Building Technologies & Urban Systems Division
Energy Technology Area
Lawrence Berkeley National Laboratory

Integrated Whole-Building Zero Net Energy Retrofits for Small Commercial Offices

Task 4 Commercial Building Energy Saver (CBES) Update Report

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Acknowledgements

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Table of Contents

Table of Figures

Table of Tables

Executive Summary

Commercial Building Energy Saver (CBES), intended use for small- to medium-sized office and retail buildings in California, provides energy benchmarking and three levels of retrofit analysis considering the project goal, data availability, and user experience. CBES offers prototype building models for seven building types, six vintages, in 16 California climate zones and 80 energy conservation measures (ECMs) for lighting, envelope, plug-in equipment, HVAC, and service hot water retrofit upgrades. CBES Detailed Retrofit Analysis employs advanced automated calibration algorithms to attune inputs prior to simulating energy savings of ECMs. For the detailed retrofit analysis, on-demand energy simulations using OpenStudio and EnergyPlus calculates the energy performance of the building with user configurable ECMs. CBES is flexible enough that the user can jump to any level of evaluation, after the common inputs are provided. A national version can be found at CBESPro.lbl.gov or the 2030 Districts. CBES targets broad audience including building owners, facility managers, energy managers, building operators, energy auditors, designers, engineers and consultants. CBES won the 2019 R&D 100 Award.

New features and energy conservation measures have been implemented in CBES to enable the ZNE retrofit analysis. They have been activated in the CBES Web App (cbes.lbl.gov). Overall, the simulation is based on EnergyPlus and OpenStudio, and the implementation is using Ruby and OpenStudio Software Development Kit (SDK) as the development languages. The CBES App has been updated with the new ZNE modeling capabilities. Updates are live on cbes.lbl.gov. The detailed simulation approaches, assumptions, and implementation are described as follows.

1. The implementation of new features in CBES

Four new features, including rooftop PV system, electric battery, solar shading, and the Time Dependent Valuation (TDV) energy metric, were implemented in CBES to enable the ZNE retrofit analysis.

1.1 Rooftop PV system.

Renewable energy is essential to achieve the ZNE goal. Therefore, we added a new "Renewables" section, including PV system and electric battery, under the "Detailed Retrofit Analysis" feature.

The rooftop PV system is simulated in EnergyPlus using the following objects, which represent different components of the system:

- Generator:Photovoltaic
- PhotovoltaicPerformance:EquivalentOne-Diode
- ElectricLoadCenter:Generators
- ElectricLoadCenter:Inverter:Simple
- ElectricLoadCenter:Distribution

A number of shading objects (using EnergyPlus object "Shading:Building:Detailed") need to be created as well to represent the physical surfaces of PV panels. In CBES, algorithms were developed to automatically detect the geographical coordinates of the roof areas that are available for installing PV panels. When tubular daylighting devices (TDDs) are installed on the roof, the roof area available for PV installation will be reduced accordingly. In this case, the algorithms will identify the locations of TDDs and adjust the coordinates of roofs-to-install-PV, so the PV panels will not overlap with TDDs or block the skylight coming through TDDs.

For different application purposes, we implemented two methods that a PV system can be added: (1) by capacity for modeling a new PV system, and (2) by panel details for modeling an existing PV system. If the building doesn't have a PV system and there is a need to evaluate the ZNE potential, the new feature allows the users to add a new one by selecting the PV cell type and entering the design capacity in kW, as shown in Figure 1. Then CBES will calculate how much roof area the system covers in percentage, based on which the users can evaluate the possibility of installing such a system on their roof and adjust the design capacity if needed. If the building has already installed a PV system, the users can define the system in details with the new feature, evaluate the current ZNE readiness, and explore potential ZNE strategies through retrofit analysis. As shown in Figure 2, the new feature allows the users to enter the detailed characteristics of their installed PV system, including (1) parameters of the PV module, which are usually available from the manufacturer's specifications, and (2) characteristics of PV arrays (i.e., panels), such as tilt angle, orientation, number of modules in parallel, and number of modules in series. In case the users don't have access to PV module specifications, we provide default settings, which are compiled from several manufacturers' products on the market. Figure 3 illustrates the estimated PV generations included in the Single Measure Analysis Results.

