

Optimization Model and Algorithm for Capacity Planning and Operation of Reliable and Carbon-neutral Power Systems with High Penetration of Renewable Generation

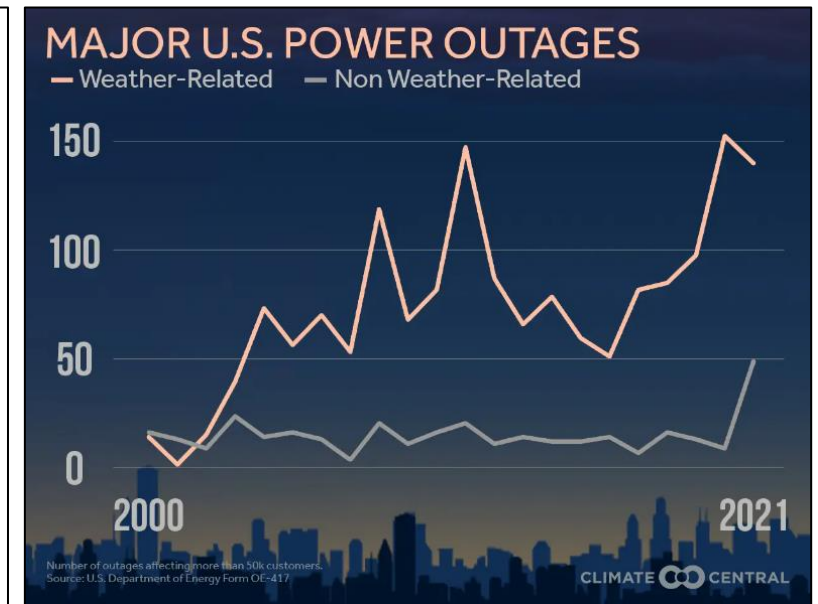
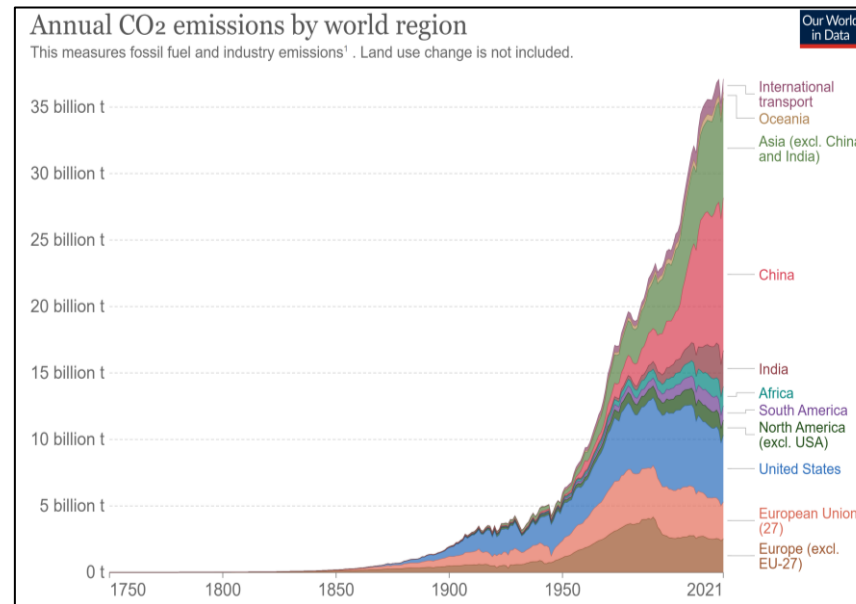
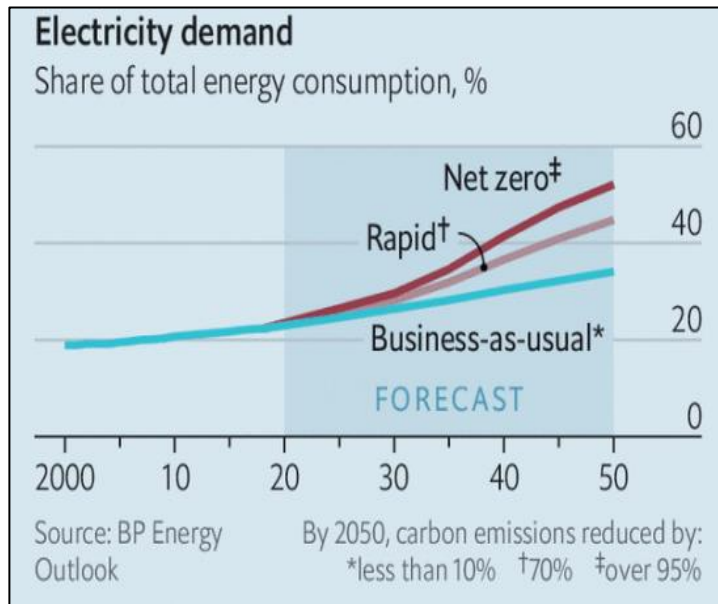
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Importance of carbon-neutrality and reliability in power systems

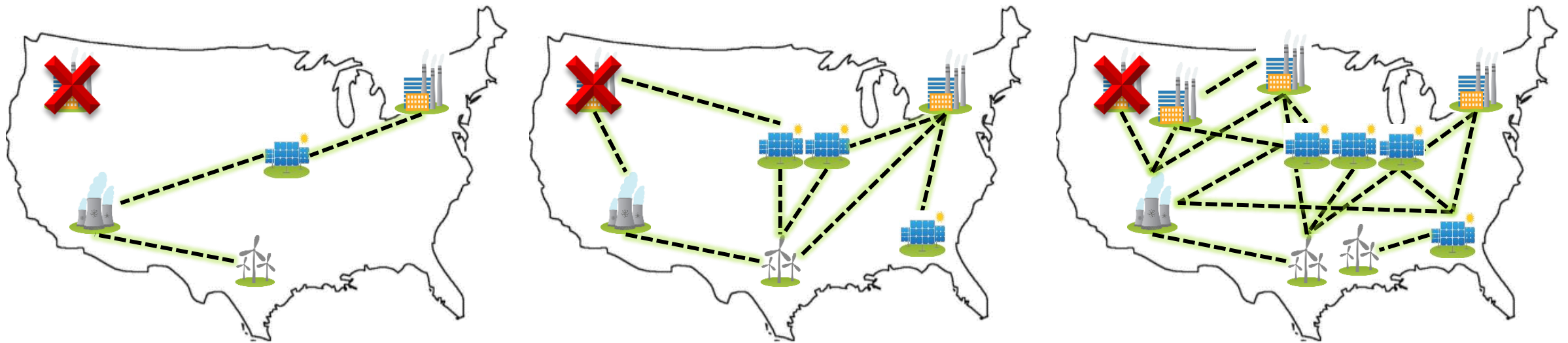
- Electricity demand will increase more than expected due to increased interest in electrification^[1].
- CO₂ emission has sharply increased over the last few decades, and reducing CO₂ emissions is one of the urgent issues in modern energy systems^[2].
- The number of large-scale power outages has increased by 78% during 2011-2021, compared to 2000-2010^[3].



