Optimal Generation Expansion Planning with Integration of Variable Renewables and Bulk Energy Storage Systems

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Agenda

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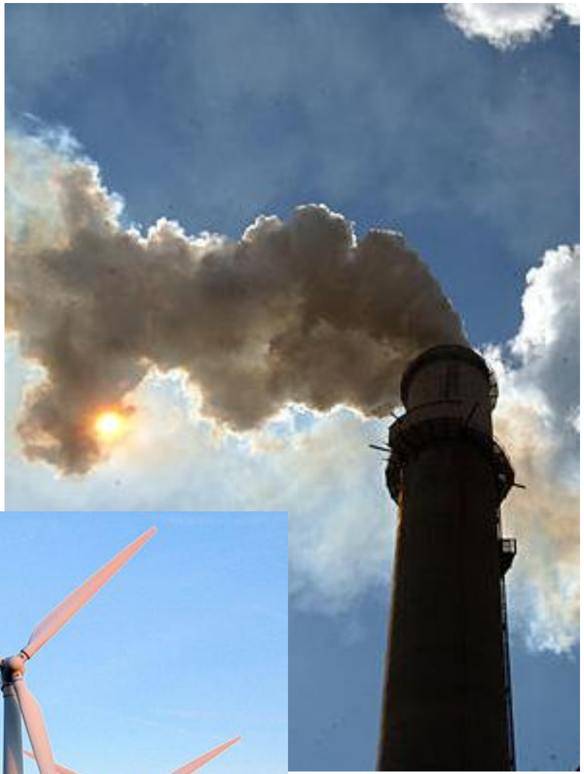
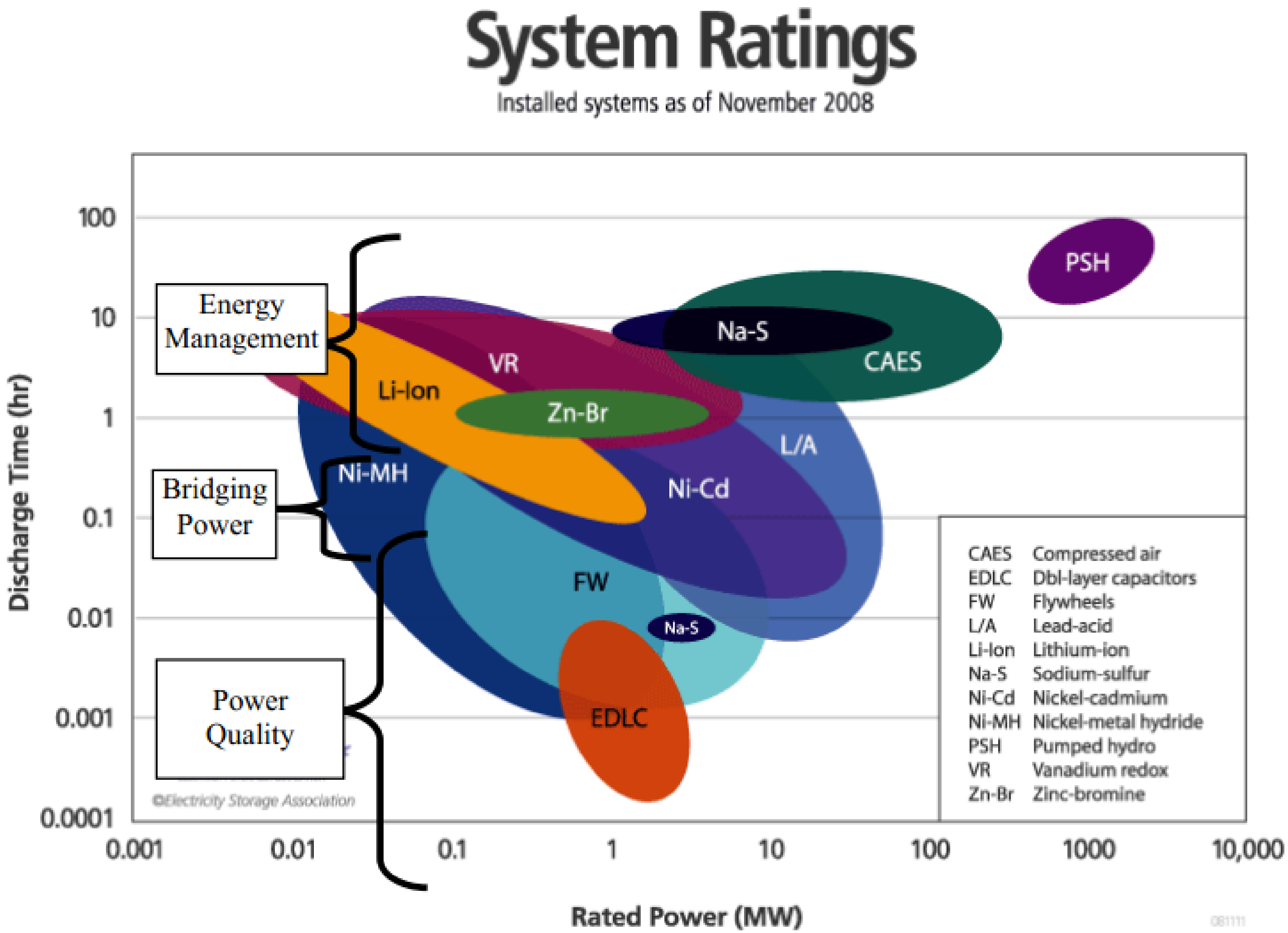
Research Scope and Background