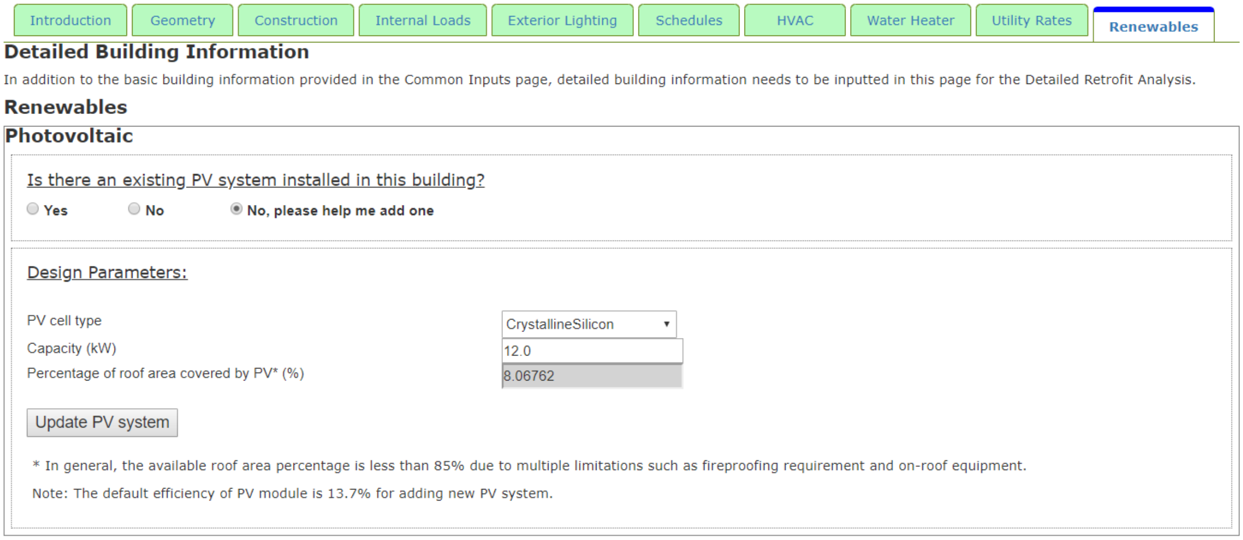


Figure 1. CBES Screenshot: Adding a new PV System

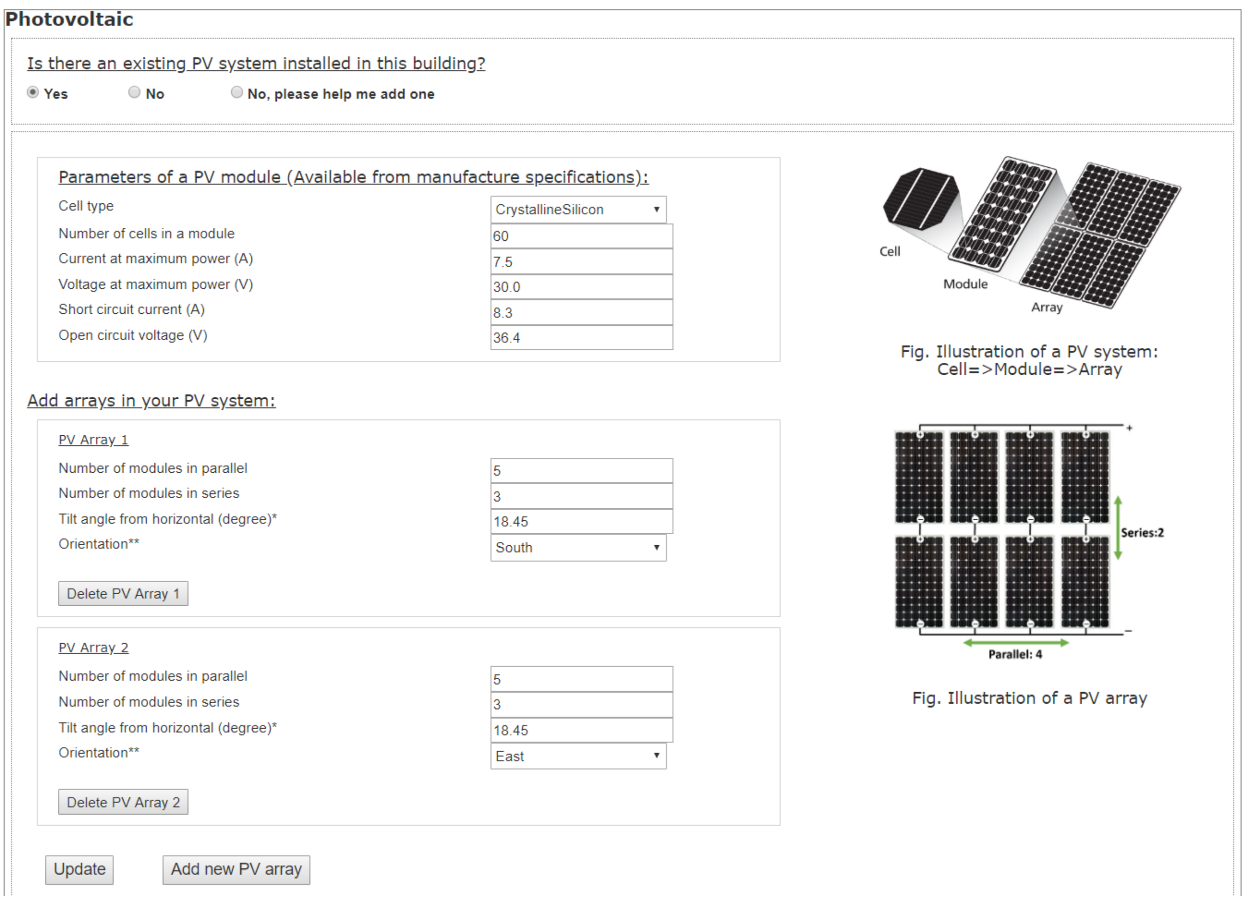
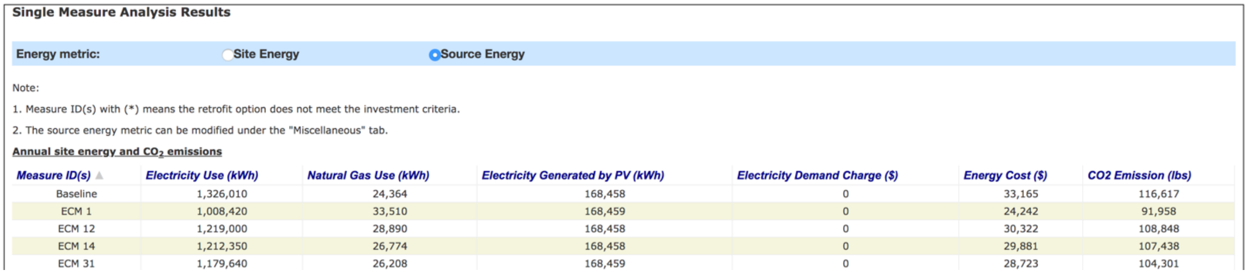


Figure 2. CBES Screenshot: Defining an existing PV system



Single Measure Analysis Results

Energy metric: Site Energy Source Energy

Note:

1. Measure ID(s) with (*) means the retrofit option does not meet the investment criteria.
2. The source energy metric can be modified under the "Miscellaneous" tab.

