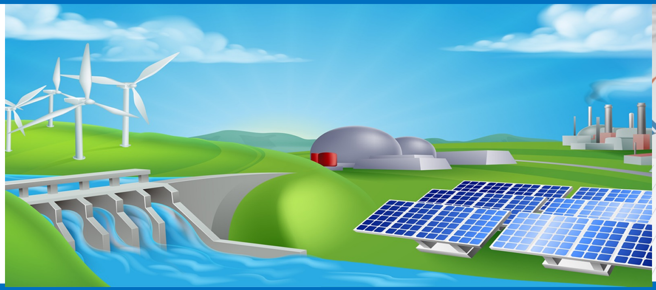



ECONOMICS OF MODERN POWER SYSTEMS

M5 –Distributed Energy Resources– Energy Storage

Prof. Luana Medeiros Marangon Lima, Ph.D.

Learning Goals

- DER: Energy Storage
  - Technologies
  - Grid applications
- Storage management
  - Intro to solving LPs in Python
  - case study for a customer with (PV + battery) system

Recap: Distributed Energy Resources (DER)

- Small-scale power generation sources located close to where electricity is used
- Provide an alternative or enhancement of the traditional electric power grid
- Technologies
  - **Energy Generation** (e.g., fuel cells, microturbines, PVs)
  - **Storage systems**
  - *Demand Side Management*
  - *Energy Efficiency*

Energy Storage Service Provision

“A next-generation smart grid without energy storage is like a computer without a hard drive: severely limited.”

- Katie Fehrenbacher, GigaOm

Electrical Energy Storage Technologies

Mechanical
- Pumped Hydro Storage
- Compressed Air Energy Storage
- Flywheels

Electrochemical Energy (batteries)
- Conventional Battery
- Rechargeable batteries
- Flow Batteries

Electromagnetic
- Capacitors
- Supercapacitors
- Superconducting Magnetic Energy Storage

Chemical Energy Storage
- Hydrogen storage with fuel cells

High Temperature Thermal
- Heat storage

Applications of Energy Storage to PS

- Energy storage allows the grid to run more efficiently, i.e.,
  - lower prices
  - less emissions
  - more reliable

- Benefits
  - Store energy produced by sun and wind and deliver it ON DEMAND
  - Create a continuous reliable stream of power throughout the day
  - Improve quality of power by providing frequency regulation
  - Allow power to be produced when cheapest and most efficient
  - Uninterruptable source of power for critical infrastructures

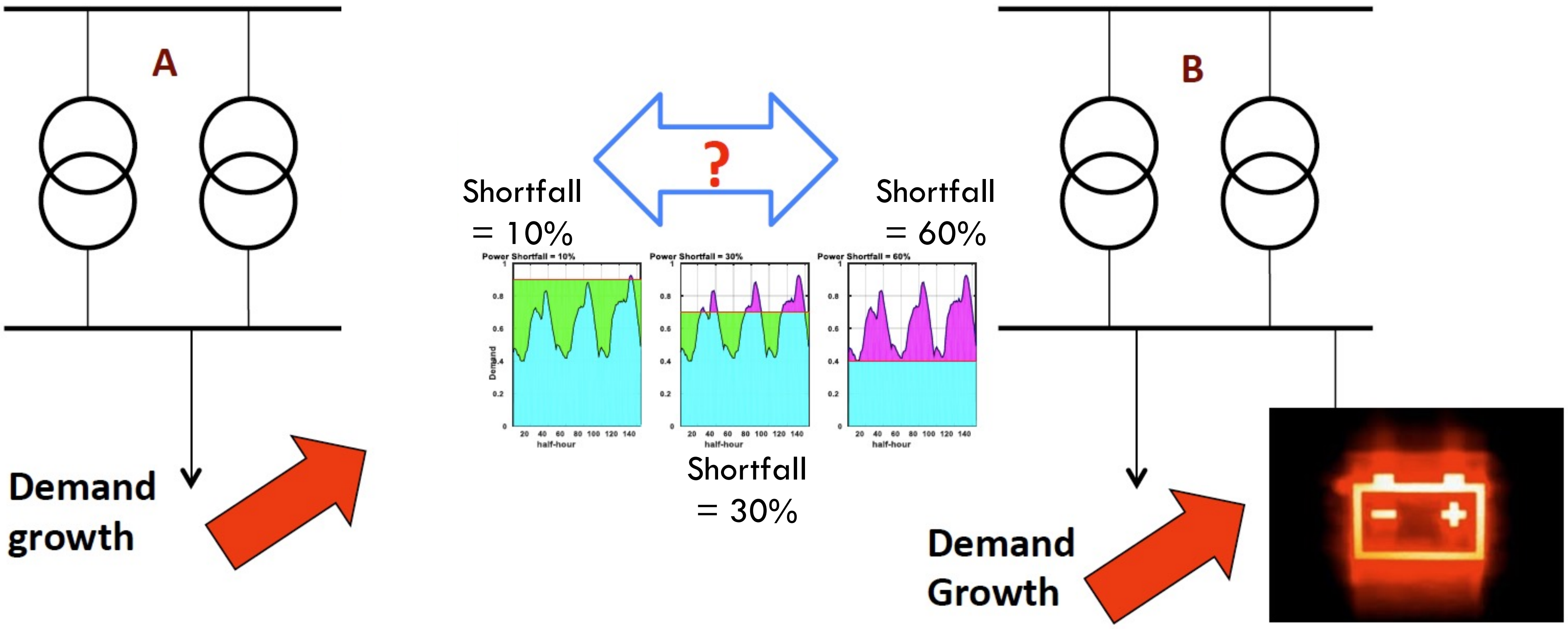
Applications of Energy Storage to PS

Renewable Support	Investment Deferral	Ancillary Services	Load Management
Renewable Energy Time Shift	Electric Supply Capacity Deferral	Area Regulation	Electric Energy Time Shift
Renewables Capacity Firming	T&D Upgrade Deferral	Load Following	Transmission Congestion Relief
Wind Generation, Grid Integration, Short Duration	Substation Onsite Power	Electric Supply Reserve Capacity	Time-of-Use Energy Cost Management
Wind Generation, Grid Integration, Long Duration	Electric Service Reliability	Voltage Support	Demand Charge Management
		Electric Service Power Quality	
		Transmission Support	

Multi-service provision by storage

- Arbitrage
  - Participate in day-ahead energy market
- Balancing services
  - Participate in real-time balancing market
- Frequency regulation services
  - Providing primary/secondary/tertiary freq regulation services
- Contribution to meeting peak demand
  - Reducing need for peaking plant
- Network support
  - Reducing need for network reinforcement
- Low carbon generation mix
  - Meeting carbon targets with minimum LC generation
- Option value
  - Providing flexibility to deal with uncertainty

Avoiding network reinforcement



Energy Storage Technologies for Grid Applications

Energy Storage technologies for Grid Applications

- Solid State Batteries – chemistry batteries and capacitors
- Flow Batteries – electrolyte solution for longer cycle
- Flywheels – mechanical devices that harness rotational energy to deliver instantaneous electricity
- Compressed Air Energy Storage (CAES) – create a potent energy reserve
- Thermal – capture heat and cold to create energy
- Pumped Hydro-Power – large reservoir of energy with water

Solid State Batteries

- Battery first created by Alessandro Volta in 1800
- Definition: device consisting of electromechanical cells that convert stored chemical energy into electrical energy
- Each cell contains a positive and a negative terminal
- Electrolytes allow ions to move between electrodes and terminal which allow current to flow out to perform work
- Example: Lead-acid, Lithium Ion, Nickel-Cadmium, Capacitors

