge_level = charge_level + charge_power*η_charge
else if charge_power < 0  // discharging
    charge_level = charge_level + charge_power/η_discharge
else:
    charge_level = charge_level
```

D6 Battery Control Strategies

There are three battery control strategies enabled in CBECC-Res and CBECC: "Basic", "Time of Use" (TOU), and "Advanced DR Control". These strategies are responsible for the timestep-by-timestep charge requests that are sent to the CSE battery module.

Basic Strategy

The Basic strategy charges when a) production exceeds demand and b) the battery is not fully charged and discharges when a) demand exceeds production and b) the battery is not fully drained. That is, the battery both charges and discharges as soon as it can.

charge_request = -load_seen

By charging from any excess production and discharging as soon as it can to serve load, the basic strategy maximizes self-consumption of the on-site PV production. The other strategies account for the time-varying value of electricity (e.g., as measured by TDV) to varying degrees to increase the TDV-savings the battery provides.

If the battery system is standalone (no PV system), then basic control is not an available control option.

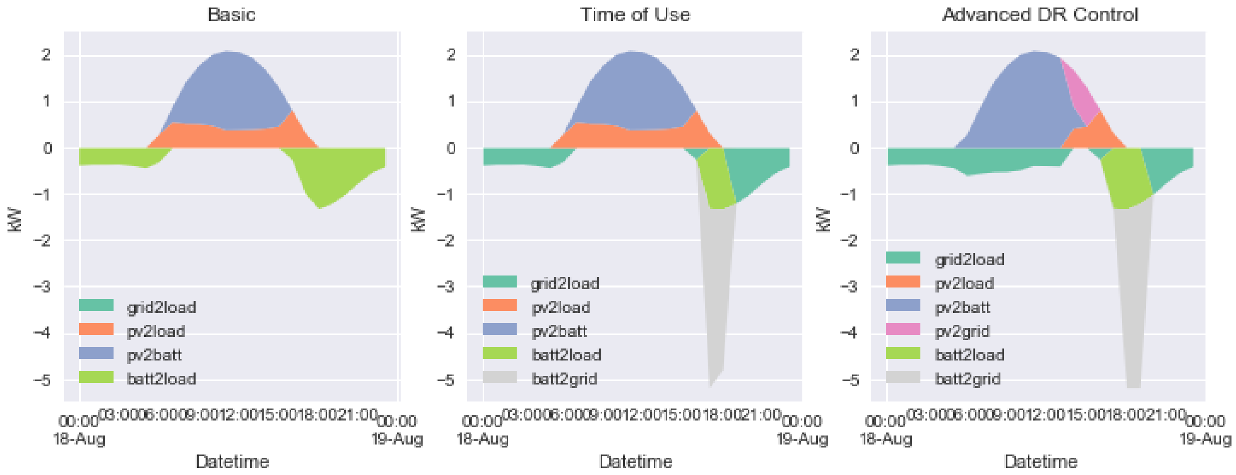


Figure 2: Illustrations of the battery control strategies' different responses to a single day. Note that the TOU and Advanced strategies can discharge directly to the grid. Also notice that Advanced charges the battery from PV while serving loads from the grid.

Time of Use Strategy

The TOU strategy attempts to preferentially discharge during high-value hours during a selected period of months. For a PV-tied system, the default duration for TOU months is July through September. For a standalone battery storage system, the default duration for TOU months is all year. Users can optionally input custom values for the first and last months to apply TOU control.

Charging rules are the same as the basic strategy for battery storage systems paired with a solar PV system. For standalone battery storage systems, the software provides a prescribed input to specify the hour of each day to start charging called "Charge Start Hour". The charging starts at midnight (hour 1) of each day.

Battery discharge follows the same approach for PV-tied and standalone batteries. The discharge period is statically defined (per climate zone) by the first hour of the expected TOU peak, which is a user-input within CBECC-Res and CBECC called "Discharge Start Hour." The default value for "Discharge Start Hour" is 19:00 for Climate Zones 2, 4, 8-15, and 20:00 for all other Climate Zones. The user has the option to change this value within CBECC-Res and CBECC if desired.

