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

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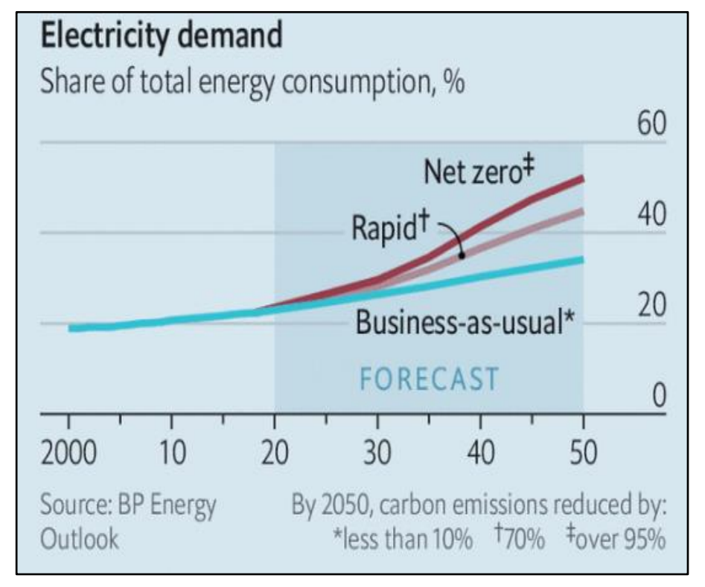
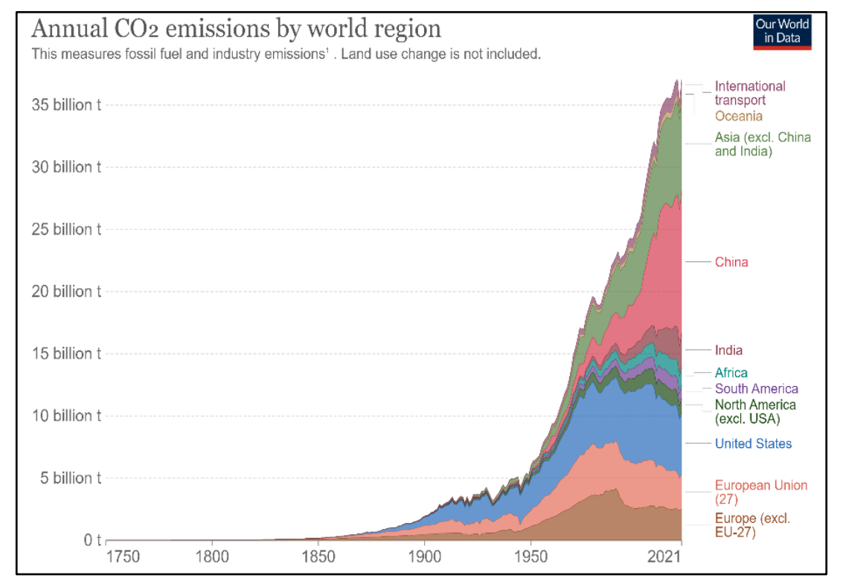
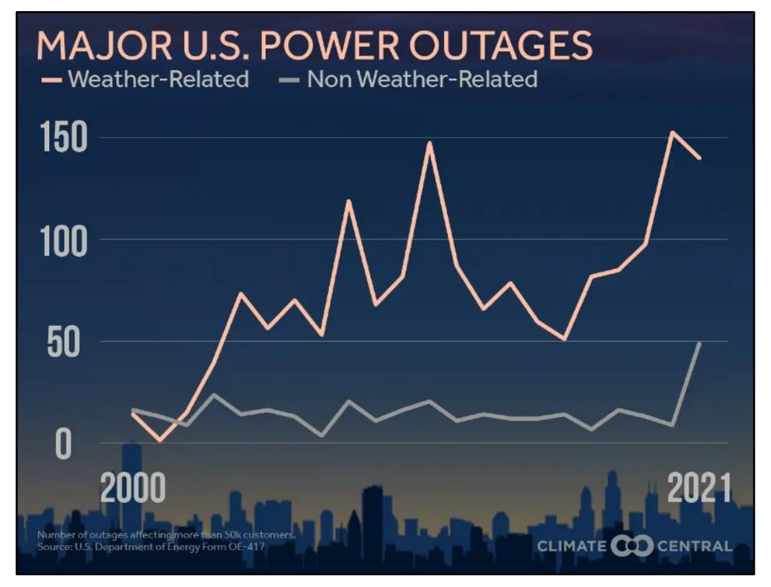
Motivation