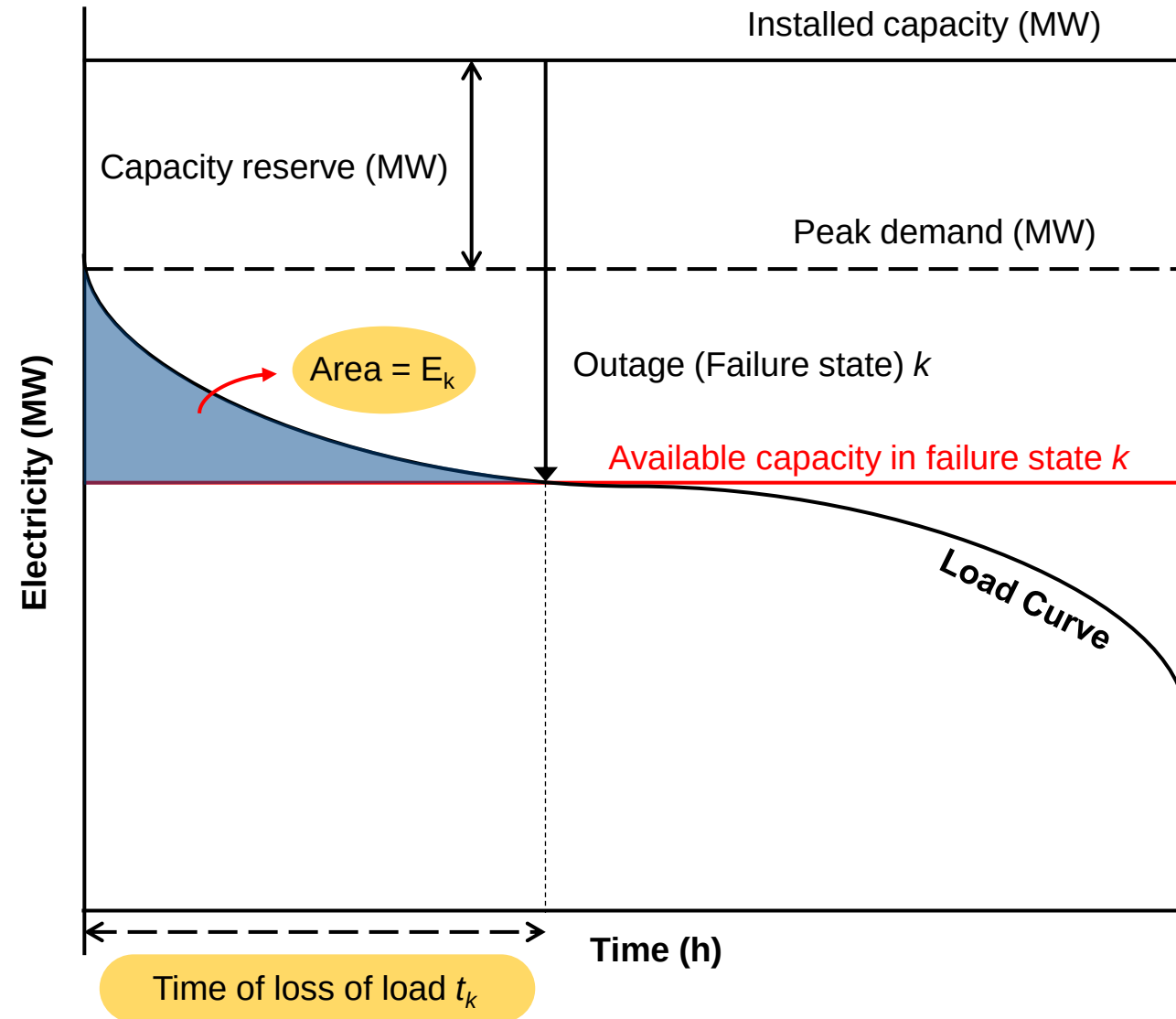
Power systems should be carbon-neutral and reliable to improve sustainability and to satisfy growing electricity demand effectively while preventing power outages.

How can we improve the reliability of power systems?

- **Reliability** An ability to supply uninterrupted electricity to customers to satisfy the load demand.
- Adding extra generators, batteries, and transmission lines can improve the reliability of power systems.
- In case the main facilities fail, extra facilities can replace the workload of failed ones to minimize power loss → The power infrastructure gets complex, the reliability can improve.
- **Issue:** optimize where, when, and what type and size of facilities should be added to satisfy the load demand while improving reliability at a minimum cost.



How can we evaluate power system reliability?



- 1) **LOLE[#]** (Loss of Load Expectation, unit: **hours**):
the time of not satisfying the load demand.

$$LOLE = \sum_{k=1}^n p_k t_k$$

p_k : Probability of capacity failure state k
 t_k : Outage time of capacity failure state k

- 2) **EENS^{*}** (Expected Energy Not Served, unit: **MWh**):
the amount of demand that is not satisfied.