Research Scope

- How do we respond to the future energy and environmental policies?
- New challenges in the generation expansion planning study: integrating variable resources and energy storage systems.
- Modeling challenge for planning: detailed hour-by-hour operational simulation vs. computational cost.
- MATPOWER: a MATLAB based open-source toolbox suite for academic research purposes.
- Basic formulation: multi-period optimization based optimal planning.



Energy Storage Technologies



P. Denholm, E. Ela, B. Kirby and M. Milligan, "The Role of Energy Storage with Renewable Electricity Generation," Technical Report, NREL/TP-6A2-47187, Jan. 2010.

Methodology of Modeling

Objective Function

$$\min_{\theta_k, P_{ijt}, R_i, I_j, IP_j, IE_j} \left\{ \begin{array}{c} \tau \sum_t C_g^V P_{gt} + \sum_i [C_i^F (P_i^0 - R_i)] + \\ \sum_j \left[\tau \sum_t C_j^V P_{jt} + \left(C_j^I + C_j^F\right)\left(I_j + IP_j + IE_j\right) \right] \end{array} \right\}$$

- 1^{st} term – hourly production cost (i.e. fuel and O&M cost).
- 2^{nd} term – cost savings from retiring units.
- 3^{rd} term – additional cost from investing (i.e. constructing and operating) in new units including energy storage.

Constraints

- Variable boundaries
- DC network constraints
- Generation expansion planning constraints
- Energy storage optimal planning constraints