Annual site energy and CO_2 emissions

Measure ID(s)	Electricity Use (kWh)	Natural Gas Use (kWh)	Electricity Generated by PV (kWh)	Electricity Demand Charge ($)	Energy Cost ($)	CO2 Emission (lbs)
Baseline	1,326,010	24,364	168,458	0	33,165	116,617
ECM 1	1,008,420	33,510	168,459	0	24,242	91,958
ECM 12	1,219,000	28,890	168,458	0	30,322	108,848
ECM 14	1,212,350	26,774	168,458	0	29,881	107,438
ECM 31	1,179,640	26,208	168,459	0	28,723	104,301

Figure 3. CBES Screenshot: Single Measure Analysis Results with estimated PV generation

1.2 Electric battery

An electric battery system stores surplus solar power for later use. The battery extends the use of a PV system's generated energy and will provide free, sustainable power even when the sun is not shining and the panels don't produce energy. It is simulated in EnergyPlus with the object "ElectricLoadCenter:Storage:Battery" representing the battery modules, and with the object "ElectricLoadCenter:Distribution" linking battery with the PV system.

The users can define an electric battery system by specifying the characteristics of the battery modules, as shown in Figure 4. Similar to the PV system, this information is usually available in the manufacturer's specifications. In case the users don't have access to the above data, we provide default settings, which are compiled from several manufacturers' products on the market. CBES will automatically link this electric battery to the PV system in the building.

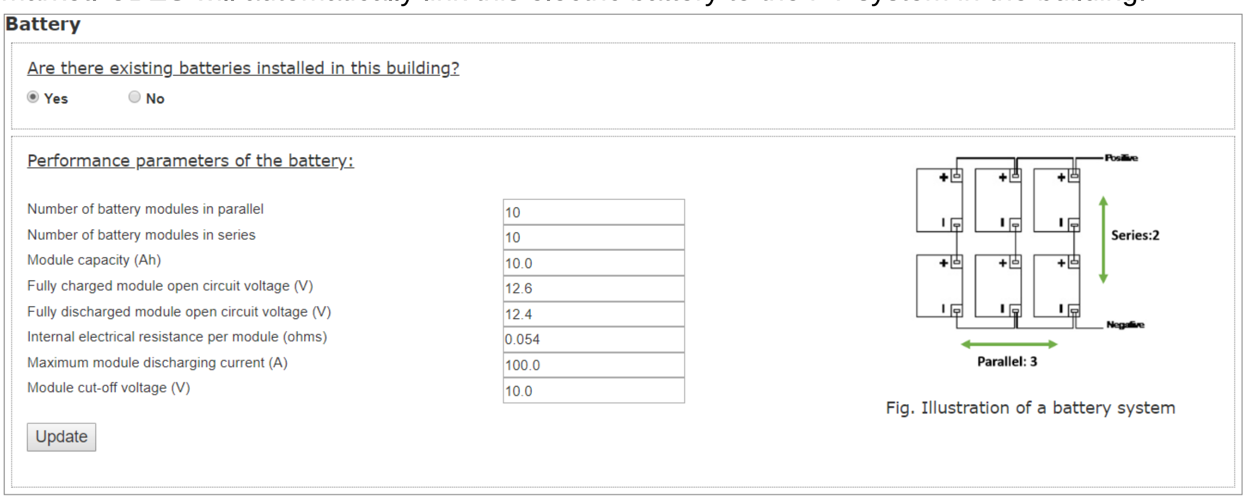


Figure 4. CBES Screenshot: Adding Electric Battery

1.3 Shading objects

Shading from adjacent buildings, trees, and obstructions on the roof can play an important role in the estimation of building energy consumption, as well as the electricity generation of PV panels. For more accurate simulation of energy use, PV generation, and skylight effect, it is critical to take the shading effect into account in building energy modeling.

For this reason, three types of solar shading objects were implemented in CBES: neighbor buildings, trees, and rooftop equipment or structure. The neighbor buildings and rooftop obstructions are assumed to be cuboids (Figures 5 and 6), and the trees are simplified to have a rectangular bole and trapezoid crown (Figure 5). Shading objects are usually created in EnergyPlus using the object “Shading:Building:Detailed”. The new feature allows the users to describe the shape of the shading objects via parameters like height, length, width, and distance from the building edge. CBES will take the user inputs and calculates the shape coordinates as EnergyPlus inputs.

