Optimization Model and Solution Strategy for Infrastructure Planning of Reliable and Carbon-neutral Power Systems: Application to San Diego County

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I. Motivation

- Electricity demand will increase more than expected due to increased interest in electrification[1]
- CO_2 emissions have increased sharply over the last few decades[2]
- 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.

Definition of design reliability & operation reliability

- In **power grid**,
  - **Design Reliability (called resource adequacy):**
    Focus on securing sufficient generation capacity
    Evaluation criteria: loss of load expectation (LOLE) and expected energy not served (EENS)
  - **Operation Reliability (called flexibility):**
    Focus on constantly satisfying a load demand. Evaluation criterion: minimize load shedding

II. Problem statement

Goal

Develop an optimization model that determines **long-term (yearly) investment decisions** and **short-term (hourly) operation decisions** and explicitly evaluates power system reliability for reliable and carbon-neutral power system infrastructure planning.

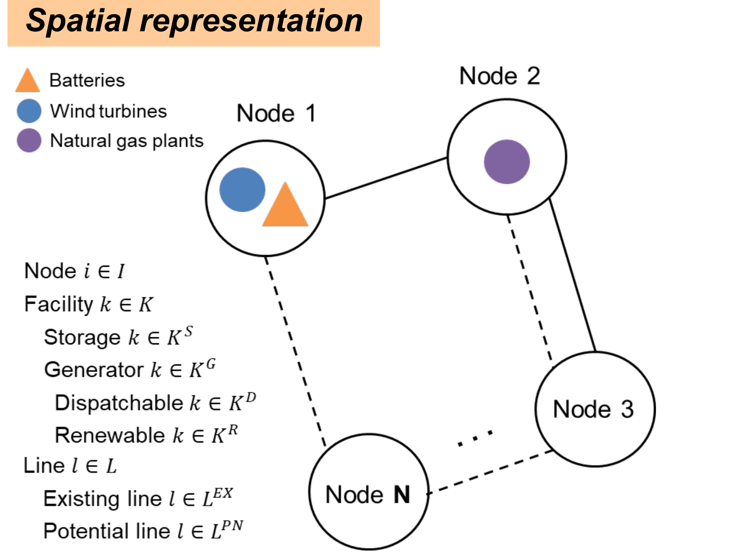
Given

- Load demand projection over a planning horizon
- Capacity factor for renewable generators
- Capacity of existing facilities and transmission lines
- Operational constraints: charging/discharging rates, ramp rates, etc.
- Capital and operational costs for all technologies

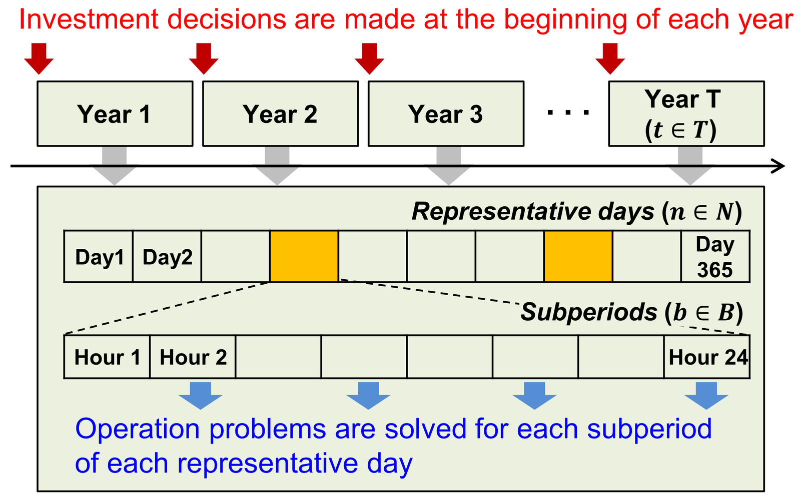
Determine

- Installed capacity of generators, batteries, and lines
- Location and timing to install, retire & extend facilities
- Operating and reserve capacity for reliability
- Operation schedules of generators and battery
- Power output, level of charge, and power flows

Spatial representation



Temporal representation



III. Generalized Disjunctive Programming (GDP) model

- Two models have been proposed: **i) expansion planning model without reliability** & **ii) reliability-constrained planning model**

Additional constraints for reliability-constrained planning model

Min Cost = CAPEX + OPEX + Curtailment penalty
+ Design reliability penalties (LOLE and EENS penalties)

s.t.