$$0 \le P_{it} + R_i \le P_i^{max}$$

$$P_{jt} \le \delta_{jt} I_j$$

$$\sum I_j^s \le I^{s,max}$$

$$\sum_i \Delta_i R_i \le \sum_j \Delta_j (I_j + IP_j)$$

$$0 \le P_{jt}^c \le IP_j$$

$$0 \le P_{jt}^d \le IP_j$$

$$0 \le P_{jt}^c \le \frac{IE_j - E_j^{t-1}}{\eta_j^c}$$

$$0 \le P_{jt}^d \le \eta_j^d E_j^{t-1}$$

$$E_j^t = E_j^{t-1} + \eta_j^c P_{jt}^c - \frac{P_{jt}^d}{\eta_j^d}$$

$$0 \le E_j^t \le IE_j$$

$$E_j^T = E_j^0 = \alpha IE_j$$

MATPOWER’s Extendable OPF Framework

- Objective function

$$\min_{\mathrm{x,z}} \; f(x) + \boxed{f_u(x,z)}$$

- Constraints

$$g(x) = 0$$

$$h(x) \le 0$$

$$x_{min} \le x \le x_{max}$$

$$\boxed{\begin{gathered} \mathrm{l} \le \mathrm{A}\begin{bmatrix} x \\ z \end{bmatrix} \le u \\ z_{min} \le z \le z_{max} \end{gathered}}$$

R. D. Zimmerman, C. E. Murrillo-Sanchez, and R. J. Thomas, “MATPOWER: Steady-State Operations, Planning, and Analysis Tools for Power Systems Research and Education,” *IEEE Trans. Power Syst.*, vol. 26, no. 1, pp. 12-19, Feb. 2011.

Data Preparation and Test System

Data Collection

- Resource planning data:
  - Levelized fuel cost and O&M cost in 2015 ($/MWh)
  - Annual fixed O&M cost in 2015 ($/MW)
  - Capital cost in terms of annual capital recovery (ACR) in 2022 ($/MW)
- Energy storage planning data:
  - ACR of power capacity ($/MW) and energy capacity ($/MWh)
  - O&M cost ($/MWh)
  - Cycle efficiency

Data retrieved from two reports by PNNL and NREL.

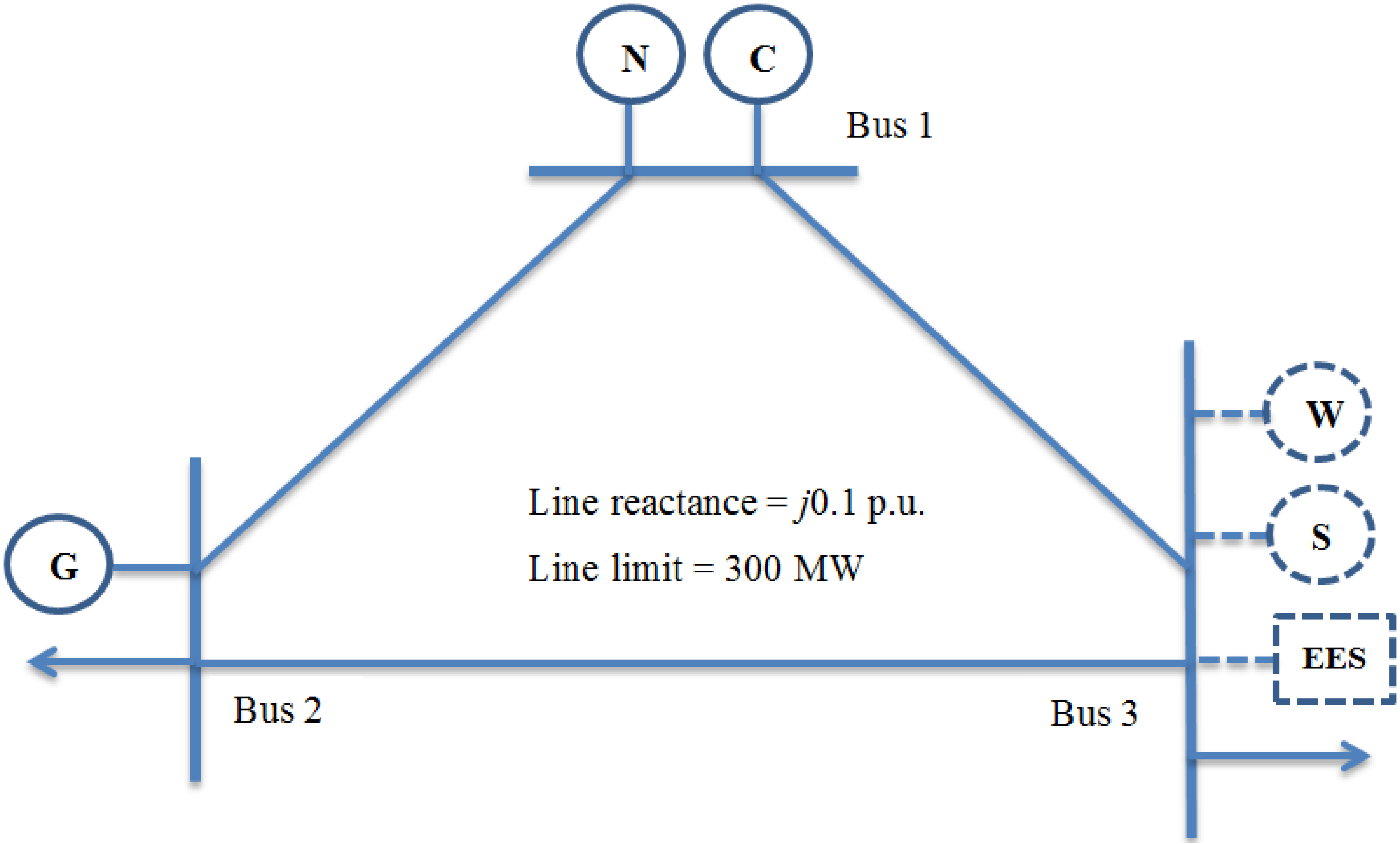
Average CO_2 Emission Rate (ton/MWh)