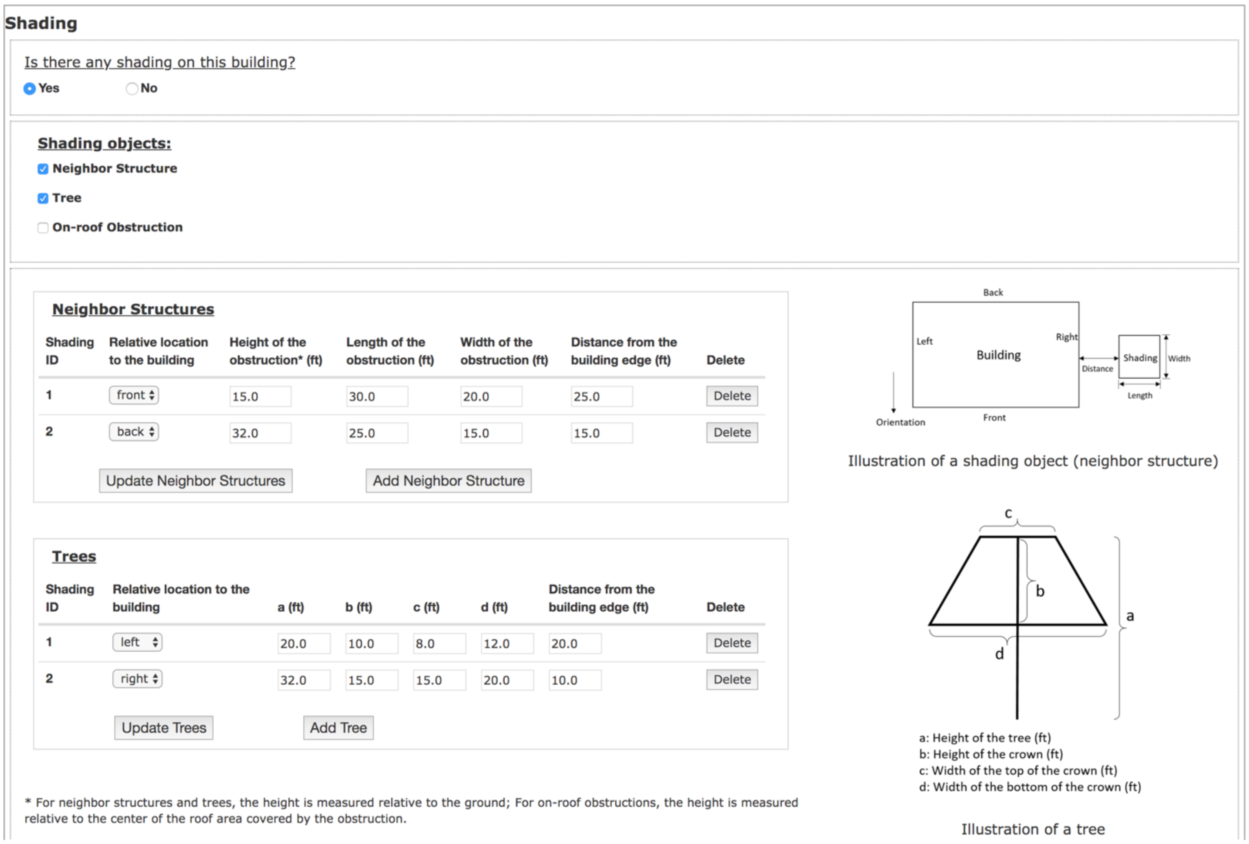


Figure 5. CBES Screenshot: Adding Shading objects (Neighbor Structure Tree)

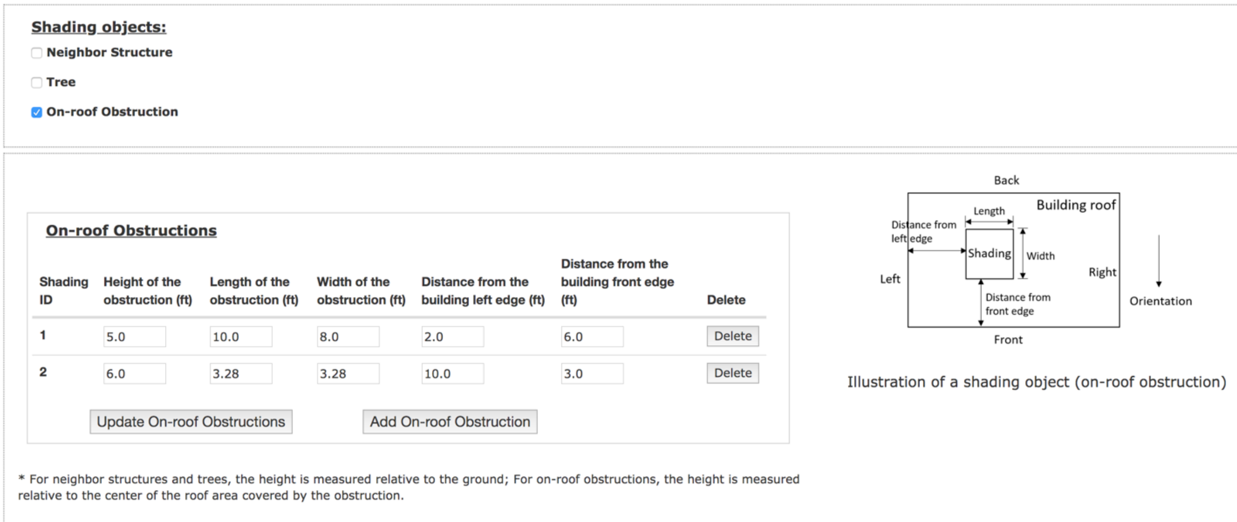


Figure 6. CBES Screenshot: Adding Shading objects (On-roof Obstruction)

1.4 TDV metric

CEC uses time-dependent valuation (TDV) energy in California's Building Energy Code Compliance software to set the target energy budgets for newly constructed buildings, and to value the design trade-offs during the development and construction of those buildings. The TDV metric determines (in part) the long-term cost-effectiveness of proposed energy efficiency measures. TDV is the metric adopted in the Integrated Energy Policy Report for the measurement of zero net energy (ZNE) buildings.

For this reason, the TDV metric was added in CBES for evaluating ZNE buildings in California, as shown in Figure 7. Multiple years (2013, 2016, and 2019) of TDV data were available for selection. TDV varies by hour throughout the year, so it was added as "Schedule:File" objects for electricity and natural gas respectively in EnergyPlus. They are referenced in the "FuelFactors" object, functioning as a source energy factor. When the TDV metric is selected in CBES, the retrofit analysis results will present the TDV energy as "source energy", as shown in Figure 3.

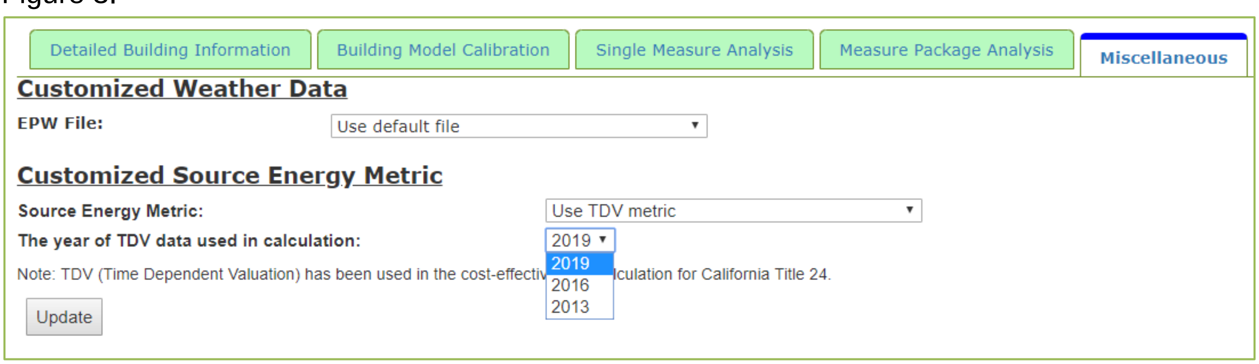


Figure 7. CBES Screenshot: Selecting TDV Energy as the Source Energy Metric

2. The implantation of new ECMs in CBES

A list of new ECMs were proposed by the research team to provide more retrofit options to achieve the ZNE goal. They have been implemented in CBES. Table 1 lists all the new ECMs. The estimated unit costs of these measures are compiled from a few sources and added in the CBES ECM database. The users can either use the default costs or adjust the costs according to their project needs. The details of each new ECM are introduced as follows.

