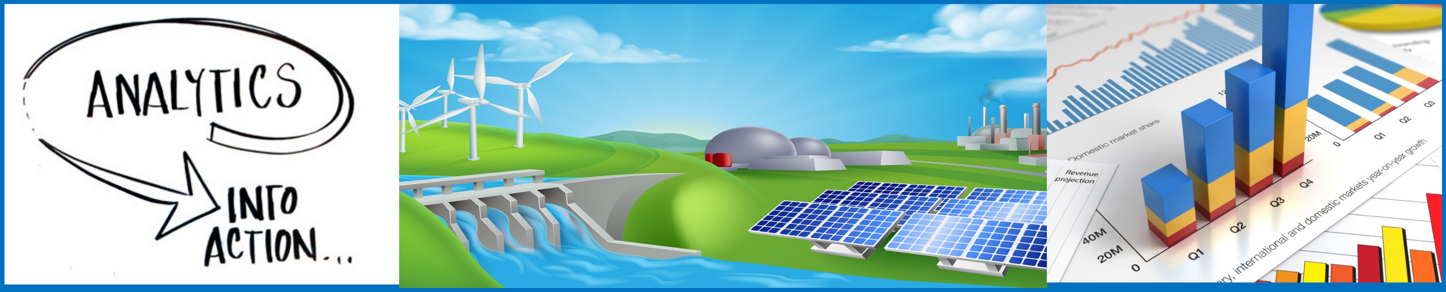


ECONOMICS OF MODERN POWER SYSTEMS

M6 – Behind-the-Meter (BTM) Energy Management Systems: PV + battery

Prof. Luana Medeiros Marangon Lima, Ph.D.

Learning Goals

- Storage management
  - More on solving LPs in Python/R
  - case study for a customer with (PV + battery) system

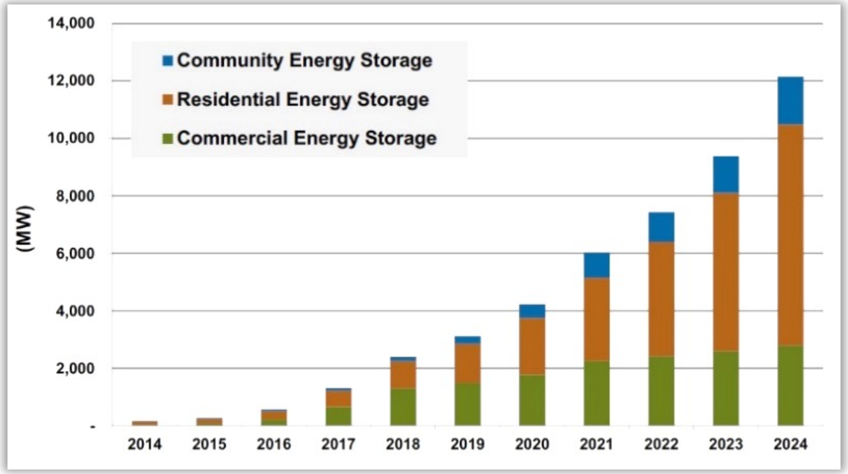
Energy Storage Management

Study case: Behind-the-meter Solar + Storage

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

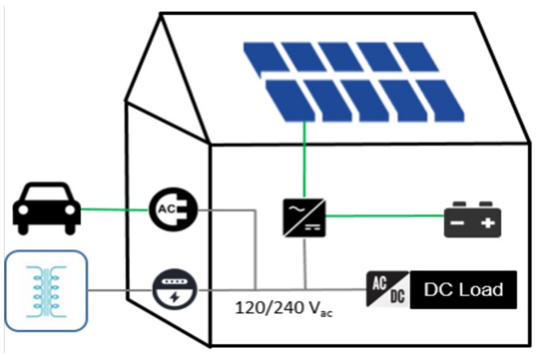
- DC and AC storage options
- Storage connects directly to DC service to avoid the loss incurred by DC/AC conversion
- Options for PV system and electric vehicle(s) and/or other storage