Applications of Batteries to PS

Selected lead–acid battery energy storage facilities

Name/locations	Characteristics	Application area
BEWAG, Berlin	8.5 MW/8.5 MW h	Spinning reserve, frequency control
Chino, California	10 MW/40 MW h	Spinning reserve, load leveling
PREPA, Puerto Rico	20MW/14 MW h	Spinning reserve, frequency control
Metlakatla, Alaska	1 MW/1.4 MW h	Enhancing stabilization of island grid
Kahuku Wind Farm, Hawaii	15 MW/ 3.75 MW h	Power management, load firming, grid integration
Notrees EES project, U.S.	36 MW/24 MW h	Solving intermittency issues of wind energy

Source: X Luo et al., Applied Energy 137 (2015) 511-536

Flow Batteries

- Difference from conventional batteries
  - Energy is stored as electrolyte instead of electrode material
- a.k.a. Redox Flow Batteries (RFB)
  - **Red**uction and **ox**idation reactions
  - Power rating from 10kW – 10 MW
    - Storage duration 2 to 10 hours
  - Common
    - Vanadium Redox
    - Zinc-Bromine

Applications of Flow Batteries to PS

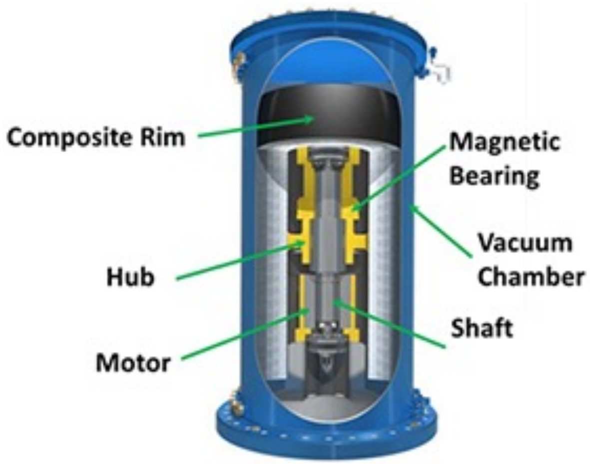
Table 6
Selected vanadium redox flow battery energy storage facilities

Name/locations	Power/capacity	Application area
Edison VRB EES facility, Italy	5 kW, 25 kW h	Telecommunications back-up application
Wind power EES facility King Island, Australia	200 kW, 800 kW h	Integrated wind power, foil fuel energy with EES
Wind Farm EES project, Ireland	2 MW, 12 MW h	Wind power fluctuation mitigation, grid integration
VRB EES facility installed by SEI, Japan	1.5 MW, 3 MW h	Power quality application
VRB facility by PacifiCorp, Utah, U.S.	250 kW, 2 MW h	Peak power, voltage support, load shifting
VRB EES system build by SEI, Japan	500 kW, 5 MW h	Peak shaving, voltage support

Source: X Luo et al., Applied Energy 137 (2015) 511-536

Flywheel energy storage system (FES or FESS)

- FES works by accelerating a rotor (flywheel) to a very high speed and maintaining the energy in the system as rotational energy
- Integrated motor-generator
- The energy is discharged by drawing down the kinetic energy using the same motor-generator
- They have very fast response and ramp rates
  - Frequency regulation



Source: Beacon Power, LLC

Applications of FES to Power System

- Flywheel plant in Stephentown, NY (Beacon Power) – 2 years of commercial operation

In general:

Low operational costs

Fast discharge

Low storage capacity

Compressed Air Energy Storage (CAES)

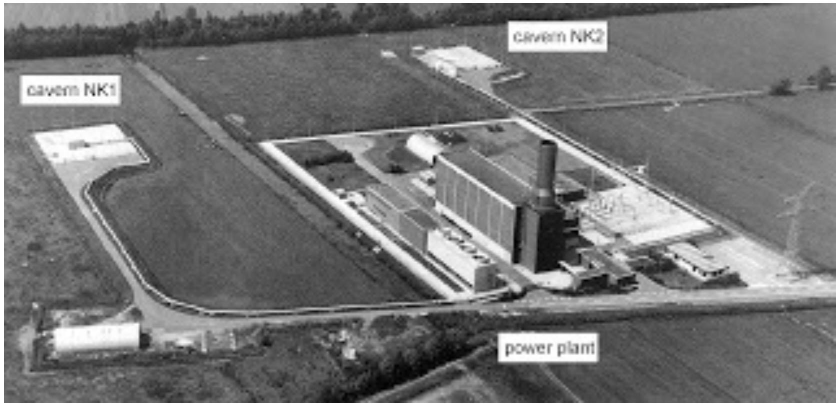
- "Similar to pumped hydro", but instead of water, air is compressed using "energy excess" and stored underground
- When electricity is needed, pressurized air is heated and expanded in a turbine driving a generator for power production
- Potential for small-scale, on-site energy storage solutions
- And also large installations that can provide immense energy reserves for the grid
- The first utility-scale CAES system was put in place in the 1970's with over 290 MW nameplate capacity

Advantages of CAES

- Price arbitrage
- Balancing energy
- Higher utilization and greater integration of renewable energy
- Ancillary services (regulation, spinning reserve, MVAR generation)
- Provision of black start services

Applications of CAES to PS

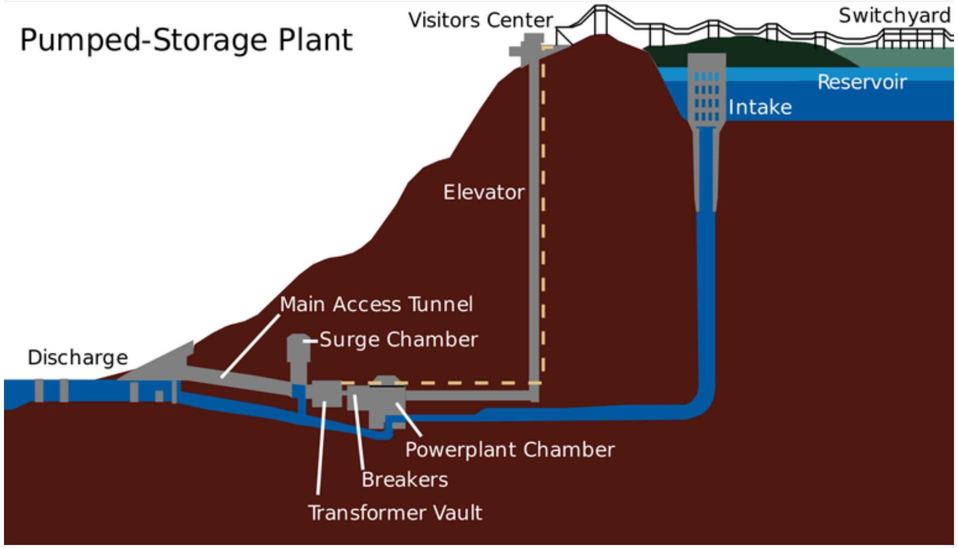
- 110 MW CAES system, MacIntosh Alabama, 1991