Consider a summer day in which the evening peak is defined to start at 20:00 but during which simulation load exceeds PV production during the 19:00 hour. While a simulation utilizing the Basic strategy would discharge to neutralize the net load during the 19:00 hour, a simulation on the TOU strategy would reserve the battery until 20:00 before commencing discharge. Because the TDV at 20:00 is likely to be higher than the TDV at 19:00, this strategy of reserving the battery for higher-value hours results in a lower (better) annual TDV.

A second difference: During the peak window, the battery is permitted to discharge at full power, even exceeding the site's net load. This is in contrast to the Basic strategy, which is limited to the net load.

```
if charge_start_hour <= this_hour < discharge_start_hour:
        charge_request = -min(load_seen, 0)   // only charge
else:
        charge_request = -1000   //  maximum discharge
```

Outside of selected months for the TOU strategy, control reverts to the Basic strategy.

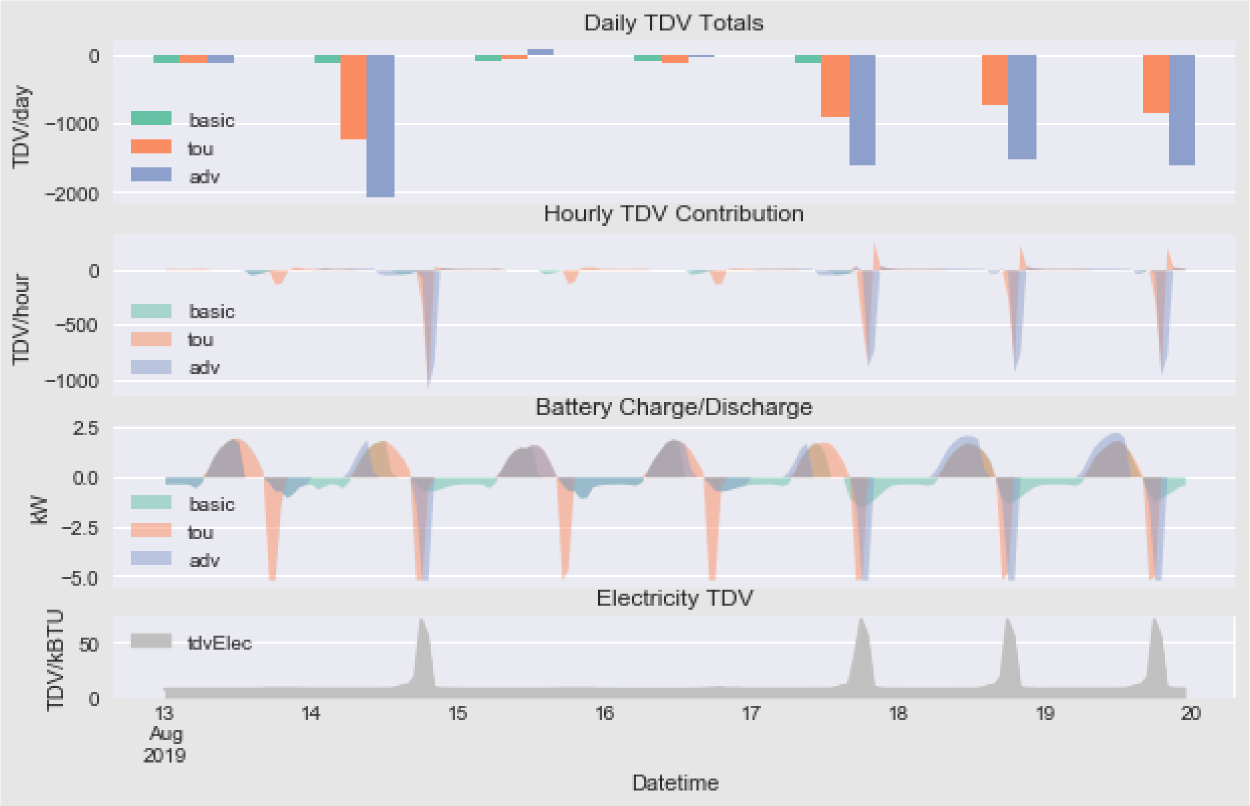


Figure 3: *On days with high Electricity TDV, the TOU and Advanced control strategies can accumulate large negative TDV by discharging to the grid during peak hours. The Advanced strategy specifically targets the top three TDV hours each day for discharging.*

Advanced DR Control

The Advanced DR (i.e., Demand Response) strategy uses the current day's TDV schedule to make dynamic time-of-use priorities. This strategy activates on days that have their peak TDV value ranking amongst the highest of all days of the year. The default value is the top 20 days. This value is hardcoded by CBECC-Res and CBECC unless EnableResearchMode is ON, in which case this value may be changed by the user. On all other days, the simulation reverts to the Basic strategy for PV-tied battery storage systems and to the Time of Use strategy for standalone battery storage systems.

