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Understanding the Role of Long Duration Energy Storage (LDES) in California's Evolving Energy System

Final Public Workshop, October 9, 2023

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Agenda

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1. Summarize recent advancements in available long-duration energy storage (LDES) technologies and the inputs used in the modeling
2. Present how cost targets for LDES depend on efficiency and how the cost targets will change relative to Li batteries in 2030, 2035, 2040, and 2045
3. Identify durations that would be most beneficial to California
4. Effects of scenario modifications on types and amounts of storage
   - EV charging profiles (Farzan ZareAfifi)
   - Solar and wind generation profiles (Zabir Mahmud)
   - Use of oxy-combustion (Mariela Colombo)
   - Electrolyzers as flexible loads to stabilize the grid & increase value of storage (Mariela Colombo)
   - Role of LDES in the transmission system at the CAISO and WECC levels (UC San Diego partners)

Summarize key conclusions for CEC and LDES companies/customers

LDES: Many headlines today

- LDES experienced a surge in investment → today's headlines
- Gravity, compressed air, thermal storage
  - Historically the largest
  - Closed-loop pumped hydro systems & Hydrostor PPA in California
- Electrochemical headlines surpass 10 MWh to 1 GWh deals
  - Vanadium flow batteries (e.g. Invinity)
  - Zinc bromine (Redflow)
  - Aqueous zinc (EOS)
  - Iron air (Form Energy)
  - Iron flow (ESS)
- Demand management
  - EV charging
  - Electrolyzers (investment in green hydrogen is huge)

Core scenario definition for RESOLVE studies

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- Guidance: The Final Core Scenario will include baseline assumptions to reflect the 2021 CPUC IRP PSP and the 2020 PATHWAYS High Electrification analysis for the growth of EV loads

- Additionally:
  - Use fixed hydropower profiles for dry year
  - Offer 85%-efficient lithium batteries with specified 4-hour duration
  - Vary the duration and efficiency of candidate storage resources without assigning to specific technology
  - Use the Critical-time-steps approach we developed to enable many calculations
  - No planning reserve margin

Capacity expansion for Core scenario

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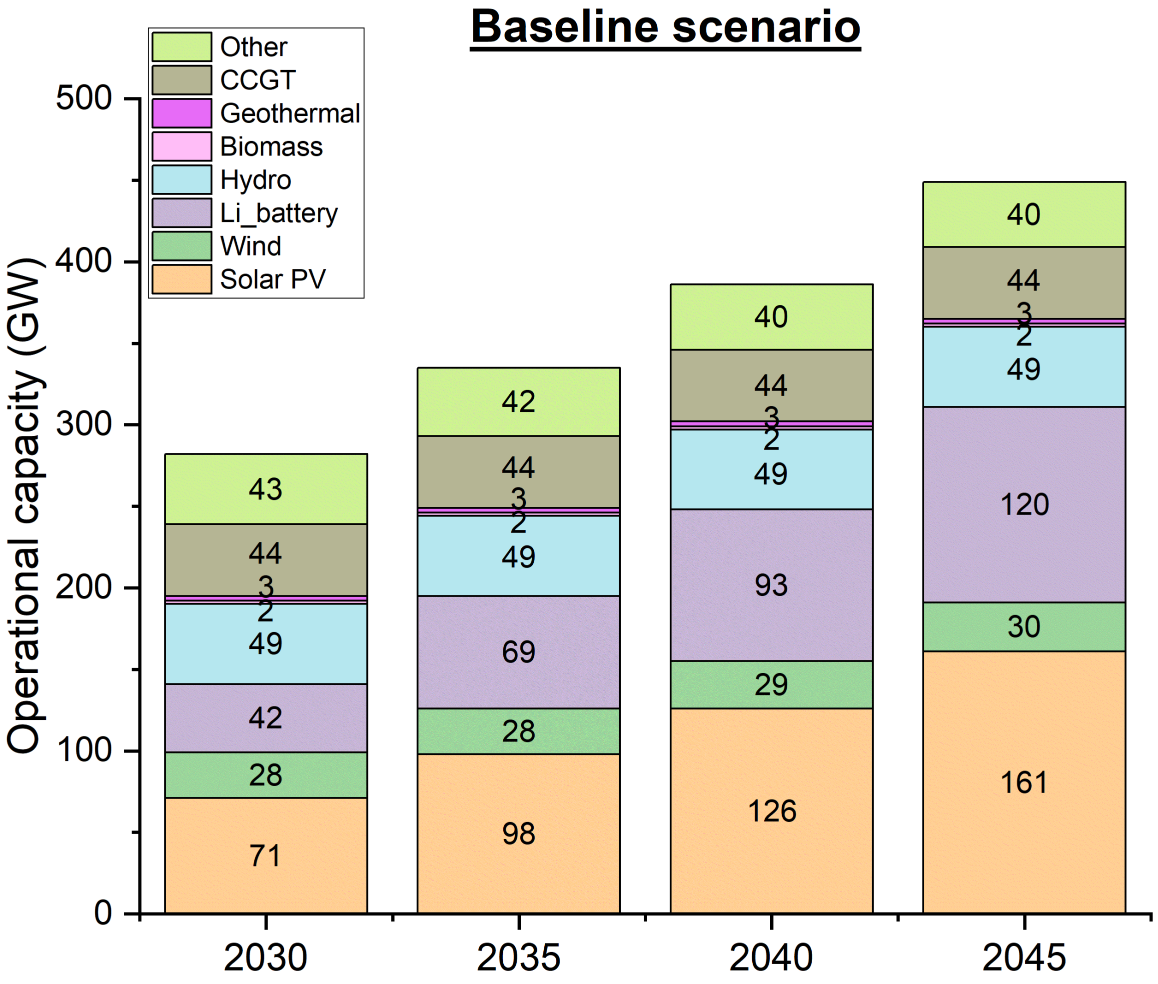

- With the baseline assumptions *(without LDES)*, **solar PV** and **Lithium-ion battery capacities expand significantly** to meet 2045 energy demand.

**For the next slides, the capacities of Hydro, Biomass, Geothermal, CCGT and other are not shown as they remain unchanged.*

What duration is optimal?

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- Simplistically, California needs > 50 GW of storage for a windless night
- How many hours duration do we want for the 50 GW of storage?
- A duration that is too small → overbuild the power
- A duration that is too long → overbuild the energy

- Strategy to identify the optimal duration: quantify the total storage power and storage energy as a function of duration

Comparison of LDES modeling strategies

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RESOLVE (UC Merced)

- Input *defined* duration, but vary the duration
- Assign cost = cost of Li battery with same *power* rating for next graphs

SWITCH (UC San Diego)

- *Model selects* duration based on input $/kW *and* $/kWh

Note: assume charging efficiency = discharging efficiency

Optimal LDES duration?