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

Definition of reliability

- In the area of **Reliability, Aerospace, Nuclear, and Chemical Engineering**,
  - ➢ **Reliability:** A probability that a device, a machine, or a process can perform its required function **without failures** for a given time.
  - ➢ The definition is more related to the performance of **individual** units or processes.
- In **power grid**,
  - ➢ **Reliability:** An ability to supply uninterrupted power always to satisfy the load demand[4].
  - ➢ **As the power grid comprises numerous power generators and transmission lines, it focuses on securing sufficient generation and line capacity to satisfy the load demand.**
  - ➢ The definition is more related to the performance of the network.

Problem statement

Goal: To plan an infrastructure of reliable and carbon-neutral power systems
– Application to San Diego County

Details

a) Develop an optimization model that determines **long-term (yearly) investment decisions** and **short-term (hourly) operation decisions** and explicitly evaluates power system reliability.
b) Solve the San Diego County case study and compare the performance of two models (IDAES model and RESOLVE) for the case.

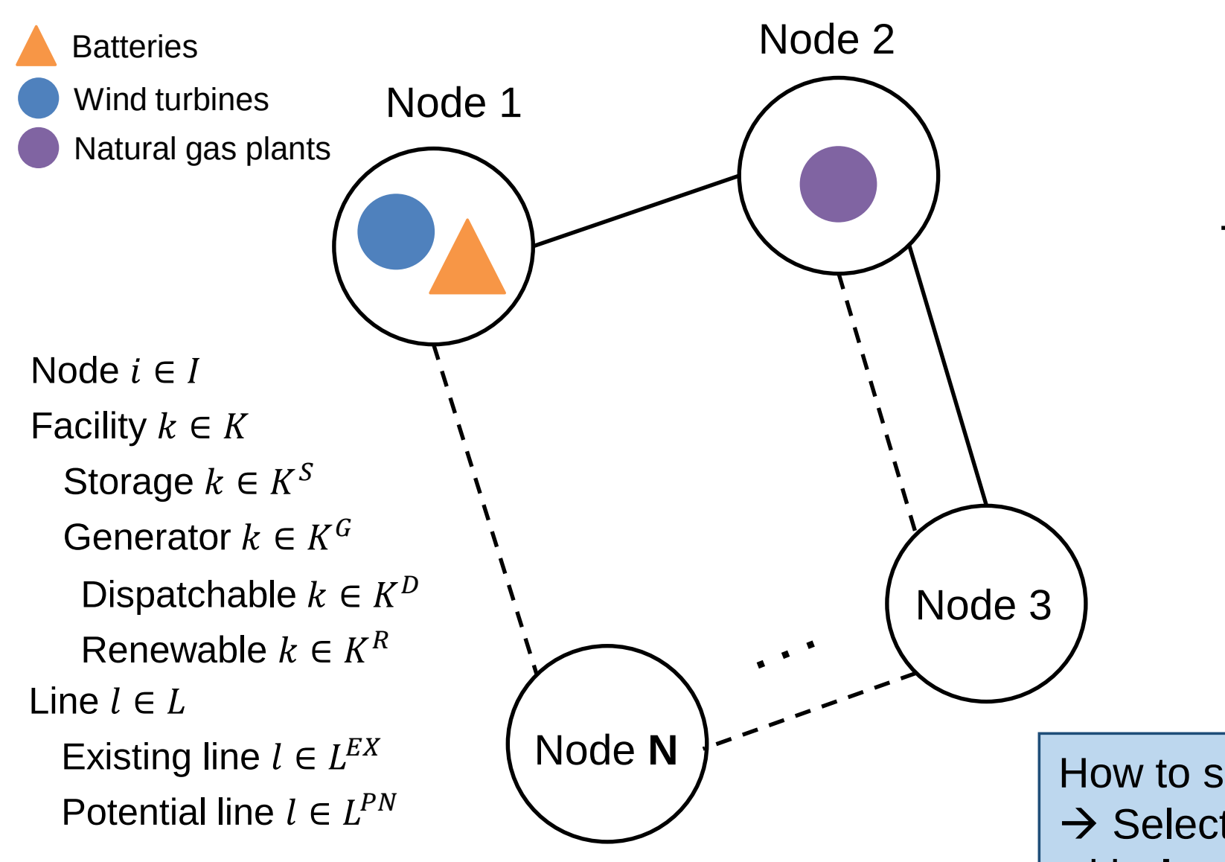
Given

- Load demand projection over a planning horizon
- Capacity factor for renewable generators
- Capacity of existing facilities and transmission lines
- Ramping up/down rate, charging/discharging rate