Generator Type	CO2 Emission Rate
Coal	0.8333
Natural gas (combustion turbine)	0.5117
Natural gas (combined cycle)	0.3411

$$avg.\,CO_2\,emission\,rate\left(\frac{ton}{MWh}\right) = avg.\,CO_2\,emission\,factor\left(\frac{ton}{MBTU}\right) \times avg.\,heat\,rate\left(\frac{MBTU}{MWh}\right)$$

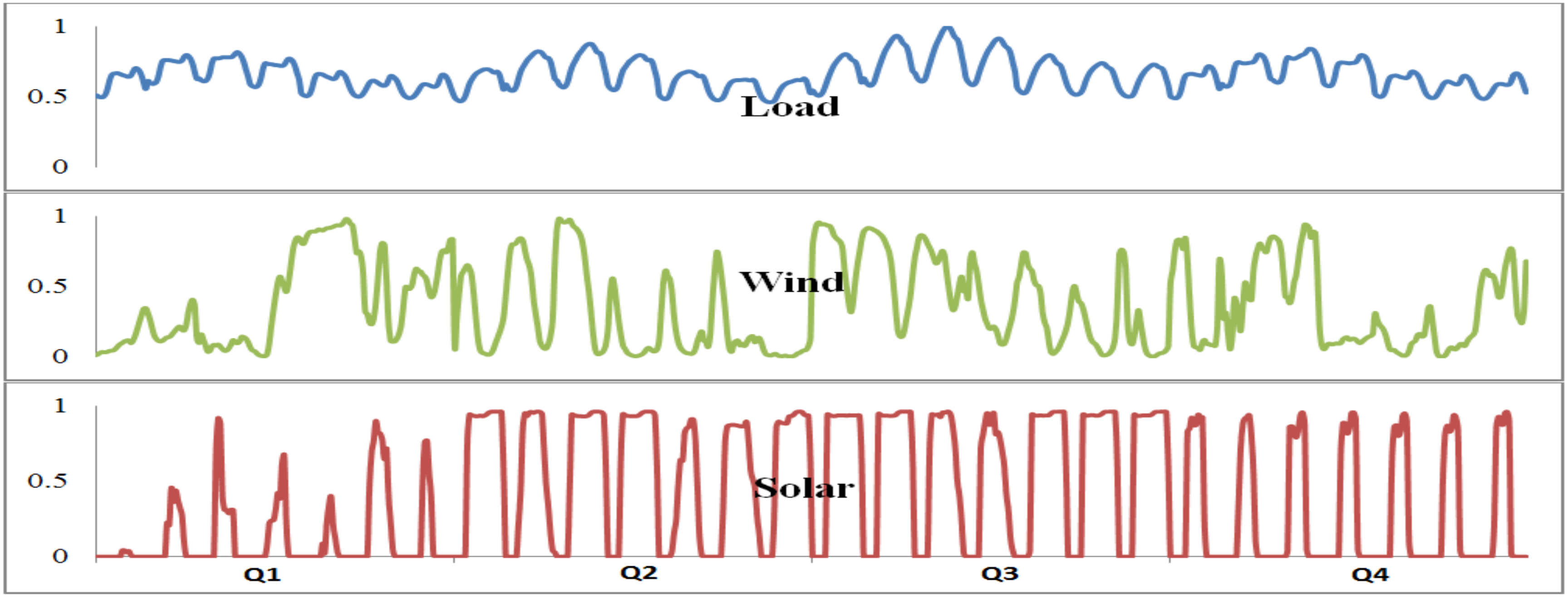
Avg. emission factor retrieved from dissertation by Miaolei Shao.
Avg. heat rate retrieved from EIA.