The algorithm calculates the duration required to fully discharge the battery. On a peak day (as defined by having a peak TDV value ranking in the top 20 days of the year), the strategy finds the top TDV Values for the number of hours in that day matching the battery discharge duration. The algorithm asks for full discharge during these top hours in order of highest TDV hour first. Charging rules are the same as the Basic strategy for battery storage systems paired with a solar PV system. For standalone battery storage systems, the charging strategy should mimic the standalone battery charging strategy defined for Time of Use control.

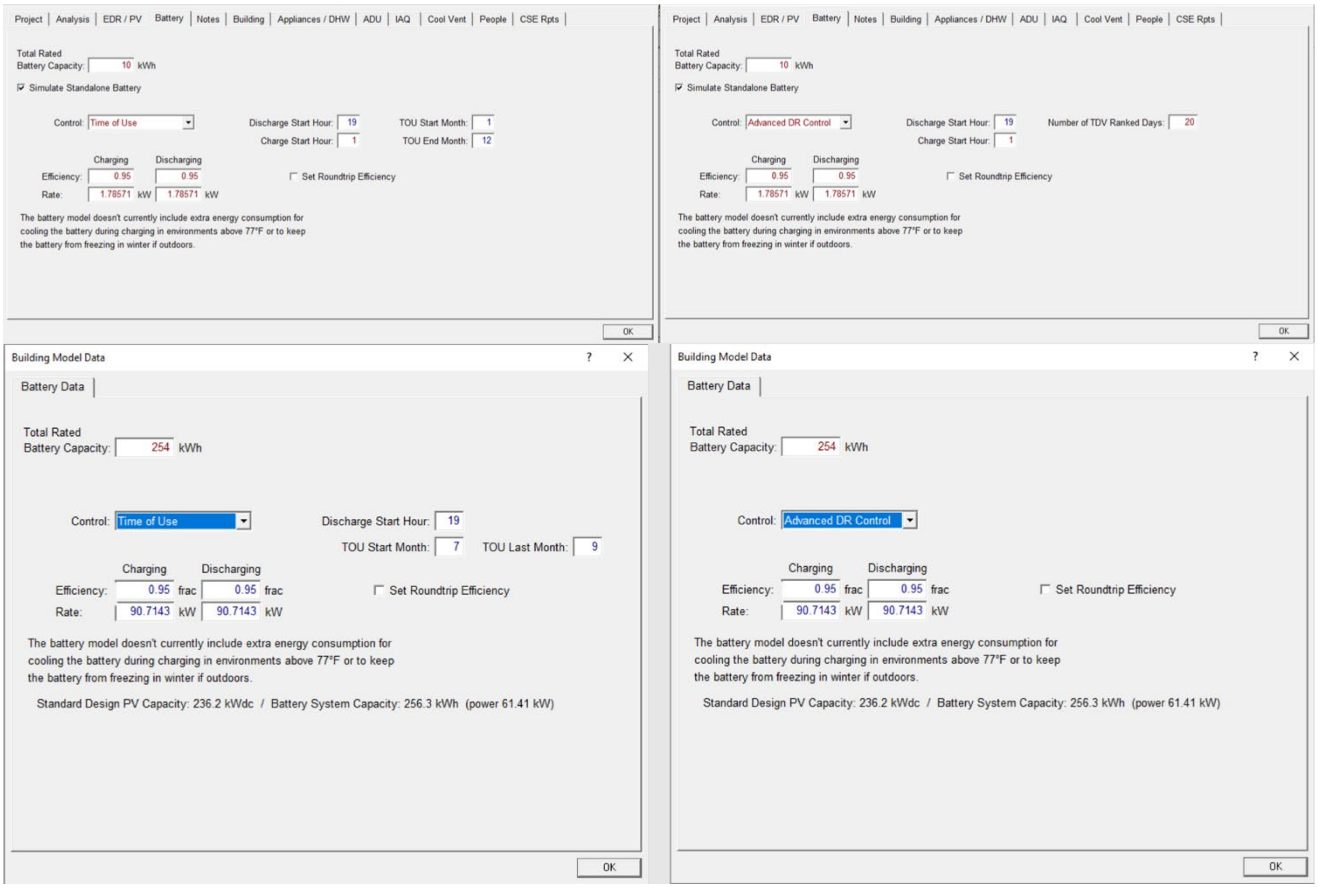
As with the TOU strategy, the battery may discharge in excess of net load during peak hours.
