Optimal Strategic Sizing of Energy Storage Facilities In Restructured Electricity Markets

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Why is large-scale electric energy storage is of Interests today?

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Energy Storage Resurgence

- Observation #1:
  - We have known and used batteries for more than 100 years!
  - Pumped hydro was first deployed in Italy in 1890s.
  - Compressed air energy storage concepts have been around since late 19th century!

Energy storage technology and concepts are not new.

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Energy Storage Resurgence

- Observation #2:
  - Forecasts 1: Worldwide installed storage capacity for grid applications to grow from 538 MW in 2014 to 21 GW in 2024;
  - Forecasts 2: Grid-scale market value of energy storage systems will grow to \$67 billion in 2020 from \$16 billion in 2015;
  - Forecast 3: Worldwide revenue from energy storage will grow from \$15.6 million in 2014 to \$15.6 billion in 2024;
  - Forecast 4: Worldwide battery installations for grid applications to grow to about \$40 GW in 2023;

Regardless of how reliable those forecasts are, the trends are all in one direction → high growth over the years to come.

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Energy Storage Resurgence

If energy storage is not a new thing, why is it gaining a lot of attention today?

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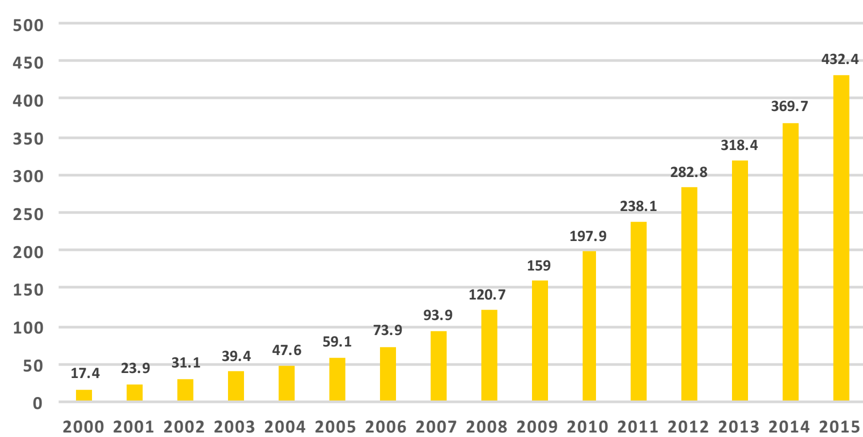
Energy Storage Resurgence

Global Installed Wind Capacity (GW)



Credit: Global Wind Energy Council

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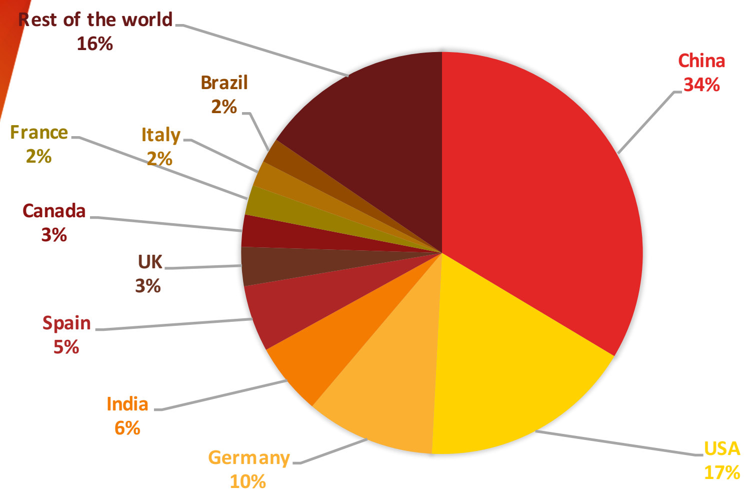
Energy Storage Resurgence

DISTRIBUTION OF WIND POWER INSTALLATIONS IN THE WORLD, 2015



Credit: Global Wind Energy Council

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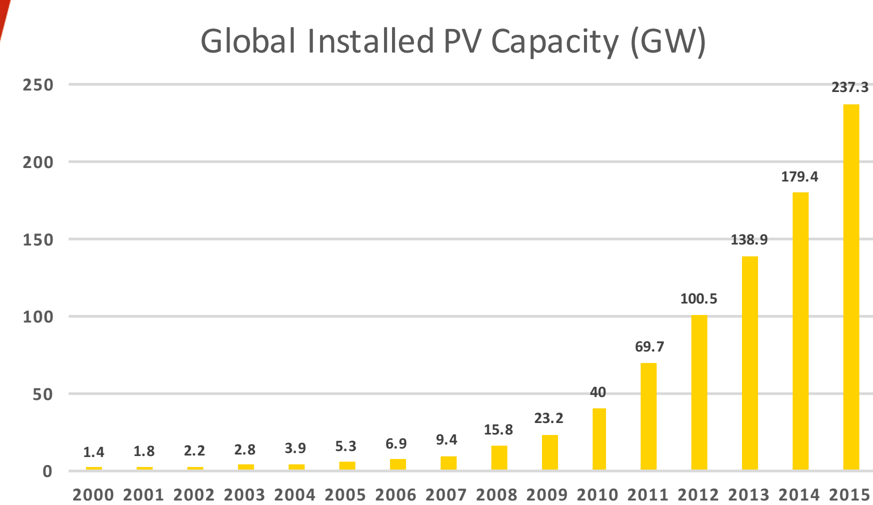
Energy Storage Resurgence