3-Bus Test System



Typical-Week Profiles of Load and Variable Renewables

- Use four typical weeks (672 hours) to represent the full 8760 hours with each week represents one calendar quarter.
- Typical week profiles preserve the peak and minimal points and effectively represent the changes between hours.
- Normalized wind and solar profiles are applied to the planning model.



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Generator Parameters in 3-Bus System

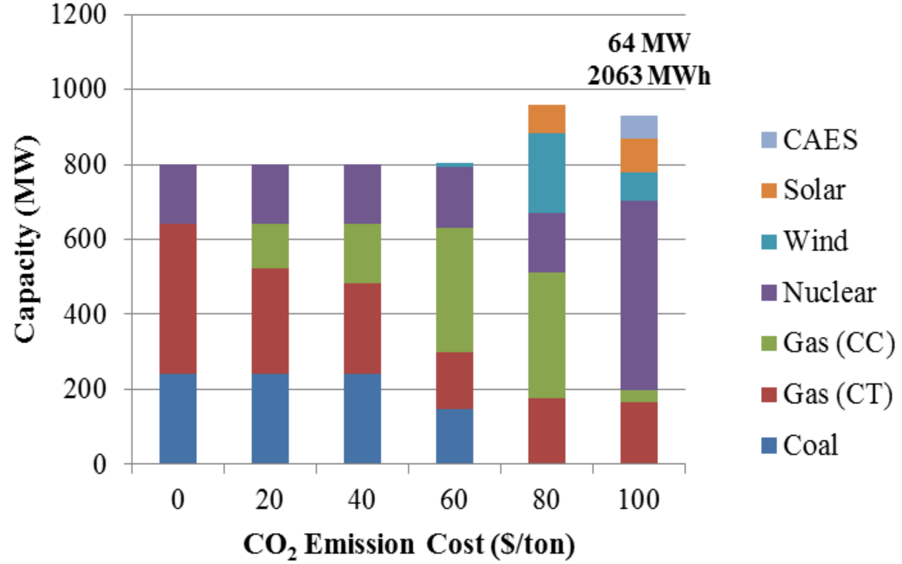
Generator Index	1	2	3	4	5	6
Bus Index	1	2	1	3	3	3
Fuel Type	Coal	Gas	Nuclear	Wind (onshore)	Solar (PV)	EES (CAES)
Existing Capacity (MW)	240	400	160	0	0	0
Maximum Investment Allowed (MW)	∞	∞	∞	∞	∞	∞
Maximum Retirement Allowed (MW)	240	400	160	N/A	N/A	N/A
Capacity Factor	0.85	0.87	0.9	0.36	0.40	0.2
Fuel Cost ($/MWh)	18.70	50 (40)	9.92	N/A	N/A	N/A
O&M Cost ($/MWh)	6.54	5.00	12.02	8.08	5.76	3
Annual Fixed Cost ($/MW)	36,780	15,000	93,770	11,980	9,920	0
Annual Capital Recovery ($/MW)	349,780	101,798	566,373	214,206	273,116	19,433 $/MW 117 $/MWh
Cycle Efficiency	N/A	N/A	N/A	N/A	N/A	0.7