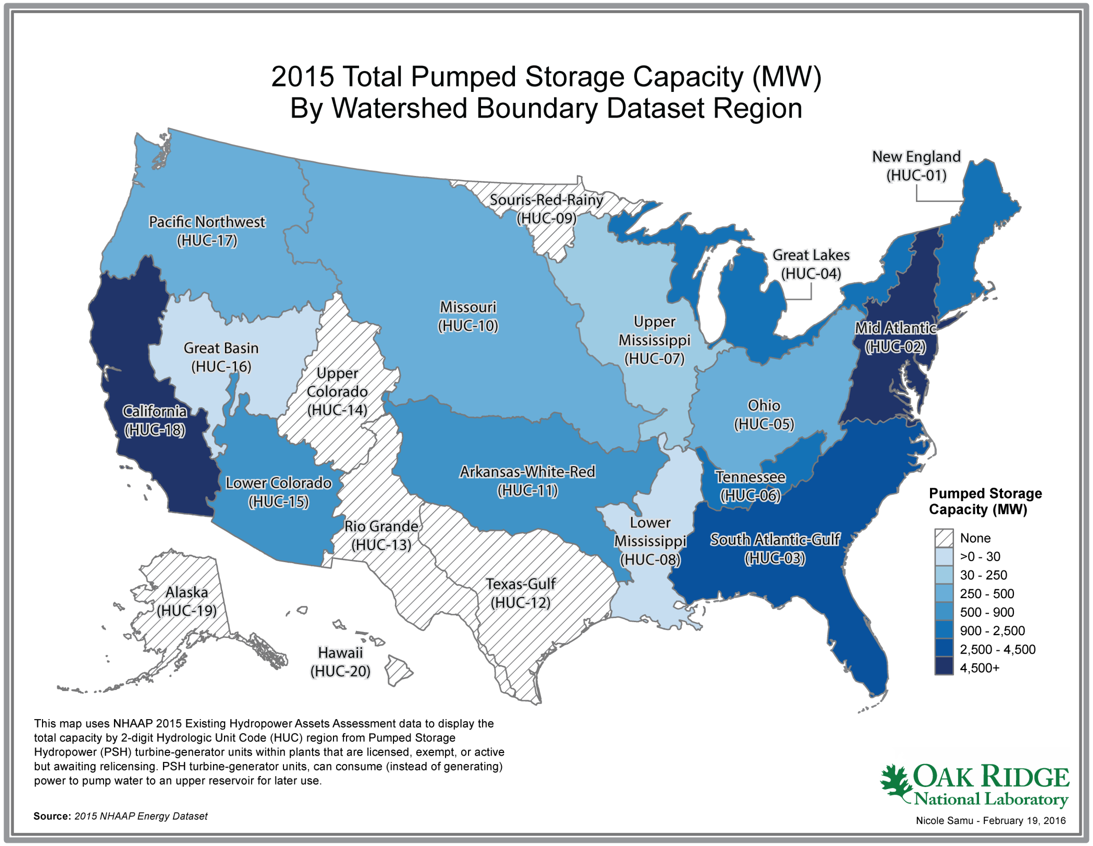
- First CAES plant, 290 MW, Huntorf Germany, 1978

Pumped Hydro-Power

- Gravity is powerful!
- Most established and common type of grid level energy storage technology
- Use pumps to elevate water into a retained pool behind a dam creating an on-demand energy source



Applications of pumped-hydro



As of 2015

As of 2017

Thermal Storage

- Pumped Heat Electrical Storage (PHES)
  - Similar to pumped hydro, heat is pumped from one thermal store to another
  - Grouping unit can provide GW sized installations
- Liquid Air Energy Storage (LAES) a.k.a. Cryogenic ES (CES)
  - Uses electricity to cool air until it liquefies, store liquid air in a tank
  - Bring air back to gas and use gas to turn a turbine

Hydrogen Energy Storage

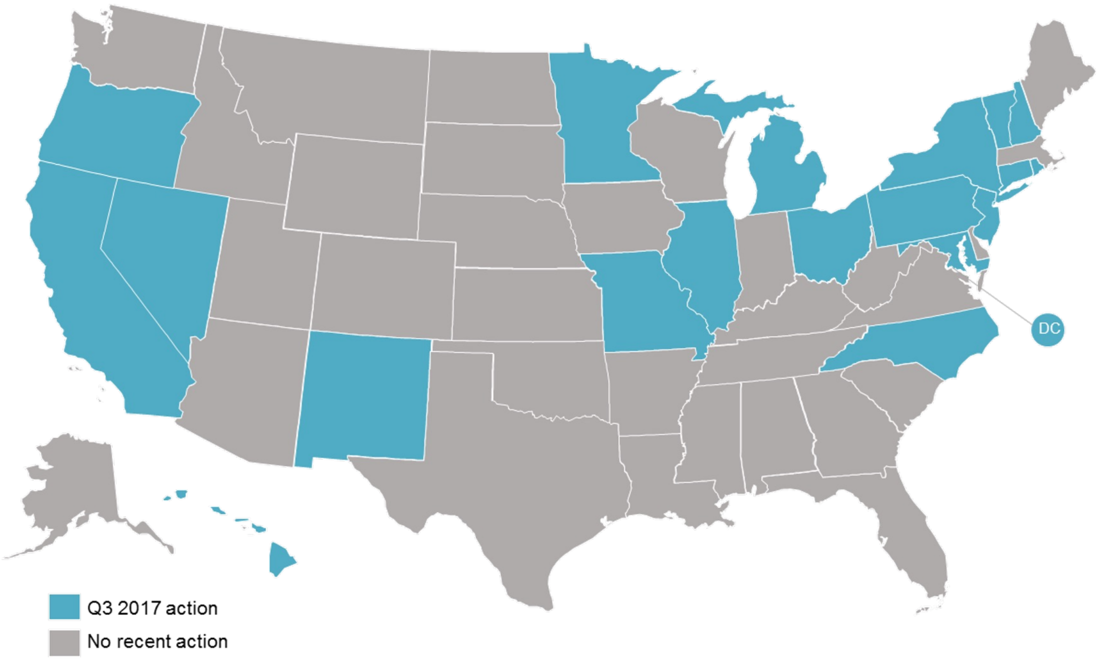
1. Electricity is converted into hydrogen by electrolysis of water
2. Hydrogen is stored (underground for large-scale projects or steel containers)
3. Further used as fuel for piston engines, gas turbines, or hydrogen fuel cells (best efficiency)

- Higher storage capacity compared to batteries, CAES
- No geographic limitation when compared to pumped hydro

Energy Storage Perspective

50 States of Grid Modernization

The most recent *50 States of Grid Modernization* study from NC Clean Energy Technology Center found that 19 states plus the District of Columbia took action to study or investigate issues related to grid modernization, energy storage, demand response and/or rate reform

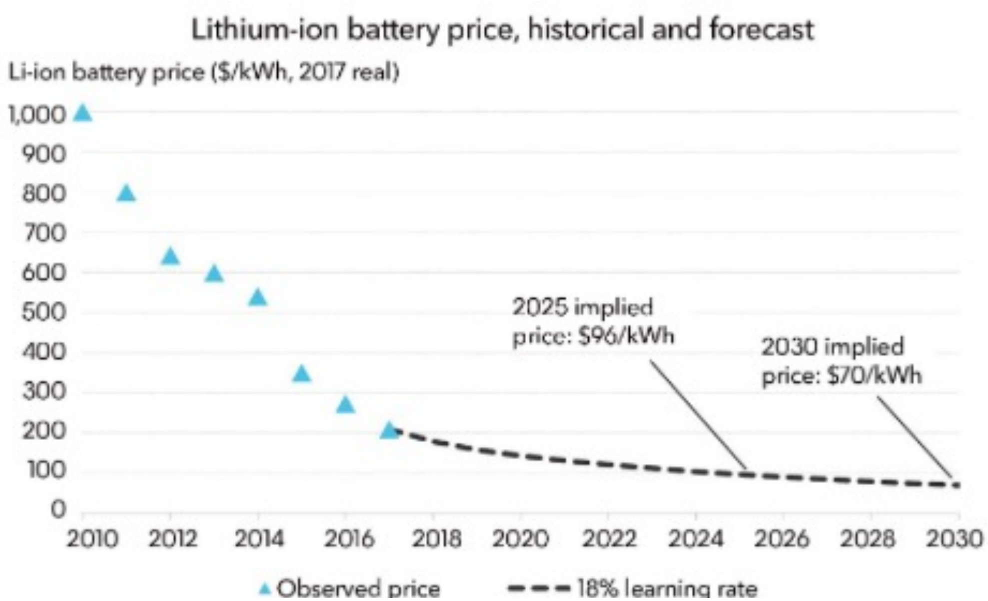


Besides North Carolina, the states of CA, CT, MD, MI, NJ, NV and VT have **energy storage specific studies planned or underway**, and are looking at impacts on wholesale and retail pricing, as well as risks to ratepayers.