Customer benefits

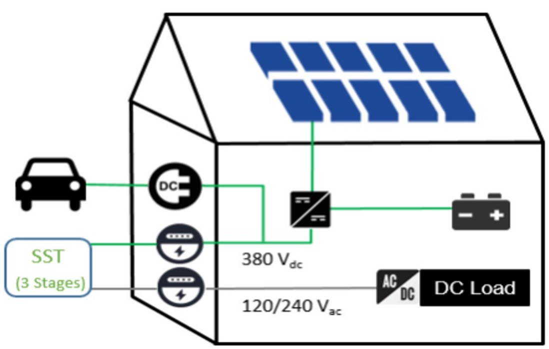
- ✓ Shift energy according to time-of-use rate
- ✓ Minimize PV curtailment
- ✓ Optimize EV charging
- ✓ Backup generation source

Model, Data & Tools

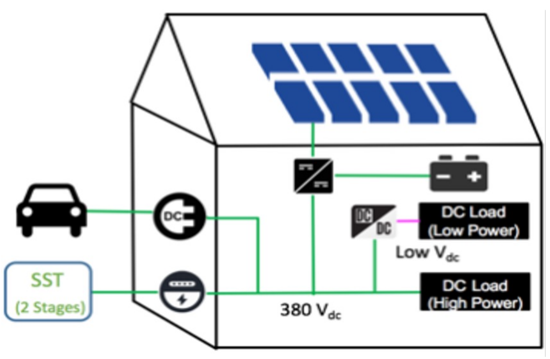
- ✓ Household load model
- ✓ Converter efficiency curve
- ✓ EV charging patterns
- ✓ Energy storage parameters