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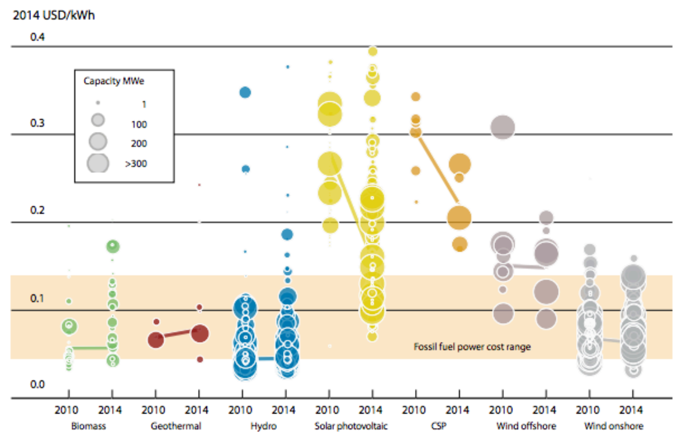
Energy Storage Resurgence

The levelised cost of electricity from utility-scale renewable technologies, 2010 and 2014



Credit: The International Renewable Energy Agency (2015)

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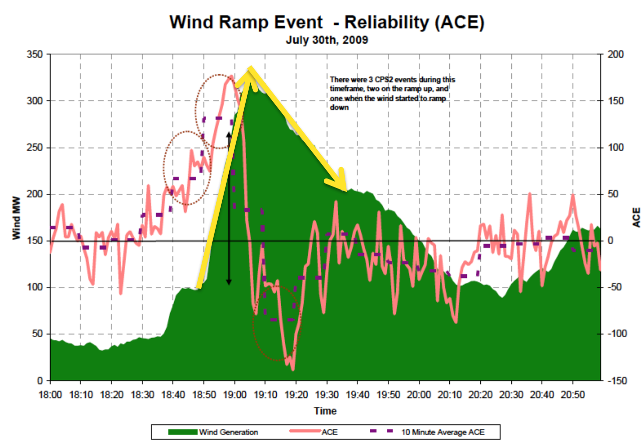
Energy Storage Resurgence

- When integrated in large-scale, *intermittent wind and solar power* could challenge power system operators.
  - We need solutions to deal with fast and unusually, unexpectedly large ramp events.



Source: Wind Integration Discussion Paper, May 7, 2010, AESO

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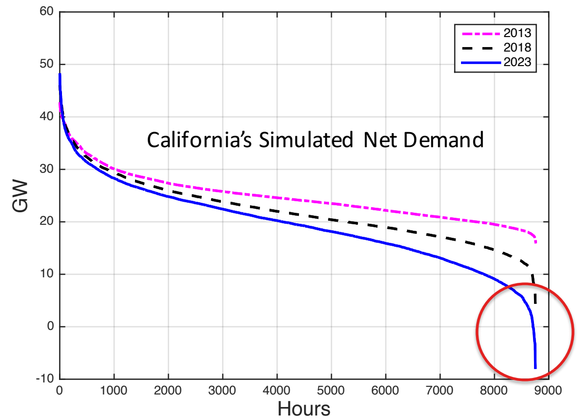
Energy Storage Resurgence

- With large amounts of intermittent resources, sometimes the energy generated from from wind/solar is more than the demand.



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Energy Storage Resurgence

- Significant growth in integration of intermittent resources:
  - New supply side variability
  - Over-supply of green energy
- Storage is the natural solution!

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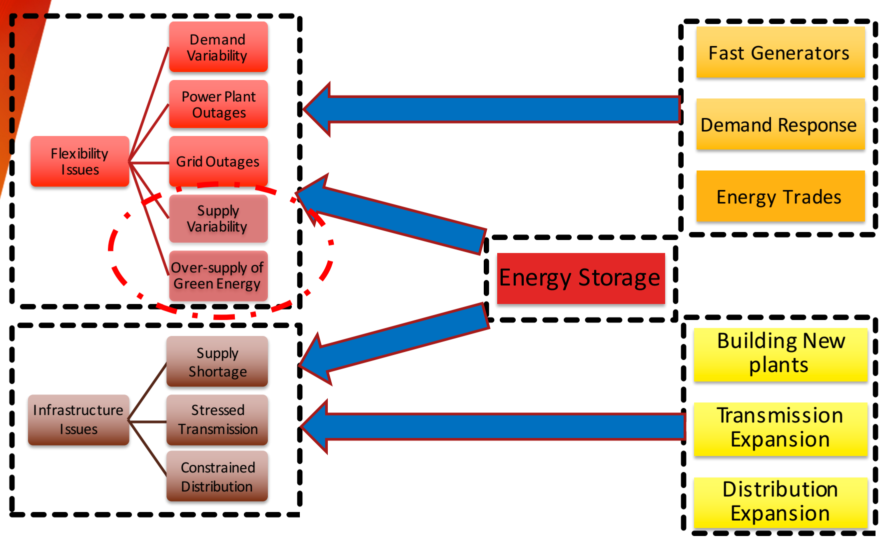
Energy Storage Resurgence



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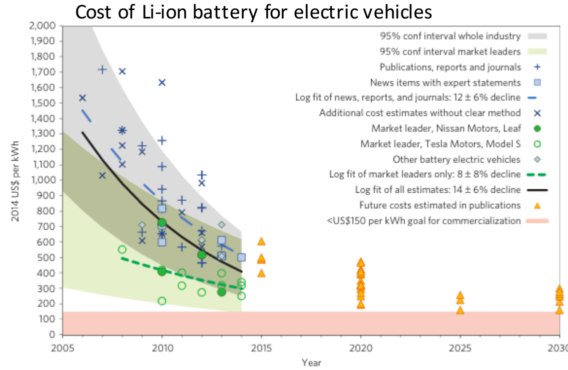
Energy Storage Resurgence

