In-class Example / Assignment – Sizing Combined Systems

Consider the following system:

- A network of twenty homes has an overall energy requirement of 3kWh per day. The effective power factor of the load is 0.75 across all the houses, and requires alternating current.
- We wish to design a combined photovoltaic-battery system such that 75% of the total required load is applied through a battery. This ratio factors in the excess energy generated by the photovoltaics compared to the load required at that point in the day being used to charge the battery, as well as the discharge of the battery at night when the load is higher. (See slide 7 of class notes.)
- This battery has 20% round-trip losses. The junction between the PV system and the battery is managed with a MPPT system that applies 4% losses of applied power. The PV system itself also experiences 6.5% losses due to dust, shading, and general degradation.
- The homes have two typical “extreme” regimes of operation outside of “normal” operation:
  - Normal operation: Baseline load, Peak sun hours 5 hours, average ambient temperature 25°C.
  - Peak summer conditions: Baseline load + 10%, Peak sun hours 5.5 hours, ambient temperature 42°C.
  - Rainy season conditions: Baseline load, Peak sun hours 4 hours, ambient temperature 25°C.

We first apply the power factor to the load. 3kWh / 0.75 \rightarrow 4kWh per day.

The wires between the homes will apply some degree of resistance and therefore necessitate more applied power to deliver the same amount of energy. In this example, we set these losses at 2.5% of the load being applied.

\[
\text{Losses from wiring} \approx 0.0025 \times 4\text{kWh} \rightarrow 100 \text{ Wh losses per day.}
\]

Each customer has some losses due to metering, which we approximate as 1W per customer.

\[
\text{Losses from metering} \approx 1\text{W} \times 20 \text{ customers} \times 24 \text{ hours} \rightarrow 480 \text{ Wh losses per day.}
\]

In class, we assume that the inverter works with roughly 90% efficiency. This factor is read from efficiency curves for the inverter in question, and will vary as a function of the total applied load; these efficiency curves can be found in literature and will experience greater losses as the load gets smaller. The losses will be equal to the load downstream of the inverter, i.e. the losses and loads already mentioned.

\[
\text{Power needed to get desired load output from inverter} \approx \frac{4\text{kWh} + 100\text{W} + 480\text{Wh}}{0.9} \rightarrow 5.09\text{kWh}
\]

Furthermore, in class we also assume a continuous, 10-watt general power loss due to overall inefficiencies within the system downstream of the inverter.

\[
\text{Power needed for inverter, with extra loss} = 5.09\text{kWh} + 10\text{W} \times 24 \text{ hours} \rightarrow 5.33\text{kWh per day.}
\]

If 75% of the load is applied through the battery, the amount of energy required from the photovoltaics to both charge the battery when it is not in use and to drive the remaining load as necessary will be higher than the load itself, due to the round-trip losses of the battery.

\[
\text{Power to be delivered by combined PV system} = (0.75 \times 5.33\text{kWh} / 0.8) + (0.25 \times 5.33 \text{kWh}) \rightarrow 6.32\text{kWh per day.}
\]

If the MPPT applies 4% power losses:

\[
\text{Power delivered by PV to battery and inverter} = 6.32\text{kWh} / 0.96 = 6.58 \text{ kWh per day.}
\]

To properly account for how many PV cells are necessary for operation, we now need to compare the output

The PV system will deviate from the power output listed in its spec sheet due to temperature, shading, and degradation effects. The Powerpoint lecture provides specs for the TrinaSolar TSM-PD14 module, for standard testing conditions and at NOCT conditions. Here, we will consider the module that has a max STC power output of 300W. Note that even between STC and NOCT conditions, a significant drop of power is observed. We consult the spec sheet of the solar module for NOCT and temperature deviations, and see that we have NOCT and thermal power losses of 45°C and \(-.44\%/{ }^\circ\text{C}\), respectively. We can now calculate losses due to temperature:
At 25°C: \[ T_{\text{cell}} = 25°C + \frac{\text{NOCT} - 20}{0.8} \] \[ T_{\text{cell}} = 56.25°C \] \[ \rightarrow 4.95\% \text{ power loss compared to spec values.} \]

At 42°C: \[ T_{\text{cell}} = 42°C + \frac{\text{NOCT} - 20}{0.8} \] \[ T_{\text{cell}} = 73.25°C \] \[ \rightarrow 12.43\% \text{ power loss compared to spec values.} \]

As stated in the question, we assume a 6.5% loss effect from dust coverage inefficiencies, which cause some shading loss effects over normal operation. (Note that these effects are not as dramatic as total coverage of parts of a module, which will only occur under aberrant or unusual circumstances compared to design conditions.)