$$EENS = \sum_{k=1}^n p_k E_k$$

E_k : Unserved energy in capacity failure state k

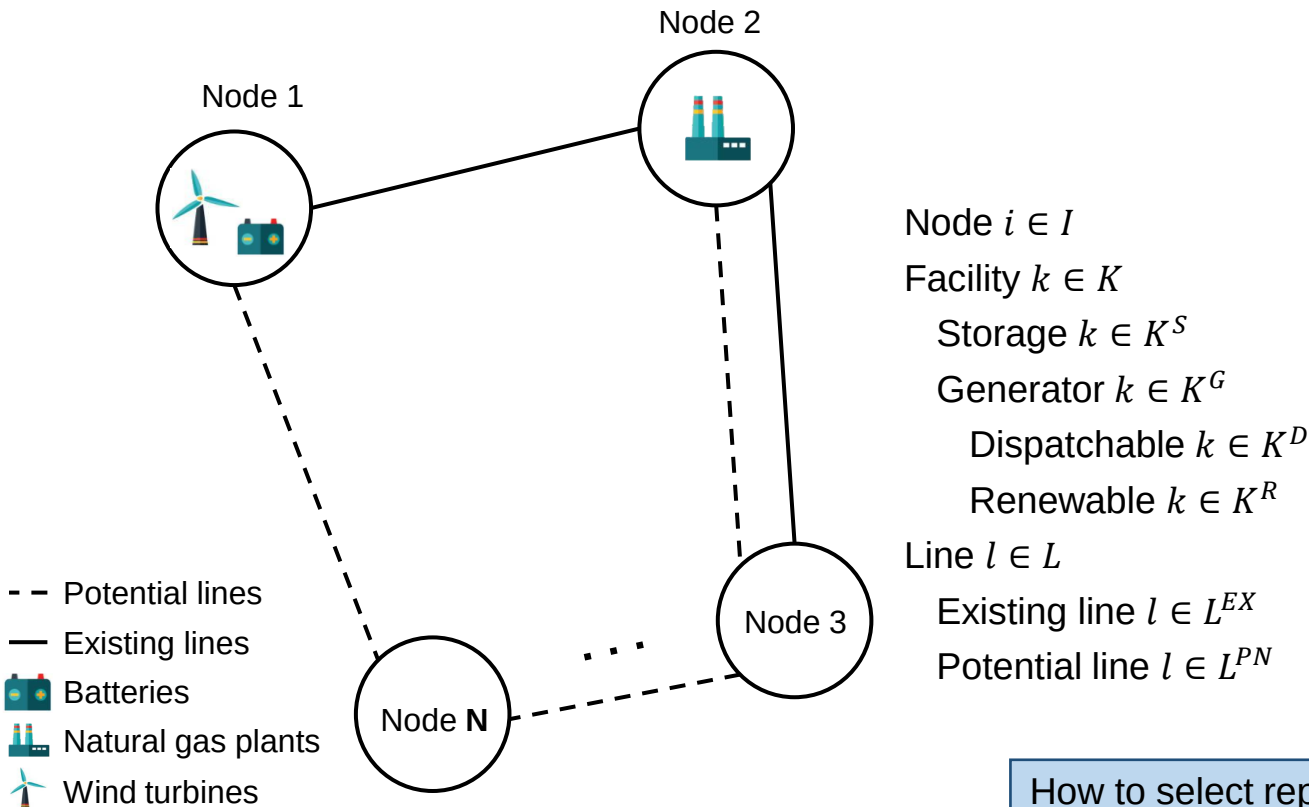
LOLE & EENS ↓

→ Power System Reliability ↑

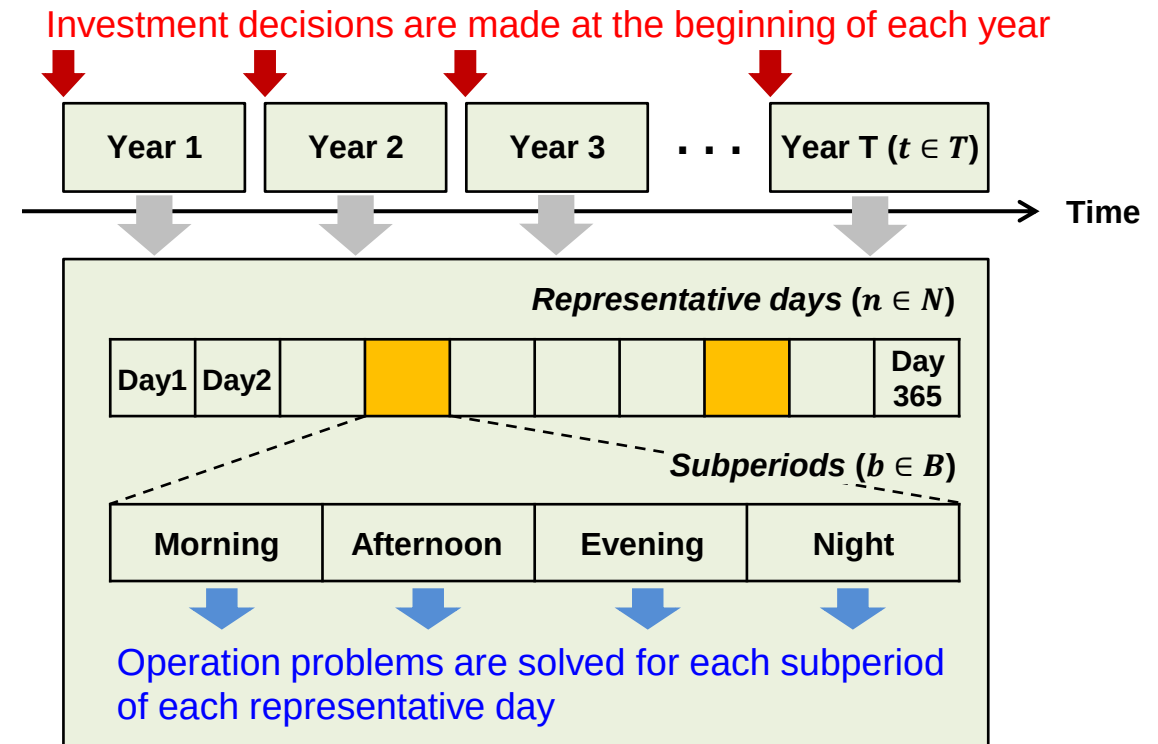
Problem statement

Goal: Develop a **Generalized Disjunctive Programming (GDP) model**^[5,6] that optimizes both **long-term investment** decisions and **short-term operation decisions** for **reliable and carbon-neutral** power systems

Spatial representation



Temporal representation



How to select representative days for reliability evaluation?
 → Select **average days** and add **extreme days** such as the days with the **largest daily demand variation** or **lowest net load**^[7].

Reliability-constrained planning model

Generalized Disjunctive Programming (GDP) model^[5,6]

Min Cost = CAPEX + OPEX + Curtailment penalty + EENS penalty

s.t.

Investment constraints

- Installation/lifetime extension/early retirement of dispatchable generators
- Installation of renewable generators and battery & transmission lines

Operation & reliability constraints

- Power balance and unit commitment for dispatchable generators
- State of charge/discharge of battery (storage systems)
- Power flow of transmission line (simple network and DC power flow)
- CO₂ emission estimation & minimum share of renewable generation
- Probability of each failure state using a forced outage rate of generators and/or transmission lines
- Estimation of power production under each failure state
- Simplified LOLE (loss of load expectation) and EENS (expected energy not served) estimation
- LOLE limit



Python 3.10.12
Pyomo 6.6.2

Rigorous LOLE and EENS analysis requires the enumeration of all capacity failure states of all facilities. However, this work only considers the failures of some critical nodes and facilities.