Bloomberg Perspective

The Bloomberg New Energy Outlook 2019 is very similar!

- Expectation
  - 1,291 GW of new battery capacity added globally between today and 2050
  - 40% of it will be placed behind-the-meter
  - Price of battery pack in 2030: $70/kWh

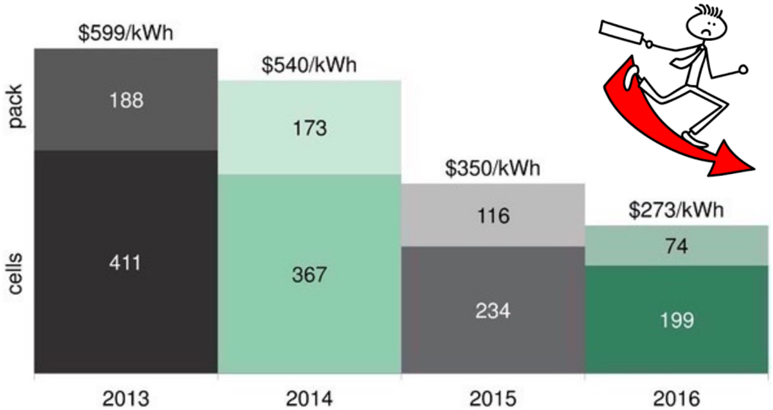


Global EV deployment drives down the cost of batteries!

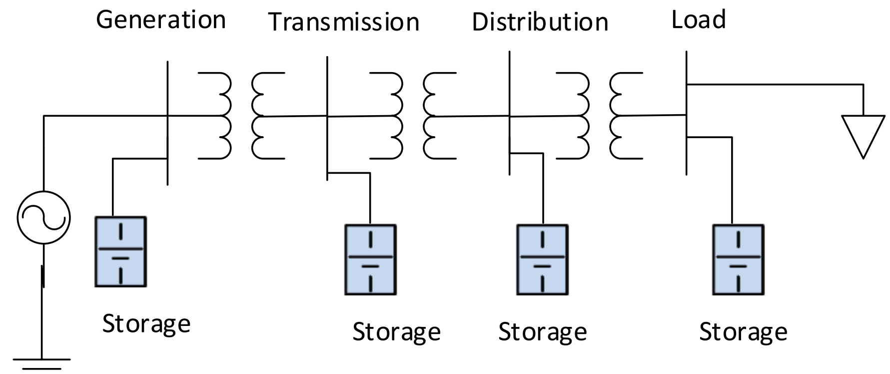
79% decrease seen in lithium-ion battery costs since 2010

Source: Bloomberg New Energy Outlook 2018

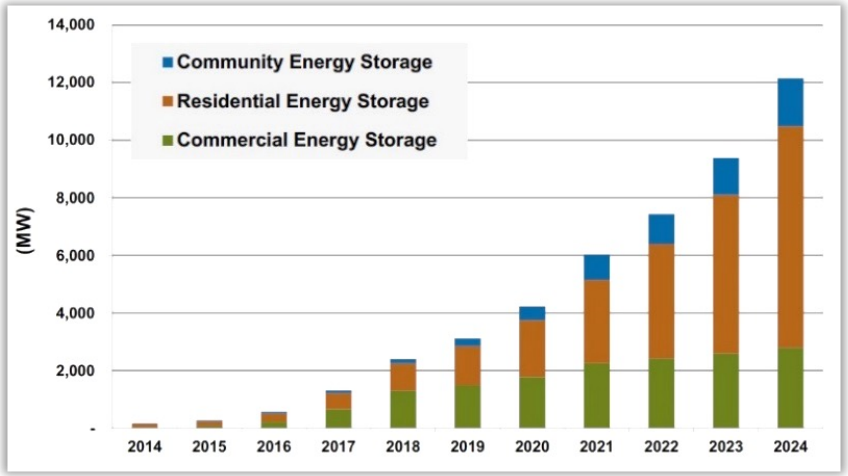
Energy Storage Deployment at Different Levels



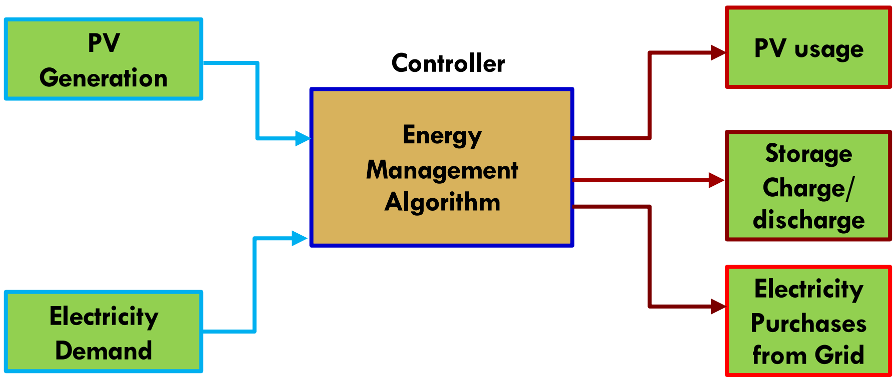
Prices per Kilowatt-hour of Storage (*Bloomberg New Energy Finance*)



Storage deployment in different levels of power system



Projections of Energy storage growth in U.S.A in different levels (*source: Navigant Research*)