Determine

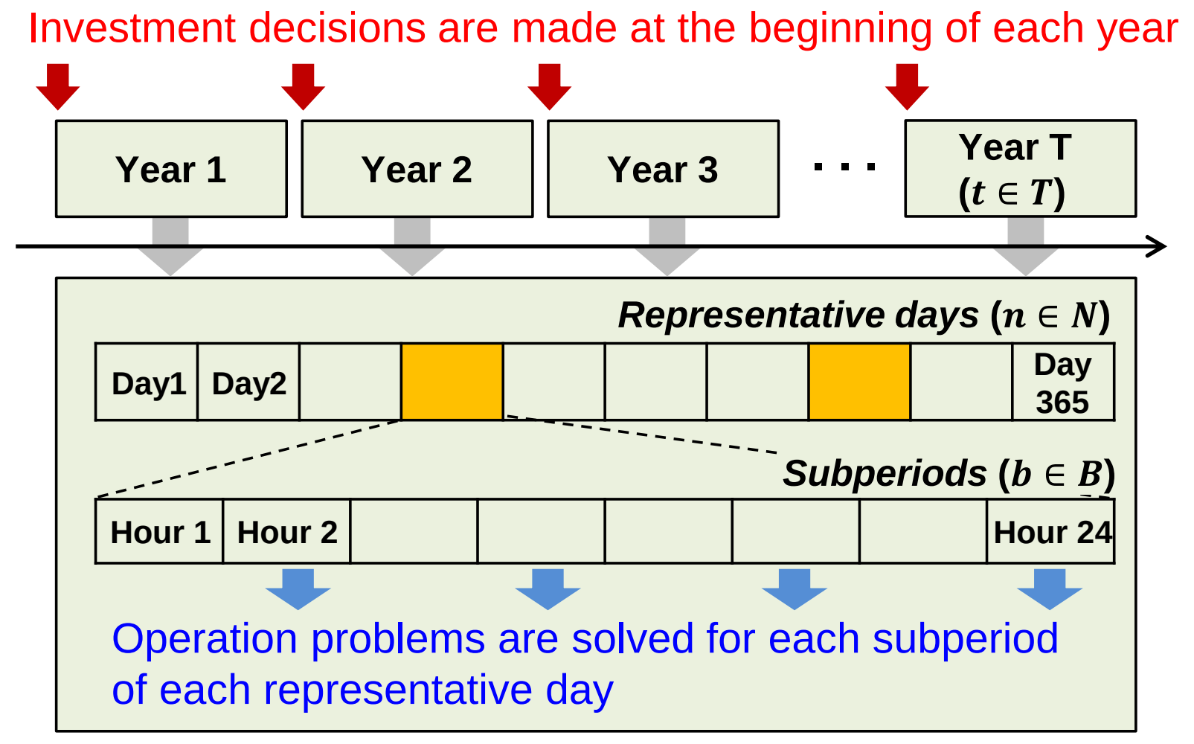
- Installed capacity of generators, batteries, and lines
- Location and timing to install, retire & extend facilities
- Operating and reserve capacity for reliability
- Operation schedules of generators and battery
- Power output, level of charge, and power flows

Spatial representation



Node $i \in I$
Facility $k \in K$
Storage $k \in K^S$
Generator $k \in K^G$
Dispatchable $k \in K^D$
Renewable $k \in K^R$
Line $l \in L$
Existing line $l \in L^{EX}$
Potential line $l \in L^{PN}$

Temporal representation


Investment decisions are made at the beginning of each year

Operation problems are solved for each subperiod of each representative day

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**[5].

