Sizing Energy Storage

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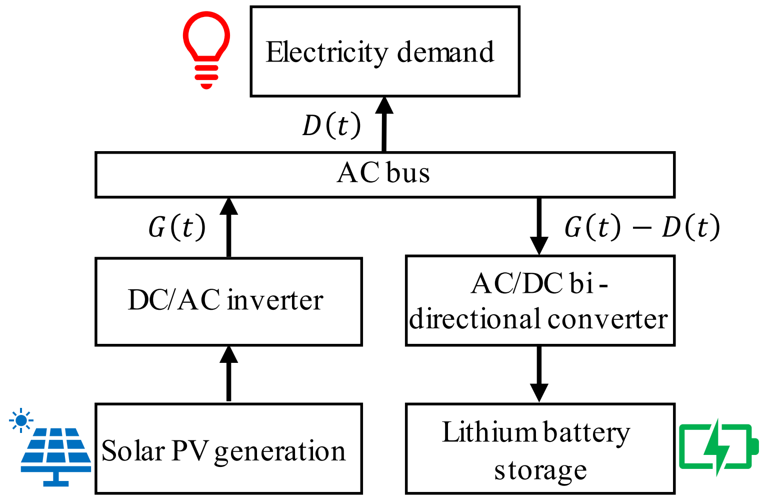
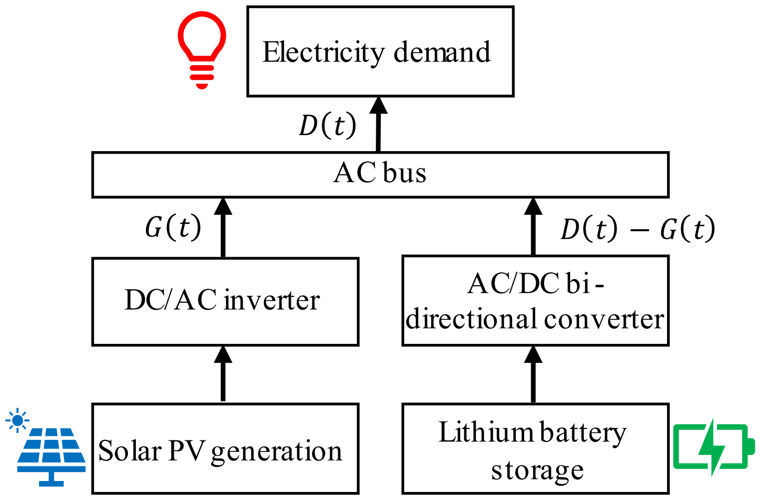
Storage Equation

(a) Surplus Generation: $G\,(t) - D(t) > 0$



$$\frac{dS(t)}{dt} = (G(t) - D(t))\eta_c$$

(b) Excess Demand: $G(t) - D(t) < 0$



$$\frac{dS(t)}{dt}\eta_d = -(D(t) - G(t))$$

$$\frac{dS(t)}{dt} = \frac{G(t) - D(t)}{\eta_d}$$

$$\frac{dS(t)}{dt} = (G(t) - D(t))\,\eta(t)\,, where: \eta(t) = \begin{cases} \eta_c\,, if\ G(t) - D(t) > 0, \\ \frac{1}{\eta_d}, if\ G(t) - D(t) < 0, \end{cases} \qquad (1)$$

G - generation power (kW)

D - demand power (kW)

S - storage energy level (kWh)

η_c - storage charge efficiency (%)

η_d - storage discharge efficiency (%)

t - time (hour)

a) Positive $G(t) - D(t)$ is surplus generation, which is charged into storage.
b) Negative $G(t) - D(t)$ is excess demand, which the storage needs to discharge energy to meet.