Two-step algorithm for reliable expansion planning

Step 1. Expansion planning model **w/o reliability**

Min Cost = CAPEX + OPEX + Curtailment penalty

- s.t.
- Installation of **generators and battery & transmission lines**
 - **Unit commitment, stage of charge/discharge, DC power flows**
 - **Fuel consumption and CO₂ emission estimation**

Using the optimal results,

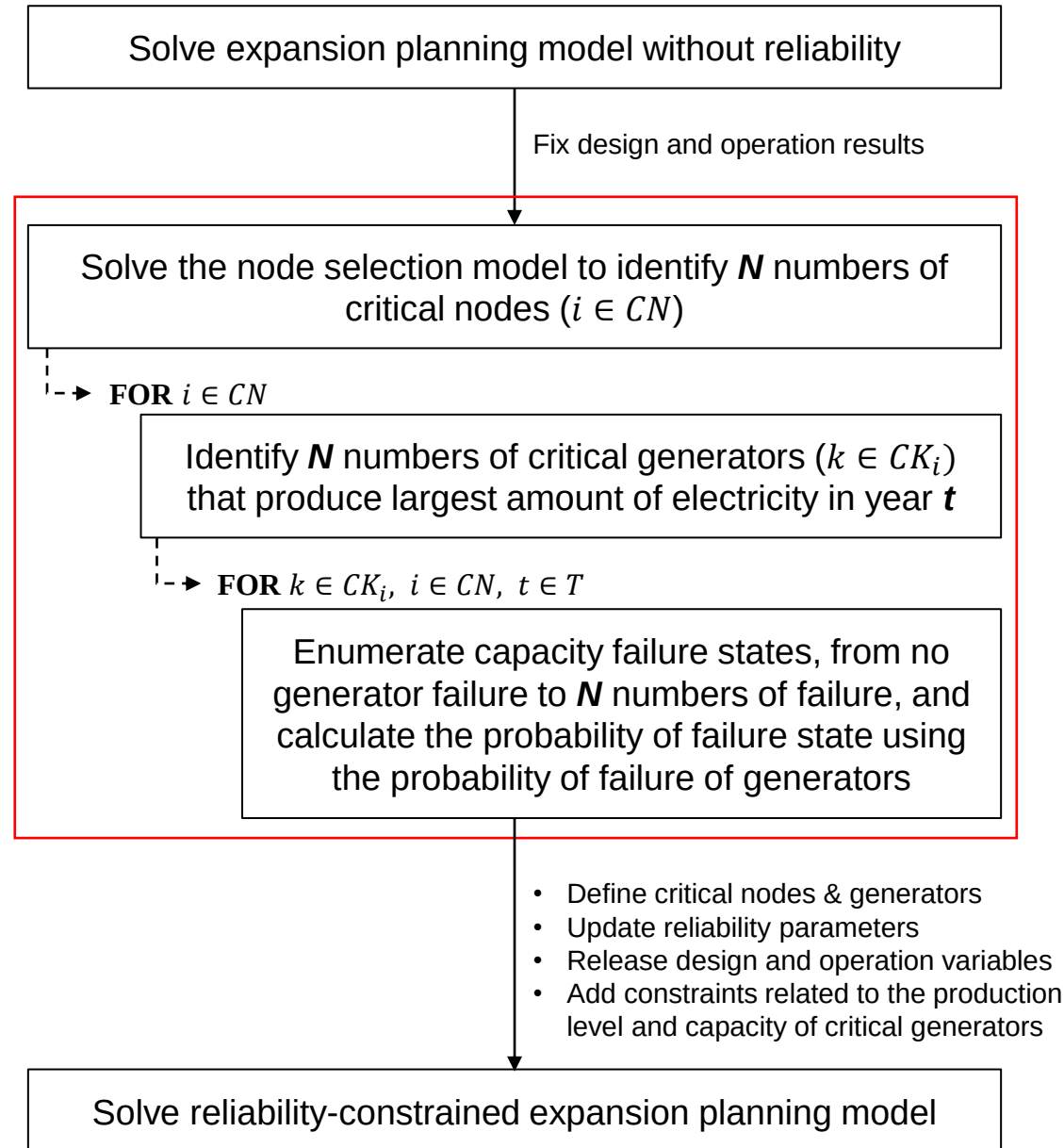
- ✓ Identify ***N*** numbers of **critical nodes** where the power loss is expected to be significant in the event of a failure.
- ✓ Select ***N*** numbers of critical **generators** that largely account for demand satisfaction.