Other factors:
- Technological improvements and innovations on batteries, driven mainly by mobile applications (auto, consumer electronics, etc.).
- The price of battery energy storage has been declining and is expected to further decline in coming years.
- Regional factors,
- Strong industry advocacy

Cost of Li-ion battery for electric vehicles



Credit: Nature Climate Change, March 2015

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Power versus Energy

- Unit of Energy: Joule (J)
- Unit of Power: Watt (W) =Joule/Second (J/Sec)
- *Power* is the rate of delivering *Energy*
- Energy(J)=Power(J/sec)✕Time (sec)
- 1 Wh=(1 J/sec)(3600 sec)=3600 J
- 1 MWh=3.6 GJ

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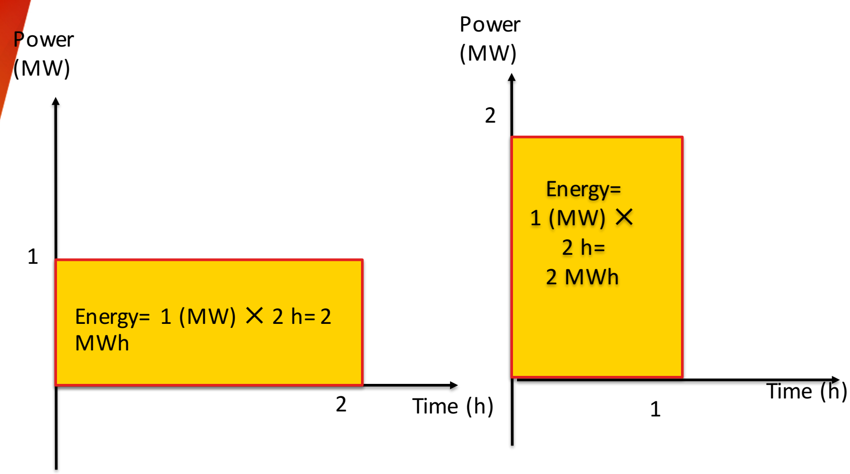
Power versus Energy



Energy delivered in both cases is 2 MWh

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Power versus Energy

- In conventional power generation and consumption systems:
  - The unit of time is typically one hour
  - 10 MW ✕ 1 hour= 10 MWh→10MW=10MWh
  - Sometimes MW and MWh are used interchangeably without paying too much attention! In fact, does not matter there!
- For energy storage systems, it is important to distinguish power from energy!

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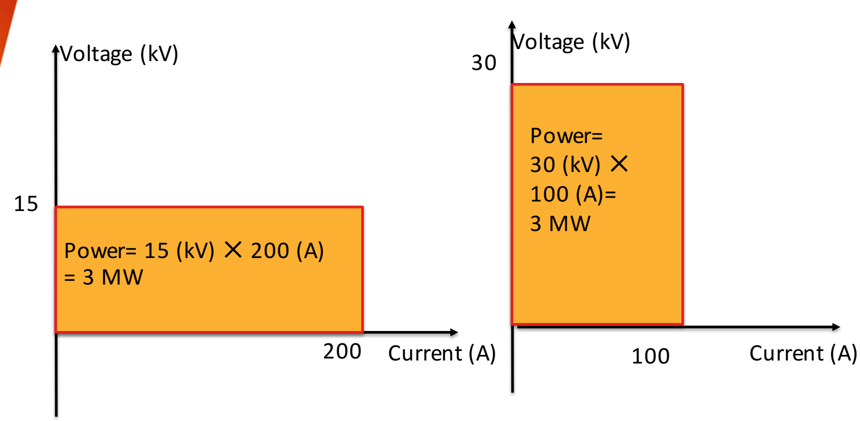
Power versus Energy

- Power (W)=Voltage (V) ✕ Current (Ampere)



Power available in both cases is 3 MW

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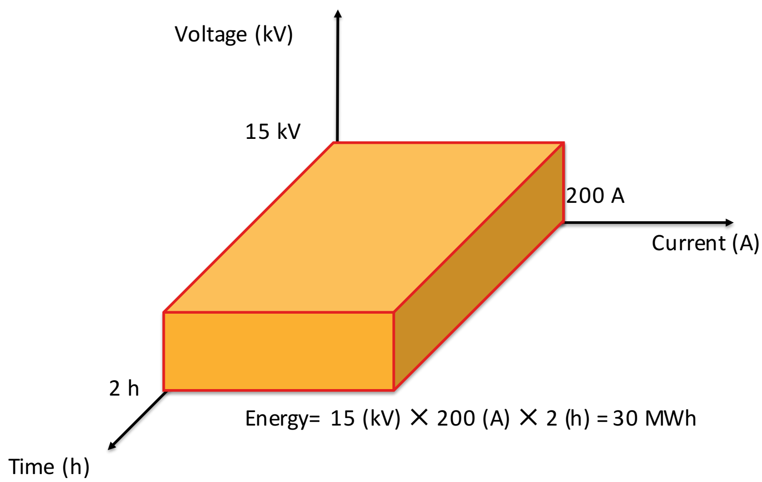
Power versus Energy

- Energy (Wh)=Voltage (V) × Current (Ampere) × Time



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Energy Storage Applications

- **Bulk Energy Services**
  - Time-shift
    - Arbitrage
    - Green energy management
    - Utility load management
  - Supply capacity
- **Ancillary Services**
  - Regulation
  - Spinning and non-spinning reserves
  - Ramp products
  - Voltage support
  - Black start
- **Transmission Services**
  - Transmission Deferral
  - Congestion support
  - Stability issues
  - Sub-synch resonance damping
- **Distribution Services**
  - Investment deferral
  - Voltage support
- **Behind-the-Meter**
  - Power quality
  - Power reliability
  - Energy time-shift
  - Demand charge management

Energy Storage Resurgence

- A few questions on energy storage need to be answered. In particular:
  - How to *optimally size* an energy storage facility for its power and energy capacities?
  - How to *optimally site* an energy storage facility within a power grid?
  - How to *optimally operate* an energy storage facility to gain maximum benefits?
  - In this presentation, we focus on *optimal sizing*.