Table 1. List of new ECMs in CBES

Measure Name	Category
Apply Demand Response Strategy of Thermostat Reset	Demand Response
Add Tubular Daylighting Device	Envelope - Skylight
Upgrade to VRF heat recovery type coupled with DOAS Energy Recovery Ventilator plus Demand Control Ventilation system	HVAC - Whole System
Upgrade to VRF heat recovery type coupled with DOAS Enthalpy Wheel plus Demand Control Ventilation system	HVAC - Whole System
Upgrade to Packaged Heat Pump system with thermafuser	HVAC - Whole System
Add Window Film	Envelope - Window
Add Exterior Storm Window Layer	Envelope - Window
Add Interior Storm Window Layer	Envelope - Window
Add Exterior Overhang Shades	Envelope - Window
Efficiency Upgrade to Electric Instantaneous Water Heater and low-flow fixtures	Service Hot Water
High efficiency exterior light fixture	Exterior Lights
Add detailed guidance to the measure of plug load energy use reduction	Plug load

2.1 Demand Response and Peak Day Pricing rates

Demand response (DR) is a change in the power consumption of an electric utility customer to better match the demand for power with the available supply. Utilities signal demand requests to their customers to encourage load shedding and shifting via economic incentives. A typical DR strategy, thermostat reset, was implemented in CBES, in which case the building responds to DR by resetting cooling thermostat to a higher temperature (78.8F) at 1pm for four hours in the hottest 15 days of a calendar year. Such DR strategy is simulated in EnergyPlus using objects “DemandManagerAssignmentList” and “DemandManager:Thermostats”.

Peak Day Pricing (PDP) is a demand response pricing plan being rolled out by the Pacific Gas and Electric Company (PG&E) to complement current time-of-use pricing or replace flat rates that do not vary with time. PDP provides lower energy prices during the summer in exchange for higher rates during certain hours on 9 to 15 peak event days per year. PDP rates were also added to enable the benefit analysis of demand response strategies, as shown in Figure 8. Related EnergyPlus objects include “UtilityCost:Tariff” and “UtilityCost:Charge:Simple”.

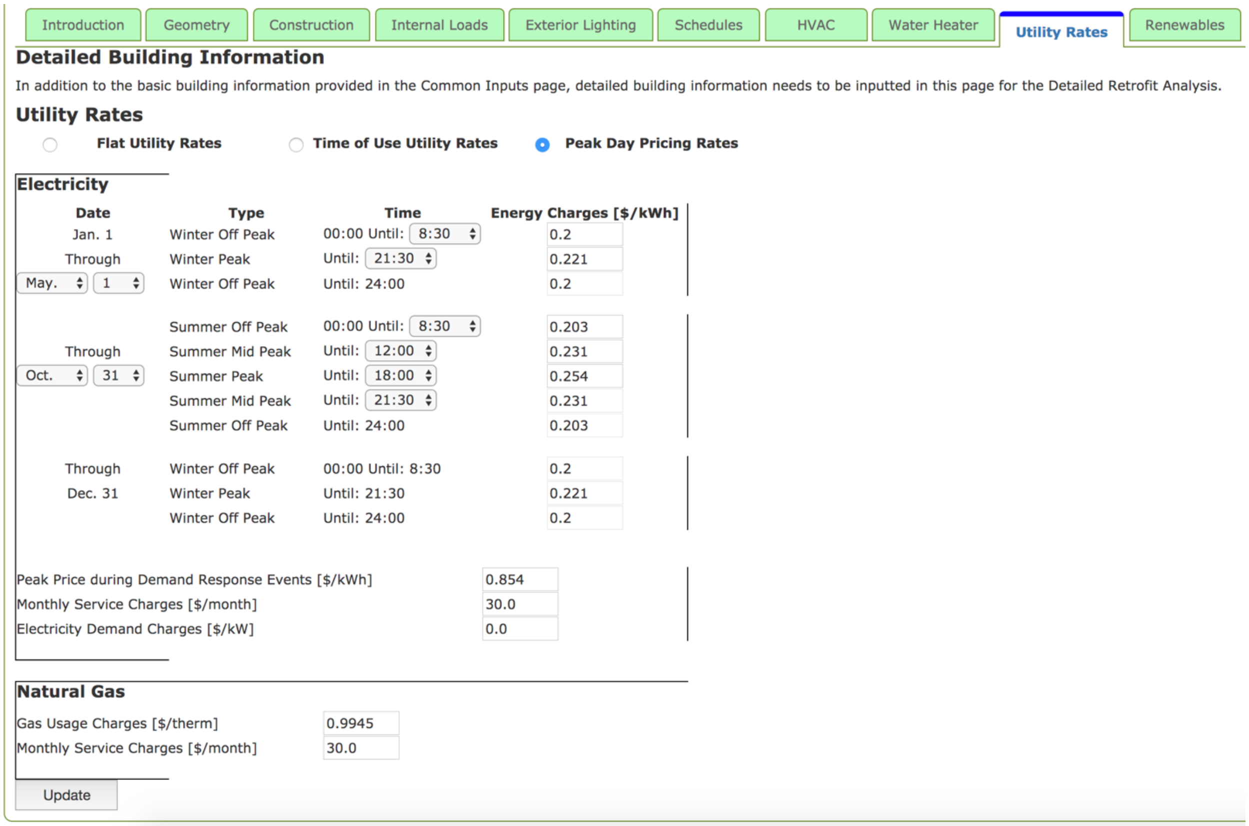


Figure 8. CBES Screenshot: Peak Day Pricing Rates

2.2 Skylight through Rooftop Tubular Daylighting Devices

Tubular daylighting devices (TDDs), sometimes referred to as light tubes or light pipes, provide an option for facility owners to incorporate daylighting into buildings from the roof without installing large skylights. TDDs capture sunlight using a rooftop dome, then transfer it indoors through a reflective tube that runs from the roof to the ceiling. From there, the light is evenly dispersed into the interior space using a diffuser.