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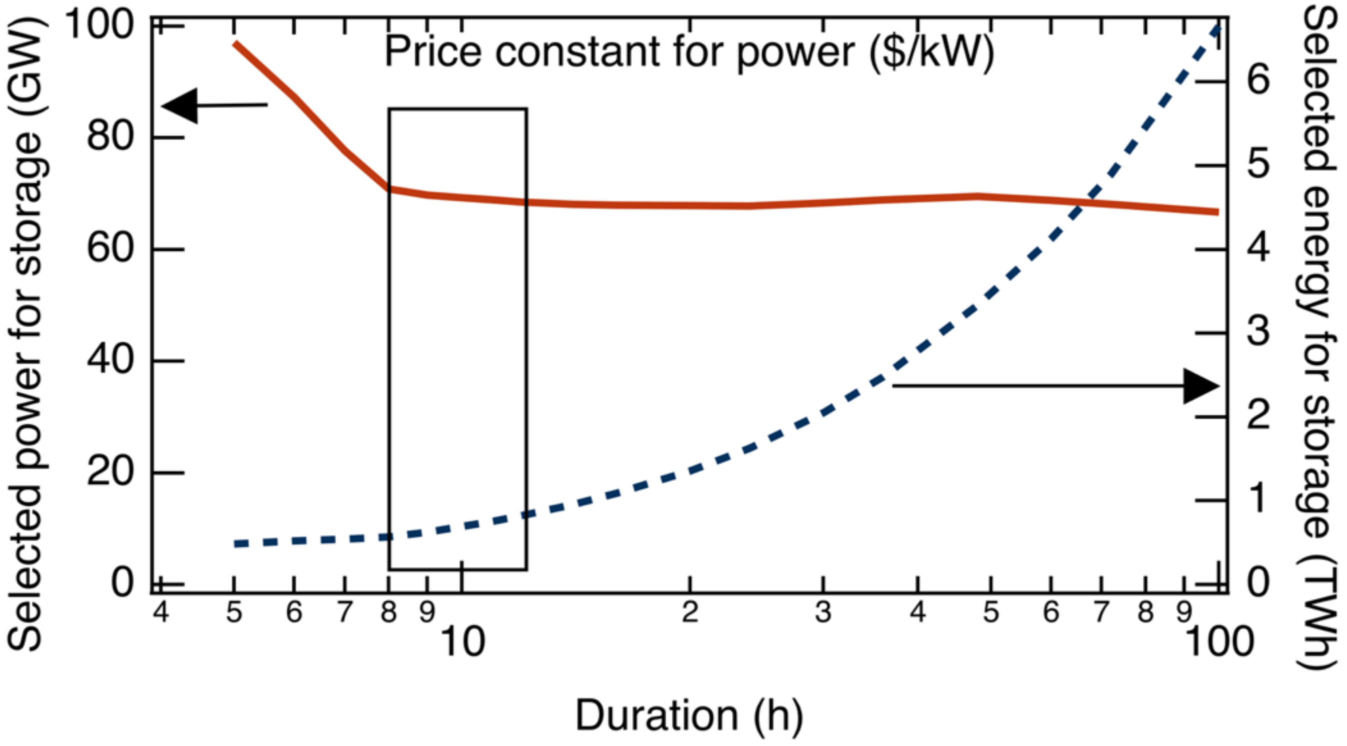
Offer storage with specified (varied) duration, but constant power cost



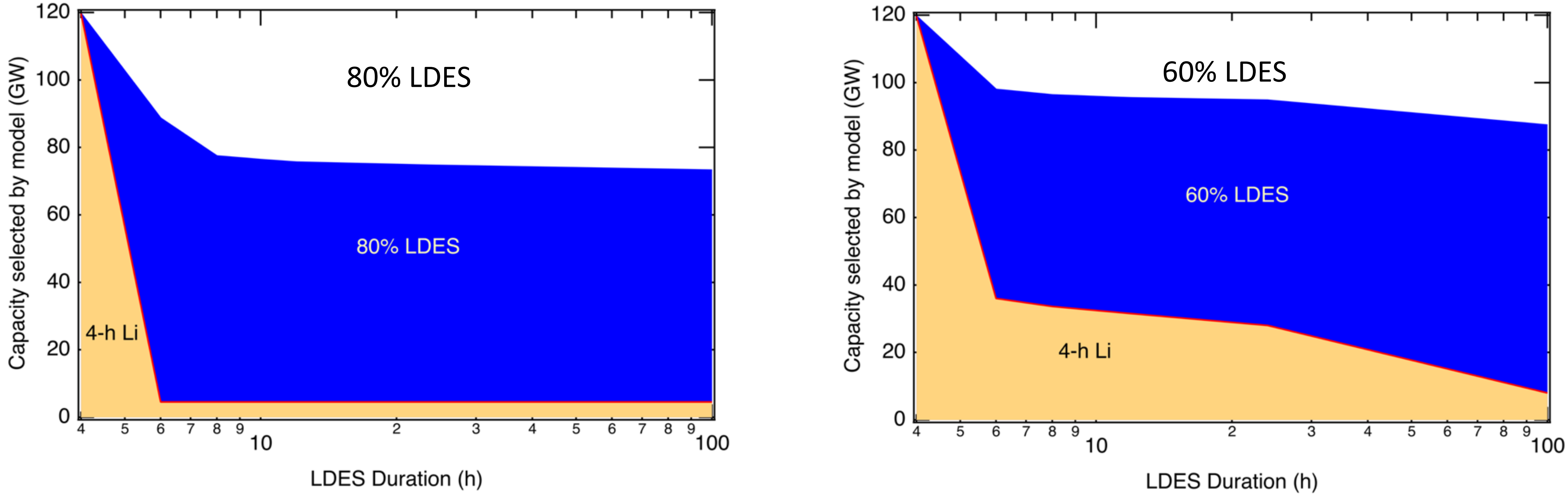
This calculation requires all storage has same duration

We will want a mixture of durations

Storage built for 2045 baseline scenario:
Sweet spot for duration: 8-12 hours

Offer two types of storage

Offer 85%-efficient 4-h Li plus 80% or 60% LDES (vary duration); Constant power cost



Storage built for 2045 baseline scenario:
The needed power drops for 8-h compared with 4-h
After 8 h, the power is relatively constant

Optimal LDES duration? - Conclusion

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Conclusion for core scenario:

• 8-12 hours is sweet spot for 80% efficient storage because of large amount of solar electricity in California

• Optimal durations depend on cost assumptions and efficiency (next slides)

What cost LDES to compete with Li batteries?

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- Marketplace is asking for LDES: *e.g.* In 2020, Silicon Valley Clean Energy sought 500 MW "Joint Long Duration Storage Request for Offers"
- Currently these select Lithium-ion battery systems
- What is target cost for a new technology to displace Li batteries?

Defining "Cost target"

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- Why focus on "cost target"?
  - CEC needs to set goals for solicitations
  - Companies need to identify target to enter market
- What is "enter market"
  - 1% adoption?
  - 10% adoption?
  - Replace 50% of Li batteries?
- How does cost target depend on:
  - Duration? Efficiency? Time in the future?

What cost?