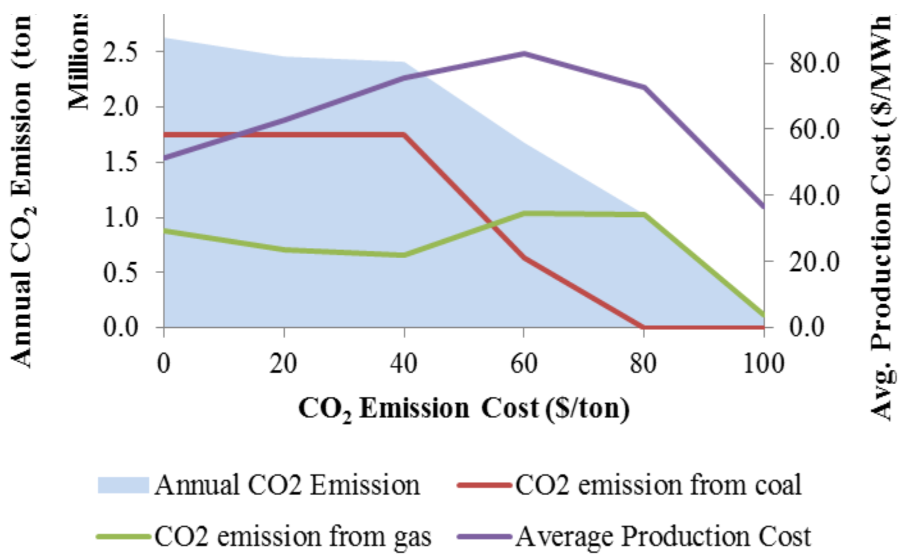
Simulation Results

Study Cases for 3-Bus System

Case Number	CO_2 Price ($/ton)	Wind and Solar Subsidy ($/MWh)	Natural Gas Price ($/MBTU)	EES
1	[0 20 40 60 80 100]	0	5	CAES (best)
2	0	[0 10 20 30 40 50]	5	CAES (best)
3	40	22	[2 4 6 8 10 12]	CAES (best)
4	40	22	8	ALL

Case 1: CO_2 Price [0 – 100 $/ton], Wind and Solar Subsidy [None], Natural Gas [5 $/MBTU]