TDDs are composed of three major components: dome, diffusers, and pipes. Their properties are defined in EnergyPlus through objects “Construction”, “WindowMaterial:Glazing”, and “Material”. They are assembled into TDD system through EnergyPlus objects “FenestrationSurface:Detailed” and “DaylightingDevice:Tubular”. In CBES, TDDs can be either specified in the baseline model to represent an existing TDD system (Figure 9) or be added as a retrofit measure.

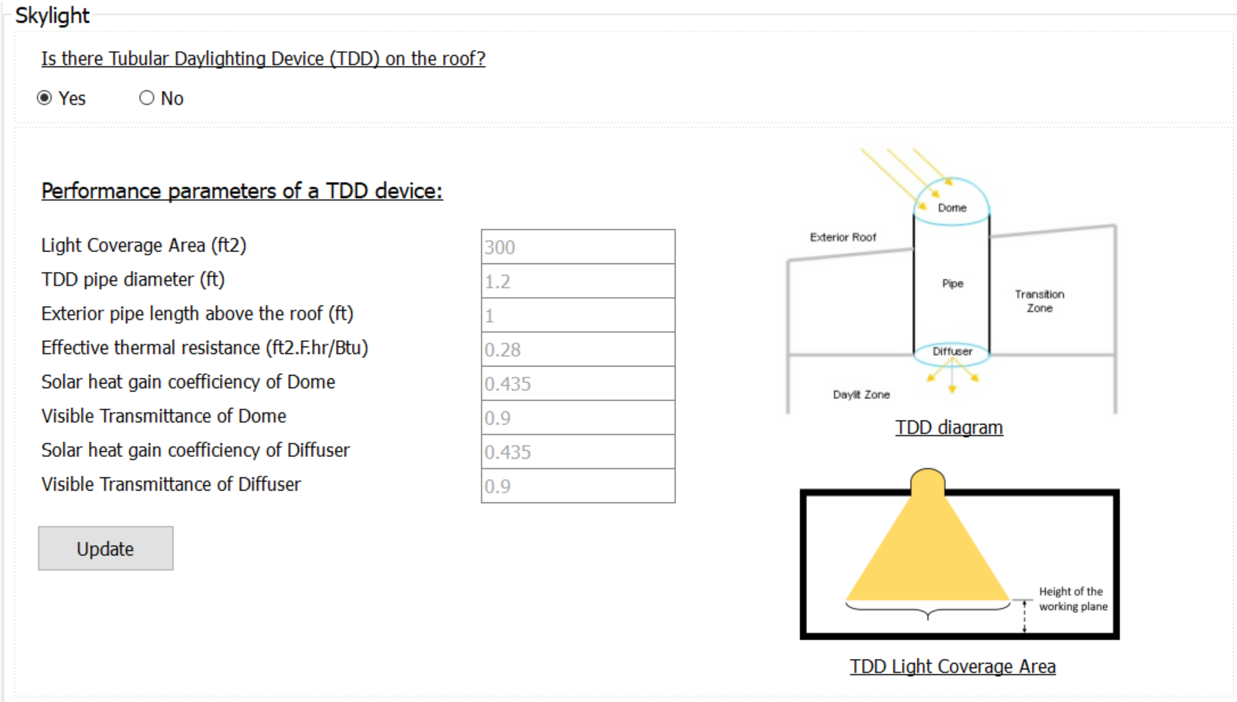


Figure 9. CBES Screenshot: Adding Tubular Daylighting Device for Skylight under "Geometry"

2.3 Advanced HVAC systems

2.3.1 Three types of advanced HVAC systems coupled with dedicated outdoor air system (DOAS) and energy recovery ventilator as well as demand control ventilation

Heat recovery VRF technology allows simultaneous cooling and heating for different indoor units, and the compressor load benefits from the internal heat recovery. This also results in greater control of the building's interior temperature by the building's occupants. VRF systems are not purpose-built for ventilation, and as a system's compressors run slower during partial load conditions, its coils handle less refrigerant and are less active. While this is great for energy efficiency, a warm evaporator coil in cooling mode does not dehumidify effectively. Therefore, VRF systems are often integrated with specialized ventilation systems such as dedicated outdoor air system (DOAS) and/or energy recovery ventilators to handle ventilation and moisture removal.

This new system specifies a VRF heat recovery system integrated with DOAS and energy recovery ventilator. It includes demand control ventilation to enhance energy saving at partially occupied hours. Energy recovery ventilator can further save energy by recycling heat/cool energy from exhaust air to preheat/precool the outside air supplied to the DOAS system.

This system is simulated in EnergyPlus using the following objects:

- AirConditioner:VariableRefrigerantFlow
- ZoneHVAC:TerminalUnit:VariableRefrigerantFlow
- Coil:Cooling:DX:VariableRefrigerantFlow
- Coil:Heating:DX:VariableRefrigerantFlow

- HeatExchanger:AirToAir:SensibleAndLatent (as ERV)
- AirTerminal:SingleDuct:Mixer (as DOAS terminal)

DOAS is specified in the object “Sizing:System” by assigning “Yes” to the fields “100% Outdoor Air in Cooling” and “100% Outdoor Air in Heating”.

2.3.2 Variable refrigerant flow (VRF) multi-zone heat recovery system coupled with dedicated outdoor air system (DOAS) and enthalpy wheel as well as demand control ventilation

The only difference from the system described in 2.3.1 is that this system is using enthalpy wheel instead of energy recovery ventilator. An enthalpy wheel is composed of a rotating cylinder filled with an air permeable material resulting in a large surface area. It is the most effective devices to transfer both sensible and latent energy, but consumes extra power from rotating the wheel. On the other hand, an energy recovery ventilator usually refers to a fixed plate heat exchanger, which consists of alternating layers of plates that are separated and sealed. As it doesn’t have moving parts, there is not extra energy use, but its efficiency is generally not as high as that of enthalpy wheels. The default efficiency settings of energy recovery ventilator and enthalpy wheel were obtained from AHRI certified products.