Expansion planning model comparison

	RESOLVE	IDAES expansion planning – Ver. 1	IDAES expansion planning – Ver. 2
Major constraints	• Installation and retirement • Unit commitment • Storage balance & ELCC constraints[4], Demand response & CO_2 emission limits • Minimum renewable share • Network flow model	• Installation and retirement • Unit commitment • Storage balance • CO_2 emission limits & Minimum renewable share • DC flow model	• Installation and retirement • Lifetime expansion of facilities • Unit commitment • Storage balance • CO_2 emission limits & Minimum renewable share • Reliability constraints & DC flow model
Computational features	• **Linearized** unit commitment • Continuous capacity → **determine the optimal size within a range** • **Fixed reserve systems** • No tailored solution method	• Unit commitment **with integer/Boolean variables** • Available capacity is fixed → **optimize the number of facilities** • **Fixed reserve systems** • Nested and Tailored Benders decomposition	• Unit commitment **with binary (Boolean) variables** • **Facility can choose different sizes** • **Optimize planning and operating reserve systems depending on the reliability target** • A decomposition method will be proposed

[1]: California; Balancing Authority of Northern California (BANC), California Independent System Operation (CAISO), Los Angeles Department of Water and Power (LADWP), Imperial Irrigation District (IID), and two zones out-of-state
[2]: Texas; Panhandle, Northeast, West, South, and Coast
[3]: Users can choose different days and hours for each planning year
[4]: Effective Load Carrying Capability, used to evaluate the reliability of power systems with high penetration of renewables

Generalized Disjunctive Programming (GDP) model

Min Cost = CAPEX + OPEX + Load shedding penalty

s.t.

Investment constraints

- Installation/lifetime extension of dispatchable generators
- Installation/capacity expansion of **renewable generators and battery**
- Installation of **transmission lines**

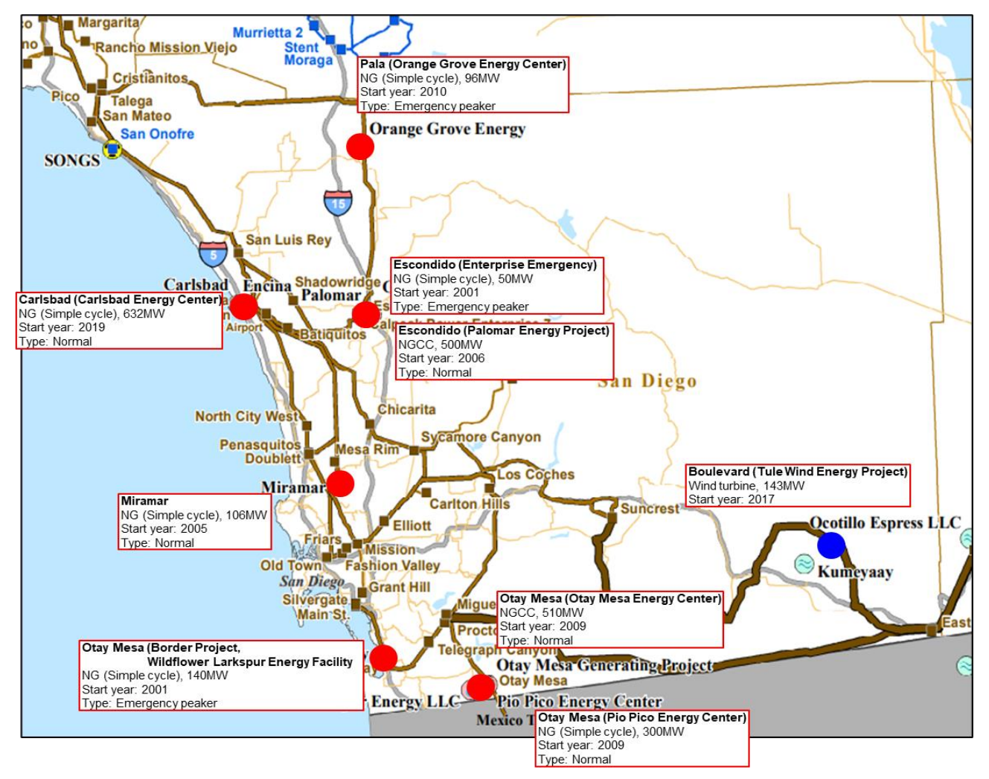
Operation constraints

- Ramping up/down, start-up/shut-down, and **unit commitment**
- **Charging/discharging levels** of storage
- **DC power flow and power balance**
- Fuel consumption and CO_2 emission estimation
- Loss of load expectation (LOLE) and expected energy not served (EENS) estimation
- CO_2 emission limit and minimum share of renewable generation

