# Hybrid Systems to Enable High Penetration PV

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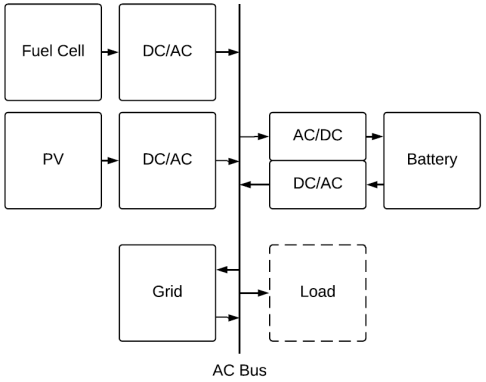
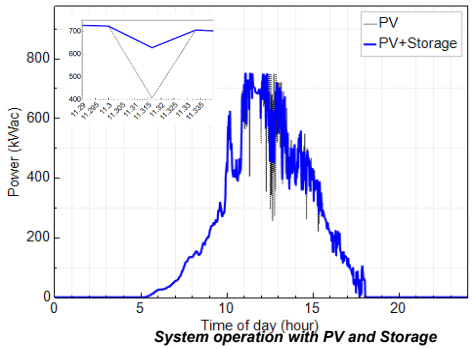
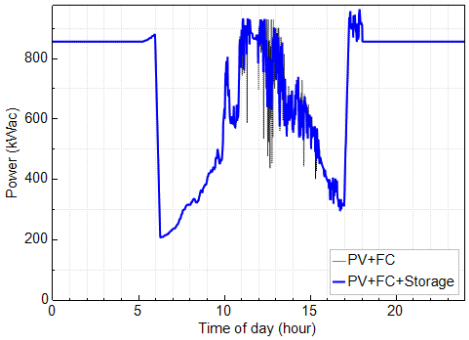



***Hybrid PV+Fuel Cell+Storage System***




***System operation with PV and Storage***




***System operation with PV and Fuel Cell with Storage***

## Project Overview

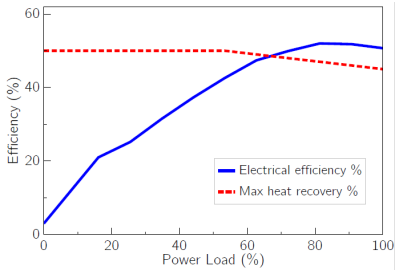
A model for PV plus energy storage and fuel cells was developed in the System Advisor Model (SAM). This model was used to evaluate the ramp rate and interconnection capacity factor for a hypothetical utility-scale plant for several configuration options.

| Variable | PV Only | PV+Storage | PV+Fuel Cell | PV+Fuel Cell+Storage |
|---|---|---|---|---|
| Year 1 Capacity Factor | 17.61% | 17.60% | 78.10% | 77.36% |
| Year 1 Ramp Up Violations | 3345 | 154 | 3341 | 20 |
| Average up violation | 73.4 kW/min | 1.84 kW/min | 73.4 kW/min | 7.02 kW/min |
| Average up violation % | 81.5% | 2.04 % | 81.6 % | 7.80 % |
| Year 1 Ramp Down Violations | 3195 | 519 | 3199 | 95 |
| Average down violation | -72.6 kW/min | -2.71 kW/min | -72.7 kW/min | -2.26 kW/min |
| Average down violation % | -80.7% | -3.01 % | -80.7 % | -2.50 % |

***Ramp Rate Scenario Results***

## Fuel-Cell Model

The fuel cell model is a linear model which requires inputs of the electrical efficiency and heat recovery as a function of power load Through this representation, the model can represent multiple types of generators, including Solid Oxide, Molten Carbonate, Phosphoric Acid, or Proton Exchange Membrane fuel cells.




***Inputs for fuel-cell model.***

| PV capacity (kWdc) | Inverter capacity (kWac) | Fuel cell capacity (kWac) | Battery capacity (kWdc) | Battery energy (kWhdc) |
|---|---|---|---|---|
| 900 | 750 | 900 | 500 | 1000 |

## Ramp-rate control scenario

To illustrate the utility of the hybrid-system model, a hypothetical small utility scale plant was developed near Los Angeles, CA using 1-minute irradiance data. For this case-study, it was assumed that there was an interconnection requirement limiting ramps of 10% of the PV system capacity per minute (90 kW/min).

$$RR_{max} = P_{pv,nameplate} * 0.10$$

$$RR(i) = |\frac{dP}{dt}(i)| = |\frac{P(i) - P(i-1)}{t(i) - t(i-1)}|$$

$$P_{battery} = RR_{max} - RR(i)$$

$$P_{battery} = -RR(i) - RR_{max}$$

$$CF_{interconnect} = \frac{\sum_{i=1}^{N} P(i)\Delta t}{P_{interconnect} N \Delta t}$$

## Results

**PV only**
The plant experienced 3345 violations of a 10%/minute ramp up limitation and an interconnection capacity factor of 17.6%.

**PV + Storage**
Reduced the violations to 154 per year and the magnitude of the average violation to 2%.

**PV + Fuel Cell**
Increased the capacity factor to 78% without improving ramp violations.

**PV + Fuel Cell + Storage**
Maintained the improved capacity factor while reducing ramp up violations to 23, illustrating the potential to operate a hybrid system both to enable grid integration requirements and increase utilization of the interconnection.

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