$$f = \frac{1}{sT+1} \qquad y = 1 - e^{\frac{-1}{T}} = 1 - e^{-1}$$

$$u(t) = \frac{1}{s} \qquad = 1 - 0.36788$$

$$Y(s) = \frac{1}{T}\cdot\frac{1}{s} - \frac{1}{T}\cdot\frac{1}{sT+1} \qquad = 0.63212$$

ECE 530: Contemporary Energy Applications

Energy Storage

Energy Storage

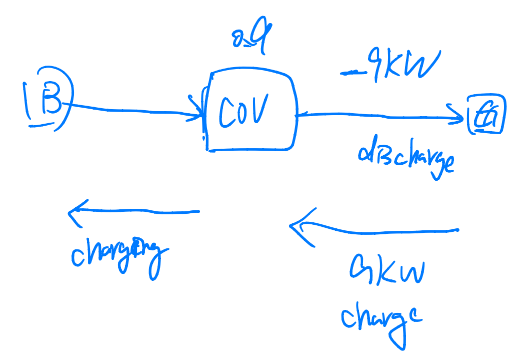
- Batteries
- Capacitors
- Compressed air
- Pumped hydro (potential energy)
- Flywheels (kinetic energy)

put a mass at high level
is nearly 100% energy storage

- Generally two components:
  - The storage medium itself
  - A converter to couple the storage medium to electricity
  - Each component can have its own dynamics and efficiencies

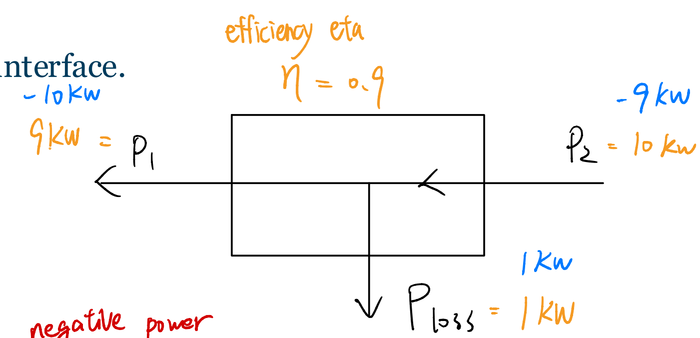
one way efficiency
~90 ~ 95%

round trip
~80%



Energy Storage Modeling

- Must be mindful to properly account for power loss in both directions: charge and discharge. Power flow is bi-directional, but power loss is unidirectional.
- Put loss in terms of power at one interface.



$$P_{loss} = P_2 - P_1$$

$$P_2 = P_{loss} + P_1$$

positive power

Discharging: $\underline{\underline{P_1 > 0}}$

$$P_1 = \eta \cdot P_2$$

$$= \eta \cdot (P_{loss} + P_1)$$

$$\rightarrow P_{loss} = P_1 \left(\frac{1}{\eta} - 1\right)$$

$P_2 = 10kW$, $P_1 = 9\,kW$

$$P_{loss} = 9\left(\frac{1}{0.9} - 1\right) = 1kW$$

negative power

Charging: $\underline{\underline{P_1 < 0}}$

$$P_2 = \eta \cdot P_1$$

$$P_{loss} + P_1 = \eta \cdot P_1$$

$$P_{loss} = P_1 (\eta - 1)$$

$$-10kW\,(0.9 - 1) = 1\,kW$$

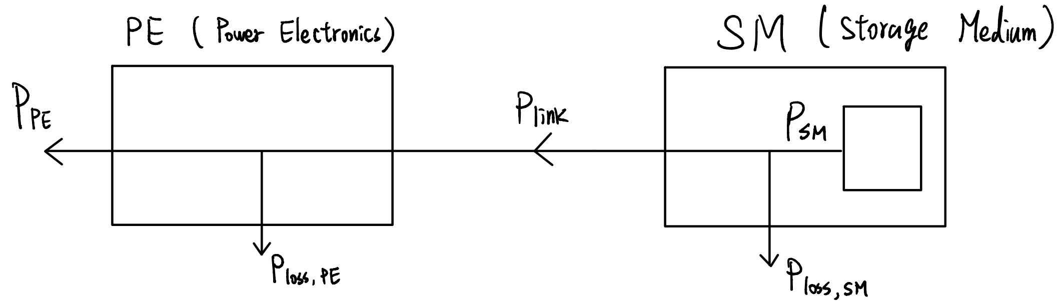
$$\boxed{P_{loss} \text{ is always positive !}}$$

one-way efficiency : $\eta = 0.9$

round-trip efficiency : $\eta^2 = 0.81$

Energy Storage Medium and Power Electronics

- Each component has its own efficiency and dynamics



$$P_{PE} = P_{link} - P_{loss,PE}$$

$$P_{link} = P_{SM} - P_{loss,SM}$$

$P_{PE} > 0$ (discharge)	$P_{PE} < 0$ (charge)
$P_{loss,PE} = P_{PE}\left(\frac{1}{\eta_{PE}} - 1\right)$	$P_{loss,PE} = P_{PE}(\eta_{PE} - 1)$

$P_{link} > 0$ (discharge)	$P_{link} < 0$ (charge)
$P_{loss,SM} = P_{link}\left(\frac{1}{\eta_{SM}} - 1\right)$	$P_{loss,SM} = P_{SM}(\eta_{SM} - 1)$

$$E_{SM} = -\int P_{SM} \cdot dt$$

$$SOC = \frac{E_{SM}}{E_{SM\_rated}}$$

State of Charge

(幾%電)

$$\left.\begin{array}{l} P_{link} = 9kW \\ P_{loss} = 1kW \end{array}\right\} 10kW$$

Energy Storage Protection

- Power and energy limits: keep power within rated values, and keep from overcharging or undercharging.

Power electronics power limits : P_{PE_upper}, P_{PE_lower}

if $\overset{12\,kW}{P_{PE\_ref}} > \overset{10\,kW}{P_{PE\_upper}} \Rightarrow P_{PE} = P_{PE\_upper}$

if $\overset{-11\,kW}{P_{PE\_ref}} < \overset{-10\,kW}{P_{PE\_lower}} \Rightarrow P_{PE} = P_{PE\_lower}$

if $SOC \leq 0$, then $P_{PE\_upper} = 0$ Not allow to discharge , P_{PE} should ≤ 0

if $SOC \geq 1$, then $P_{PE\_lower} = 0$ Not allow to Charge , P_{PE} should ≥ 0