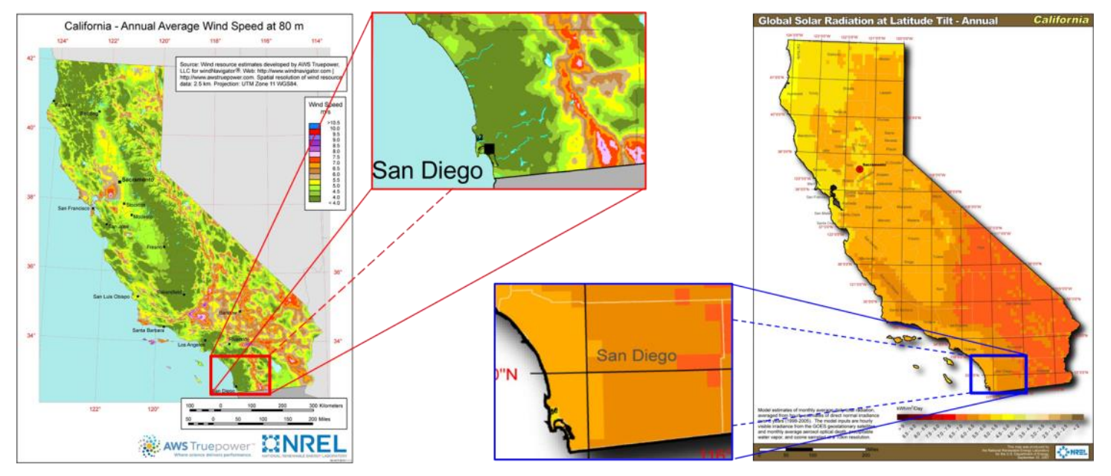
Python 3.10.12, Pyomo 6.6.2

Case study: San Diego County, California

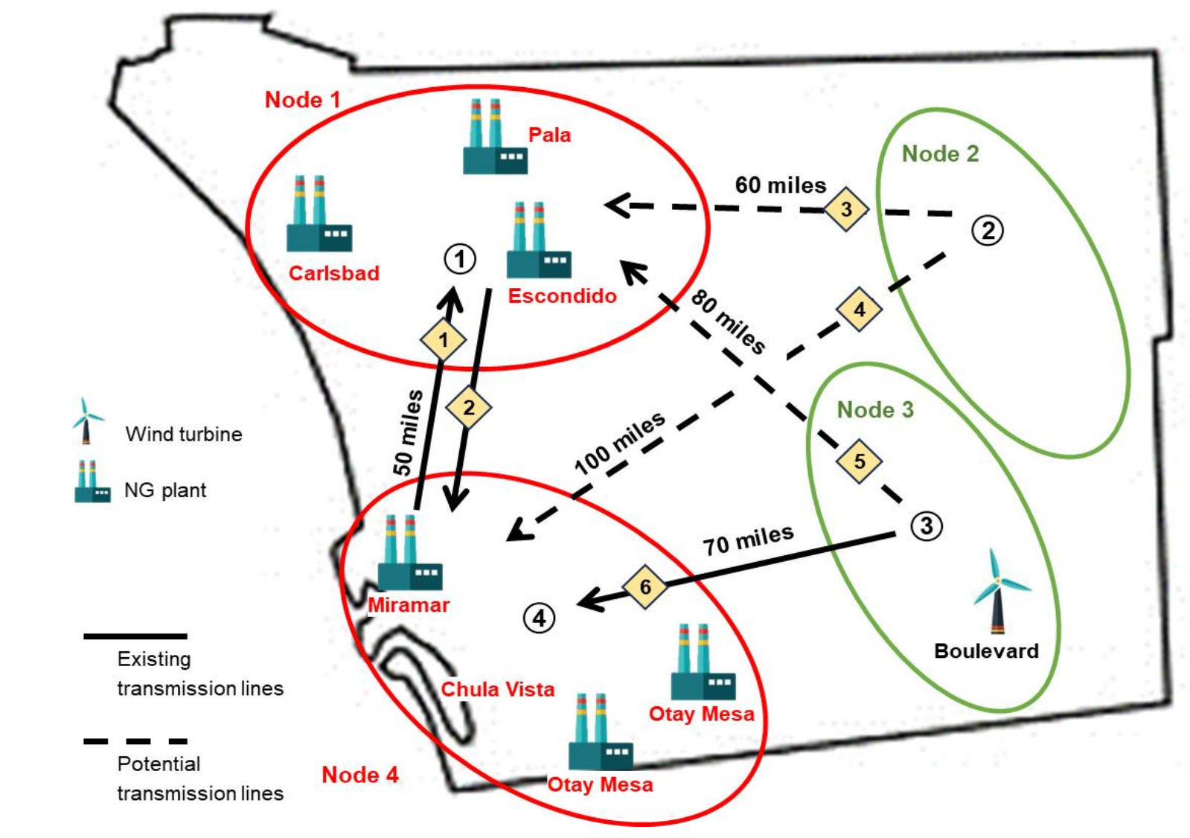
Generation & transmission network in 2021[6]