Flow diagram of PV-based storage control

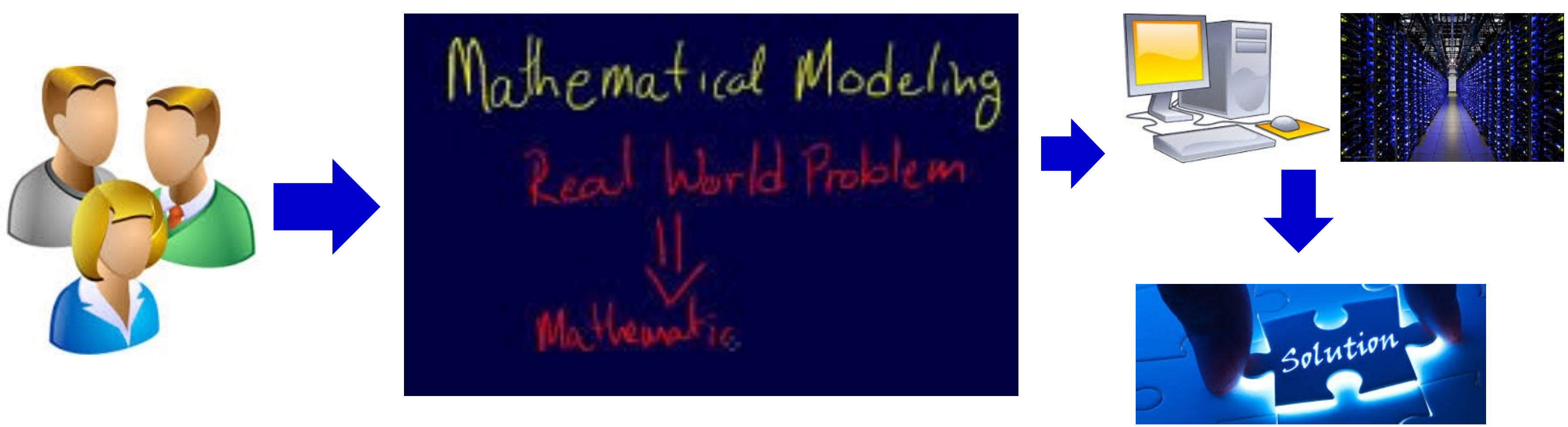
Intro to Operations Research (OR)

An Introduction to Modeling

- **Operations research (OR)** is a scientific approach to decision making that seeks to **best design and operate a system**, usually under conditions requiring the **allocation of scarce resources**
  - Term OR was introduced during the world war II when leaders asked scientists and engineers to analyze several military problems
- A **system** is an organization of interdependent components that work together to accomplish the goal of the system

An Introduction to Modeling (*cont.*)

- The scientific approach to decision making requires the use of one or more **mathematical models**
- A mathematical model is a mathematical representation of the actual situation that may be used to make better decisions or clarify the situation



An Introduction to Modeling (*cont.*)

- **Prescriptive models** "prescribe" behavior for an organization that will enable it to best meet its goals
  - Components of the mathematical model:
    - objective function
    - decision variables
    - constraints

- An **optimization model** seeks to **find values** of the **decision variables** that optimize (max or min) an objective function among the set of all values for the decision variables that satisfy all the constraints

Example

A production plant manufactures two types of water heaters (type 1 & 2). Find the production schedule (number of units type 1 and 2 to be manufactured) that maximizes profits.

- profits for selling type 1 = $800, per unit
- profits for selling type 2 = $600, per unit
- Both types need to be processed in two different machines in any order
  - Type 1 requires:
    - 4 hours of processing in machine A
    - 2 hours in machine B
  - Type 2 requires:
    - 2 hours in machine A
    - 4 hours in machine B
  - There is a limited number of processing hours available at each machine
    - 60 hours for machine A
    - 48 hours for machine B

Can this be formulated as a mathematical program?

Very important

- We will formulate this optimization problem as one of **linear programming (LP)**

- This means that
  - Our decision variables will be represent by linear relationships
  - And we assume that the decision variables can be any positive real number

Final LP Formulation

- Maximizing profits in the water heaters' production plant

$$
\begin{aligned}
\max_{x_1,x_2} \quad & z = \$800\,x_1 + \$600x_2 \\
s.t. \quad & 4x_1 + 2x_2 \le 60 \\
& 2x_1 + 4x_2 \le 48 \\
& x_1, x_2 \ge 0
\end{aligned}
$$

Solving LP in Python

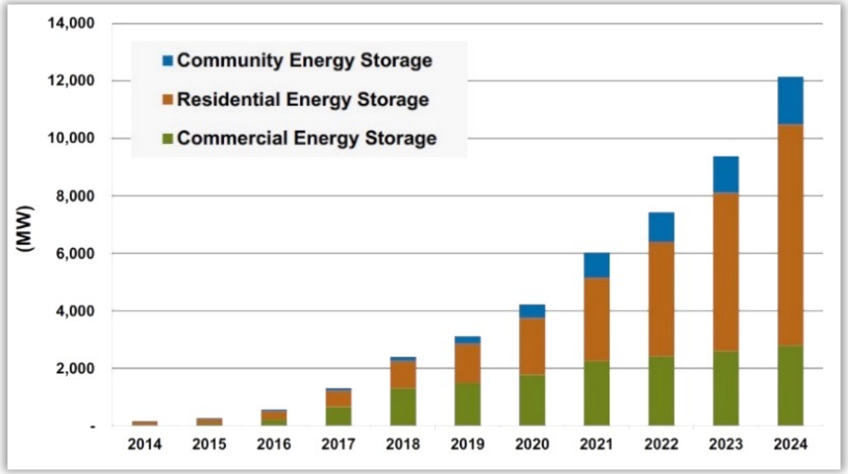
Let's open Google Colaboratory

Energy Storage Management

Study case: Behind-the-meter Solar + Storage in NC

Approaches to Solar Storage

- Utility Scale Storage
- Customer Sited Storage
  - Commercial / Industrial
  - Residential



Projections of Energy storage growth in U.S.A in different levels (*source: Navigant Research*)

Customer Sited Storage: Commercial/Industrial

- May be incentivized through existing or new tariffs
- If existing **demand charges** are ≥ $15/kW, customer storage may already be feasible with current technologies and pricing
- New tariffs with time-varying or dynamic rates to promote demand reduction are an option
  - High peak kW demand rate at certain hours reflecting seasonal patterns (e.g. 4-6pm in May-Sep)
  - Low off-peak kW demand rate
  - Low energy rate for kWh (2-3 cents)
- According to 2017 NREL whitepaper on behind-the-meter battery energy storage, demand rates in NC are as high as $25.65 per kW, average $15.61

Source: NREL, 2017; "Identifying Potential Markets for Behind-the-Meter Battery Energy Storage: A Survey of U.S. Demand Charges"

Customer-sited storage: Residential

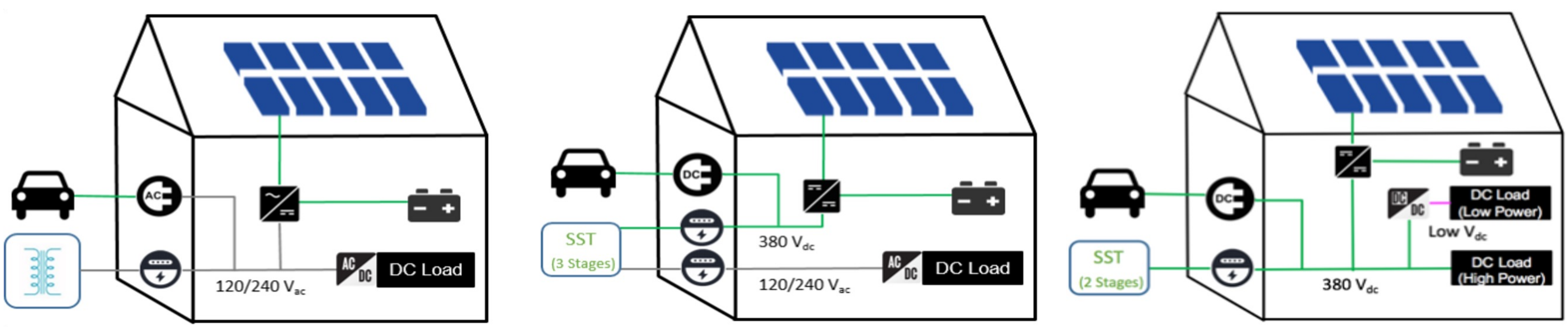
- DC and AC storage options
- Storage connects directly to DC service to avoid the loss incurred by DC/AC conversion
- Options for PV system and electric vehicle(s) and/or other storage