The Advanced DR strategy is also allowed to charge from the PV system before production overtakes load. Whereas the Basic and TOU strategies only charge with surplus production, this strategy will—on a peak day—charge from the first PV production available.

```
if day_tdv_peak_ranking <= 20:
    if tdv_rank(this_hour) in [1, 2, …, discharge_duration-1]:
            // maximum discharge top TDV hours
            charge_request = -1000
    else if tdv_rank(this_hour) == discharge_duration:
            // in next highest TDV hour, use remaining charge
            charge_request = max_capacity -
            2*(max_discharge_rate/η_discharge)
    else:
            // charge from PV, without subtracting load
            charge_request = pv_production
else if system_type == PV-tied:
    // on non-peak days, revert to basic strategy for PV-tied sys
    charge_request = -load_seen
else if system_type == standalone:
    // on non-peak days, revert to TOU strategy for standalone sys
    if charge_start_hour <= this_hour < discharge_start_hour:
        charge_request = -min(load_seen, 0)   // only charge
    else:
        charge_request = -1000   //  maximum discharge
```

Battery Parameters Included in CBECC-Res/CBECC/CSE

CBECC-Res and CBECC allow the modeler to adjust several battery parameters (Figure 4):

- Battery capacity (kWh): the CBECC-Res and CBECC software enforces a 5kW minimum size for the battery to qualify for the Self Utilization Credit.
- A checkbox to indicate if a standalone battery (no PV system) is modeled.
- Control strategy, chosen from the three options described in the Battery Control Strategies section of this appendix.
    - Note that “Basic” control is not an available control option for standalone battery systems



Total Rated Battery Capacity: 10 kWh

☑ Simulate Standalone Battery

Control: Time of Use

Discharge Start Hour: 19

Charge Start Hour: 1

TOU Start Month: 1

TOU End Month: 12

	Charging	Discharging
Efficiency:	0.95	0.95
Rate:	1.78571 kW	1.78571 kW

☐ Set Roundtrip Efficiency

The battery model doesn't currently include extra energy consumption for cooling the battery during charging in environments above 77°F or to keep the battery from freezing in winter if outdoors.

Total Rated Battery Capacity: 10 kWh

☑ Simulate Standalone Battery

Control: Advanced DR Control

Discharge Start Hour: 19

Charge Start Hour: 1

Number of TDV Ranked Days: 20

	Charging	Discharging
Efficiency:	0.95	0.95
Rate:	1.78571 kW	1.78571 kW

☐ Set Roundtrip Efficiency

The battery model doesn't currently include extra energy consumption for cooling the battery during charging in environments above 77°F or to keep the battery from freezing in winter if outdoors.

Total Rated Battery Capacity: 254 kWh

Control: Time of Use

Discharge Start Hour: 19

TOU Start Month: 7

TOU Last Month: 9

	Charging	Discharging
Efficiency:	0.95 frac	0.95 frac
Rate:	90.7143 kW	90.7143 kW

☐ Set Roundtrip Efficiency

The battery model doesn't currently include extra energy consumption for cooling the battery during charging in environments above 77°F or to keep the battery from freezing in winter if outdoors.

Standard Design PV Capacity: 236.2 kWdc / Battery System Capacity: 256.3 kWh (power 61.41 kW)

Total Rated Battery Capacity: 254 kWh

Control: Advanced DR Control

	Charging	Discharging
Efficiency:	0.95 frac	0.95 frac
Rate:	90.7143 kW	90.7143 kW

☐ Set Roundtrip Efficiency

The battery model doesn't currently include extra energy consumption for cooling the battery during charging in environments above 77°F or to keep the battery from freezing in winter if outdoors.