Potential sites for wind turbines and PV panels[7]



Representation of case study



- ✓ **10-year planning,** 3 representative days, 24 hours for each day
- ✓ Size: **4 nodes** Demand & supply ○ Supply-only ○

Assumptions

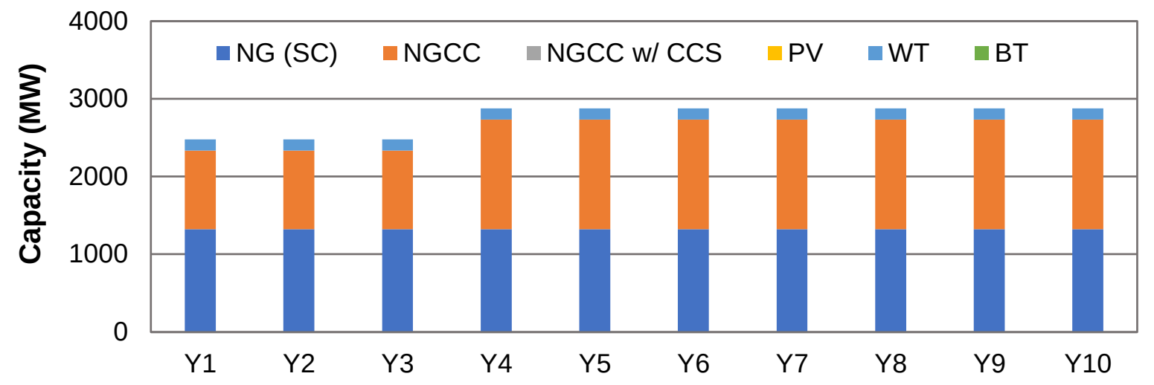
- ✓ Generator types: NG (Simple cycle), NGCC (w/o CCS), NGCC (w/ CCS), Wind turbine, PV, and Li-ion battery.
- ✓ **Supply-only nodes** can only install **renewable generator and batteries.**
- ✓ **Dispatchable generators in demand and supply nodes** can be extended, new dispatchable and renewable generators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

Results of Case study

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

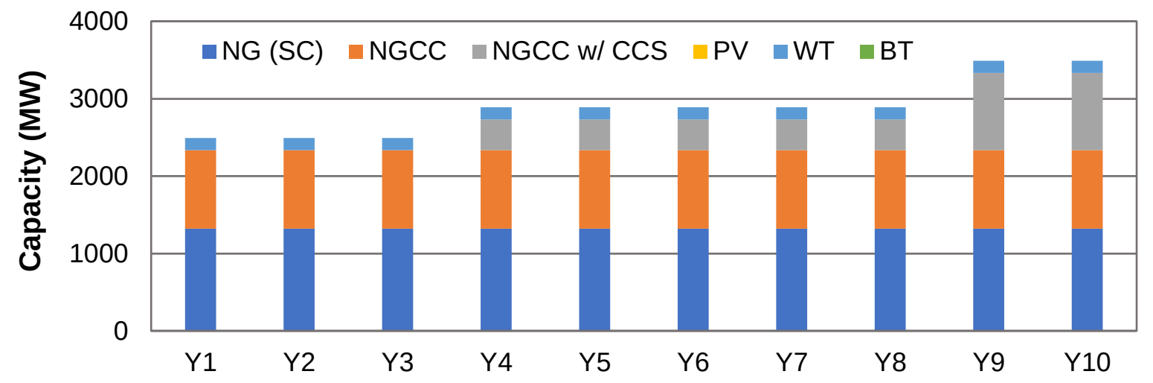
	Scenario #1	Scenario #2	Scenario #3	Scenario #4
CO_2 emission limits (30% reduction by 2030)	X	O	O	O
Renewable generation (60% of the total generation by 2030)	X	X	O	O
Battery installation (50% new installation compared to 2021)	X	X	X	O