Customer benefits

- ✓ Shift energy according to time-of-use rate
- ✓ Minimize PV curtailment
- ✓ Optimize EV charging
- ✓ Backup generation source

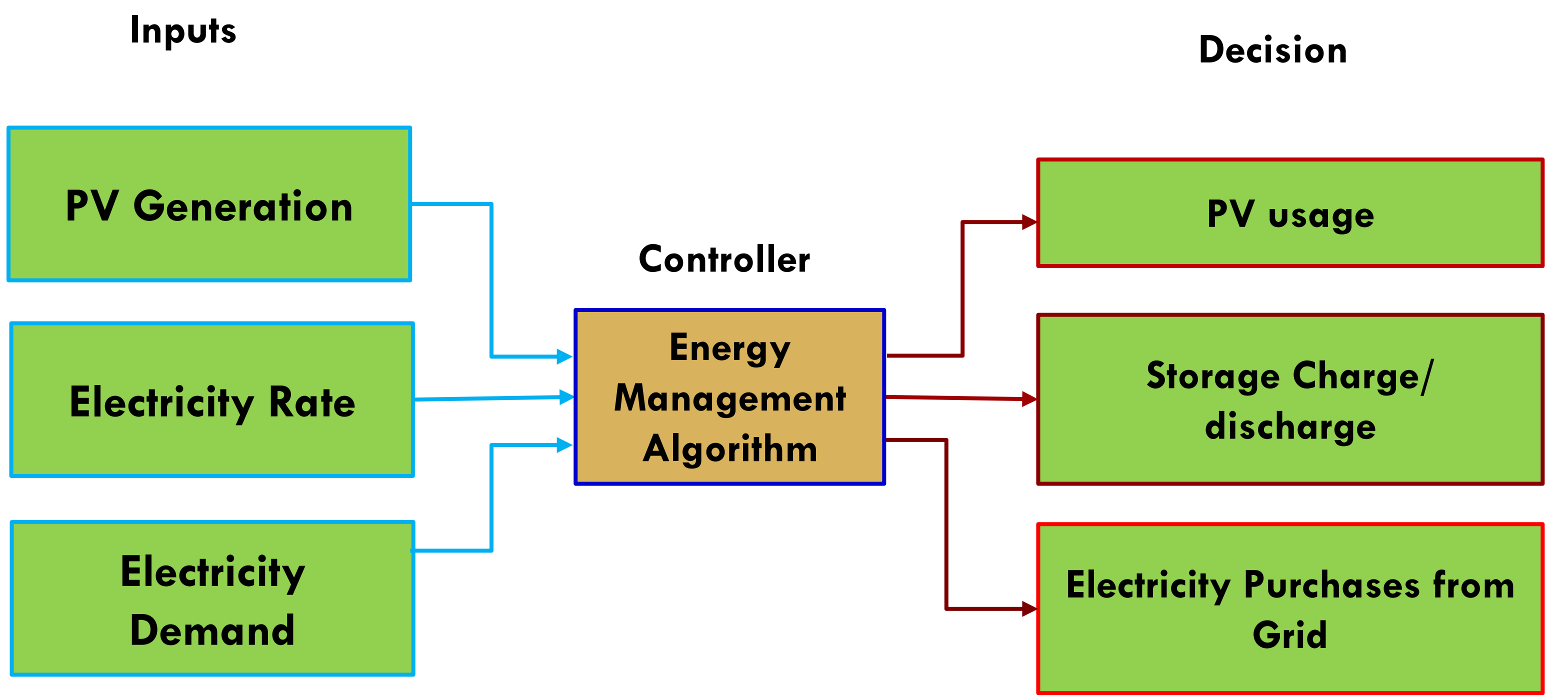
Model, Data & Tools

- ✓ Household load model
- ✓ Converter efficiency curve
- ✓ EV charging patterns
- ✓ Energy storage parameters



AC House | Hybrid House (both AC & DC) | Pure DC house

PV-based Storage Control



Study Case Description

- Customer Sited PVs with Storage
- We will use data from Assignment #1
  - Same Residential Customer
  - Same PV system
  - But now he will also have battery and he needs help with storage management to minimize cost of electricity
- Assumptions
  - He will not send power to the grid (e.g. suppose there is no net metering, so that is no incentive for him to feed the grid)
  - Inverter DC to AC ratio is 1 (matches PV installed capacity)

Try to think about this problem

- Planning horizon – 1 day
- Time step hours
- Write down your decision variables

- Write down your constraints
  - If you can't come up with a mathematical expression, just describe with words what they would be

Mathematical Model Formulation

- Our goal is

  minimize cost

- Cost here is not related to investment, but daily expenses related to electricity supply
- Cost function depends on how much electricity I am using from utility and electricity rate I am paying, assuming there is no cost to generate and/store electricity with the PV + battery system
- And we want to minimize cost for all hours of the day

Mathematical Model Formulation

$$\min \quad z = \sum_{t=1}^{T} [P_{grid,t} \cdot C_t \ ]$$

Mathematical Model Formulation

$$\min \quad z = \sum_{t=1}^{T} [\boxed{P_{grid,t}} \cdot \boxed{C_t}\ ]$$

Electricity from grid

ToU Rate

Mathematical Model Formulation

$$\min \quad z = \sum_{t=1}^{T}\Big[\underbrace{\boxed{P_{grid,t}}}_{\text{Electricity from grid}} \cdot \underbrace{\boxed{C_t}}_{\text{ToU Rate}}\ \Big]$$

- Now let's think about constraints…

Power Balance at each time t

Power in >= Power out

Power_grid + P_PV + P_disch >= P_charge + P_load

input   input

Power_grid + P_disch - P_charge >= + P_load - P_PV

Power_grid + P_disch - P_charge + P_slack = + P_load - P_PV

Mathematical Model Formulation

$$\min \quad z = \sum_{t=1}^{T} [\underbrace{\boxed{P_{grid,t}}}_{\text{Electricity from grid}} \cdot \underbrace{\boxed{C_t}}_{\text{ToU Rate}}]$$

subjected to:

Equality constraints:

(i) Power Balance: **Input and output power should be equivalent**

- $$P_{grid,t} - \underbrace{\boxed{P_{b_{ch},t}}}_{\text{Charge}} + \underbrace{\boxed{P_{b_{disch},t}}}_{\text{Discharge}} - P_{slack,t} = \underbrace{\boxed{P_{load,t}}}_{\text{Actual Demand}} - \underbrace{\boxed{P_{PV,t}^{\omega_t}}}_{\text{PV}}; \ (\forall \boldsymbol{t} \in \boldsymbol{T})$$

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- What's next?