Vary cost to identify when LDES is selected

Before we show the results, let's discuss cost uncertainty

Li battery cost – better defined than LDES cost

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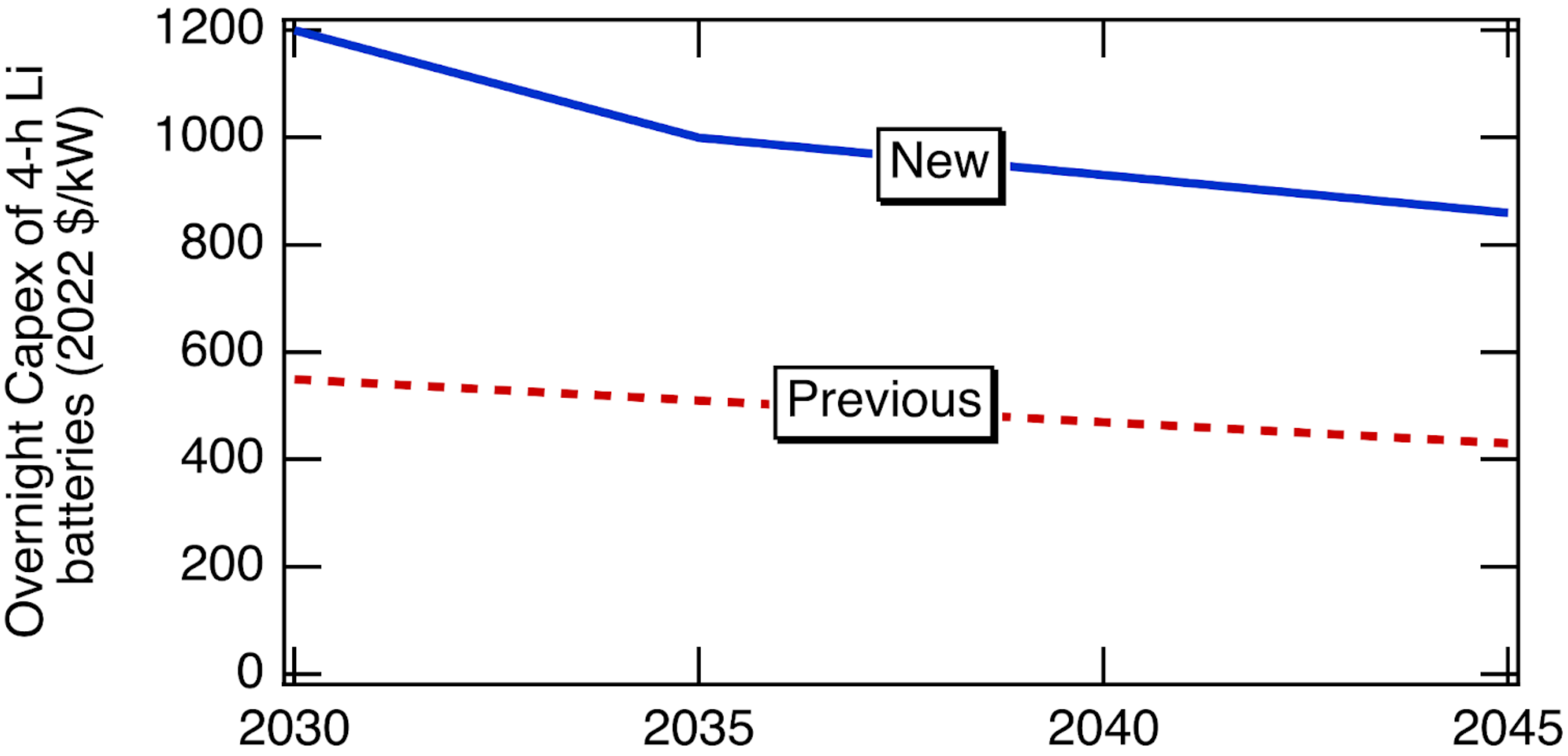

2022-2023 Integrated Resource Planning (IRP) suggested changing the Li battery cost model

Factor of 2 uncertainty!

We know even less about LDES cost

draft_2023_I_and_A.pdf, 81

How do Li battery & LDES compare today?

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- IRP says: “It is worth observing that the current quoted price for a 5-MW, 4-hr Tesla MegaPack is $1,900+/kW (pre-tax), which is nearly double the value reported in Lazard ($973/kW in $ 2022) and 25% more expensive than the value reported for 2022 in the 2022 NREL ATB ($1,527/kW).”

draft_2023_I_and_A.pdf, p. 81

- Form Energy suggests $20/kWh or $2000/kW for 100-h battery

https://singularityhub.com/2023/01/11/form-energys-new-factory-will-churn-out-iron-air-batteries-for-grid-scale-storage/#:~:text=Iron%20is%20cheaper%20and%20far,for%20100%20to%20150%20hours.

- Tesla’s $1900/kW and Form Energy’s $2000/kW are amazingly similar.
- **$/kW** ($1900/kW vs $2000/kW) varies less than
- **$/kWh** ($475/kWh vs $20/kWh)

Comparison of LDES modeling strategies

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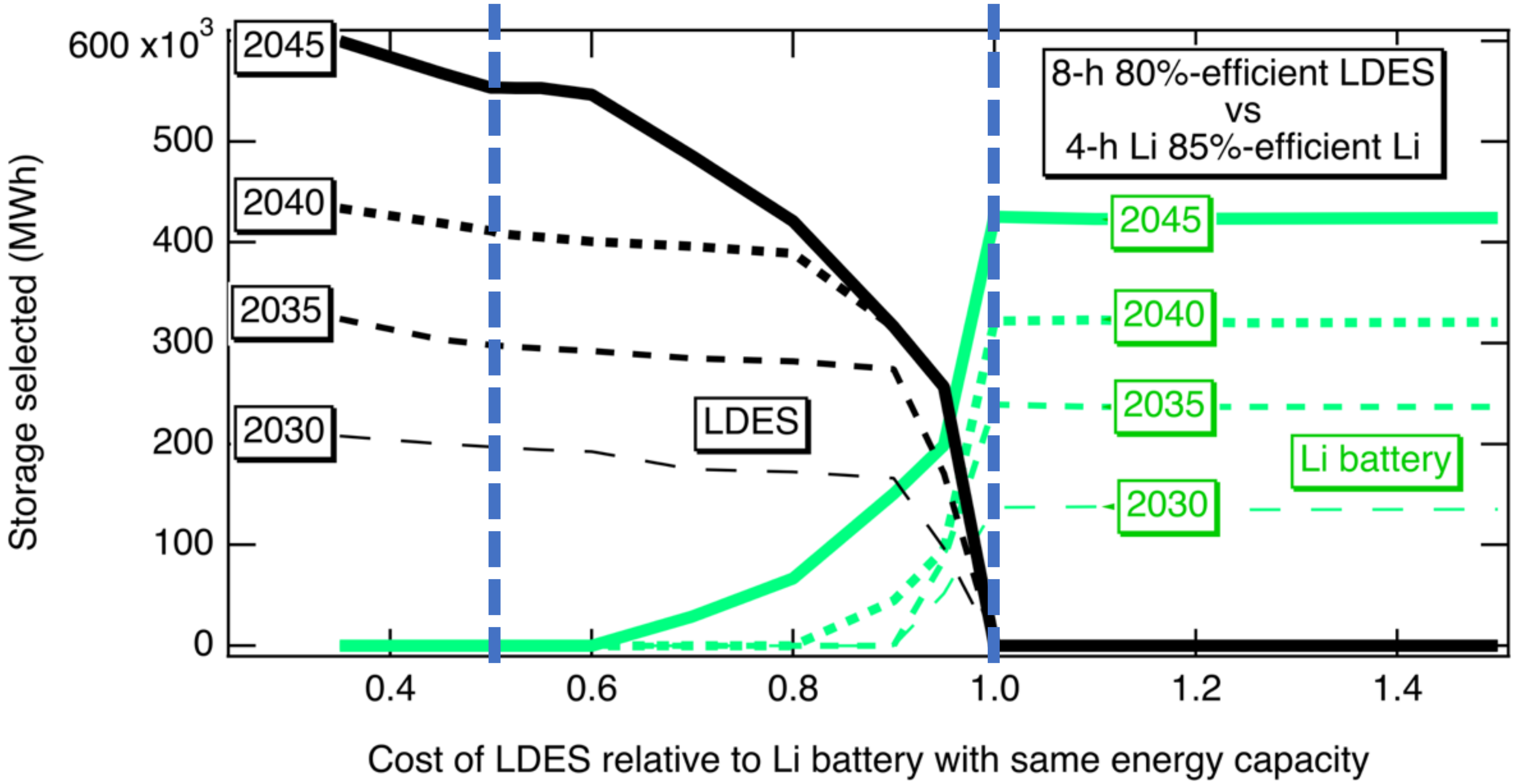
RESOLVE (UC Merced)