2.3.3 Single zone heat pump with VAV Diffusers (e.g. Therma-fuser™)

Each Therma-Fuser diffuser is an independent zone of VAV control with built-in room thermostats and modulating dampers for varying the air volume. The dampers are continuously adjusting to vary the volume of air flow (warm or cold) into the room, in response to room temperature. Unlike fixed opening diffusers, which dump cold air on occupants at low volumes, the variable air opening within all Therma-Fuser diffuser models creates high air velocity even at lower supply volumes. This maintains the Coanda effect where high velocity air hugs an adjacent surface, holding cold air up to the ceiling and prevents dumping.

Apart from a higher efficiency heat pump system, the additional energy saving feature of this unit is that Therma-Fuser requires a low pressure drop design in the air distribution system. The Therma-Fuser terminal is simulated in EnergyPlus using the object “AirTerminal:SingleDuct:VAV:NoReheat”, with reduced pressure drop on the supply fan.

2.4 Window measures

2.4.1 Add window film

Window film has low solar transmittance and can reduce solar heat gain by reflecting infrared radiation. When the building owners or facility managers have a limited budget for retrofit, adding window film is a relatively affordable but effective option compared with replacing entire windows.

Window films help block solar heat gain and protect against glare and ultraviolet exposure. They are best used in climates with long cooling seasons, because they also block the sun's heat in the winter. They can be useful for building owners who don’t want to block views with other window treatments, but who have issues with glare and solar heat gain. Especially when the building owners have a limited budget for retrofit, adding window film is a relatively affordable but effective option compared with other window treatment like full window replacements.

Window film is added as an additional layer to the existing windows. The simulation method is based on the method described in the LBNL report (Arasteh, 2009). This method determines the solar heat gain coefficient (SHGC) and U-value of a window fitted with a film applied to its interior surface, when only the SHGC and U-value of the original window are known. This kind of approximation is useful when performing energy simulations based on energy codes, which usually only specify minimum requirements for windows in terms of simple parameters, as the baseline case in CBES. Three major steps are performed under this method: (1) Determine the properties of the original window, (2) Determine the properties of the film, and (3) Determine properties of window with applied film. The simulation method was implemented in CBES. The properties of window film were based on available solar control film products on the market.

2.4.2 Add storm window layer (interior/exterior)

Storm windows add an additional layer of insulation to your windows. They effectively serve to create an air space between the existing window and the storm window, which functions similar to replacing single-pane windows with double-pane windows. This air space improves the energy-efficiency of a building by reducing air flow through the window glass and around the window frame. The enclosed air space provides the actual insulation value. Storm windows with a low-e coating reflect heat back inside the building during the winter and reflect it outside during the summer, keeping the indoor environment more comfortable.

Storm windows can be installed on the interior or exterior of the primary window. Interior storm windows are almost identical to exterior models in material and function. For the most part, interior storm windows offer greater convenience than exterior storm windows. They're easier to install and remove; they require less maintenance because they're not exposed to the elements; and, because they seal tightly to the primary window, they're more effective at reducing air infiltration. Both interior and exterior storm windows are implemented in CBES as new ECMs.

The simulation method is similar to that of adding window film, only that the properties of the storm window layer is different from those of the window film. The storm window is assumed to be a typical 3mm low-e glass layer.

2.4.3 Add overhang shading

An overhang is a crucial element in passive solar design because it blocks the sun’s heat when it is not desired, especially during cooling seasons. It is simulated in EnergyPlus by adding the object “Shading:Overhang” to each window as long as it is not facing north. North-facing windows tend to have more heating load than cooling load because they get much less solar heat gain than windows facing other orientations. As a result, it may even lead to more energy use if overhang is applied to north-facing windows.

The overhang is assumed to be 1.8 ft above the upper edge of window and 2.5 ft depth/projection. This is based on the recommended overhang dimensions for latitude 36° (California average) and Mixed Climate type (warm or hot summer, mild spring and fall, and cool or cold winter), on the Sustainable By Design website (Sustainable By Design, 2020).

2.5 More advanced domestic hot water system: Instantaneous electric water heater with reduced water flow rate

An instantaneous electric water heater, also known as demand-type or tankless water heaters, provides hot water only as it is needed. They don't produce the standby energy losses associated with storage water heaters, which can save energy cost. The initial cost of a tankless water heater is greater than that of a conventional storage water heater, but tankless water heaters will typically last longer and have lower operating and energy costs, which could offset its higher purchase price.

Instantaneous electric water heater is simulated in EnergyPlus using the object “WaterHeater:Mixed” by specifying the heater fuel type as electricity, reducing the tank volume to 0, and removing the pump from the system.

Reducing water flow rate is a step further to more energy savings by installing low-flow fixtures. This is simulated in EnergyPlus by reducing the flow rate in “WaterUse:Equipment”.

2.6 High efficiency exterior light fixture

The exterior lights consume a significant amount of energy, especially for building type like retail that needs an attractive outlook and high visibility and security. It can help reduce the energy use by replacing the exterior lighting fixture with high efficiency fixture (e.g., 50W/fixture) while keeping the same number of fixtures. This is simulated in EnergyPlus using the object “Exterior:Lights”.

2.7 Add detailed guidance to the measure of plug load energy use reduction

Detailed “how to” guidance was added to the existing ECMs that reduce plug load energy use. Strategies to reduce plug loads include:

- Utilize “smart” occupancy-controlled plug strips or outlets at workstations
- Use laptops instead of desktop computers
- Replace equipment/appliances with high efficiency (e.g. EnergyStar) models
- Consolidate printers, fax machines, etc. to minimize the number of pieces of equipment. Also consolidate them to connect to a common branch electrical panel and enable branch panel security system power off control
- Virtualize servers or use offsite servers

3. A test case demonstrating path to ZNE

In this section, an example case study was conducted to demonstrate the applications of the new features and ECMs for an existing building to achieve ZNE. The example building, shown in Figure 10, is a one-story prototype office building built in 1977, located in San Francisco. The gross floor area is 10,000 ft2. The energy use intensity (EUI) is 56.7 kBtu/ft2. Benchmarking was first performed on the building to evaluate its performance compared with its peer buildings. An EnergyStar score of 38 was obtained, which infers that the building has significant potential for improvement.