Step 2. **Reliability-constrained** planning model

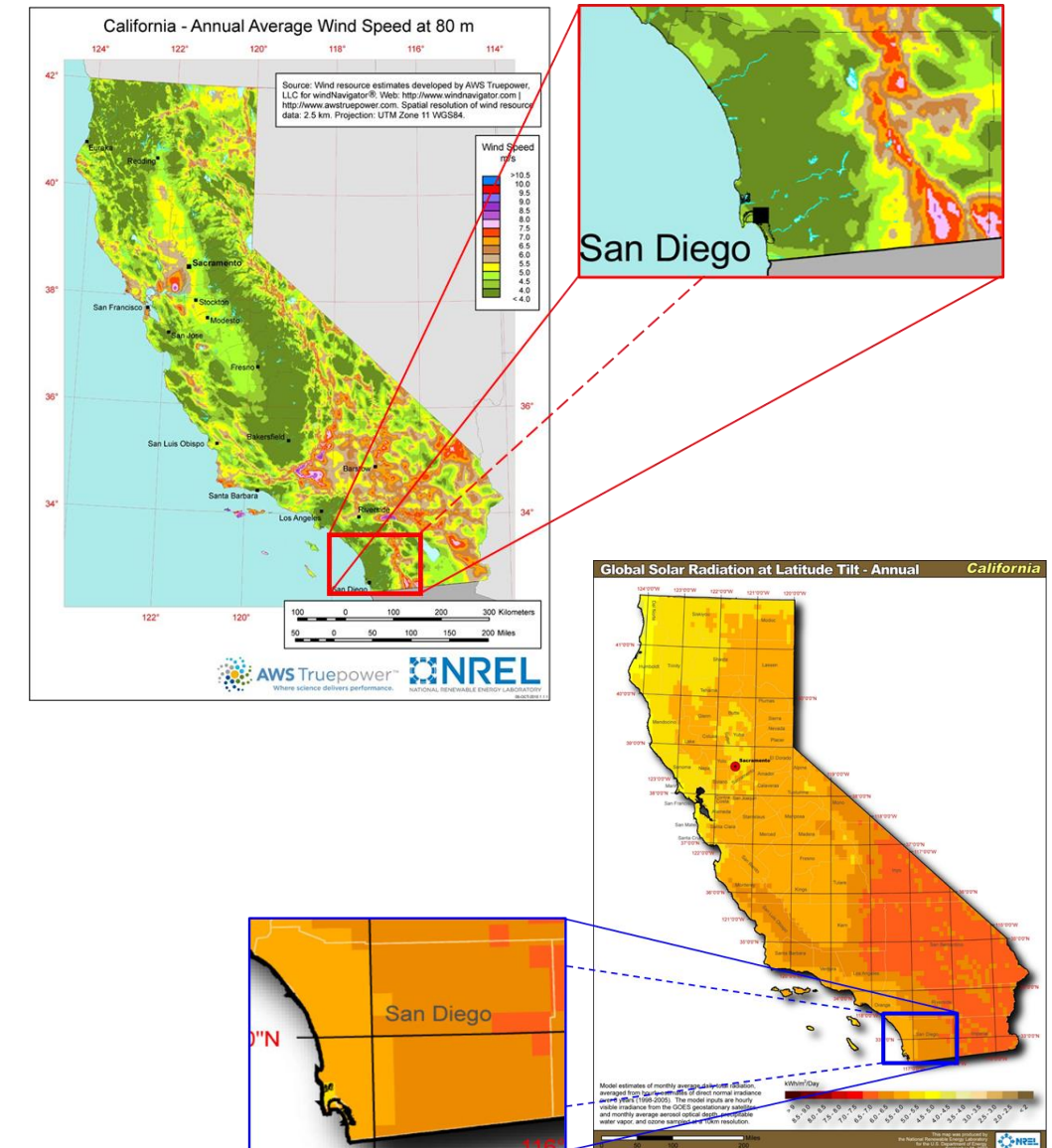
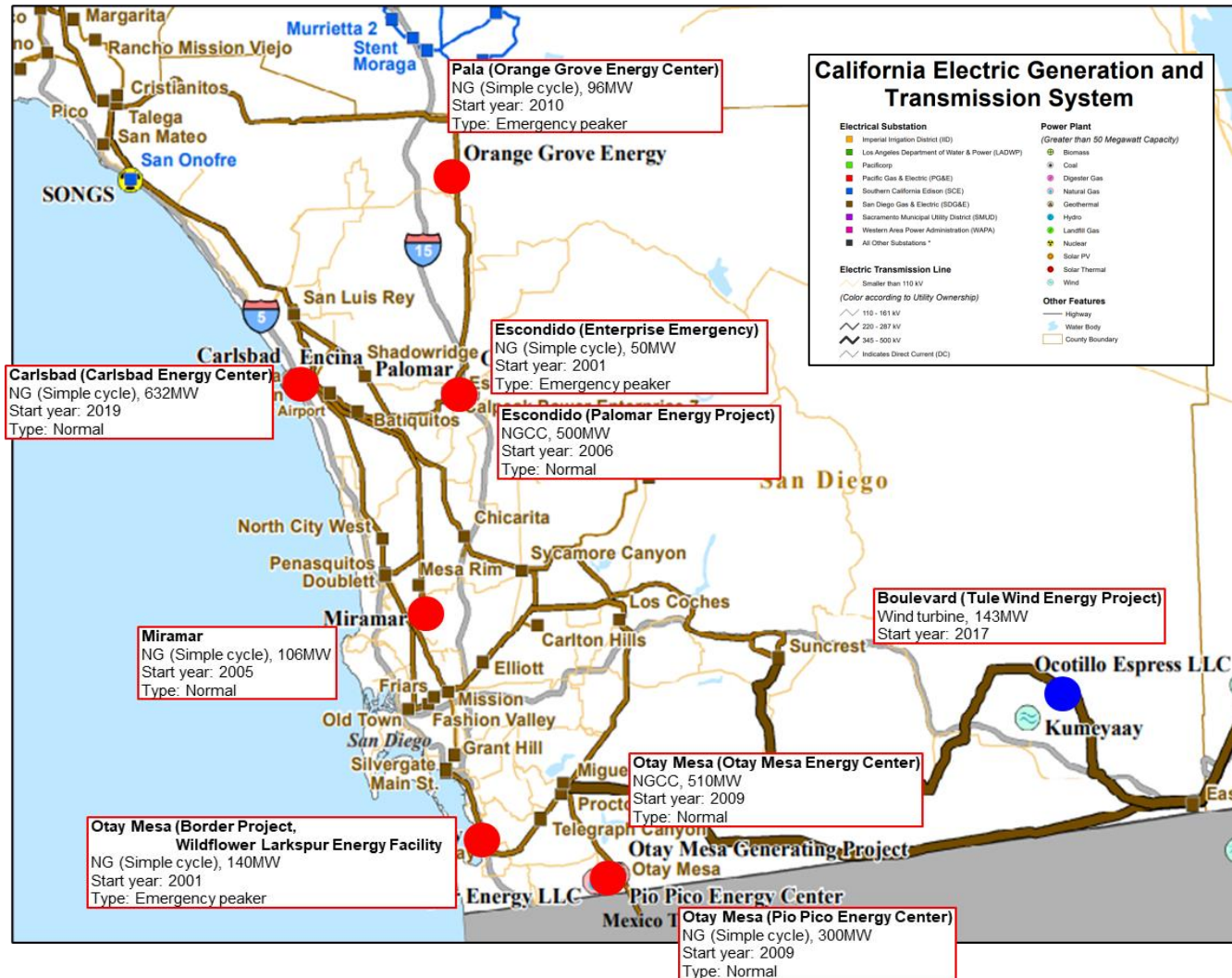
Min Cost = CAPEX + OPEX + Curtailment penalty + **EENS penalty**

- s.t.
- Installation of **generators and battery & transmission lines**
 - **Unit commitment, stage of charge/discharge, DC power flows**
 - **Fuel consumption and CO₂ emission estimation**
 - **Enumeration of capacity failure state and probability of state**
 - **LOLE and EENS estimation & LOLE limit**