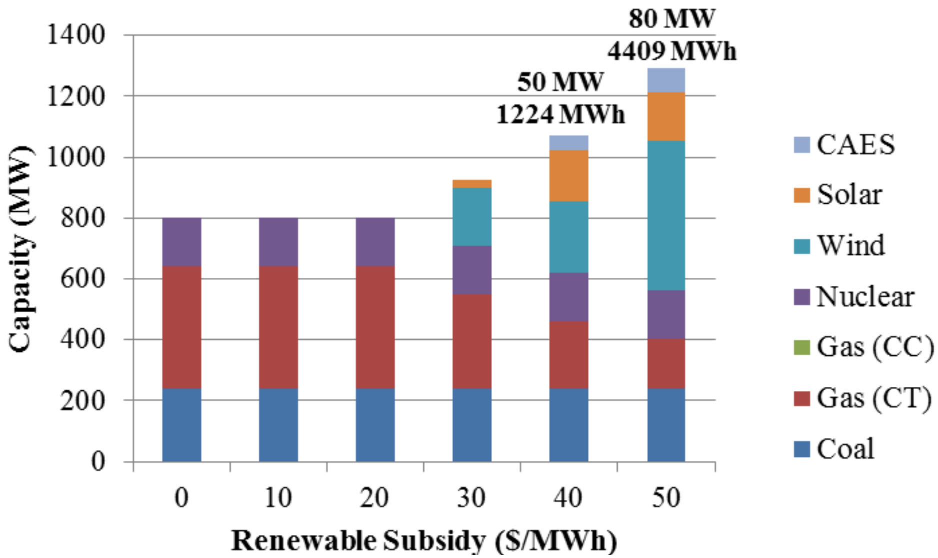


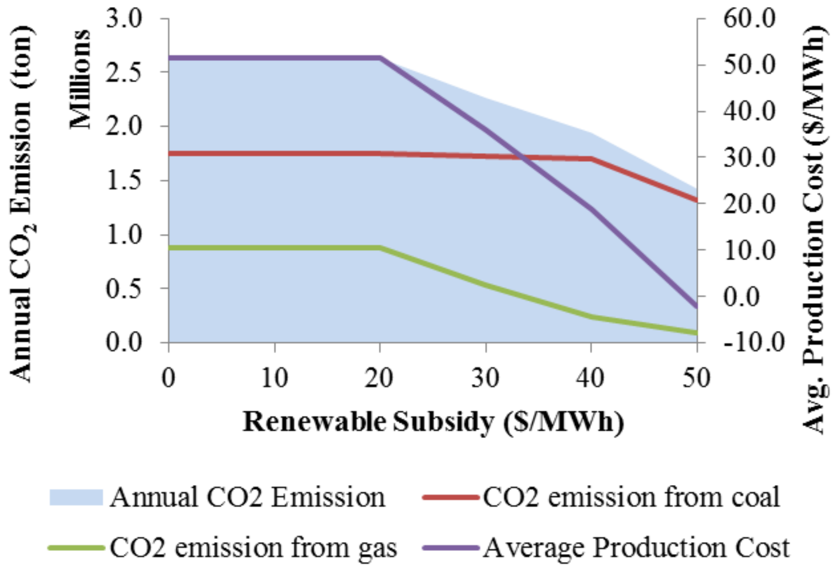


Responses to the increase of CO_2 Price:

- Natural gas technology upgrade
- Coal retirement
- Renewables investment
- Energy storage investment
- Nuclear investment
- CO_2 emission decreasing
- Production cost peaking around 60 $/ton

Case 2: CO_2 Price [None], Wind and Solar Subsidy [0 – 50 \$/MWh], Natural Gas [5 \$/MBTU]