Equation (1) says:

$\frac{dS(t)}{dt}$ (rate of change in storage energy level) = $G(t) - D(t)$ (surplus generation or excess demand) $\times$ $\eta(t)$ (multiply by the charge efficiency or divide by the discharge efficiency)

Storage Profile

$$\frac{dS(t)}{dt} = \big(G(t) - D(t)\big)\,\eta(t)\,, where\!: \eta(t) = \begin{cases} \eta_c\,, if\ G(t) - D(t) > 0, \\ \dfrac{1}{\eta_d}, if\ G(t) - D(t) < 0, \end{cases} \qquad (1)$$

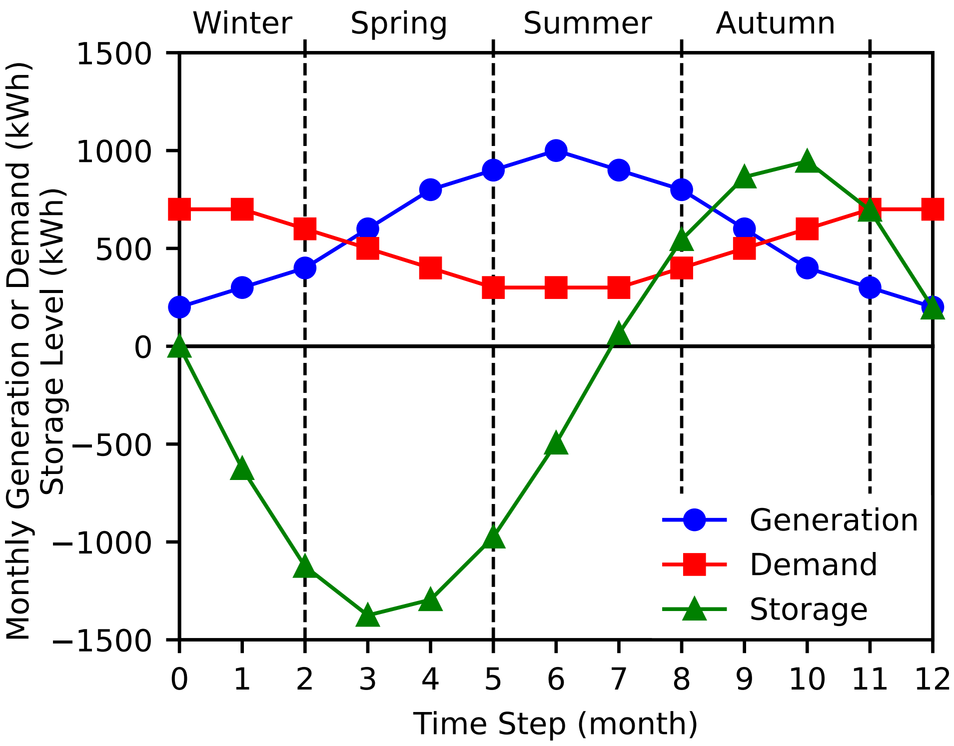
$$\int_t^{t+\Delta t} \frac{dS(t)}{dt} dt = \int_t^{t+\Delta t} \big(G(t) - D(t)\big)\,\eta(t)dt, \qquad \text{Integration}$$

$$S(t + \Delta t) - S(t) = \big(G(t) - D(t)\big)\,\eta(t)\Delta t, \qquad \text{Linear Approximatior}$$

$$S(t + \Delta t) = S(t) + \big(G(t) - D(t)\big)\,\eta(t)\Delta t\,, where\!: \eta(t) = \begin{cases} \eta_c\,, if\ G(t) - D(t) > 0, \\ \dfrac{1}{\eta_d}, if\ G(t) - D(t) < 0, \end{cases} \qquad (2)$$