- *Input* duration & efficiency and vary cost
- Document competitive cost of a single LDES option relative to Li battery (compare by $/kW or $/kWh)

SWITCH (UC San Diego)

- *Model selects* duration based on input $/kW *and* $/kWh
- UC San Diego will describe

Example data set



Vary LDES cost *relative to* Li
Results vary (A LOT) with cost

Uncertainty in future costs can easily vary by factor of 2, giving very different results

Defining "cost target"

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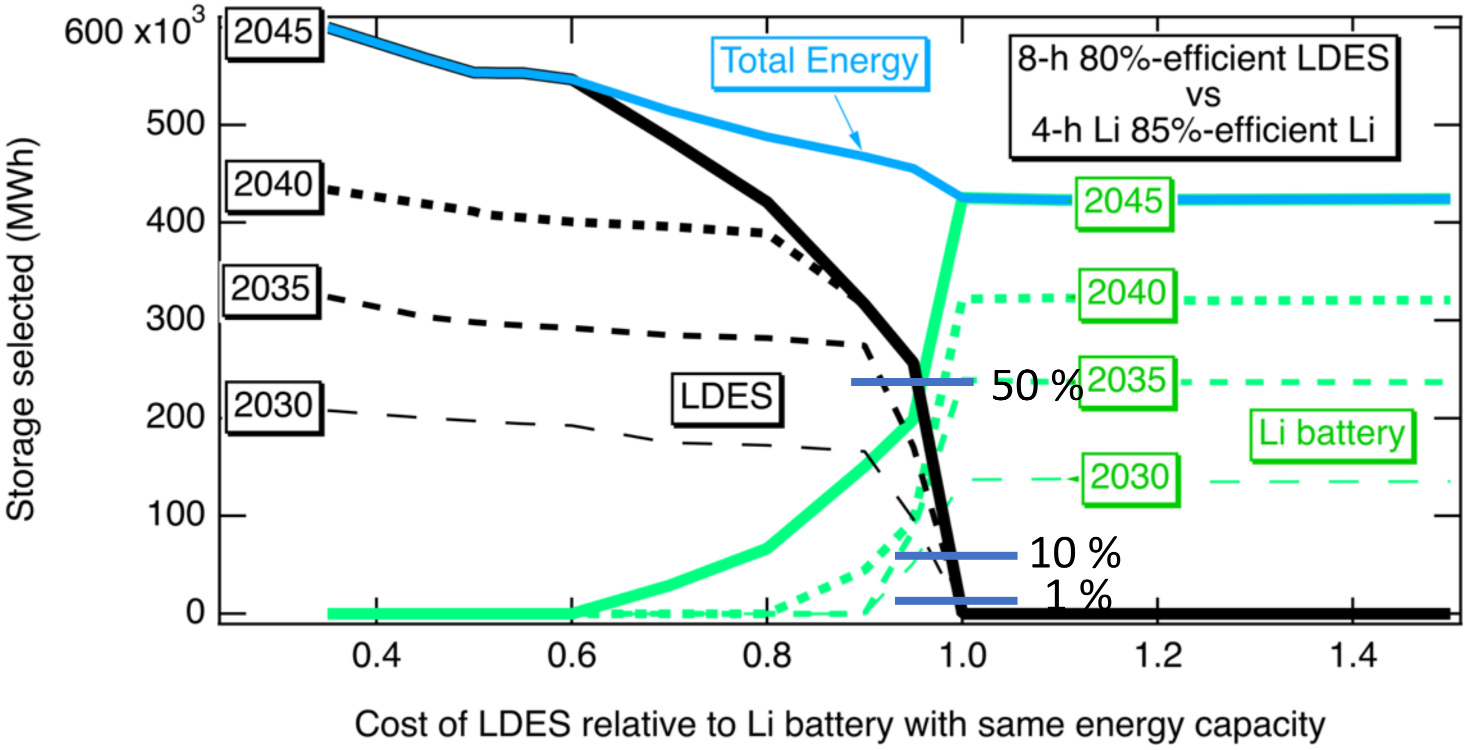

First calculate total energy

Then identify cost needed to capture a fraction of the market

What cost is needed to compete with 4-h Li?

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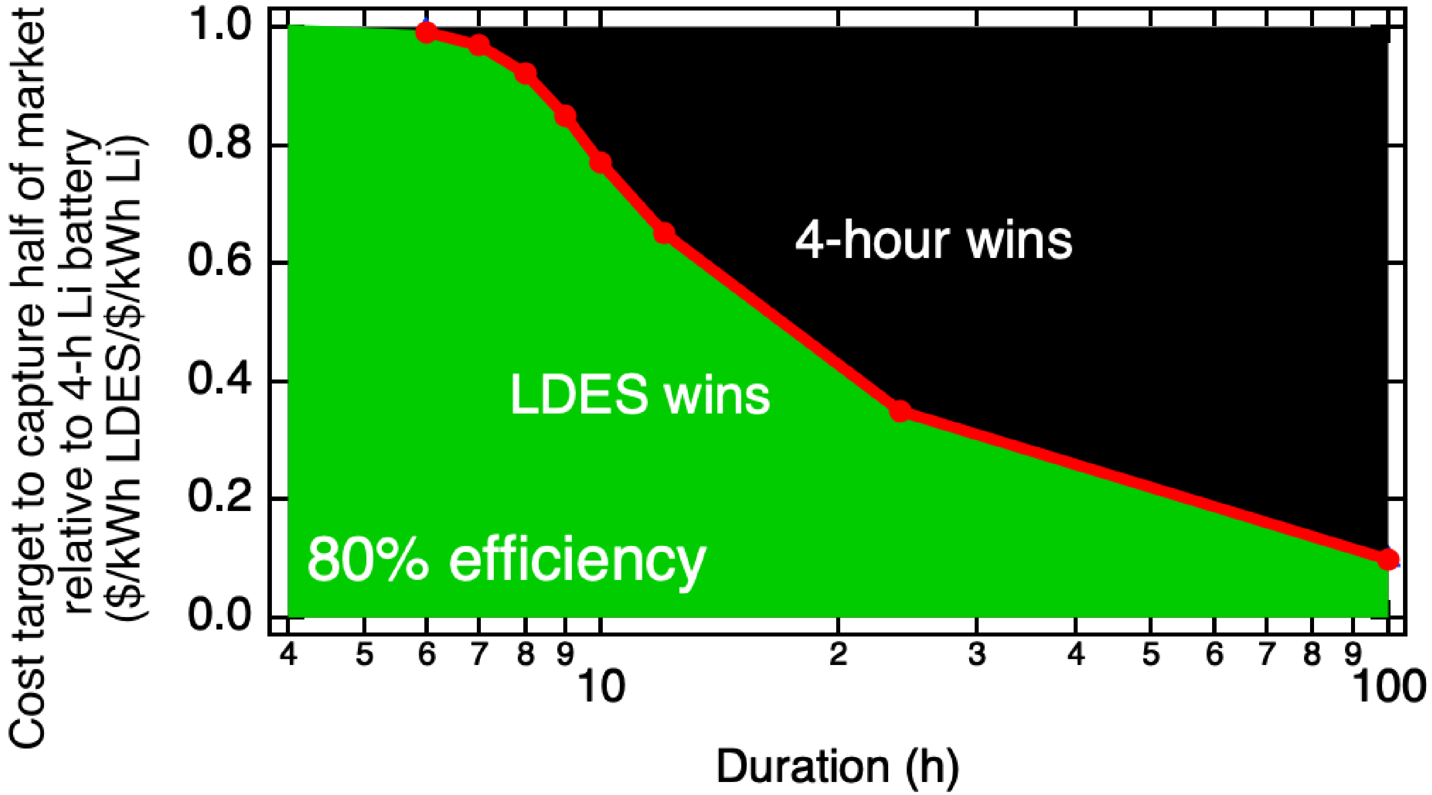
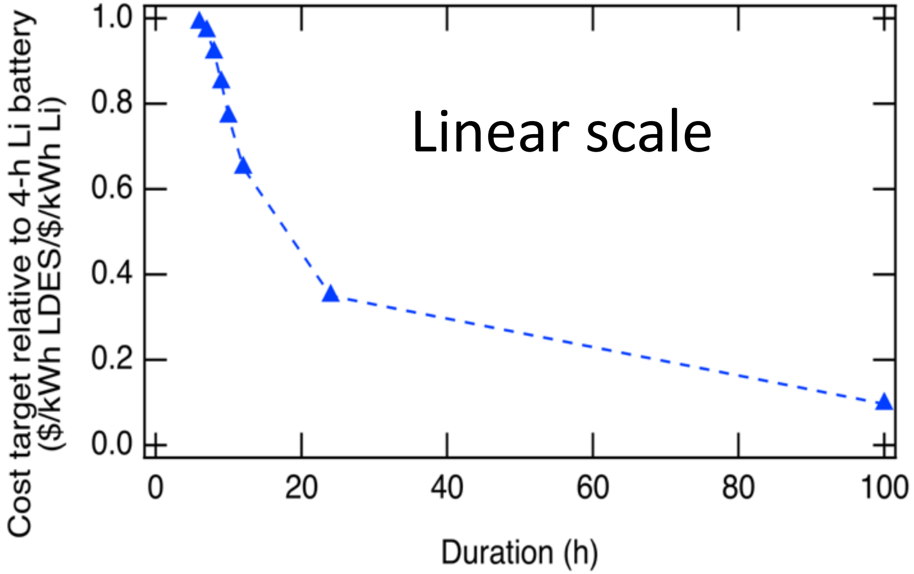