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Optimal Energy Storage Sizing Problem Formulation

Storage Optimal Sizing: Setting the Stage

- The problem is solved from the investor's point of view, who is in the electricity market to make money from energy arbitrage. Other sources of revenue are not considered.
- The storage facility participates in a competitive electricity market along with other generation facilities and consumer entities.
- All suppliers must submit offers to sell into the market.
- The demand is price inelastic and is considered as system's net demand, i.e., the uncertainty in non-dispatchable units' outputs (e.g., wind power) is included in the uncertainty of net load.
- The Independent Market Operator clears the market with the objective of maximizing social welfare.
- This is a long-term planning problem that takes into account short term operation patterns.

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Storage Optimal Sizing: Setting the Stage

- Sources of uncertainty considered through scenarios:
  - Uncertainty in the hourly net demand in the market
  - Uncertainty in the price of other suppliers' offers
- Sources of uncertainty *not* considered:
  - Market exit and entry of major suppliers or consumers
  - Reliability of generation facilities or other physical systems
  - Policy and regulatory uncertainties

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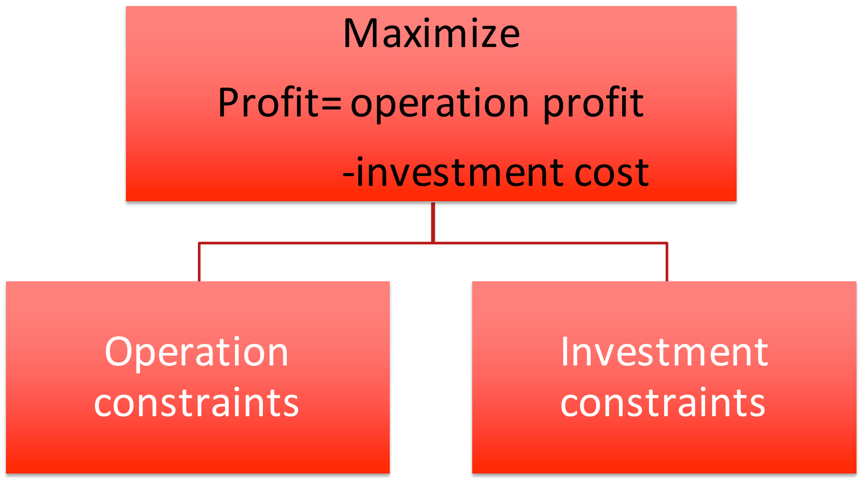
Optimal Storage Sizing Problem



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Optimal Storage Sizing Problem

$$\textbf{Max.} \quad -g^{inv} + \sum_{w=1}^{N_w}\sum_{r=1}^{N_r} \varphi_r . g_{w,r}^{opr} \qquad \text{(a.1)}$$

$$g^{inv} = \sum_{s=1}^{N_s} \left[AC_s^{res}.k_s^{res} + AC_s^{ch}.k_s^{ch} + AC_s^{dis}.k_s^{dis}\right] \qquad \text{(a.2)}$$

$$g_{w,r}^{opr} = \sum_{s=1}^{N_s}\sum_{t=1}^{N_t}\big[-(\lambda_{w,t,r} + MC_s^{ch}).p_{s,w,t,r}^{ch} + (\lambda_{w,t,r} - MC_s^{dis}).p_{s,w,t,r}^{dis}\big] \quad \forall w, \forall r \qquad \text{(a.3)}$$

$$0 \le k_s^{ch} \le K_s^{ch,max} \quad \forall s \qquad \text{(a.4)}$$

$$0 \le k_s^{dis} \le K_s^{dis,max} \quad \forall s \qquad \text{(a.5)}$$

$$0 \le k_s^{res} \le K_s^{res,max} \quad \forall s \qquad \text{(a.6)}$$

$$u_{s,w,t,r}^{ch} + u_{s,w,t,r}^{dis} + u_{s,w,t,r}^{idl} = 1 \quad \forall s, \forall w, \forall t, \forall r \qquad \text{(a.7)}$$

$$0 \le \overline{p}_{s,w,t,r}^{ch} \le k_s^{ch} \quad \forall s, \forall w, \forall t, \forall r \qquad \text{(a.8)}$$

$$0 \le \overline{p}_{s,w,t,r}^{ch} \le u_{s,w,t,r}^{ch}.M^{ch} \quad \forall s, \forall w, \forall t, \forall r \qquad \text{(a.9)}$$

$$0 \le \overline{p}_{s,w,t,r}^{dis} \le k_s^{dis} \quad \forall s, \forall w, \forall t, \forall r \qquad \text{(a.10)}$$

$$0 \le \overline{p}_{s,w,t,r}^{dis} \le u_{s,w,t,r}^{dis}.M^{dis} \quad \forall s, \forall w, \forall t, \forall r \qquad \text{(a.11)}$$

$$o_{s,w,t,r}^{ch} \ge 0 \quad \forall s, \forall w, \forall t, \forall r \qquad \text{(a.12)}$$

$$o_{s,w,t,r}^{dis} \ge 0 \quad \forall s, \forall w, \forall t, \forall r \qquad \text{(a.13)}$$