Python 3.10.12, Pyomo 6.6.2

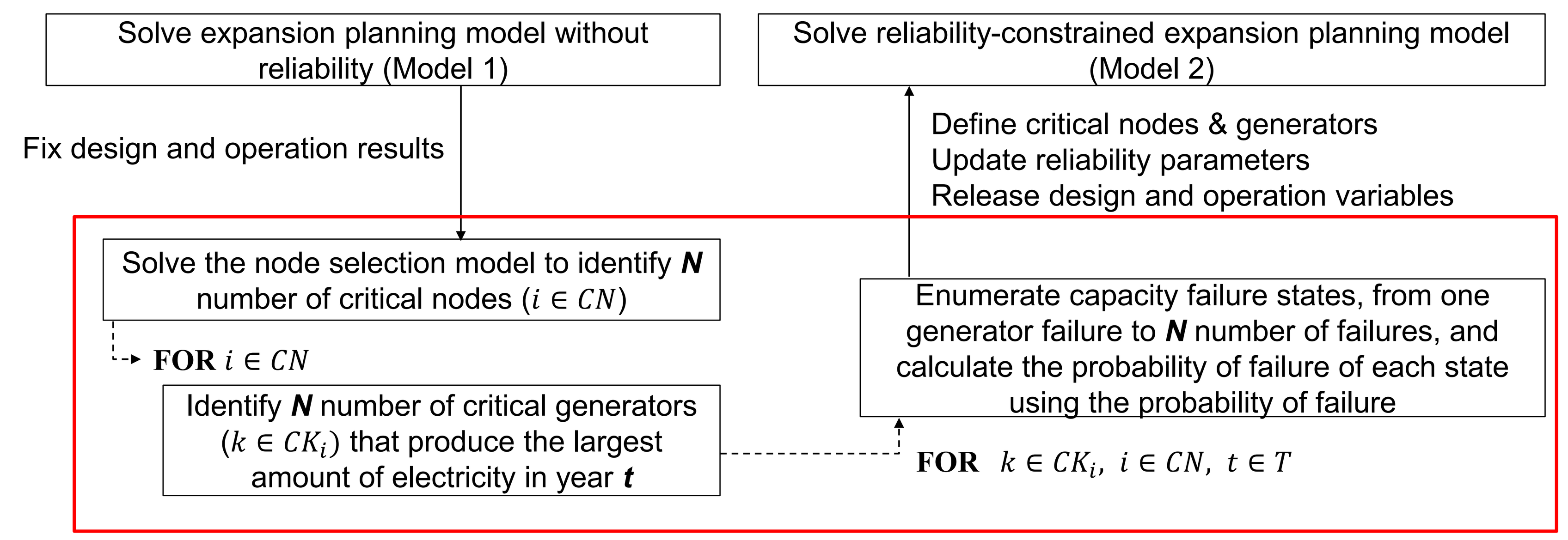
Investment constraints

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

Operation constraints

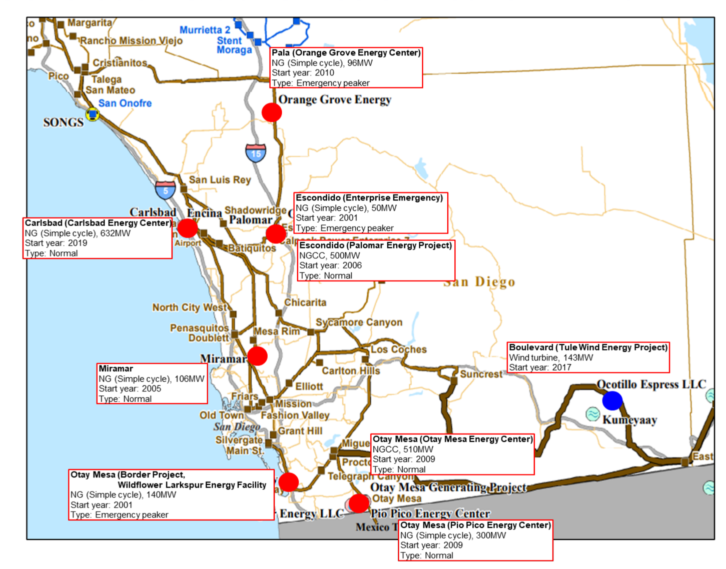
- Power balance and unit commitment for dispatchable generators
- State of charge/discharge of battery
- Power flow of transmission lines (simple network flow or DC power flow)