For 6-h LDES, 1% lower $/kWh wins over 4-h Li battery
For 8-h LDES, 8% lower $/kWh wins
Then target cost drops quickly



Any duration can be competitive, but target changes with duration, efficiency, and penetration

What cost is needed to compete with 4-h Li?

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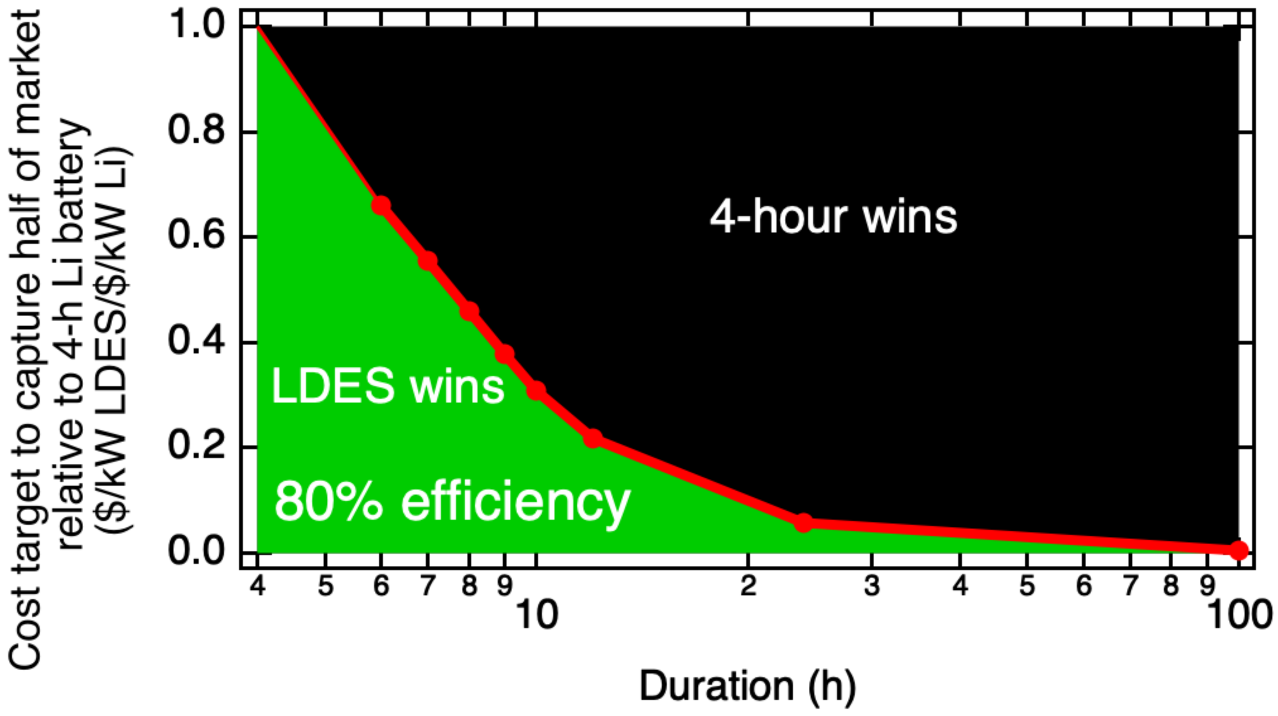