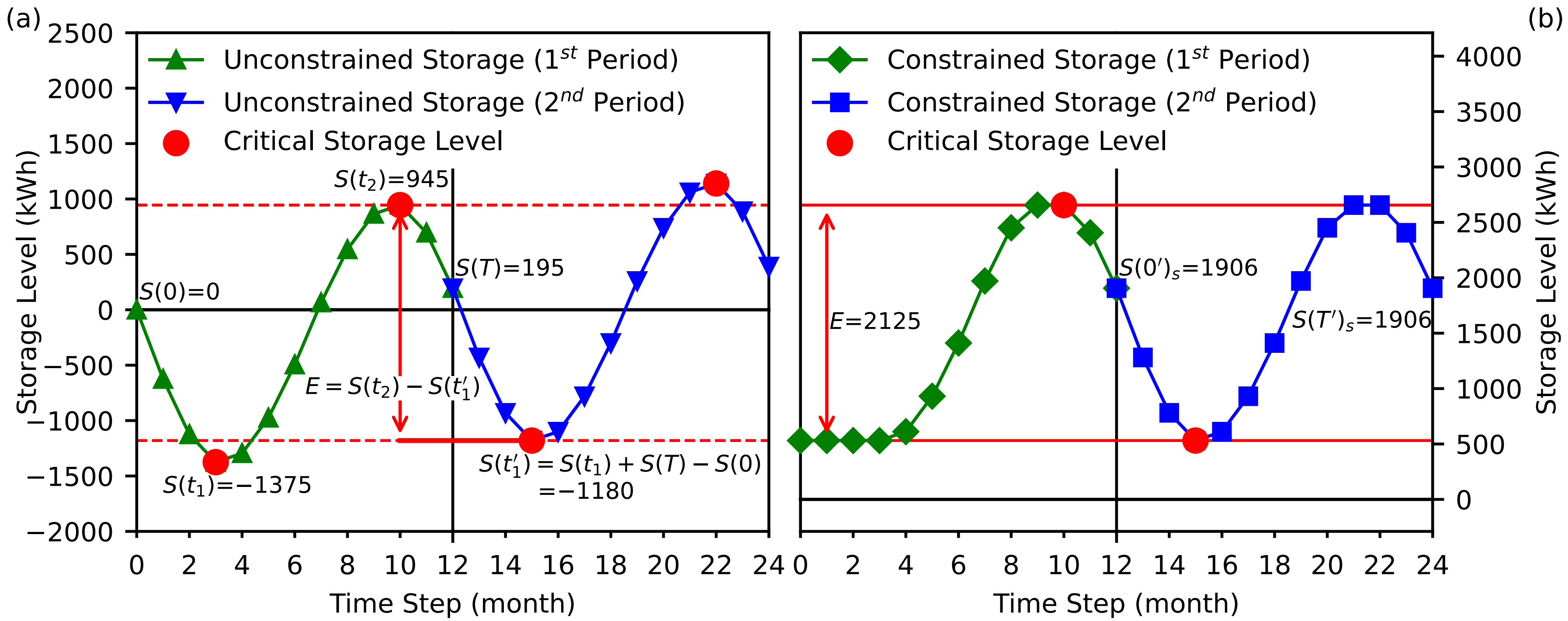
Equation (2) says:

$S(t + \Delta t)$ (storage energy level at a future time) =
$S(t)$ (current storage level) +
$G(t) - D(t)$ (surplus generation or excess demand) ×
$\eta(t)$ (multiply by the charge efficiency or divide by the discharge efficiency) ×
Δt (time interval)



- Solar generation is high during summer and low during winter in the northern temperate climate zone.
- Electricity demand is high during winter and low during summer in northern temperate climate.
- Storage profile decrease (discharge) during winter, and increase (charge) during summer.
- Storage profile increased between start and end, suggesting generation can support the system