- CO_2 emission estimation & minimum share of renewable generation
- Probability of each failure state using a forced outage 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

IV. Algorithm for reliable expansion planning

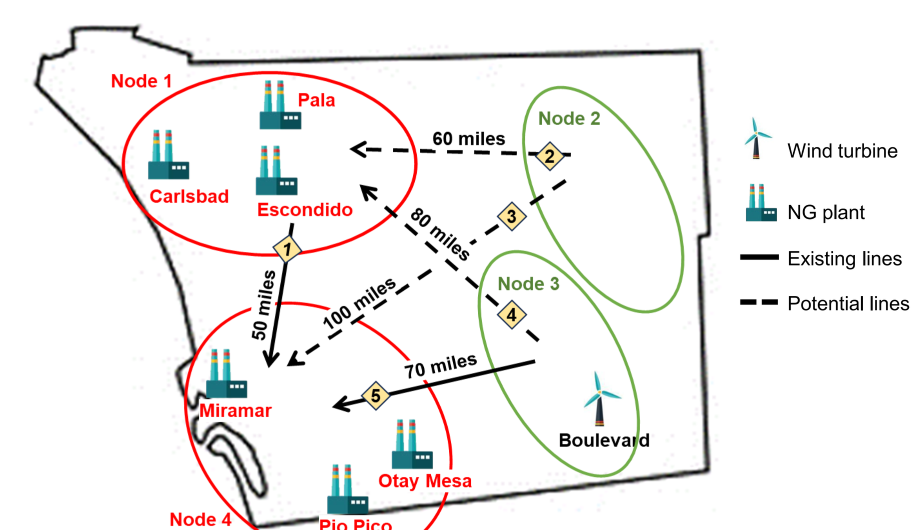


V. Case study: San Diego County, California

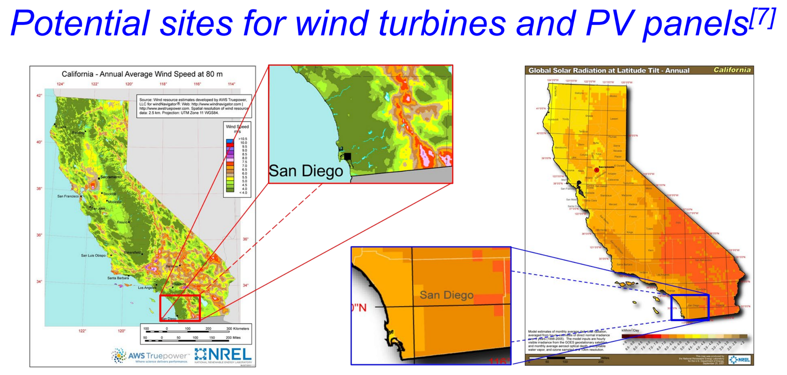
Generation & transmission network in 2021[6]