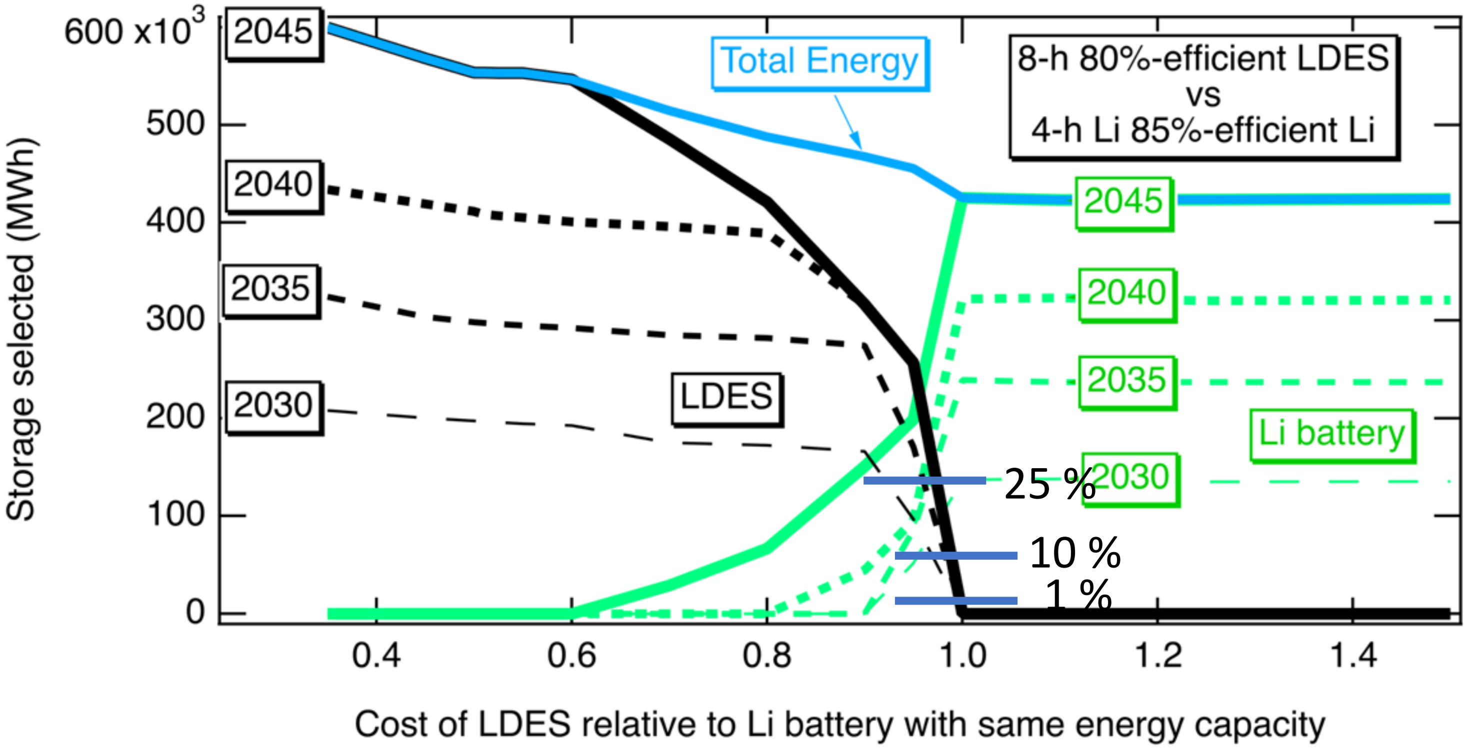
For 6-h duration, $/kW LDES needs to be < 2/3 the cost of a 4-h Li battery

For 8-h duration, $/kW LDES needs to be < ½ the cost of a 4-h Li battery

These are for 80%-efficient LDES – efficiency matters

Any duration can be competitive, but the cost target changes with duration and market penetration target

Next slides show “cost target”



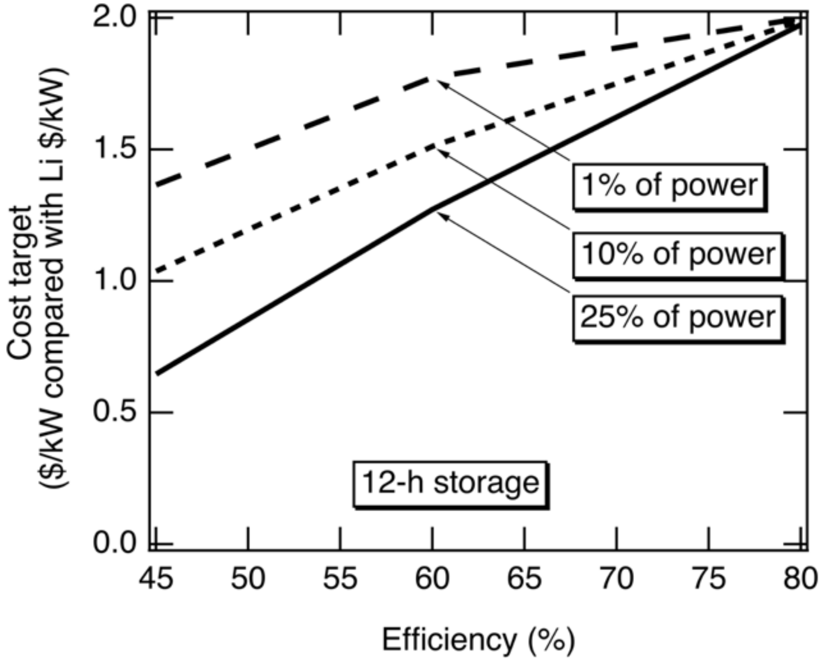
First calculate total energy

Then identify cost needed to capture a fraction of the market

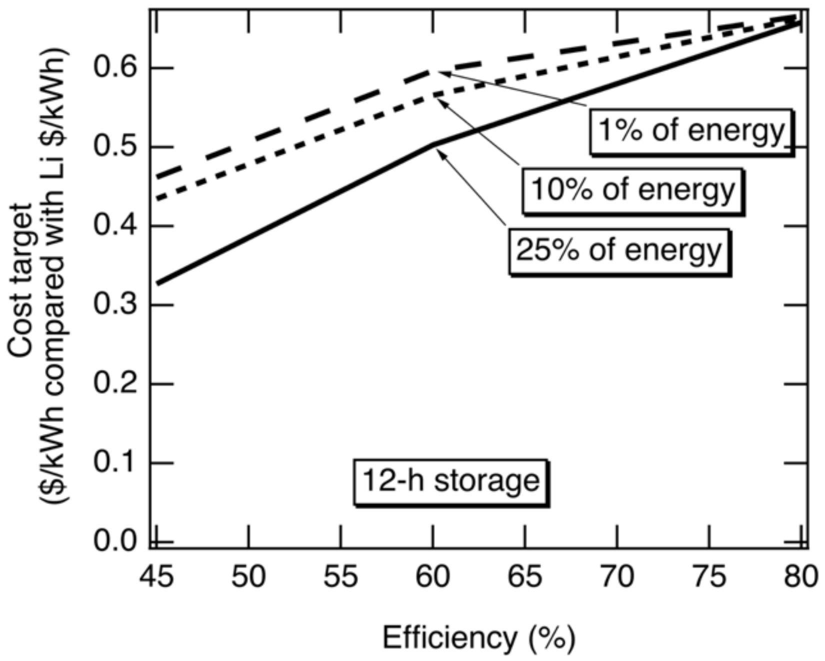
Expect a higher cost target for lower penetration (niche markets sell product at higher price)