Scenario #1 (No CO_2 emission and renewable constraints)



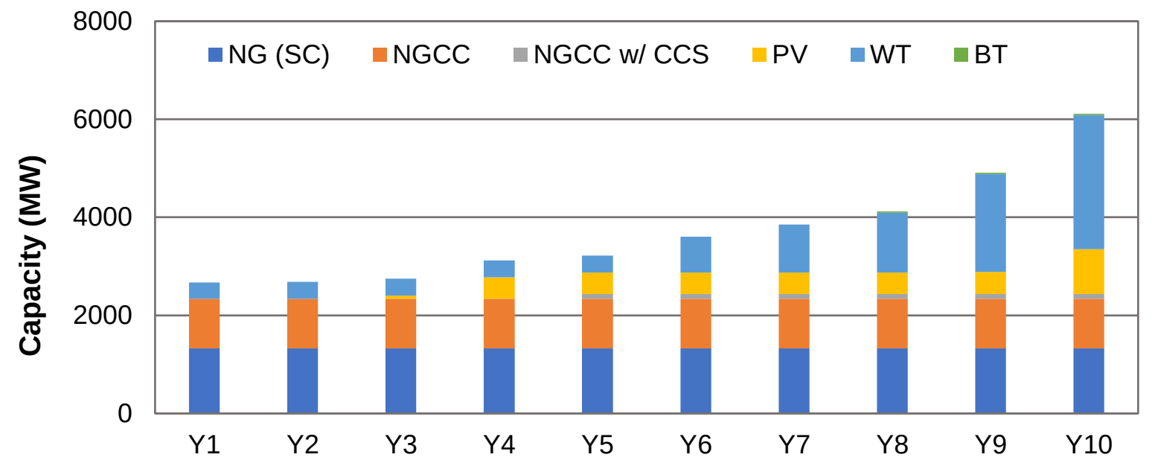
- Maintain existing infrastructure, and 1 NGCC without CCS (400MW) and PV (10MW) & battery (10MW) are installed in Node 4 at Year 4 and Year 10, respectively.
- Only 5% of large-scale renewable generators (such as large-scale wind turbines and solar panels) is available.

Scenario #2 (CO_2 emission constraint included)



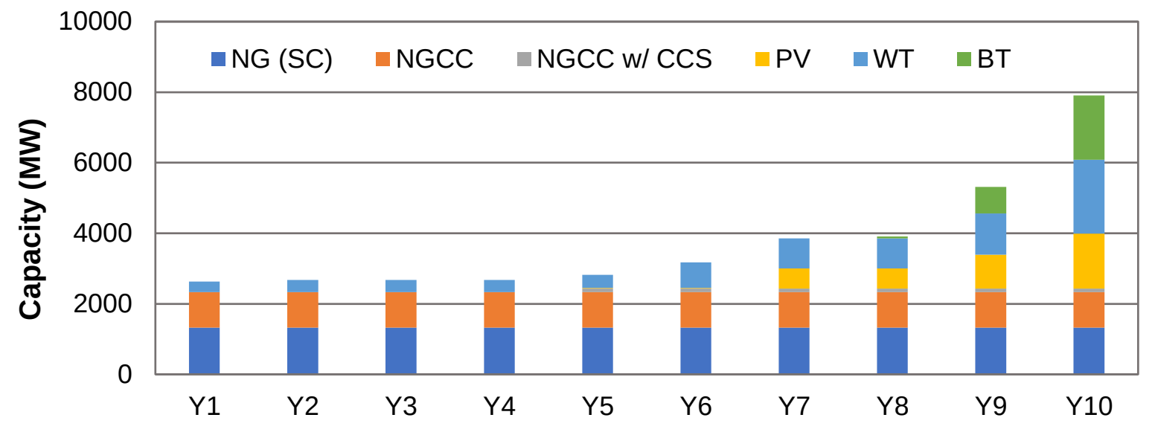
- Maintain existing infrastructure, and 2 NGCC with CCS (600MW in Node 1 and 400MW in Node 4) are installed at Year 8 and Year 4, respectively.
- The capacity of wind turbines in Node 3 is expanded (~15MW).