$$0 \le e_{s,w,t,r} \le k_s^{res} \quad \forall s, \forall w, \forall t, \forall r \qquad \text{(a.14)}$$

$$e_{s,w,t,r} = E_s^{ini} + \eta_s.p_{s,w,t,r}^{ch} - p_{s,w,t,r}^{dis} \quad \forall s, \forall w, t = 1, \forall r \qquad \text{(a.15)}$$

$$e_{s,w,t,r} = e_{s,w,(t-1),r} + \eta_s.p_{s,w,t,r}^{ch} - p_{s,w,t,r}^{dis} \quad \forall s, \forall w, \forall t > 1, \forall r \qquad \text{(a.16)}$$

$$e_{s,w,t,r} = E_s^{ini} \quad \forall s, \forall w, t = N_t, \forall r \qquad \text{(a.17)}$$

$$p_{s,w,t,r}^{ch}, p_{s,w,t,r}^{dis}, \lambda_{w,t,r} \in$$

$$\textbf{arg minimize} \quad \Bigg\{ \sum_{g=1}^{N_g} \beta_{g,w,t,r}.p_{g,w,t,r} - \sum_{s=1}^{N_s} o_{s,w,t,r}^{ch}.p_{s,w,t,r}^{ch} + \sum_{s=1}^{N_s} o_{s,w,t,r}^{dis}.p_{s,w,t,r}^{dis} - \sum_{d=1}^{N_d} U_{d,w,t}.p_{d,w,t,r} \qquad \text{(a.18)}$$

$$\sum_{s=1}^{N_s}[p_{s,w,t,r}^{ch} - p_{s,w,t,r}^{dis}] - \sum_{g=1}^{N_g} p_{g,w,t,r} + \sum_{d=1}^{N_d} p_{d,w,t,r} = 0 : \lambda_{w,t,r} \qquad \text{(a.19)}$$

$$0 \le p_{g,w,t,r} \le P_g^{max} : \mu_{g,w,t,r}^{min}, \mu_{g,w,t,r}^{max}; \quad \forall g \qquad \text{(a.20)}$$

$$0 \le p_{d,w,t,r} \le P_{d,w,t,r}^{max} : \mu_{d,w,t,r}^{min}, \mu_{d,w,t,r}^{max}; \quad \forall d \qquad \text{(a.21)}$$

$$0 \le p_{s,w,t,r}^{ch} \le \overline{p}_{s,w,t,r}^{ch} : \mu_{s,w,t,r}^{ch,min}, \mu_{s,w,t,r}^{ch,max}; \forall s \qquad \text{(a.22)}$$

$$0 \le p_{s,w,t,r}^{dis} \le \overline{p}_{s,w,t,r}^{dis} : \mu_{s,w,t,r}^{dis,min}, \mu_{s,w,t,r}^{dis,max}; \forall s \qquad \text{(a.23)}$$

$$\Bigg\} \; \forall w, \forall t, \forall r.$$

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Storage Optimal Sizing: Facility Operator's Investment Problem

- The main decisions variables are:
  - The size of charging component,
  - the size of discharging component
  - and the size of energy storage.
- May Include limitations on sizing, and budget and technology specific investment limitations.
- The decisions made in this problem set the base for the operation decisions.
- These decisions define investment costs.

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Storage Optimal Sizing: Facility Operator's Market Strategy Problem

- The storage facility operator's market strategy problem:
  - Is an hourly operation scheduling problem over a operation scheduling horizon (e.g., a week),
  - The decisions variables are the amount to charge, or to discharge or stay idle over a given hour,
  - When charging, both the price and quantity are decided.
  - When discharging, similarly, both price and quantity are decided.
  - State of charge equation models the physical operation.
  - The facility "balances the books" at the end of the operation scheduling horizon.
  - In a given time interval (e.g., an hour), the storage facility either offers to sell energy in discharging mode, bids to buy energy in charging mode, or stays idle→ makes the problem mixed integer.

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Storage Optimal Sizing: Market Operator's Clearing Problem

- The Market Operator's market clearing problem:
  - To receive hourly bids and offers from all entities and clear the market ,i.e., who will generate how much, who is in to consume how much, and what the market price would be for a given hour.
  - The total generated energy equals the total consumed energy, i.e., supply and demand are balanced.
- The price and quantities cleared in the market become the basis for calculating operation profit.
- Looking at the investment costs and operation profits, the optimal sizes and operation strategies are decided.

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Optimal Storage Sizing Problem

- The optimal sizing problem:
  - Is mixed integer linear,
  - Is a bi-level problem,
  - Becomes very large when many scenarios are considered in a real-life case study.
- Sizing decisions are *complicating variables* that if fixed, the problem can be decomposed in a master investment planning problem and a set of operation strategy/market clearing sub-problems.
- The problem is a good candidate for Benders Decomposition.