Standard Design PV Capacity: 236.2 kWdc / Battery System Capacity: 256.3 kWh (power 61.41 kW)

Figure 4: *The CBECC-Res (top) and CBECC (bottom) battery dialog box allows the modeler to set battery capacity, control strategy, charge/discharge efficiencies, and other control parameters related to charging and discharging hours and TOU months. Example images are shown for the TOU and Advanced DR Control options.*
(Source: screenshot of CBECC-Res and CBECC software user interface.)

- Charging and discharging efficiency (fraction): CSE allows charging and discharging efficiencies to be defined independently. The CBECC-Res and CBECC default is 0.95 for each, resulting in a default round-trip efficiency of 0.9025.
    - A single input for round-trip efficiency may be input by selecting the checkbox “Set Roundtrip Efficiency” (as shown in Figure 4). When checked, the inputs for charge and discharge efficiency are hidden and only the round-trip efficiency input is shown. Round-trip efficiency inputs less than 80% will result in no battery included in the simulation.
- Charge start hour may be input for standalone battery systems. Discharge start hour may be input for standalone and PV-tied battery systems. Allowable inputs are integers between 1 and 24 (inclusive).

- TOU period start and end months may be input. Allowable inputs are integers between 1 and 12 (inclusive).

CBECC-Res and CBECC also makes a set of assumptions to set CSE battery parameters. These are parameters that can be set in the lower-level CSE but that CBECC-Res and CBECC define itself.

- CBECC-Res and CBECC assume that the input battery capacity is the capacity of a brand new system. To account for aging across the battery’s life cycle, the software derates the effective battery capacity to 85% of the input battery capacity. A nominal 10 kWh battery gets 8.5 kWh of usable capacity in the simulation.
- The 85%-of-input-capacity figure interrelates with the fact that battery systems often have different published values for total and usable capacity. The battery management system prevents complete discharges, so the usable capacity is typically single-digit percentages lower than the total capacity (e.g., the Powerwall 2 has 14 kWh total and 13.5 kWh available energy). CBECC-Res and CBECC should clarify whether the input capacity should be total or useful, and the degradation derate figure should be consistent with the input CBECC-Res and CBECC expect.
- CBECC-Res and CBECC derive the CSE parameters Maximum charge rate and Maximum discharge rate (kW/hr) from the battery capacity. They are each defined to be battery capacity * 0.42. That is, the battery is sized to have 2.38 hours of storage at full discharge. (1/0.42 = 2.38). That ratio is likely derived from the 14 kWh capacity and 5 kW discharge power of the Powerwall 2: 14 * 0.85 / 5 = 2.38.
- The battery is assumed to start the simulation fully discharged. It is not required to be fully charged at the conclusion of the simulation.
- Battery-PV installations come in a range of electrical configurations, sometimes with independent inverters for each component (AC-coupled), sometimes sharing an inverter (DC-coupled). CSE assumes an AC-battery-module electrical configuration as shown in Figure 5. The modeling implication of that configuration is that the user-input battery charge and discharge efficiencies should include the losses associated with the battery module’s onboard inverter. In CSE, the PV system always has a dedicated PV inverter.

Figure 5: *General diagram of an AC battery module layout of a residential PV-battery system. (Source https://www.cleanenergyreviews.info/blog/ac-coupling-vs-dc-coupling-solar-battery-storage.)*

Simulated battery performance is static in the current CSE implementation. In particular, charge and discharge efficiencies do not vary with either charge rate or temperature. In real-world battery systems, efficiency falls from the benchmark a) with age, b) under rapid charging/discharging, and c) when temperatures are outside an ideal range (e.g., 25 °C/77 °F).

A real-world battery's available capacity is also subject to age and external conditions. Low temperatures, especially, reduce a battery's in-the-moment available capacity. CSE neglects those effects as well. The long-term dynamics of how batteries age warrants its own section, below.

The existence of a battery in the CBECC-Res and CBECC models also relaxes size limits on PV systems. Without onsite storage, the PV system is limited by the interconnection rule: solar generation must not exceed the building's electricity consumption over the course of a year. Title 24, Part 6 allows a building with a battery larger than 5 kWh to have a PV system that produces up to 1.6 times the building's annual electricity consumption. The CBECC-Res and CBECC software implement this change.