  Storage balance constraint

  Storage_level_t = Storage_level_t-1 + P_charge_t - P_charge_t

Mathematical Model Formulation

$$\min \quad z = \sum_{t=1}^{T}\Big[\underbrace{\boxed{P_{grid,t}}}_{\text{Electricity from grid}} \cdot \underbrace{\boxed{C_t}}_{\text{ToU Rate}}\Big]$$

subjected to:

Equality constraints:

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(ii) Charge Balance: **State of charge will change based on charging/ discharging power**

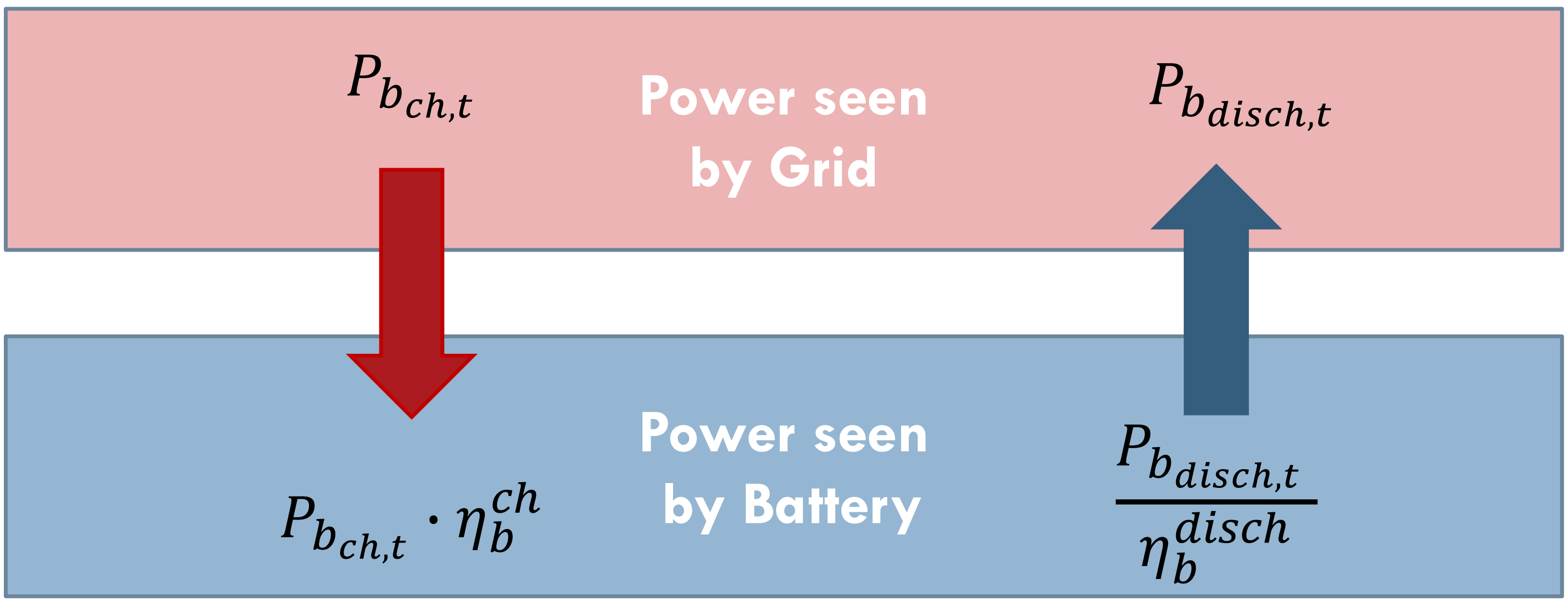
- $$\underbrace{\boxed{SoC_t}}_{\text{State of charge for storage device}} = SoC_{t-1} + \frac{P_{b_{ch,t}} \cdot \eta_b^{ch}}{Q_b \cdot \Delta t} - \frac{P_{b_{disch,t}}}{Q_b \cdot \Delta t \cdot \eta_b^{disch}} \ ; \ (\forall \boldsymbol{t} \in \boldsymbol{T})$$

Think of it as $\frac{power_{in} * eff}{bat\_capacity}$
so the SoC is in %

Think of it as $\frac{power_{out}/eff}{bat\_capacity}$
so the SoC is in %

Understanding SOC equation

$$SoC_t = SoC_{t-1} + \frac{\boxed{P_{b_{ch,t}} \cdot \eta_b^{ch}}}{Q_b \cdot \Delta t} - \frac{P_{b_{disch,t}}}{Q_b \cdot \Delta t \cdot \eta_b^{disch}}$$



Defining Boundary Conditions

- What's next?

  Boundary conditions

Defining Boundary Conditions

Inequality Constraints:

- Storage device will be charged only from PV-generated power

$$P_{b_{ch,t}} \leq P_{PV,t}^{\omega_t}, \forall t \in T$$

Defining Boundary Conditions

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$$P_{b_{disch,t}} \leq P_{load,t}, \forall t \in T$$

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- Storage device will deliver power only to the household

$$P_{b\,disch,t} \le P_{load,t}\,,\forall t \in T$$

- There will be no back-feeding of power to the grid

$$P_{grid,t} \;\; \ge 0\,,\forall t \in T$$

Defining Boundary Conditions

Inequality Constraints:

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$$P_{b\,ch,t} \leq P^{\omega_t}_{PV,t}\ , \forall t \in T$$

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- There will be no back-feeding of power to the grid

$$P_{grid,t} \geq 0\ , \forall t \in T$$

Upper and lower bounds:

- $SoC_{b,min} \leq SoC_{b,t} \leq SoC_{b,max}\ , \forall t \in T$
- $P^{min}_{b_{ch}} \leq P_{b\,ch,t} \leq P^{max}_{b_{ch}}\ , \forall t \in T$
- $P^{min}_{b_{disch}} \leq P_{b\,disch,t} \leq P^{max}_{b_{disch}}\ , \forall t \in T$

The less your battery is discharged before being recharged again, the longer it will last

The default SoC for Li-ion batteries is 95%

Defining Boundary Conditions

Inequality Constraints:

- Storage device will be charged only from PV-generated power

$$P_{b\,ch,t} \leq P_{PV,t}^{\omega_t} \,, \forall t \in T$$

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Upper and lower bounds:

- $SoC_{b,min} \leq SoC_{b,t} \leq SoC_{b,max} \,, \forall t \in T$
- $P_{b_{ch}}^{min} \leq P_{b\,ch,t} \leq P_{b_{ch}}^{max} \,, \forall t \in T$
- $P_{b_{disch}}^{min} \leq P_{b\,disch,t} \leq P_{b_{disch}}^{max} \,, \forall t \in T$

The less your battery is discharged before being recharged again, the longer it will last

The default SoC for Li-ion batteries is 95%

Uncertainty generation:

$P_{PV,t}^{\omega_t}$ where ω_t is a scenario within Ω_t that is the set of all scenarios , $\forall t \in T$

Uncertainty: A Challenge

Linear programming → But PV generation is not fixed → How to deal **uncertainty** with PV generation?

↓

Stochastic Dynamic programming ensures global minimum

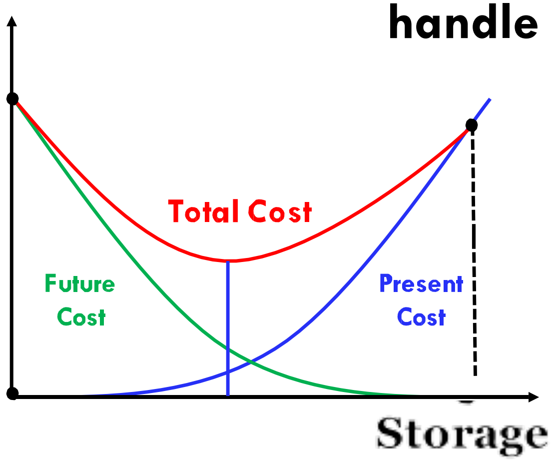
↓

Face 'Curse of dimensionality'

Requires a lot of time to calculate

Require Huge memory

→ **Stochastic Dual Dynamic Programming can handle the issue**



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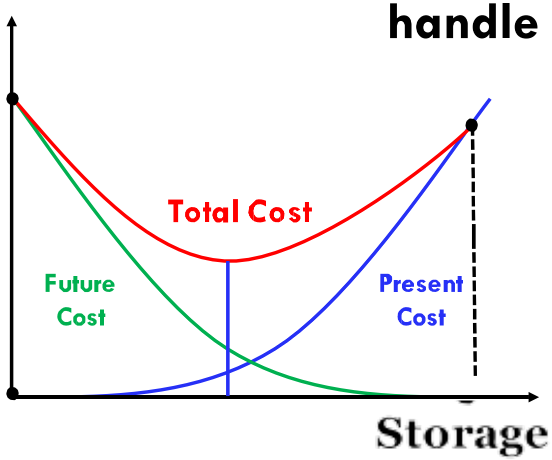


We could also incorporate load uncertainty!