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The Proposed Solution

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Optimal Storage Sizing Problem-Solution

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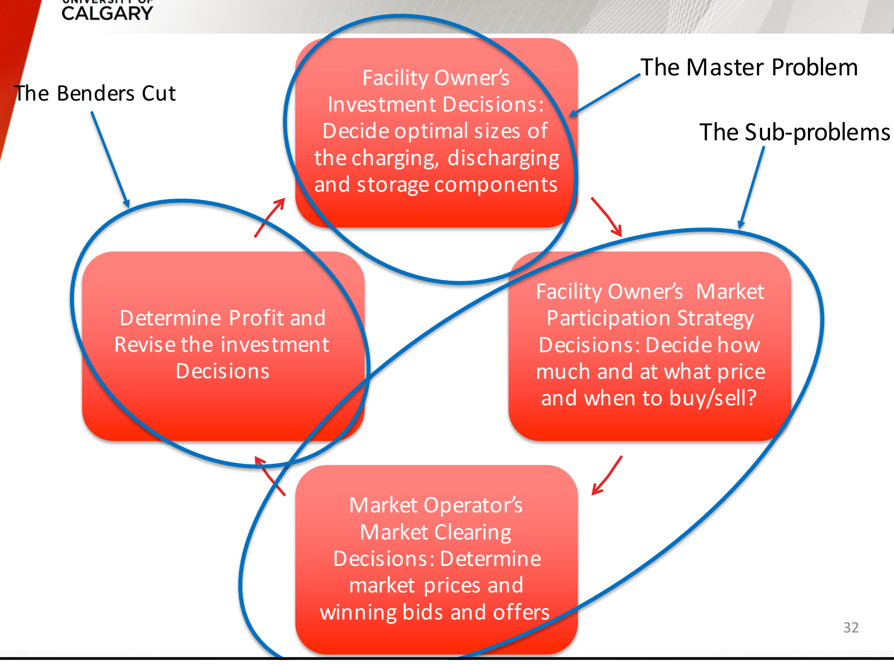

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Optimal Storage Sizing Problem-Solution

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The Master Problem

$$\textbf{Max.} \quad -\alpha^{(m)} - g^{inv,(m)} \quad \text{(b.1)}$$

$$(a.2),(a.4)-(a.6) \quad \text{(b.2)}$$

$$\alpha^{(m)} \geq \alpha^{min} \quad \text{(b.3)}$$

$$\alpha^{(m)} \geq -\sum_{w=1}^{N_w}\sum_{r=1}^{N_r}\varphi_r.\widehat{g}_{w,r}^{opr,(l)} + \sum_{w=1}^{N_w}\sum_{r=1}^{N_r}\varphi_r.\sum_{s=1}^{N_s}\pi_{s,w,r}^{ch,(l)}.(k_s^{ch,(m)} - \widehat{k}_s^{ch,(l)}) + \sum_{w=1}^{N_w}\sum_{r=1}^{N_r}\varphi_r.\sum_{s=1}^{N_s}\pi_{s,w,r}^{dis,(l)}.(k_s^{dis,(m)} - \widehat{k}_s^{dis,(l)}) + \sum_{w=1}^{N_w}\sum_{r=1}^{N_r}\varphi_r.\sum_{s=1}^{N_s}\pi_{s,w,r}^{res,(l)}.(k_s^{res,(m)} - \widehat{k}_s^{res,(l)}) \quad \forall l = \{1,2,...,m-1\}. \quad \text{(b.4)}$$

$$\left|\alpha^{(m)} + \sum_{w=1}^{N_w}\sum_{r=1}^{N_r}\varphi_r.g_{w,r}^{opr,(m)}\right| \leq \epsilon$$

The Sub-problems

$$\textbf{Max.} \quad g_{w,r}^{opr,(m)} \quad \text{(c.1)}$$

$$k_s^{ch,(m)} = \widehat{k}_s^{ch,(m)} : \pi_{s,w,r}^{ch,(m)} \quad \forall s \quad \text{(c.2)}$$

$$k_s^{dis,(m)} = \widehat{k}_s^{dis,(m)} : \pi_{s,w,r}^{dis,(m)} \quad \forall s \quad \text{(c.3)}$$

$$k_s^{res,(m)} = \widehat{k}_s^{res,(m)} : \pi_{s,w,r}^{res,(m)} \quad \forall s \quad \text{(c.4)}$$

$$(a.3),(a.7)-(a.23) \quad \text{(c.5)} \quad \Big\} \ \forall w, \forall r$$

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Optimal Storage Sizing Problem-Solution-The Sub-problems

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$$\textbf{Max.} \quad g_{w,r}^{opr,(m)} \quad \text{(c.1)}$$

$$k_s^{ch,(m)} = \widehat{k}_s^{ch,(m)} : \pi_{s,w,r}^{ch,(m)} \quad \forall s \quad \text{(c.2)}$$

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$$0 \leq \overline{p}_{s,w,t,r}^{dis} \leq u_{s,w,t,r}^{dis}.M^{dis} \quad \forall s, \forall w, \forall t, \forall r \quad \text{(a.11)}$$

$$o_{s,w,t,r}^{ch} \geq 0 \quad \forall s, \forall w, \forall t, \forall r \quad \text{(a.12)}$$

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$$e_{s,w,t,r} = e_{s,w,(t-1),r} + \eta_s.p_{s,w,t,r}^{ch} - p_{s,w,t,r}^{dis} \quad \forall s, \forall w, \forall t > 1, \forall r \quad \text{(a.16)}$$

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$$\sum_{s=1}^{N_s}[p_{s,w,t,r}^{ch} - p_{s,w,t,r}^{dis}] - \sum_{g=1}^{N_g}p_{g,w,t,r} + \sum_{d=1}^{N_d}p_{d,w,t,r} = 0 : \lambda_{w,t,r} \quad \text{(a.19)}$$

$$0 \leq p_{g,w,t,r} \leq P_g^{max} : \mu_{g,w,t,r}^{min}, \mu_{g,w,t,r}^{max}; \quad \forall g \quad \text{(a.20)}$$

$$0 \leq p_{d,w,t,r} \leq P_{d,w,t,r}^{max} : \mu_{d,w,t,r}^{min}, \mu_{d,w,t,r}^{max}; \quad \forall d \quad \text{(a.21)}$$

$$0 \leq p_{s,w,t,r}^{ch} \leq \overline{p}_{s,w,t,r}^{ch} : \mu_{s,w,t,r}^{ch,min}, \mu_{s,w,t,r}^{ch,max}; \forall s \quad \text{(a.22)}$$

$$0 \leq p_{s,w,t,r}^{dis} \leq \overline{p}_{s,w,t,r}^{dis} : \mu_{s,w,t,r}^{dis,min}, \mu_{s,w,t,r}^{dis,max}; \forall s \quad \text{(a.23)}$$

$$\Big\} \ \forall w, \forall t, \forall r.$$

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Optimal Storage Sizing Problem-Solution