Two-step algorithm for reliable expansion planning



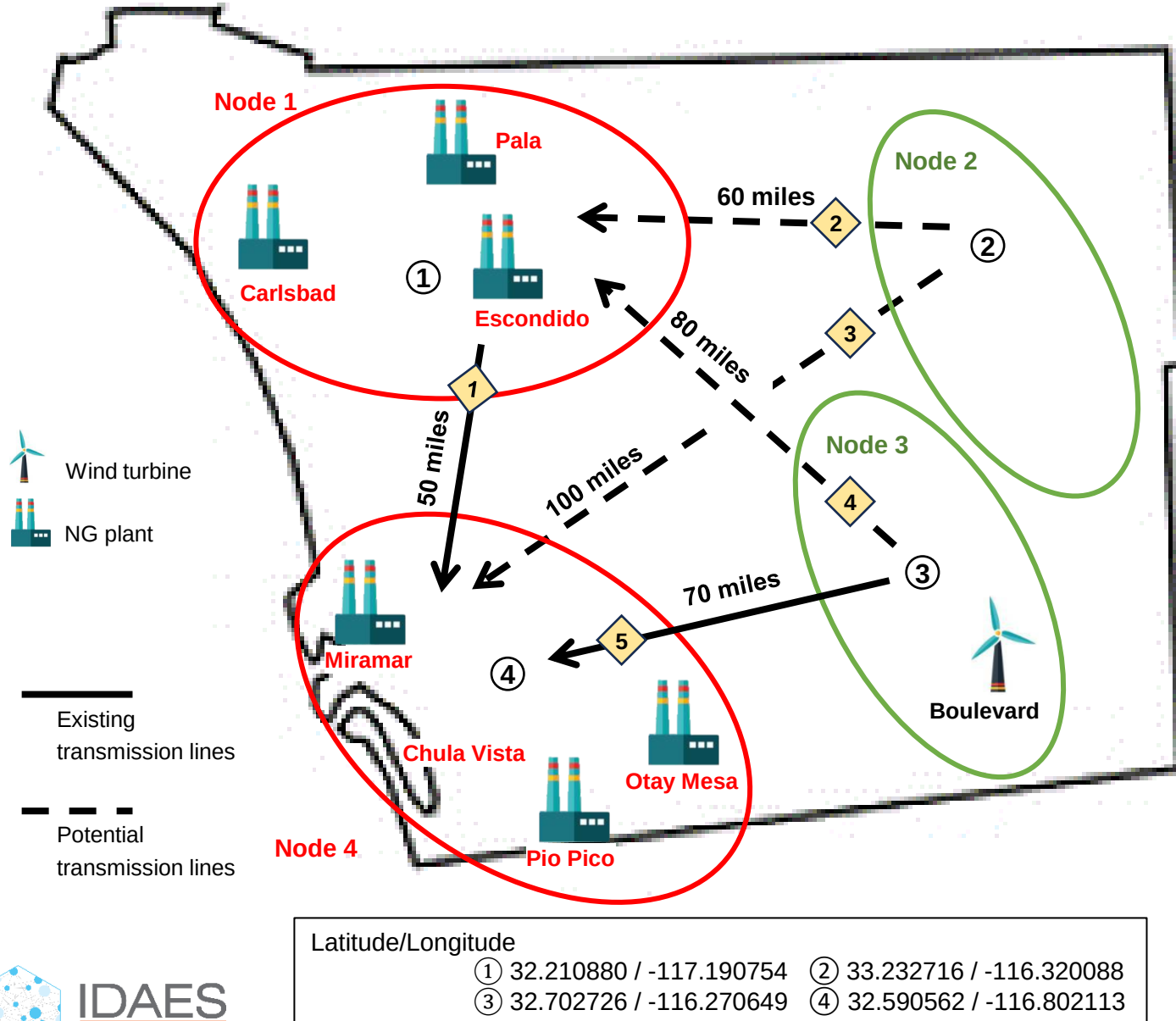
Case Study: Resource & Technology Status of San Diego County in 2021



< Generation and transmission network in 2021 >



Case Study: Representation of San Diego County



- ✓ Size: **4 nodes**
 - Demand and supply nodes
 - Supply-only nodes
- ✓ Horizon: **10-year planning (planning interval: 2 years, a total of 5 planning periods)**
- ✓ 5 representative days and 24 hours for each day (operation interval: 2 hours, a total of 12 operation periods)
- ✓ 4 average day + 1 extreme day

Assumptions

- ✓ Types: NG (Simple cycle), NGCC (w/o CCS), NGCC (w/ CCS), Wind turbine, PV, and Li-ion battery.
- ✓ **Supply-only nodes (green circle)** can only install renewable generator and batteries.
- ✓ **Dispatchable generators in demand and supply nodes (red circle)** can be extended, dispatchable generators (w/ and w/o CCS) can be installed, and renewable generators can be installed.
- ✓ Distance between nodes is estimated by measuring the distance between centers of each node.

Case Study: Scenario generation

California Policy and Regulatory Environment^[9]

	Case 1	Case 2	Case 3
CO ₂ emission limits (30% reduction by 2030) ¹	x	✓	✓
Renewable generation share (60% of the total generation by 2030) ²	x	x	✓

Case Study: Scenario generation

California Policy and Regulatory Environment^[9]

	Case 1		Case 2		Case 3	
	Solution A	Solution B	Solution A	Solution B	Solution A	Solution B
CO ₂ emission limits (30% reduction by 2030) ¹	x	x	✓	✓	✓	✓
Renewable generation share (60% of the total generation by 2030) ²	x	x	x	x	✓	✓
Reliability constraints (LOLE, EENS)	x	✓	x	✓	x	✓

¹ It is assumed that CO₂ emissions should gradually decrease over the planning horizon and reach a 30% reduction by 2030.

² 60% of the power demand should be satisfied by renewable generations and storage by 2030. It is also assumed to increase gradually.

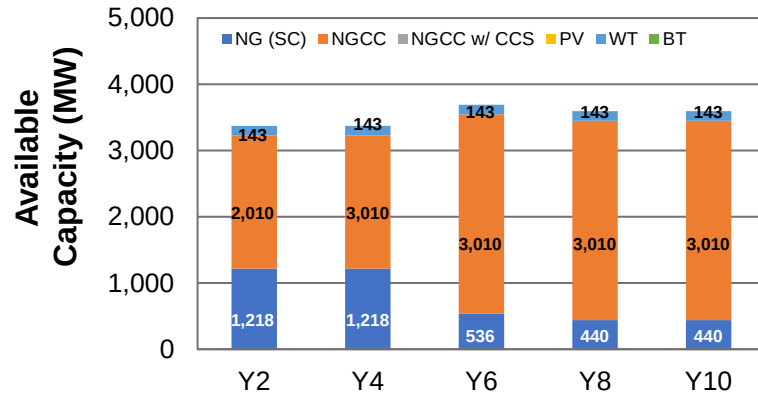
Case 1 study results

Case 1 – No regulation on CO₂ emission & renewable generation

- 5 representative days (4 representative days + 1 **extreme day** with the highest demand and lowest capacity factor)
- # of critical nodes = 2, # of critical generators = 3

