Abstract
Techno-economic analyses of energy storage currently use constant-efficiency energy flow models. In practice, (dis)charge efficiency of energy storage varies as a function of state-of-charge, temperature, (dis)charge power. Therefore, using the constant-efficiency energy flow models will cause suboptimal results. This work focuses on incorporating non-linear energy flow models based on non-linear efficiency models in the revenue maximization problem of energy storage.

Energy Flow Model of Energy Storage
Energy flow models capture the energy flow, taking into account losses from energy conversion and storage self-discharge.

- Energy flow model with constant efficiencies:
  \[ S_t = p_d c_{\text{eff}} (p_{d+1} T, S_{t-1}) - p_f (p_{d+1} T, S_{t-1}) \Delta_t \]

- Energy flow model with efficiency functions:
  \[ S_t = p_d c_{\text{eff}} (p_{d+1} T, S_{t-1}) - p_f (p_{d+1} T, S_{t-1}) \Delta_t \]

- Non-linear efficiency functions: charge and discharge efficiencies are non-linear functions of SOC, T, P.

Challenges of Incorporating Non-linear Energy Flow Model
- Non-convexity: the revenue optimization problems become non-convex due to non-convex constraints.
- Complex dynamics: the state of charge is now a non-linear function of multiple variables.
- Expensive linearization: the non-linearity state-of-charge model can be linearized but introducing a large number of binary variables.

Dynamic Programming Approach
- Algorithm:
  - Define the nodes: define feasible SOC at t
  - Find (t-1,t) links: find policies that maximize $.
  - Find max sub-paths: memorize the state at t-1 that results in max $ at t
  - Find the solution: trace backward to find the solution.

Results
- Case study: 20MW/5MWh VRB for arbitrage and frequency regulation in PJM

- Observations:
  - Revenue estimation using non-linear efficiencies is \(~30\%\) lower in comparison with that when using constant efficiencies. This is because the non-linear model can capture the low-efficient operations when following regulation signals.
  - The DP computing time is polynomial to the number of time steps and exponential to the number of states.

Future Work
- Applying the non-linear energy model and DP approach in revenue evaluation of ES in different market areas.

Incorporating the uncertainties of forecast data into the optimization problem.