Sizing Storage



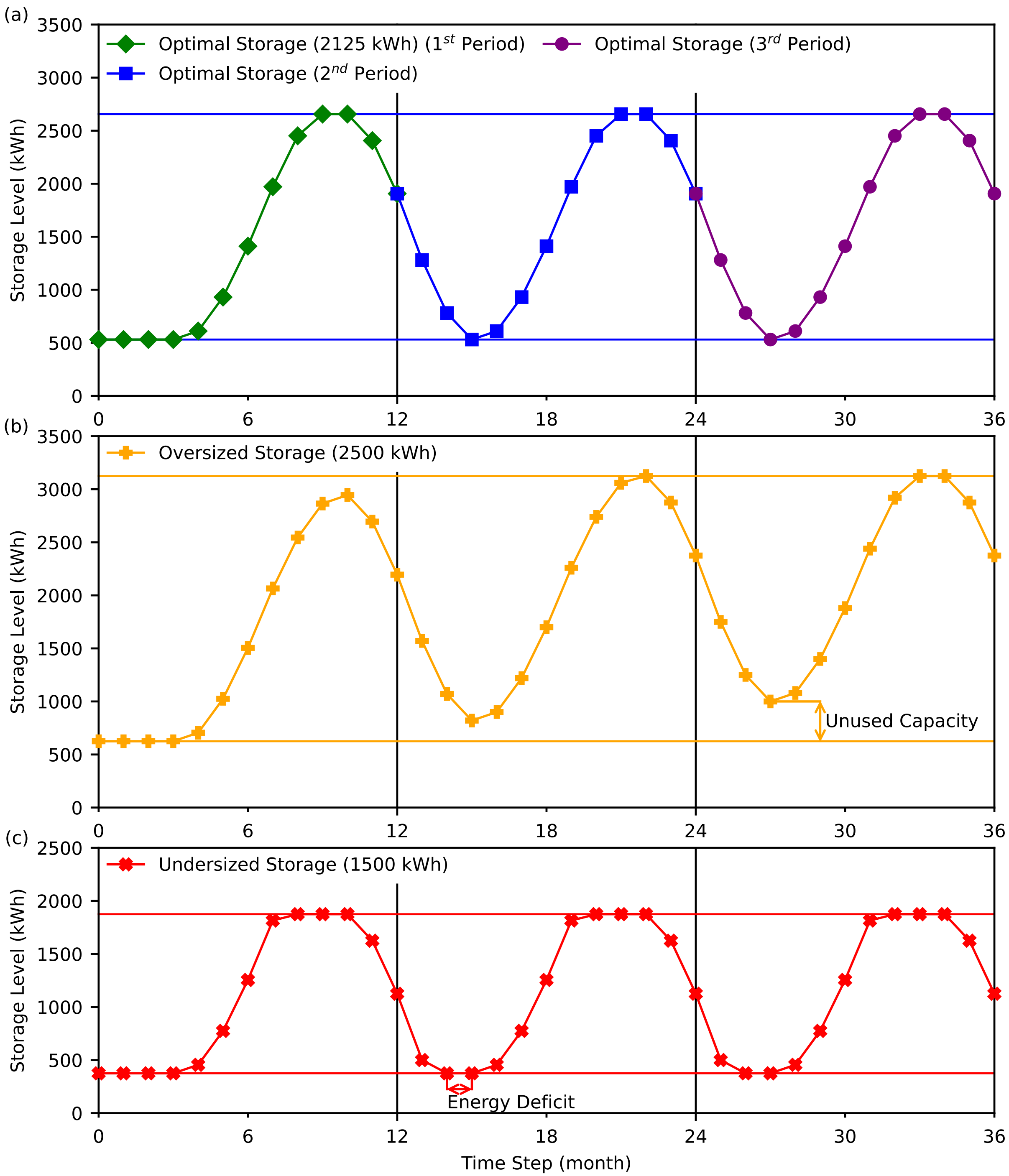
- Storage profile increased from start to end = storage has charged more energy than discharged = more surplus generation than excess demand = generation is large enough to support the system.
- When storage has charged more energy than discharged, size storage according to the largest cumulative discharge (largest decrease in the storage profile).
- When storage has discharged more energy than charged, size storage according to the largest cumulative charge (largest increase in the storage profile).