Scenario #3 (30% CO_2 reduction & 60% renewable generation)

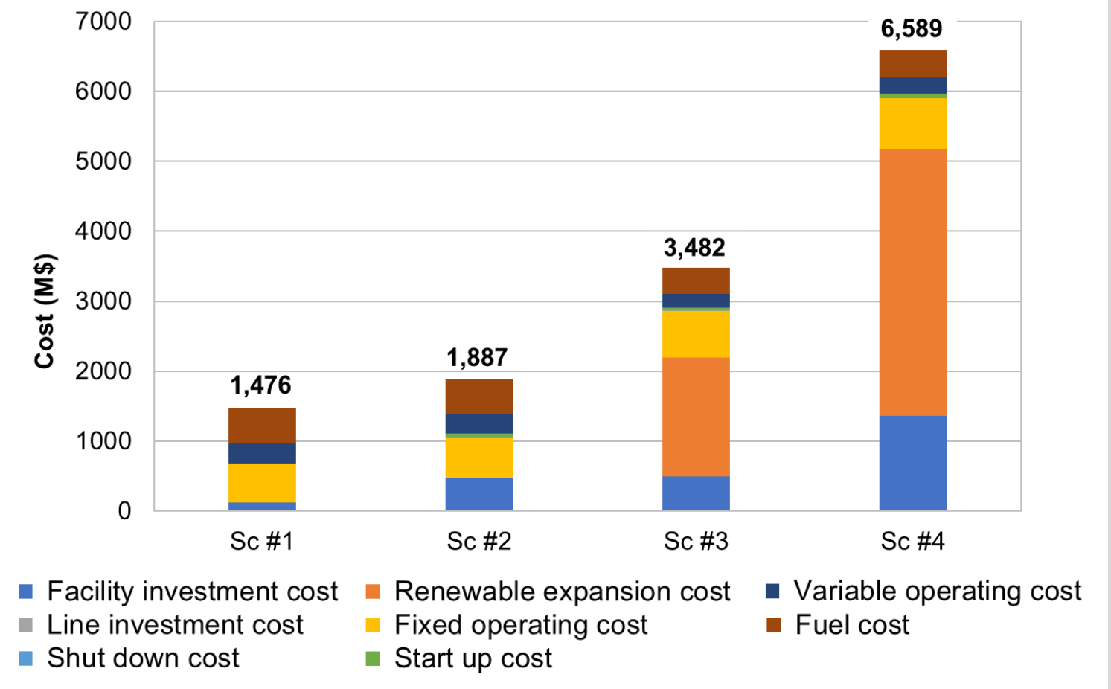


- NGCC with CCS (100MW) is installed in Node 4 at Year 5.
- The capacity of wind turbines in Node 3 is expanded every year.
- Wind turbines and solar panels are all installed in Nodes 1 (Years 4 and 6) and 4 (Years 3 and 7).
- Renewable generation share increased up to 60% but a large amount of curtailment occurred.

Scenario #4 (30% CO_2 reduction & 60% renewable generation & 50% battery)



- Overdesigned wind turbines are reduced, and the capacity of PV is increased than Scenario #3.
- 72% of electricity curtailment of Scenario #3 is reduced.



Computational results

Time limit: 3600s, optimality gap < 1%
Solver: Gurobi 10.0.2

	# Binary	# Cont. Vars	# Constraints	CPU (sec)
Scenario #1	296,624	223,791	1,247,963	**1,045.51** (Gap: 0.98%)
Scenario #2	296,624	223,801	1,247,983	**3,600.00*** (Gap: 2.03%)
Scenario #3	296,624	223,801	1,247,993	**1,811.44** (Gap: 0.67%)
Scenario #4	296,624	223,801	1,248,003	**3,600.00*** (Gap: 3.62%)

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.
- The Impact of representative days on the optimal design of power systems will be analyzed.

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