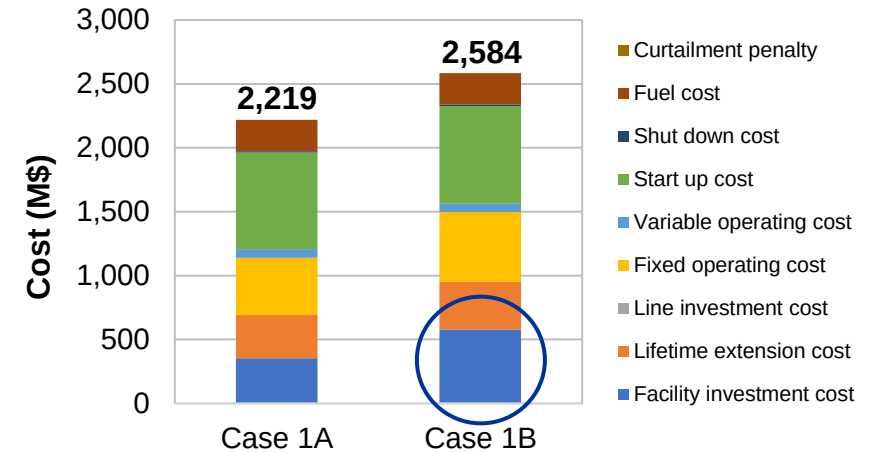
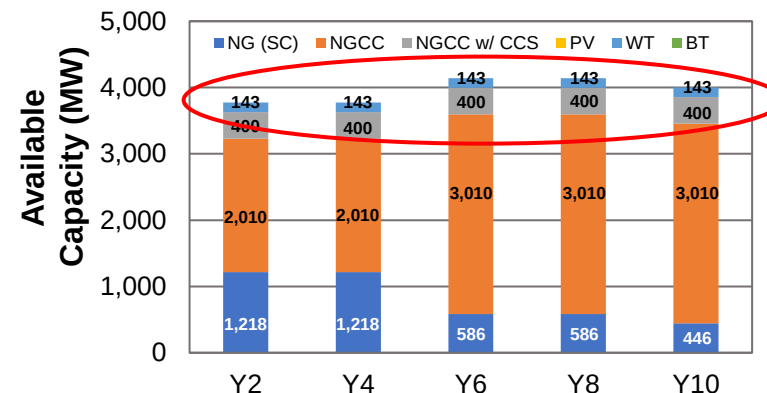
No Reliability (Case 1A)

Installed capacity



With Reliability (Case 1B)

Installed capacity



- Total available capacity in Y10: **Case 1A – 3,593MW, Case 1B – 3,999MW (12% ↑)**
- Since NG (SC) and NGCC are identified as critical generators, **other dispatchable generators (NGCC w/ CCS) is additionally installed for reliability in Case 1B.**
- Renewable generators are not installed due to relatively higher costs and lower capacity factor.
- **Total cost of Case 1B is higher than that of Case 1A because of installation of NGCC w/ CCS.**

	# Binary	# Continuous	# Constraint	CPU (sec)	Gap (%)
Case 1A	39,767	80,582	271,350	107.7	0.8609
Case 1B	49,367	92,662	326,735	13.5	0.9307

Gurobi 10.0.2

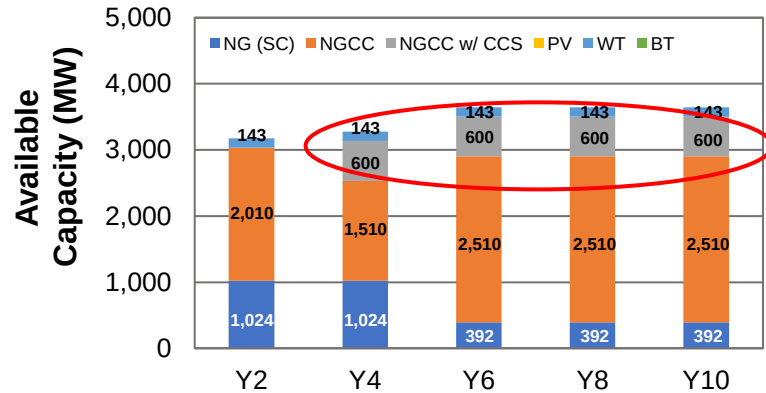
Case 2 study results

Case 2 – Only regulation on CO₂ emission (-30%)

- 5 representative days (4 representative days + 1 **extreme day** with the highest demand and lowest capacity factor)
- # of critical nodes = 2, # of critical generators = 3

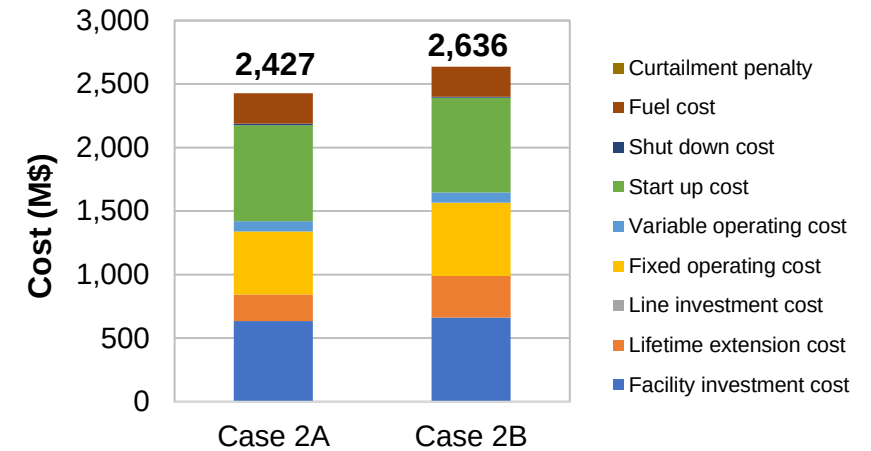
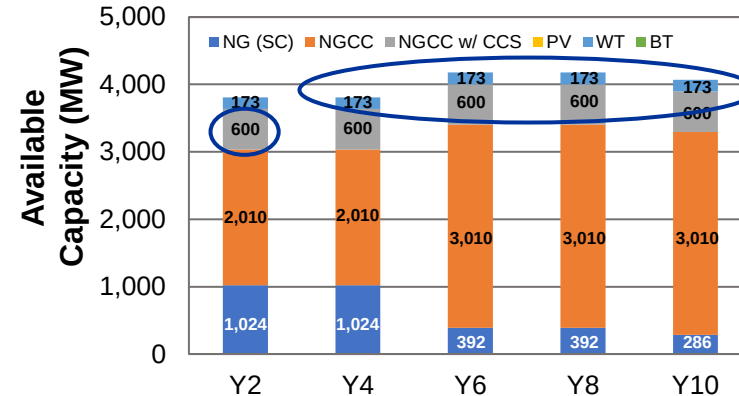
No Reliability (Case 2A)

Installed capacity



With Reliability (Case 2B)

Installed capacity



- Total available capacity in Y10: **Case 2A – 3,645MW, Case 2B – 4,069MW (11% ↑)**
- **CO₂ emission cuts largely provided by NGCC with CCS.**
- To improve reliability, NGCC with CCS is installed earlier than it is required, and the capacity of wind turbine is expanded.
- The total cost of Case 2B is higher than that of Case 2A.