Size Comparison

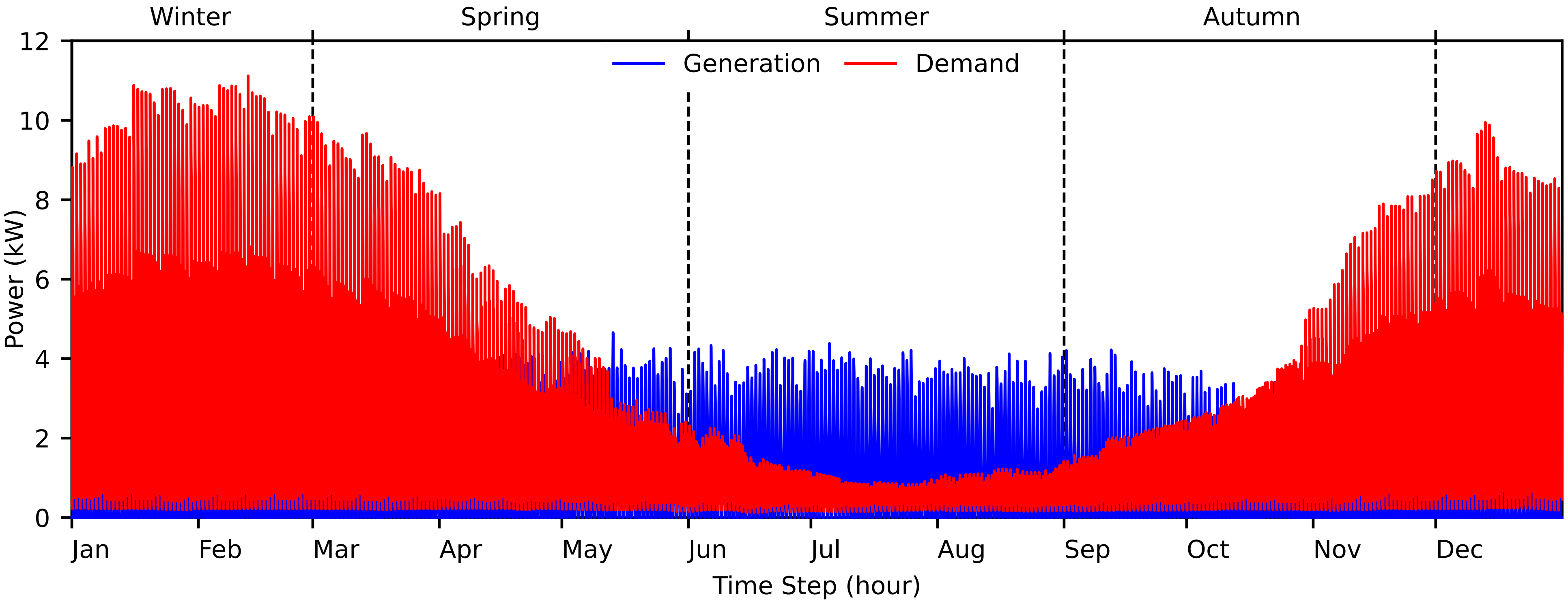
a) Optimally-sized storage does not have wasted capacity due to over-sizing, nor cause energy deficit due to under-sizing.

b) Over-sized storage never empties, so some of the storage capacity is wasted and never used.

c) Under-sized storage does not have enough capacity to accommodate the largest cumulative discharge. The storage empties early, which causes energy deficit.