Power loss at 25°C: 4.95% + 6.5% \[ \rightarrow 11.45\% \text{ power loss compared to spec values.} \]

Effective power to be generated by PV, 25°C: 6.58 kWh per day / 0.8855 \[ \rightarrow 7.43 \text{ kWh per day} \]

Power loss at 42°C: 12.43% + 6% \[ \rightarrow 18.43\% \text{ power loss compared to spec values.} \]

Effective power to be generated by PV, 42°C: 6.58 kWh per day / 0.8157 \[ \rightarrow 8.07 \text{ kWh per day} \]

This gives us the requirements for the number of modules required for the three listed conditions.

- “Baseline” conditions – 7.43 kWh per day to be generated / 5 PSH per day \[ \rightarrow 1.4kW \text{ output required.} \]
  - Module has spec. 218W output \[ \rightarrow 7 \text{ solar modules are needed.} \]
- “Rainy” conditions – 7.43 kWh per day to be generated / 4 PSH per day \[ \rightarrow 1.9kW \text{ output required.} \]
  - Module has spec. 218W output \[ \rightarrow 10 \text{ solar modules are needed.} \]
- “Summer” conditions – 8.07kWh + 10% kWh per day / 5.5PSH per day \[ \rightarrow 1.6kW \text{ output required.} \]
  - Module has spec. 218W output \[ \rightarrow 8 \text{ solar modules are needed.} \]
- *In-class example: 7.4*

Note that one can also calculate the effective power output of each module first and infer how many panels are needed for the required load, and get to the same answers. These answers indicate the total power requirement of the photovoltaic array.

With this in mind, we now need to size the battery. If we know that the battery needs to be able to discharge 75% of the daily load of the load downstream of the inverter (5.33kWh), then the battery needs to be able to discharge 4kWh per 24 hour period. The problem then arises for situations where the delivered amount of sunlight is less than the amount of sun we have sized for. Using the “rainy” conditions, and assuming a worst-case-scenario set of days where PSH goes from 4-3-1-1-5:

- After Day 1, we have the amount of sunlight that we have sized our system to, and the battery charges and discharges accordingly. At most it has discharged 4kWh of energy, but we have essentially broken even.
- After Day 2, we have one less effective hour of sunlight. The PV system is now generating 1.9kWh less power than it was originally supposed to, which must then be provided by the battery discharging.
- After Day 3, we have 3 fewer hours of sunlight and we now at 1.9kW * 3 hours = 5.7kWh deficit of generated energy in addition to the energy expended in Day 2. The battery must provide this difference.
- After Day 4, the same phenomenon occurs, incurring another 5.7kWh deficit of energy.
- After Day 5, we are operating at an excess of power, and can begin charging again.

The end result of all this is that after these four days, we have discharged a total of 1.9 + 5.7 + 5.7kWh = 13.3kWh before being recharged. The battery must therefore be sized such that it can handle this capacity of discharge. While degree of discharge and totally battery capacity are not the same, one can use this calculated amount of discharge as such as a first order approximation to achieve an estimate of the necessary energy storage capabilities of the battery. Therefore, under rainy conditions, if we expect this worst-case scenario to occur fairly often, we size the battery such that it is only discharging to half capacity rather than complete discharge, giving us a total battery size of 26.6kWh. If the battery operates at 48V, this equates to a battery capacity of 554 Ah. One can then arrange the modules comprising the PV system to deliver the necessary voltage to charge these batteries, at the required amount of power. (Note that voltage is additive in series, while amperage is additive in parallel.)