Representation of case study



Potential sites for wind turbines and PV panels[7]



- ✓ **10** year planning (planning interval: 2 years)
- ✓ **5** representative days (4 average demand and capacity factor days + 1 extreme day with the largest demand and the lowest capacity factor)
- ✓ **24** hours for each day (operation interval: 2 hours)
- ✓ Size: **4 nodes** Demand & supply ○ Supply-only ○

Assumptions

- ✓ Generator types: NG (Simple cycle), NGCC (w/o CCS), NGCC (w/ CCS), Wind turbine, PV, and Li-ion battery.
- ✓ **Supply-only nodes** can only install **renewable generators** and **batteries.**
- ✓ **Dispatchable generators in demand and supply nodes** can be extended, new dispatchable and renewable generators can be installed.

Scenario generation based on California Policy and Regulatory Environment[8,9]

	Scenario 1		Scenario 2		Scenario 3	
	Solution A	Solution B	Solution A	Solution B	Solution A	Solution B
The power load should always be satisfied (Loadshedding is not allowed) → Operation reliability should always be maximized						
Design reliability constraints (LOLE, EENS)	x	√	x	√	x	√
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	√	√

[1] It is assumed that CO_2 emissions should gradually decrease and reach a 30% reduction by Y10.
[2] At least 60% of the power demand should be satisfied by renewable generations and storage by 2030.

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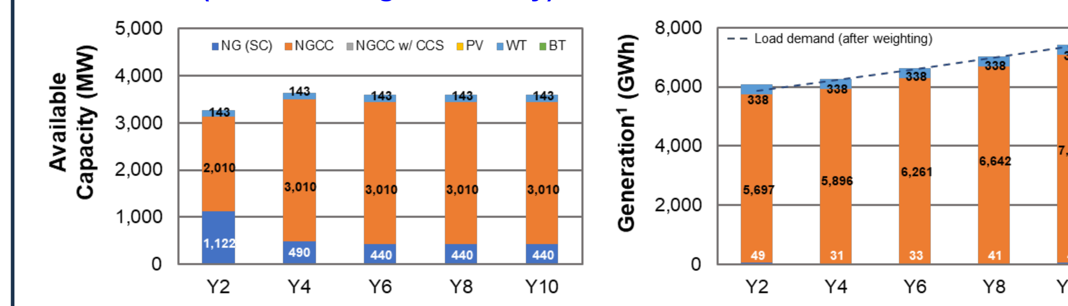
VI. Results of Case study

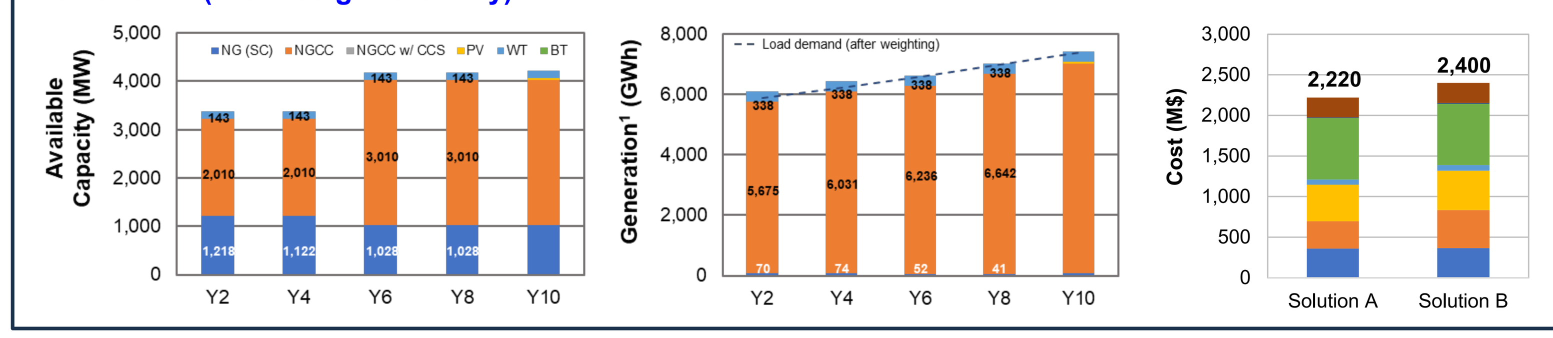
Scenario 1 (No regulation on CO_2 emission and renewable generation)