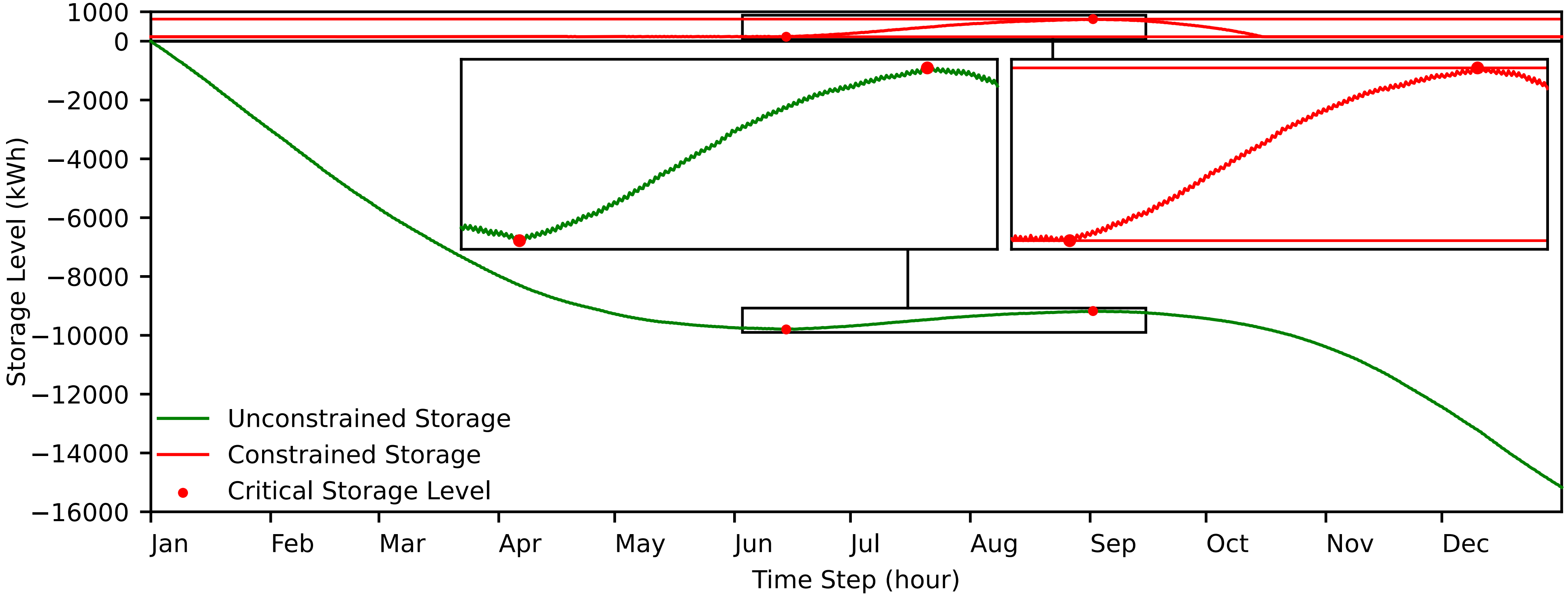


Case Study



- Solar generation from 7 kW of roof top solar PV panels, the generation duration is longer during summer, and peak generation is also higher.
- Electricity demand of a household in Oxfordshire, the demand is higher during winter, and the variation between peak and off-peak demands is also greater.
- Peak demand is greater than peak generation, and demand occurs at night while generation does not, which suggest generation cannot support the system to fully meet the demand.