- The sub-problem by itself is a non-linear, mixed-integer bi-level problem.
- By replacing the lower level problem with its KKT conditions, the sub-problems are transferred into Mathematical Problems with Mathematical Constraints (MPEC) problems, one per week, per scenario.
- Non-linearity comes from two sources:
  - Multiplication of price and quantity in the objective
  - Complementarity conditions
- Complementarity constraints are linearized using an auxiliary binary variable.
- The non-linearity of the objective is removed using strong duality.
- In order to get the sensitivities right, the sub-problems are solved, the binary variables are fixed at their optimal values, and then resolved to get the sensitivities.

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Optimal Storage Sizing Problem-Solution-The MILP sub-problems

$$\Bigg\{ \underset{\Xi_c}{\textbf{Max.}} \quad g_{w,r}^{opr,(m)} \qquad \text{(f.1)}$$

$$k_s^{ch,(m)} = \widehat{k}_s^{ch,(m)} : \pi_{s,w,r}^{ch,(m)} \quad \forall s \qquad \text{(f.2)}$$

$$k_s^{dis,(m)} = \widehat{k}_s^{dis,(m)} : \pi_{s,w,r}^{dis,(m)} \quad \forall s \qquad \text{(f.3)}$$

$$k_s^{res,(m)} = \widehat{k}_s^{res,(m)} : \pi_{s,w,r}^{res,(m)} \quad \forall s \qquad \text{(f.4)}$$

$$0 \le \overline{p}_{s,w,t,r}^{ch} \le \widehat{u}_{s,w,t,r}^{ch}.M^{ch} \quad \forall s, \forall t \qquad \text{(f.5)}$$

$$0 \le \overline{p}_{s,w,t,r}^{dis} \le \widehat{u}_{s,w,t,r}^{dis}.M^{dis} \quad \forall s, \forall t \qquad \text{(f.6)}$$

$$(a.3), (a.8), (a.10), (a.14) - (a.17), (a.19) - (a.23) \qquad \text{(f.7)}$$

$$\widehat{o}_{s,w,t,r}^{dis,(m)} - \lambda_{w,t,r}^{(m)} + \widehat{\mu}_{s,w,t,r}^{dis,max,(m)} - \mu_{s,w,t,r}^{dis,min,(m)} = 0 \quad \forall s, \forall t \qquad \text{(f.8)}$$

$$-\widehat{o}_{s,w,t,r}^{ch,(m)} + \lambda_{w,t,r}^{(m)} + \widehat{\mu}_{s,w,t,r}^{ch,max,(m)} - \mu_{s,w,t,r}^{ch,min,(m)} = 0 \quad \forall s, \forall t \qquad \text{(f.9)}$$

$$(d.5) - (d.6) \qquad \text{(f.10)}$$

$$\mu_{g,w,t,r}^{min,(m)} \ge 0, \mu_{g,w,t,r}^{max,(m)} \ge 0 \quad \forall g, \forall t \qquad \text{(f.11)}$$

$$\mu_{d,w,t,r}^{min,(m)} \ge 0, \mu_{d,w,t,r}^{max,(m)} \ge 0 \quad \forall d, \forall t \qquad \text{(f.12)}$$

$$\mu_{s,w,t,r}^{dis,min,(m)} \ge 0, \mu_{s,w,t,r}^{ch,min,(m)} \ge 0 \quad \forall s, \forall t \qquad \text{(f.13)}$$

$$\sum_{g=1}^{N_g} \beta_{g,w,t,r} \cdot p_{g,w,t,r}^{(m)} + \sum_{s=1}^{N_s} \widehat{o}_{s,w,t,r}^{dis,(m)} \cdot p_{s,w,t,r}^{dis,(m)} - \sum_{s=1}^{N_s} \widehat{o}_{s,w,t,r}^{ch,(m)} \cdot p_{s,w,t,r}^{ch,(m)} - \sum_{d=1}^{N_d} U_{d,w,t} \cdot p_{d,w,t,r}^{(m)} =$$

$$- \sum_{s=1}^{N_s} \left[\widehat{\mu}_{s,w,t,r}^{ch,max,(m)} . \overline{p}_{s,w,t,r}^{ch,(m)} + \widehat{\mu}_{s,w,t,r}^{dis,max,(m)} . \overline{p}_{s,w,t,r}^{dis,(m)} \right] - \sum_{g=1}^{N_g} \left[\mu_{g,w,t,r}^{max,(m)} . P_g^{max} \right] - \sum_{d=1}^{N_d} \left[\mu_{d,w,t,r}^{max,(m)} . P_{d,w,t,r}^{max} \right] \quad \forall t \qquad \text{(f.14)}$$

$$\Bigg\} \quad \forall w, \forall r.$$

$$g_{w,r}^{opr,(m)} = - \sum_{t=1}^{N_t} \sum_{s=1}^{N_s} \left[MC_s^{ch} . p_{s,w,t,r}^{ch,(m)} + MC_s^{dis} . p_{s,w,t,r}^{dis,(m)} \right] - \sum_{t=1}^{N_t} \sum_{g=1}^{N_g} \left[\beta_{g,w,t,r} \cdot p_{g,w,t,r}^{(m)} + \mu_{g,w,t,r}^{max,(m)} . P_g^{max} \right] + \sum_{t=1}^{N_t} \sum_{d=1}^{N_d} \left[U_{d,w,t} \cdot p_{d,w,t,r}^{(m)} - \mu_{d,w,t,r}^{max,(m)} . P_{d,w,t,r}^{max} \right] \forall w, \forall r.$$