Solution A (without design reliability)



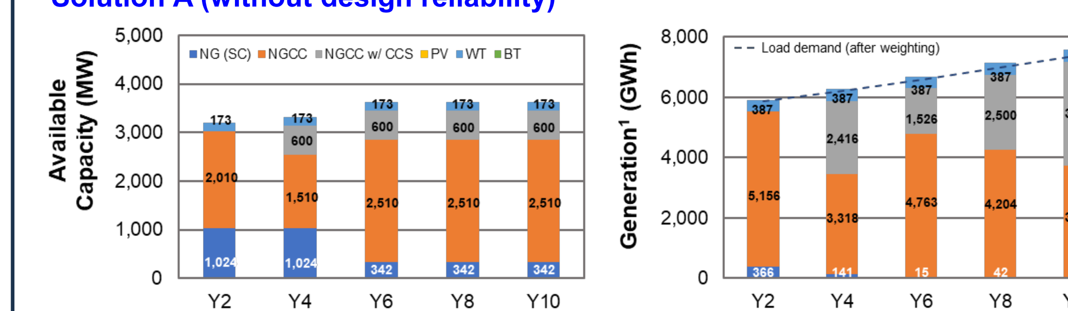
- There is no environmental regulation, NGCC is mainly installed to meet the demand.
- When reliability is included, some of exiting simple cycle natural gas power plants extend their lifetime and remain as backup generators.

Solution B (with design reliability)



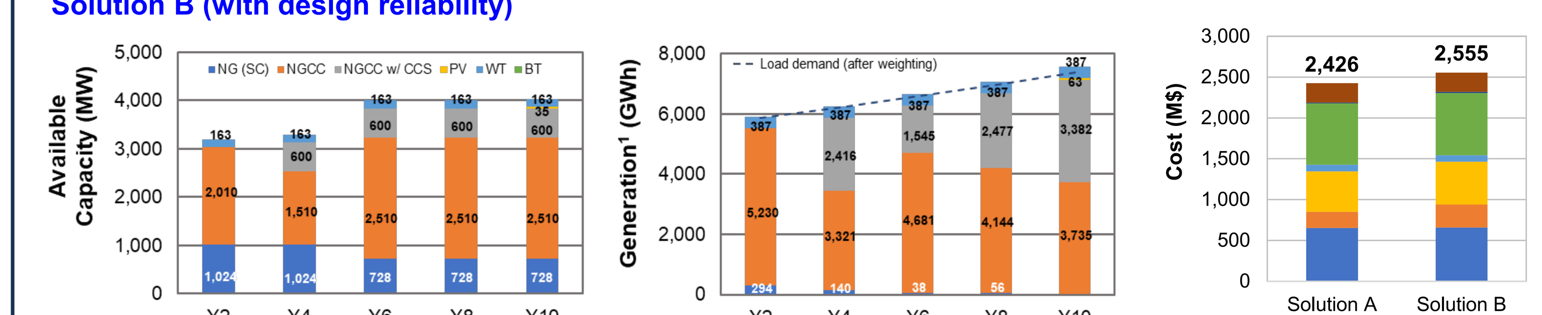
Scenario 2 (Only regulation on CO_2 emission (30% reduction))

Solution A (without design reliability)