AC House

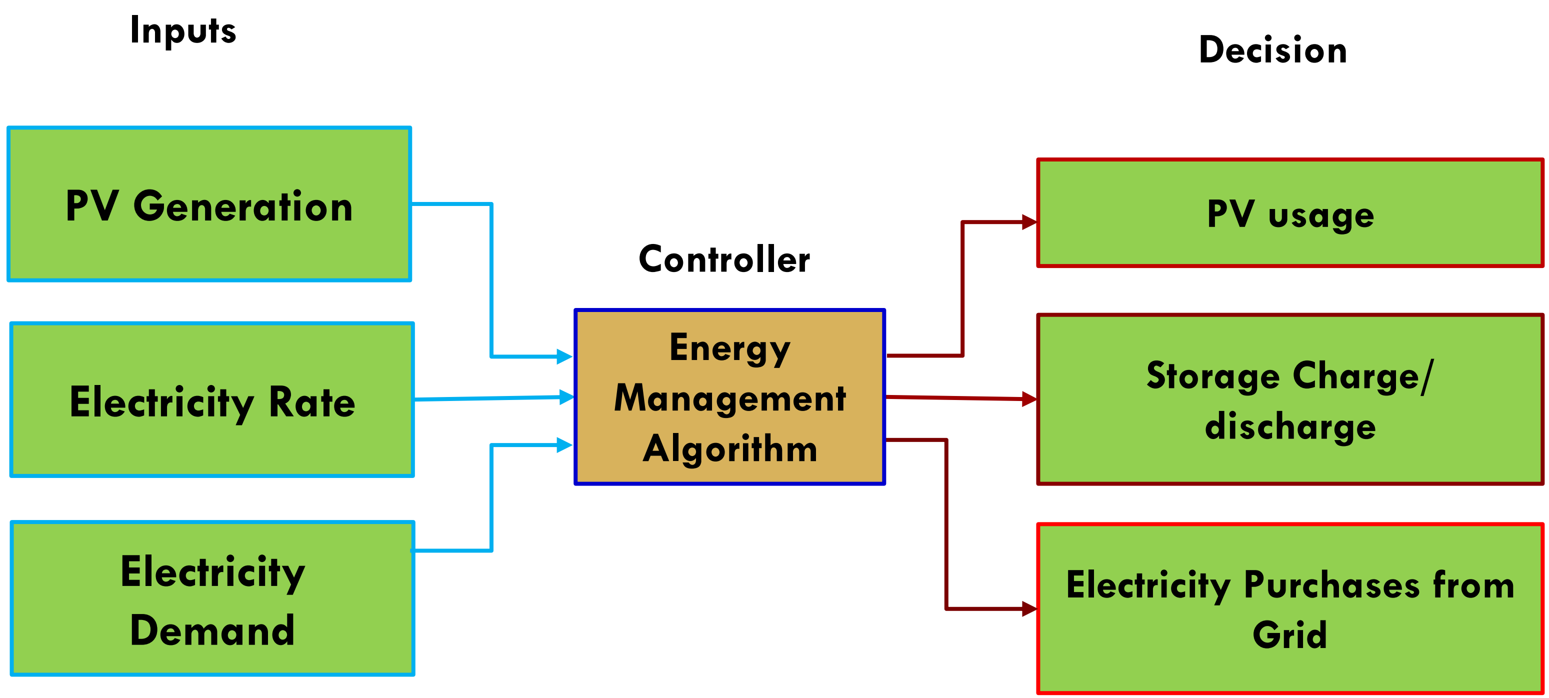


Hybrid House (both AC & DC)



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

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

Electricity from grid

ToU Rate

Mathematical Model Formulation

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

Electricity from grid

ToU Rate

- 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

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

subjected to:

Equality constraints:

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

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

Mathematical Model Formulation

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

subjected to:

Equality constraints:

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

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

- What’s next?

  Storage balance constraint

  Storage_level_t = Storage_level_t-1 + P_charge_t - P_discharge_t

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**

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

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

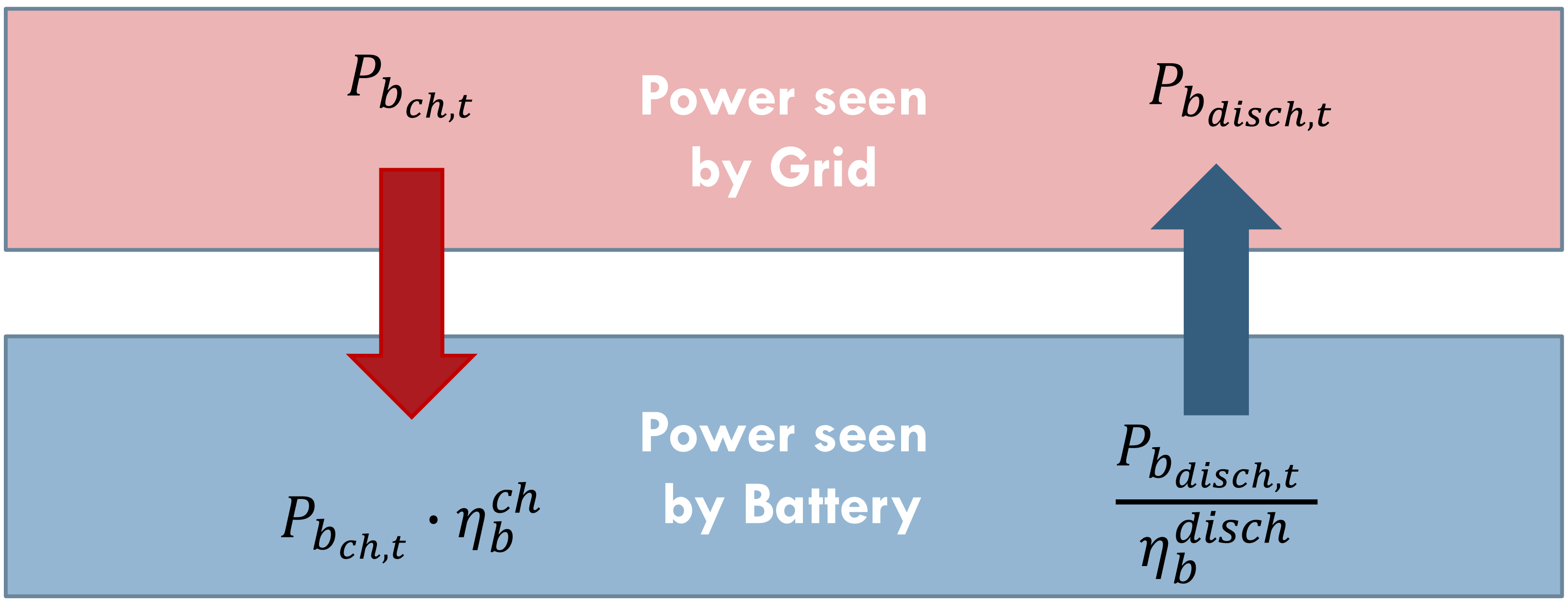
- $\underbrace{\boxed{SoC_t}}_{\text{State of charge for storage device}} = SoC_{t-1} + \frac{P_{b_{ch,t}} \cdot \eta_b^{ch}}{Q_b \cdot \Delta t} - \frac{P_{b_{disch,t}}}{Q_b \cdot \Delta t \cdot \eta_b^{disch}} \ ; \ (\forall \boldsymbol{t} \in \boldsymbol{T})$