Effect of Efficiency

Power cost targets

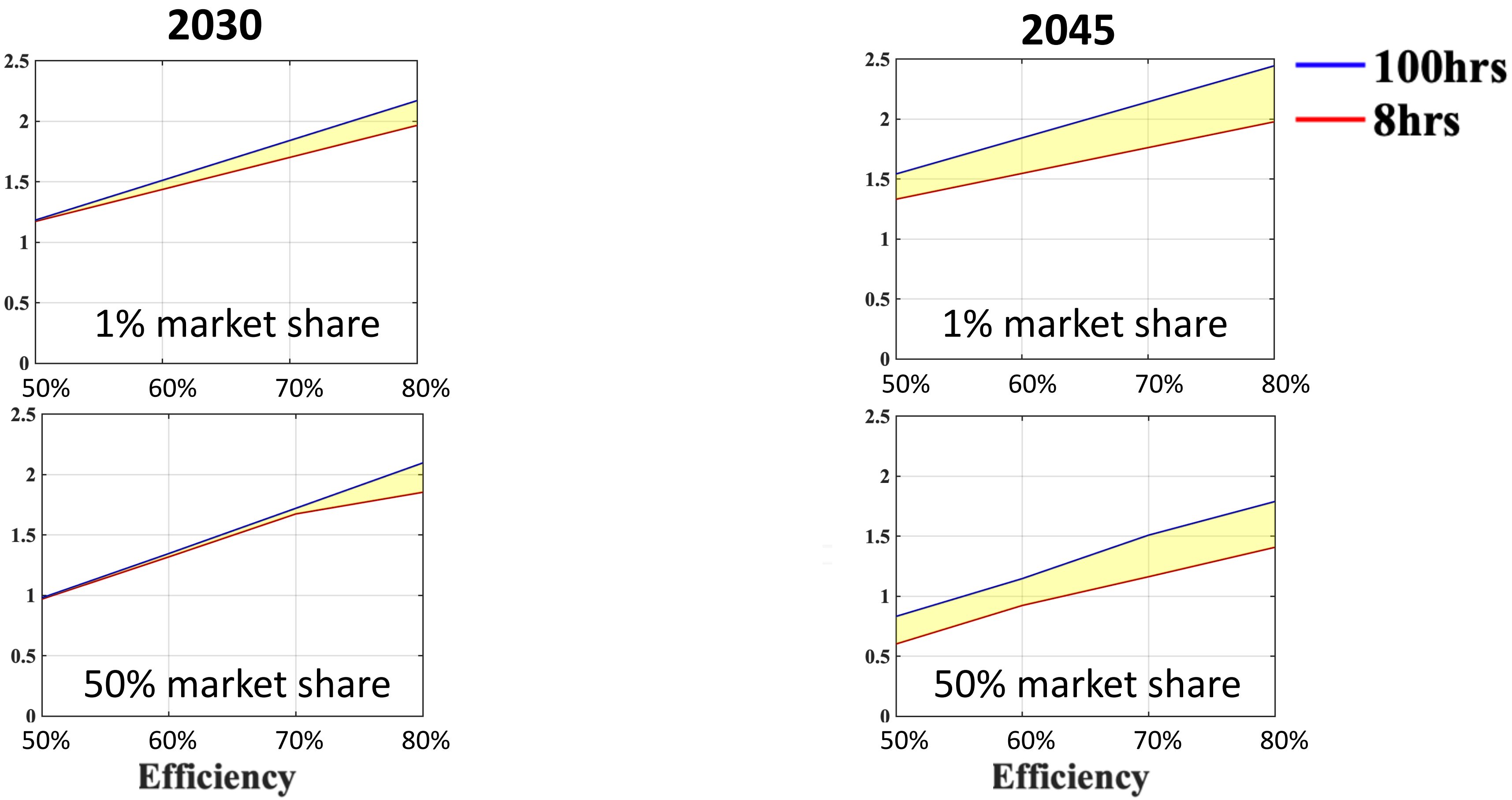


Energy cost targets



Efficiency has large effect (> factor of 2?) on cost target
Effect is smaller for low (1%) penetration – we need a few storage assets with longer duration for cloudy days

Effect of Efficiency also depends on duration



Longer duration shows the biggest advantage for higher efficiencies and for small market penetration

How does the cost target vary into the future?

Effect of Timing – launch early or late?

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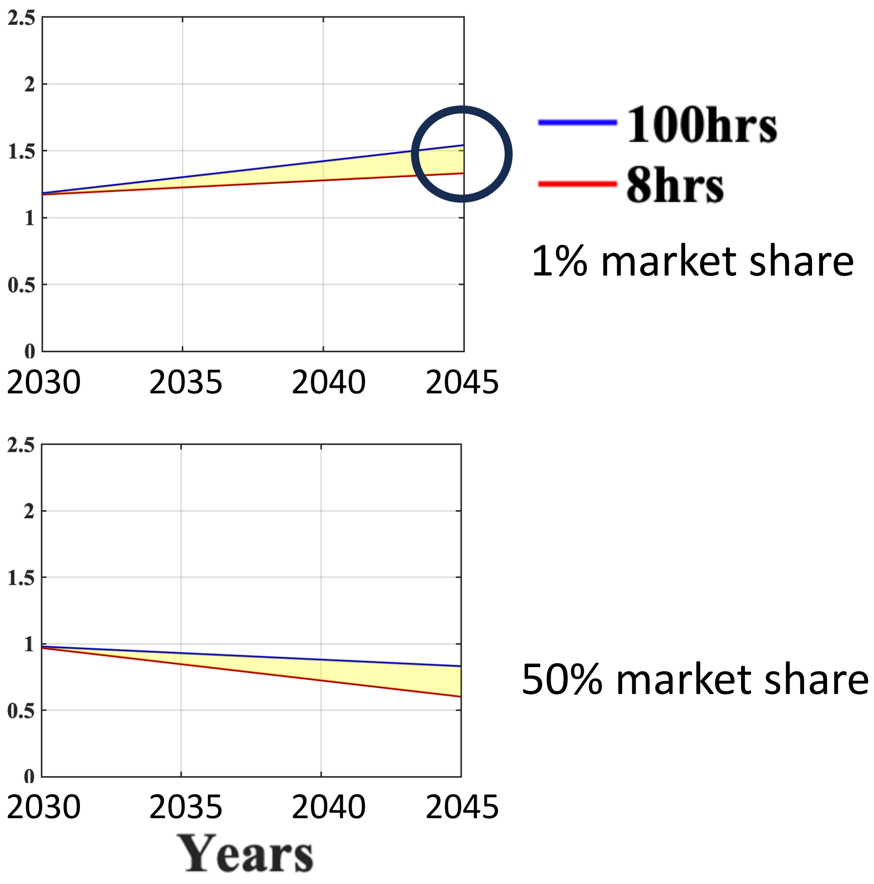
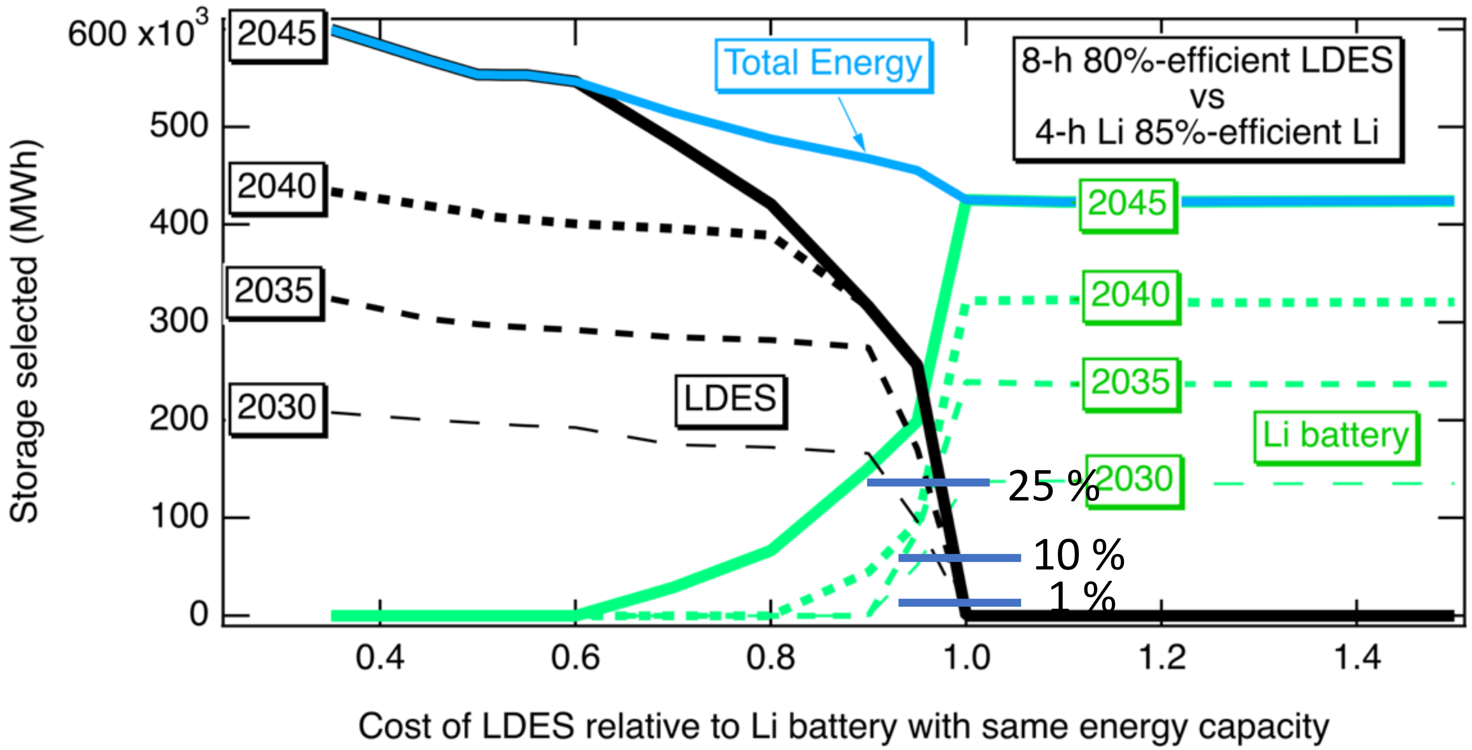