Defining Boundary Conditions

Inequality Constraints:

- Storage device will be charged only from PV-generated power

$$P_{b\,ch,t} \leq P_{PV,t}^{\omega_t}\,, \forall t \in T$$

- Storage device will deliver power only to the household

$$P_{b\,disch,t} \leq P_{load,t}\,, \forall t \in T$$

- There will be no back-feeding of power to the grid

$$P_{grid,t} \geq 0\,, \forall t \in T$$

Upper and lower bounds:

- $SoC_{b,min} \leq SoC_{b,t} \leq SoC_{b,max}\,, \forall t \in T$
- $P_{b_{ch}}^{min} \leq P_{b\,ch,t} \leq P_{b_{ch}}^{max}\,, \forall t \in T$
- $P_{b_{disch}}^{min} \leq P_{b\,disch,t} \leq P_{b_{disch}}^{max}\,, \forall t \in T$

The less your battery is discharged before being recharged again, the longer it will last

The default SoC for Li-ion batteries is 95%

Uncertainty generation:

$P_{PV,t}^{\omega_t}$ where ω_t is a scenario within Ω_t that is the set of all scenarios $, \forall t \in T$

Uncertainty: A Challenge

Linear programming or Dynamic Programming could solve the problem → But PV generation is not fixed → How to deal **uncertainty** with PV generation?

↓

Stochastic Dynamic programming ensures global minimum

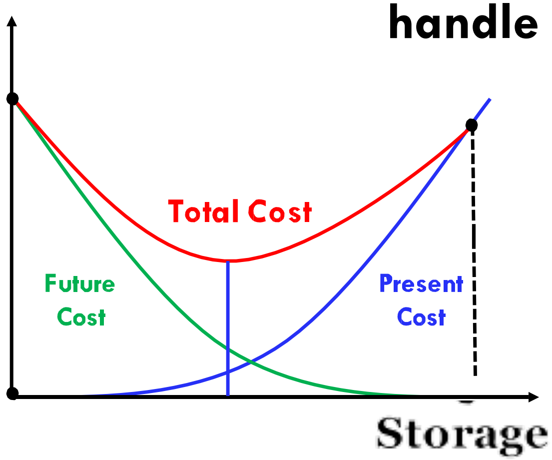
↓

Face 'Curse of dimensionality'

Requires a lot of time to calculate

Require Huge memory

→ **Stochastic Dual Dynamic Programming can handle the issue**



We could also incorporate load uncertainty!

Really???

… Thanks god I took Time Series !!

…I knew I should have taken Time series !!

- But we will not handle uncertainty it today…
- Today we will go over a **DETERMINISTIC approach!**

Our final formulation will be…

Because we are doing deterministic approach, no need to write $\forall \omega_t \in \Omega_t$

min $\quad z = \sum_{t=1}^{T} [P_{grid,t} \cdot C_t \ ]$

s.t. $\quad P_{grid,t} - P_{b_{ch},t} + P_{b_{disch},t} - P_{slack,t} = P_{load,t} - P_{PV,t}^{\omega_t} \ \forall t \in T$ ***(Power Balance)***

$SoC_t = SoC_{t-1} + \frac{P_{b_{ch,t}} \cdot \eta_b^{ch}}{Q_b \cdot \Delta t} - \frac{P_{b_{disch,t}}}{Q_b \cdot \Delta t \cdot \eta_b^{disch}} \quad \forall t \in T$ ***(Charge Balance)***

$P_{b\,ch,t} \le P_{PV,t}^{\omega_t} \quad \forall t \in T$ ***(Storage device only charged from PV)***

$P_{b\,disch,t} \le P_{load,t} \quad \forall t \in T$ ***(Storage deliver power only to household)***

$P_{grid,t} \ \ge 0 \quad \forall t \in T$ ***(No back-feeding of power to the grid)***

$SoC_{b,min} \le SoC_{b,t} \le SoC_{b,max} \quad \forall t \in T$

$P_{b_{ch}}^{min} \le P_{b\,ch,t} \le P_{b_{ch}}^{max} \quad \forall t \in T$ ***(Upper and lower bounds)***

$P_{b_{disch}}^{min} \le P_{b\,disch,t} \le P_{b_{disch}}^{max} \quad \forall t \in T$

Study Case Parameters

Known parameters

PV installed capacity	7,92	kW
Battery capacity	4	kWh
Battery Efficiency for charging and discharging	0,92	
Initial State of Charge (SOC_0)	20%	
Minimum SOC	20%	
Maximum SOC	80%	
Pb_ch_min	0	kW
Pb_ch_max	3	kW
Pb_disch_min	0	kW
Pb_disch_max	3	kW
Battery type	Li-ion	
Time steps for this analysis: t	1	h
Time Horizon: T	24	h

"Unknown" parameters – Deterministic Approach

	P_PV_t	P_load_t	C_t
Sep 18, 12:00 am	0	2.05	0.09996372
Sep 18, 1:00 am	0	0.32	0.09996372
Sep 18, 2:00 am	0	1.72	0.09996372
Sep 18, 3:00 am	0	0.34	0.09996372
Sep 18, 4:00 am	0	1.58	0.09996372
Sep 18, 5:00 am	0	0.34	0.09996372
Sep 18, 6:00 am	0.230828	0.83	0.09996372
Sep 18, 7:00 am	1.53247	1.55	0.09996372
Sep 18, 8:00 am	3.19997	0.51	0.09996372
Sep 18, 9:00 am	4.53936	1.98	0.09996372
Sep 18, 10:00 am	4.32765	0.37	0.09996372
Sep 18, 11:00 am	2.07893	2.5	0.09996372
Sep 18, 12:00 pm	3.82706	2.08	0.09996372
Sep 18, 1:00 pm	5.54551	1.86	0.09996372
Sep 18, 2:00 pm	4.79316	3.42	0.09996372
Sep 18, 3:00 pm	3.04991	1.55	0.09996372
Sep 18, 4:00 pm	1.38626	2.88	0.09996372
Sep 18, 5:00 pm	0.353036	2.34	0.09996372
Sep 18, 6:00 pm	0	3.1	0.09996372
Sep 18, 7:00 pm	0	2.22	0.09996372
Sep 18, 8:00 pm	0	2.79	0.09996372
Sep 18, 9:00 pm	0	1.05	0.09996372
Sep 18, 10:00 pm	0	1.1	0.09996372
Sep 18, 11:00 pm	0	1.47	0.09996372

From SAM ↑ From Customer ↑ ↑ From Duke Energy

Questions

- How many decision variables do we have?
  - 5*24 = 120 decision variables
- How many constraints do we have?
  - 4*24 = 96 technical constraints
  - 6*24 = 144 simple bounds
  - 2*24 = 48 nonnegativity
- Can we use Excel Solver to find optimal solution?
  - We might, but would require some rewriting
  - As it is, the problem is too big for the Solver


THANK YOU !

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