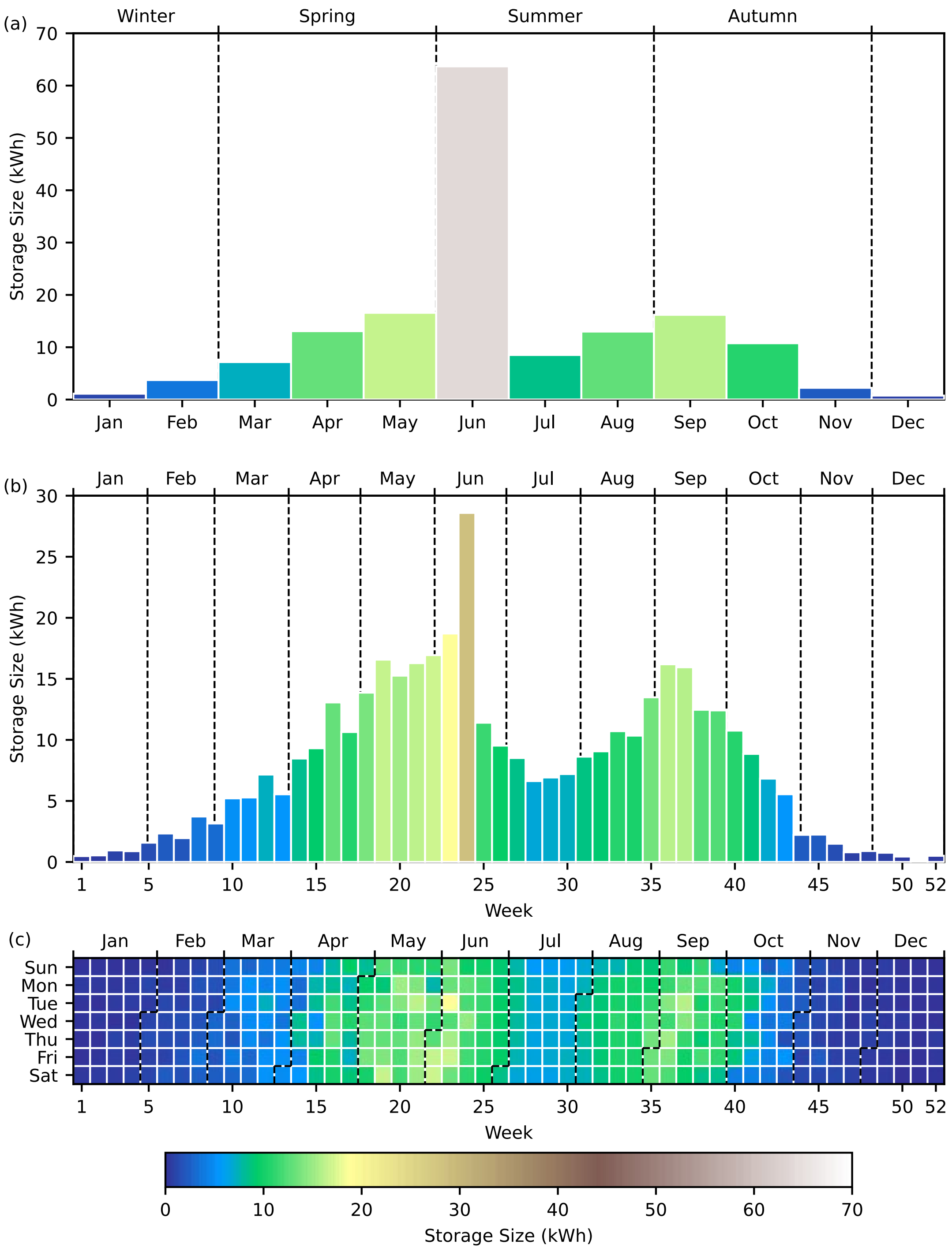
Storage Profile



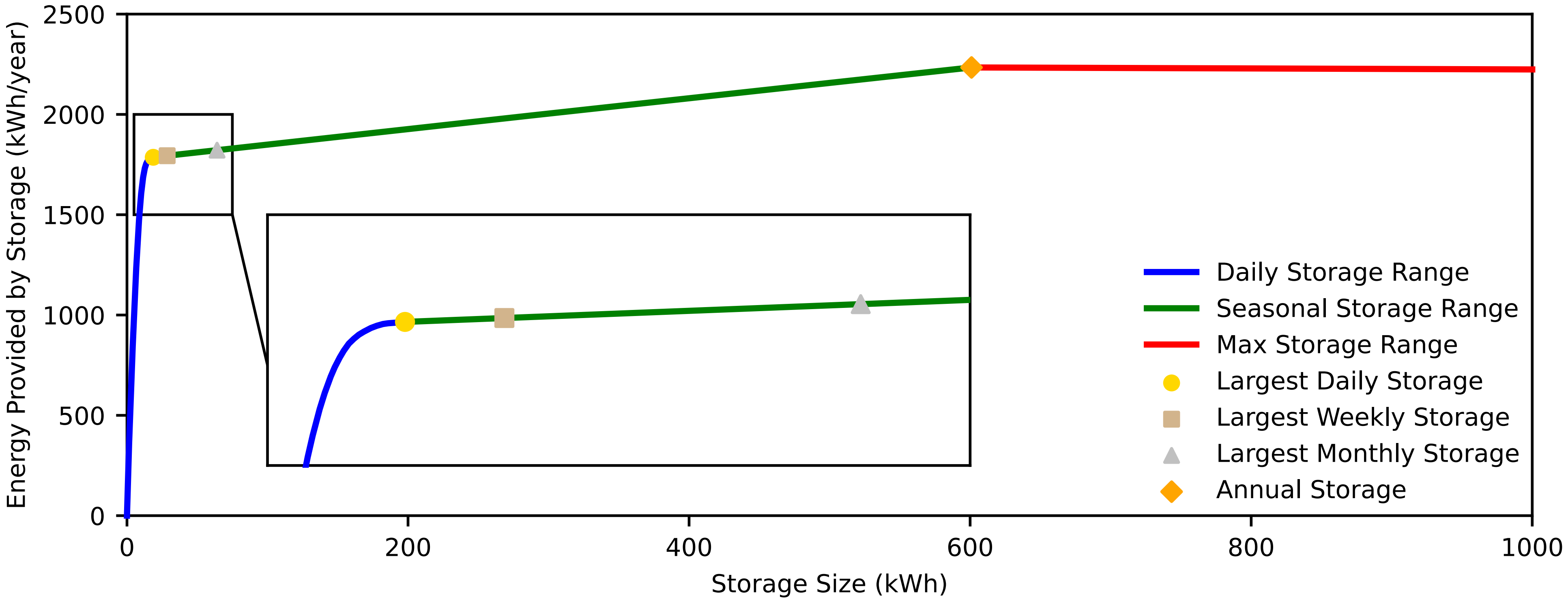
- When storage has discharged more energy than charged , size storage according to the largest cumulative charge (largest increase in the storage profile). The resulting storage size is 600 kWh.
- The curve shows seasonal storage charges during summer (Jun, Jul, Aug), then discharges during autumn (Sep, Oct).
- The small peaks and troughs in the zoomed-in curve show the daily storage charges from surplus solar generation during the day, and discharges at night to meet the excess demand.