	# Binary	# Continuous	# Constraint	CPU (sec)	Gap (%)
Case 2A	39,767	80,582	271,355	1,271.8	0.9719
Case 2B	49,367	92,662	326,740	21.2	0.7878

Gurobi 10.0.2

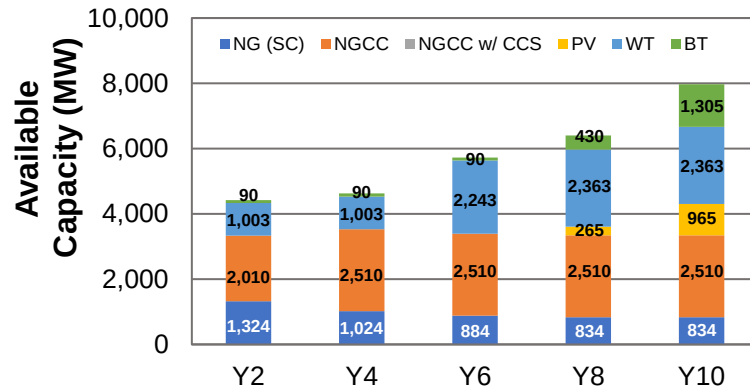
Case 3 study results

Case 3 – CO₂ emission (-30%) & renewable generation (min 60%)

- 5 representative days (4 representative days + 1 **extreme day** with the highest demand and lowest capacity factor)
- # of critical nodes = 2, # of critical generators = 3

No Reliability (Case 3A)

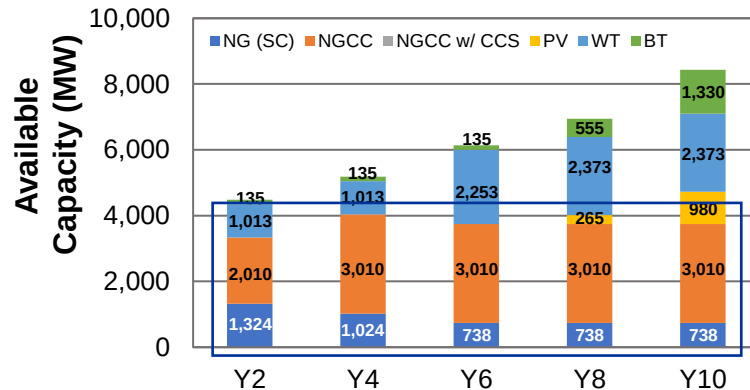
Installed capacity



- Total available capacity in Y10:
Case 3A – 7,977MW, Case 3B – 8,431MW (6%)
- No CCS installed (emission cuts achieved through renewables).
- Reliability constraints do not significantly impact to the systems with high renewable generation share.
- Min 60% renewable case results in drastically increased capacity requirements. Dispatchable power required effectively equivalent.
Case 3B disp. – 3,896MW, Case 2B disp.– 3,748MW

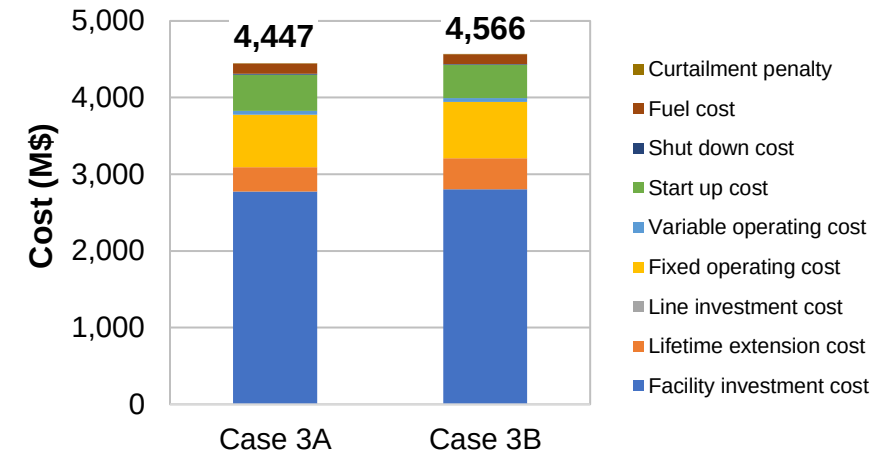
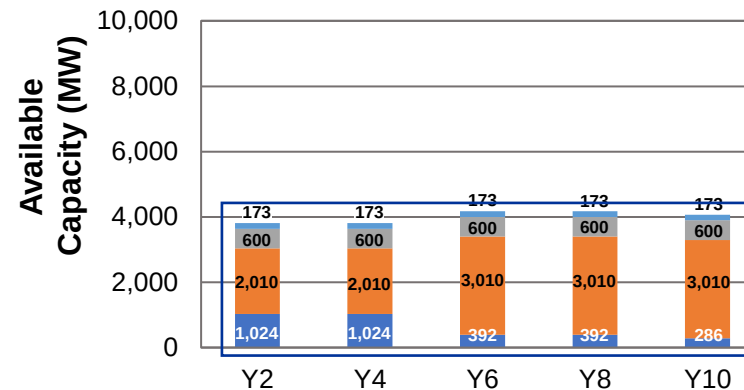
With Reliability (Case 3B)

Installed capacity



With Reliability (Case 2B)

Installed capacity



	# Binary	# Continuous	# Constraint	CPU (sec)	Gap (%)
Case 3A	39,767	80,582	271,360	21,600.3	4.7430
Case 3B	49,367	92,662	326,745	21,600.3	1.0840

Gurobi 10.0.2

- Generation only includes the amount of electricity used to meet the demand. Curtailment, the amount of electricity used to charge the battery, is not included. The generation from the battery indicates the amount of electricity discharged.
- The total cost is calculated after multiplying the weighting factor.



Conclusions

- A Generalized Disjunctive Programming (GDP) model for infrastructure planning of **reliable and carbon-neutral power systems** was proposed.
- The model was verified by solving the **San Diego County case study**.
- 3 cases with different environmental constraints were analyzed (*No CO₂ emission limit and renewable generation target, only CO₂ emission limit, both CO₂ limit and renewable target*).
- **Reliability can be improved by increasing the capacity of dispatchable generators, but renewable-based energy systems can naturally have higher reliability.**

Acknowledgement

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