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

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

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

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

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

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%

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

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

Upper and lower bounds:

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

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

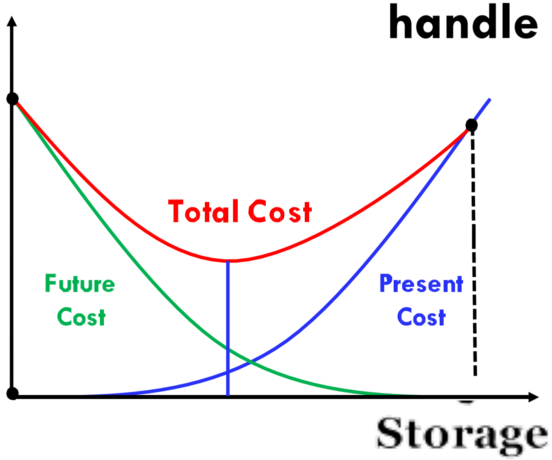
↓

Face 'Curse of dimensionality'

Requires a lot of time to calculate

Require Huge memory

Stochastic Dual Dynamic Programming can handle the issue



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

s.t.

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

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

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

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

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

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

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

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

Model Implementation in R

Study Case Model Implementation

- Download data file from Sakai
- Recall: number of columns is number of dec. variables
  - 5 x 24 = 120 columns
  - Keep track of the order of the variables in the LP
  - Our example
    - 1 to 24 $P_{grid,t}$
    - 25 to 48 $P_{b_{ch},t}$
    - 49 to 72 $P_{b_{disch},t}$
    - 73 to 96 $P_{slack,t}$
    - 97 to 120 SoC_t

Power Balance Constraint ($t = 1$)

$$P_{grid,t} - P_{b_{ch},t} + P_{b_{disch},t} - P_{slack,t} = P_{load,t} - P_{PV,t}^{\omega_t}$$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
$P_{grid,t}$	**1**																							
	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
$P_{b_{ch},t}$	**-1**																							
	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72
$P_{b_{disch},t}$	**1**																							
	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96
$P_{slack,t}$	**-1**																							
	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120
SoC_t																								

All other cells should be zero !

Power Balance Constraint ($t = 2$)

$$P_{grid,t} - P_{b_{ch},t} + P_{b_{disch},t} - P_{slack,t} = P_{load,t} - P_{PV,t}^{\omega_t}$$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
$P_{grid,t}$		**1**																						
	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
$P_{b_{ch},t}$		**-1**																						
	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72
$P_{b_{disch},t}$		**1**																						
	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96
$P_{slack,t}$		**-1**																						
	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120
SoC_t																								

All other cells should be zero !

Power Balance Constraint ($t = 24$)

$$P_{grid,t} - P_{b_{ch},t} + P_{b_{disch},t} - P_{slack,t} = P_{load,t} - P_{PV,t}^{\omega_t}$$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
$P_{grid,t}$																								1
	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
$P_{b_{ch},t}$																								-1
	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72
$P_{b_{disch},t}$																								1
	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96
$P_{slack,t}$																								-1
	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120
SoC_t																								

All other cells should be zero !

R code

- Running Simple Example ?
  - lpSolveAPI running ?
- Importing Data using read.table ?
- Understanding how R store decision variables vector
  - Jump by 24
- Understanding how constraints are entered
- Understanding how to access optimal variables values
- Plotting graphs in R

Model Implementation in Python

Study Case Model Implementation

- Please refer to the ipynb file on Sakai


THANK YOU !

luana.marangon.lima@duke.edu