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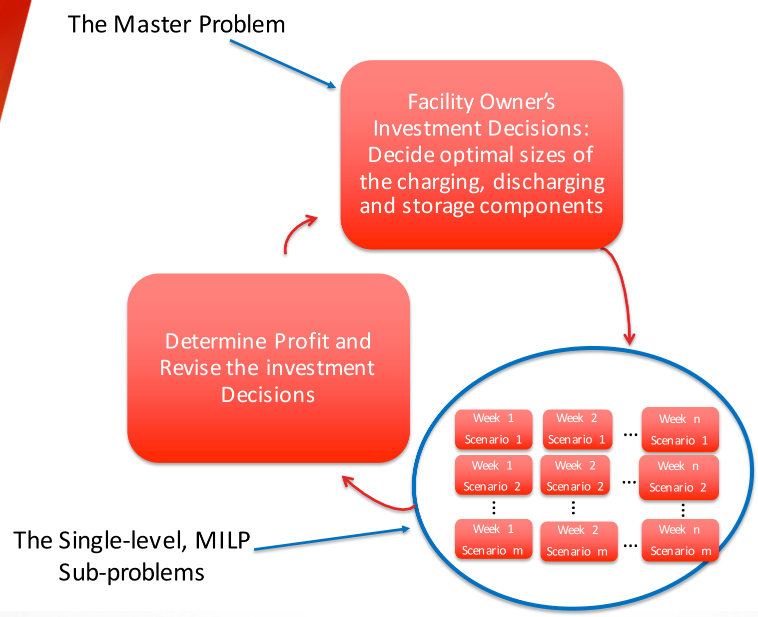
Solutions at a Glance



The Case Study

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The Case Study

- We applied this model to a pump-storage hydro facility planning in the context of Alberta's market.
- Real-life data from 2013 in Alberta's market was used.
- Hourly supply curves from the market for every single hour was constructed, with about 300 generators participating in the market.
- Typical parameters were used for operation and investment costs.
- The investment problem was solved for a year based on amortized costs and the principles of static investment analysis.
- Seven alternative look-ahead cases were considered in terms of load growth versus generation offer uncertainty.
- In each case, 3 net load growth scenarios and 5 generation offer scenarios were considered, i.e., 15 scenarios per case.
- Over a year, we are dealing with 168 million parameters and 84 million variables→ computational issue!
- We solved the problem over six typical weeks to cut computational time.

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The Case Study

	Load change (%)	Gen. offers change (%)	$k_s^{ch} = k_s^{dis}$ (MW)	k_s^{res} (MWh)
CASE1	+3,+4,+5	0,+5,+10,+15,+20	662	9853
CASE2	+1,+2,+3	0,+5,+10,+15,+20	577	6115
CAES3	+1,+2,+3	0,+2.5,+5,+7.5,+10	457	5627
CAES4	-0.01,0,+0.01	-0.02,-0.01,0,+0.01,+0.02	328	3177
CAES5	0,-1,-2	0,-2.5,-5,-7.5,-10	233	2005
CASE6	0,-1,-2	0,-5,-10,-15,-20	141	1167
CASE7	-1,-2,-3	0,-5,-10,-15,-20	85	830

Mean price impact during charging hours (%)	Mean price impact during discharging hours (%)	Running time (h)	Benders iteration
+19.71	-22.30	5:45	8
+14.98	-19.83	5:36	8
+13.99	-18.41	5:30	8
+10.21	-15.96	4.12	8
+8.51	-14.04	3:46	9
+7.22	-10.94	3:54	8
+4.33	-8.74	3:21	7

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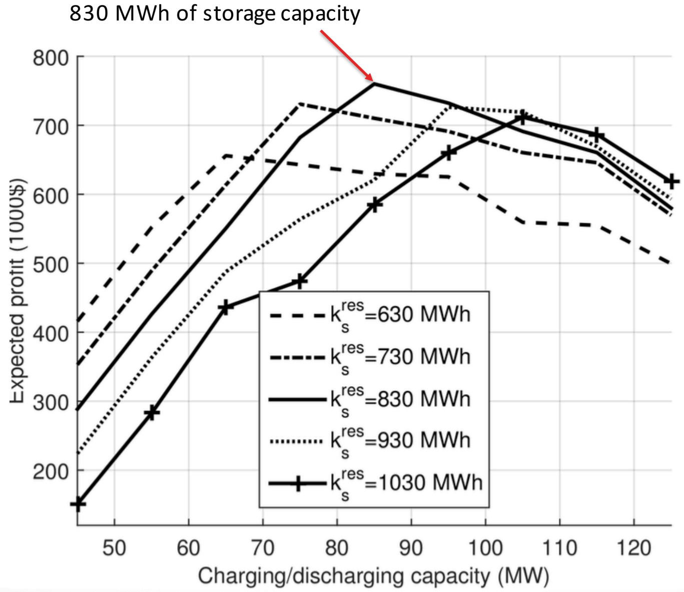
Optimality Check

Optimal solution for CASE7 (85 MW of charging/discharging capacity and 830 MWh of storage capacity



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Optimal Strategic Sizing of Energy Storage Facilities In Restructured Electricity Markets

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