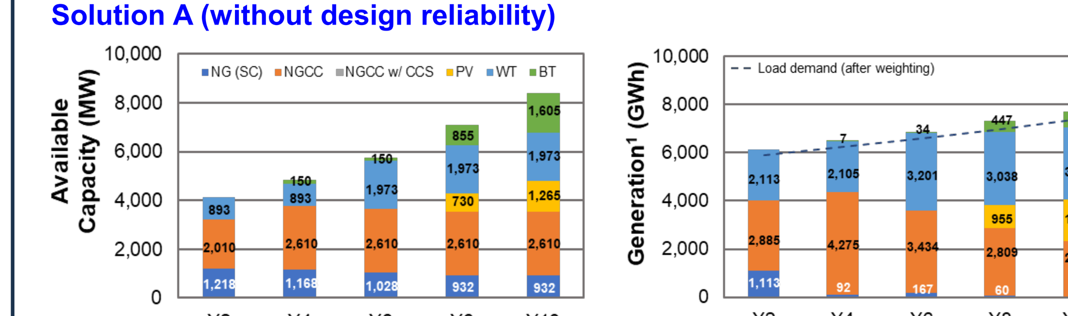
- If CO_2 emissions are regulated, then the capacity of NGCC with CCS increases to meet the emission limit.
- Likewise, when reliability is included, some of the exiting simple cycle natural gas power plants extend their lifetime and remain as backup generators.

Solution B (with design reliability)



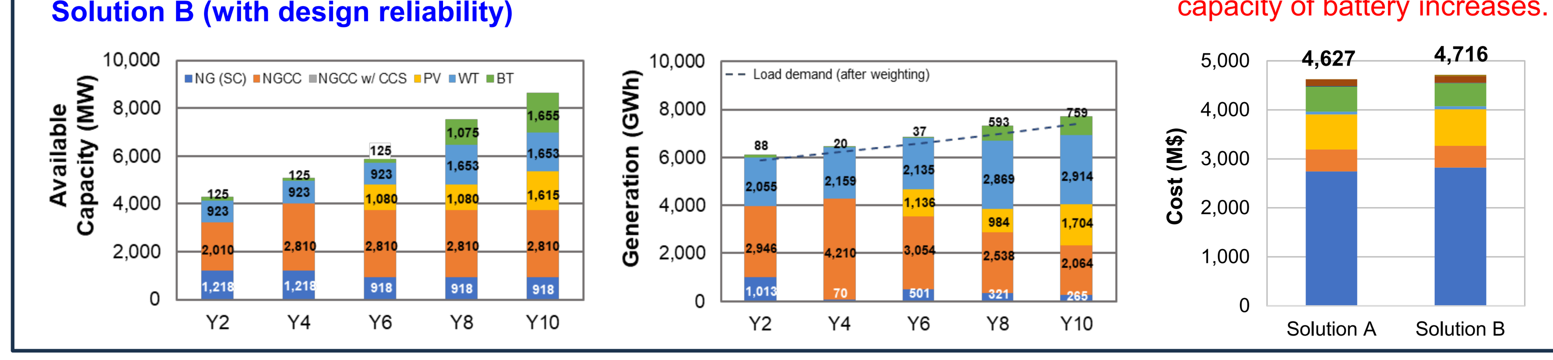
Scenario 3 (Regulation on CO_2 emission (30% reduction) and renewable generation (min 60%))

Solution A (without design reliability)



- If both CO_2 emissions and renewable generation are regulated, then the capacity of renewables, such as wind turbine and PV, significantly increases.
- When reliability is included, the capacity of PV, known to be the most reliable in terms of failure, increases. Also, the capacity of battery increases.

Solution B (with design reliability)



VII. Conclusions and future work

- Proposed an optimization model for infrastructure planning of reliable and carbon-neutral power systems
- Verified the model on a case study involving the San Diego County with different environmental constraints.
- Impact of representative days on the optimal design of power systems will be analyzed.

References

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[7] NREL, AWS Truepower, https://windexchange.energy.gov/states/ca
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