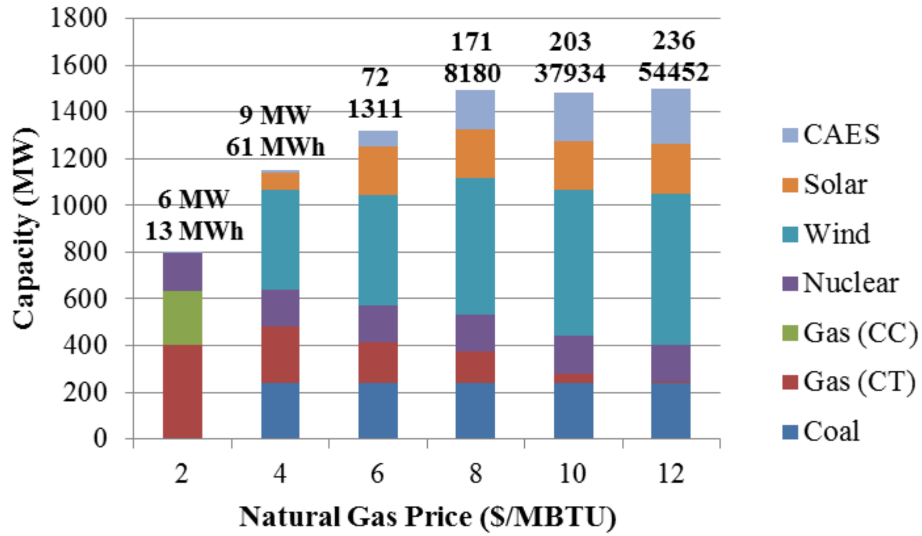


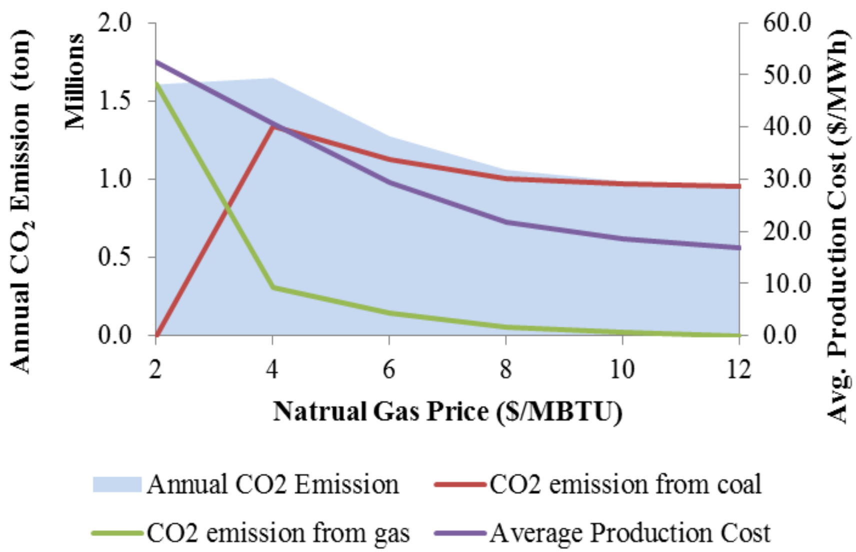


Responses to the increase of renewable subsidy:

- Renewables investment
- Natural gas retirement
- Energy storage investment
- CO_2 decreasing after 20 \$/MWh subsidy
- Production cost decreasing after 20 \$/MWh subsidy

Case 3: CO_2 Price [40 $/ton], Wind and Solar Subsidy [22 $/MWh], Natural Gas [2 – 12 $/MBTU]





Responses to the increase of natural gas price:

- Natural gas retirement
- Renewables investment
- Energy storage investment
- CO_2 emission peaking around 4 $/MBTU of gas price
- Production cost decreasing

Case 4: CO_2 Price [40 $/ton], Wind and Solar Subsidy [22 $/MWh], Natural Gas [8 $/MBTU]

Potential of Bulk EES by Technology

Technology	Level	Power Capacity (MW)	Energy Capacity (MWh)
PH	Worst	0.7	16.7
	Best	67.0	2,401.7
CAES	Worst	0	0
	Best	171.1	8,180.0
Na-S	Worst	0	0
	Best	0	0
VR	Worst	0	0
	Best	5.0	24.7
Li-ion	Worst	0	0
	Best	0	0

General Conclusions

General Conclusions

- Variable renewable resources requires more flexibility from power system operation. Meanwhile, they tend to provide more benefit for bulk energy storage systems by arbitraging energy.
- As bulk energy storage, CAES has the highest potential of the storage technologies studied when operating with high penetrations of wind and solar.
- Lower natural gas price, lack of emission regulation or insufficient renewable incentives reduce the pace of investment on renewables.
- Lower natural gas price (~ 3 $/MBTU) would phase out the traditional coal-fired plant without the help of emission regulation policies.
- Higher natural gas price (~ 10 $/MBTU) leads to a notable increment of wind, solar, nuclear and bulk energy storage.

Thank you!
Questions / Comments?