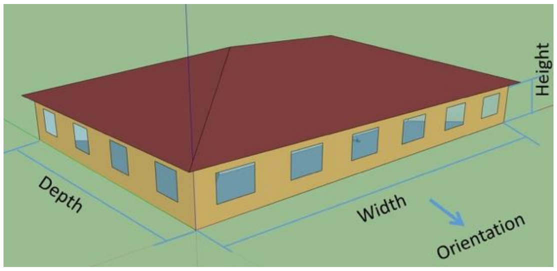
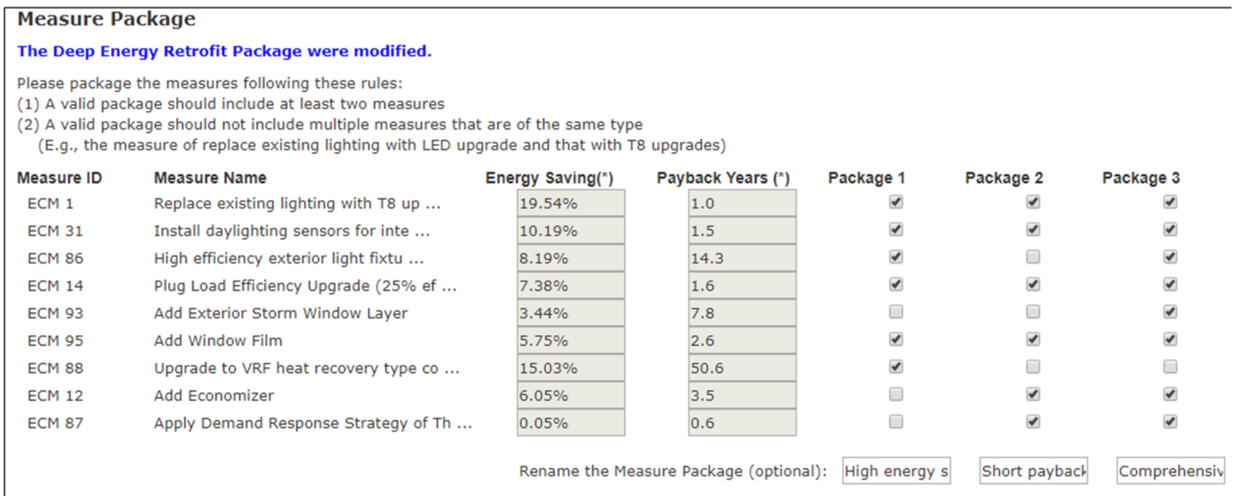


Figure 10. The 3D Model of the Example Building

Two major efforts were made to achieve ZNE for the building: (1) improve building performance to reduce basic energy use, and (2) install PV system to generate and supply electricity to the building. A list of ECMs are selected and first evaluated individually on energy savings and payback years. Based on single measure analysis results, three ECM packages are compiled with different optimization purposes (Figure 11), including high energy savings, short payback year, and comprehensive. A new PV system of 52kW capacity, which covers about 35% of the roof area, is added to the building.

TDV is selected as the energy metric to evaluate ZNE since this building is in California. According to the package analysis results illustrated in Table 2, the high energy saving package can achieve ZNE from the annual perspective. The comprehensive package is near ZNE. Though the short payback package can't achieve ZNE, it largely reduces the basic energy use with a very attractive payback year of 2.8. The test case demonstrates that the new features and ECMs enable CBES to evaluate ZNE potentials for small and medium-sized commercial buildings. The simulation accuracy of CBES was later validated using the FLEXLAB experiments, which is elaborated in a separate report.


Measure Package

The Deep Energy Retrofit Package were modified.

Please package the measures following these rules:
(1) A valid package should include at least two measures
(2) A valid package should not include multiple measures that are of the same type
(E.g., the measure of replace existing lighting with LED upgrade and that with T8 upgrades)

Measure ID	Measure Name	Energy Saving(*)	Payback Years (*)	Package 1	Package 2	Package 3
ECM 1	Replace existing lighting with T8 up ...	19.54%	1.0	☑	☑	☑
ECM 31	Install daylighting sensors for inte ...	10.19%	1.5	☑	☑	☑
ECM 86	High efficiency exterior light fixtu ...	8.19%	14.3	☑	☐	☑
ECM 14	Plug Load Efficiency Upgrade (25% ef ...	7.38%	1.6	☑	☑	☑
ECM 93	Add Exterior Storm Window Layer	3.44%	7.8	☐	☐	☑
ECM 95	Add Window Film	5.75%	2.6	☑	☑	☑
ECM 88	Upgrade to VRF heat recovery type co ...	15.03%	50.6	☑	☐	☐
ECM 12	Add Economizer	6.05%	3.5	☐	☑	☑
ECM 87	Apply Demand Response Strategy of Th ...	0.05%	0.6	☐	☑	☑

Rename the Measure Package (optional): High energy s | Short payback | Comprehensiv

Figure 11. CBES Screenshot: ECM Package Configuration Based on Single Measure Analysis Results

Table 2. Simulation Results of the Measure Packages (Energy metric is TDV energy in MWh)

	Electricity Use	**Natural Gas use**	**Electricity generated by PV**	**Total Net TDV energy**	**Payback years**
Baseline	1328	24.2		1352	
Package 1: High energy saving	591	10.4	629.6	-28.2	14.0
Package 2: Short payback	723	57.0	637.3	142.7	2.8
Package 3: Comprehensive	627	42.4	641.6	27.8	5.7

Note: The energy metric of “TDV-MWh” refers to the TDV energy in MWh, which is different from the traditional MWh.

4. References

Arasteh, D., Kohler, C., Griffith, B., 2009, Modeling windows in Energy Plus with simple performance indices, LBNL-2804E.

Sustainable By Design. Overhang Recommendations. https://susdesign.com/overhang_rececs/index.php