Design Period

- The largest monthly, weekly, daily storage size are are 64 kWh, 29 kWh, and 19 kWh, respectively.
  - Longer design period yield larger storage size, as it include the storage from smaller design period. (Annual storage size includes both seasonal and daily storage)
- In this particular case study, peak summer and peak winter have smaller storage size, while early summer and early autumn have larger storage size.
  - High generation AND high demand require larger storage size.
  - Low generation OR low demand require smaller storage size.
    - Low generation does not produce enough surplus generation to charge the storage.
    - Low demand does not produce enough excess demand that needs storage



Size in Context



- Increasing storage size has a diminishing return on the additional storage energy provided to the system.
- The diminishing return thresholds are defined by the largest daily design and the annual design.
- In this particular case study, the largest daily design only requires 3% of the storage size of the annual design, but provides 80% of the energy provided by the annual design.

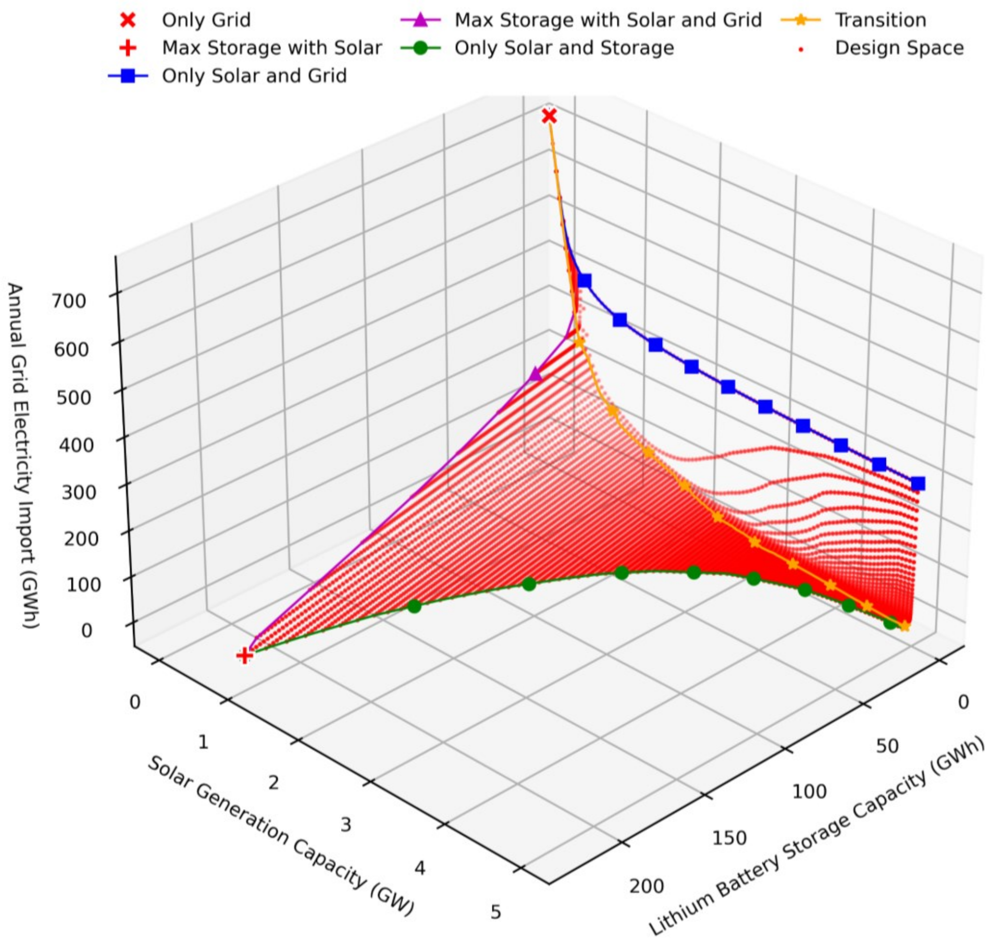
Key Takeaways

- Storage is sized according to the largest cumulative charge or discharge it can experience.
- Optimally-sized storage does not have wasted capacity due to over-sizing, nor cause energy deficit due to under-sizing.
- High generation and high demand require larger storage size, while Low generation or low demand require smaller storage size.
- Increasing storage size has a diminishing return on the additional storage energy provided to the system.



Applications

Sizing Solar PV and Storage



Storage Placement and Sizing