Cost target relative to Li *decreases* in the future – is this surprising?

Exception is low penetration of long (*e.g.* 100-h) duration

Competition with Li vs LDES Competition



We've shown the cost targets that need to be met to compete with Li

What if there are multiple LDES options?

Comparison of LDES modeling strategies

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RESOLVE (UC Merced)

- *Input set of* durations, efficiencies and costs
- If LDES has same cost in \$/kW & efficiency as Li, it will ALWAYS be selected
- We anticipate that LDES will have lower efficiency and/or the \$/kW > Li \$/kW

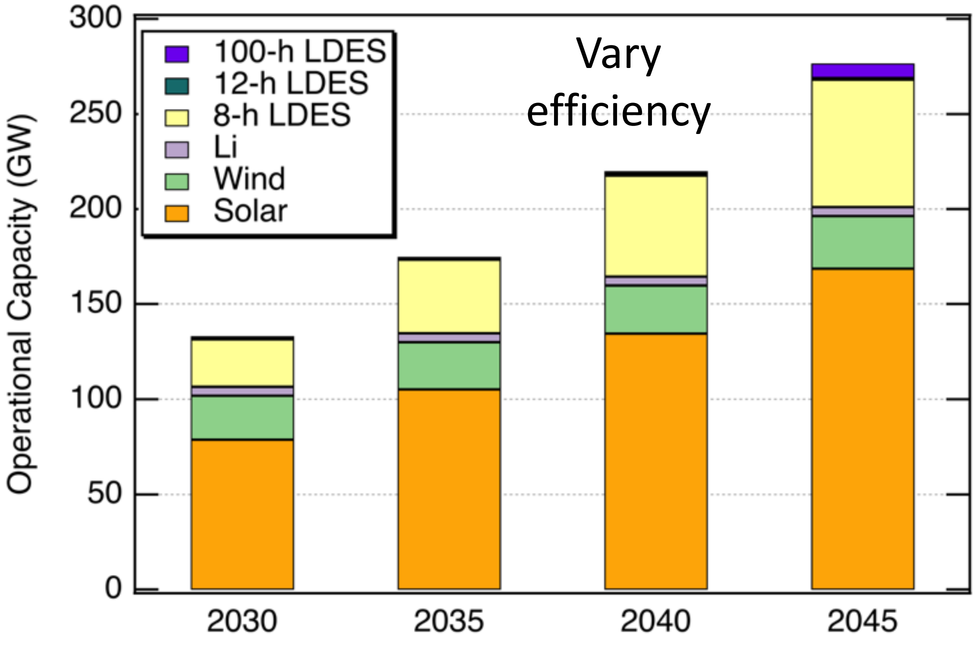
SWITCH (UC San Diego)

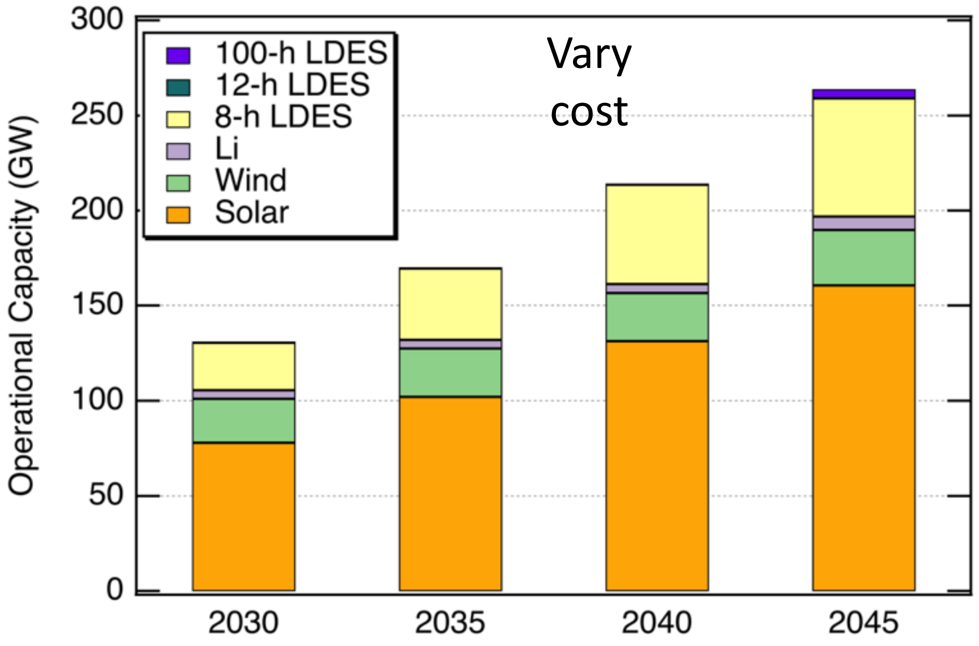
- *Model selects* duration based on input \$/kW *and* \$/kWh

X = 50% - 80%

Duration	Vary efficiency, constant power cost	Vary power cost, constant efficiency
4 h Li	1 X Li power cost or 1 X Li energy cost; 85%	1 X Li power cost or 1 X Li energy cost; 85%
8 hours	1 X Li power cost or 0.5 X Li energy cost; **75%**	**1.2** X Li power cost or **0.6** X Li energy cost; *X*%
12 hours	1 X Li power cost or 0.33 X Li energy cost; **70%**	**1.4** X Li power cost or **0.47** X Li energy cost; *X*%
24 hours	1 X Li power cost or 0.17 X Li energy cost; **60%**	**1.6** X Li power cost or **0.27** X Li energy cost; *X*%
100 hours	1 X Li power cost or 0.04 X Li energy cost; **50%**	**1.8** X Li power cost or **0.072** X Li energy cost; *X*%

Compare two LDES sets





For these inputs:
8-h Mostly
12-h Very little
24-h None
100-h only in 2045

Duration	Vary efficiency, constant power cost	Vary cost, constant efficiency
4 h Li	1 X Li power cost or 1 X Li energy cost; 85%	1 X Li power cost or 1 X Li energy cost; 85%
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Compare effect of efficiency for multiple LDES

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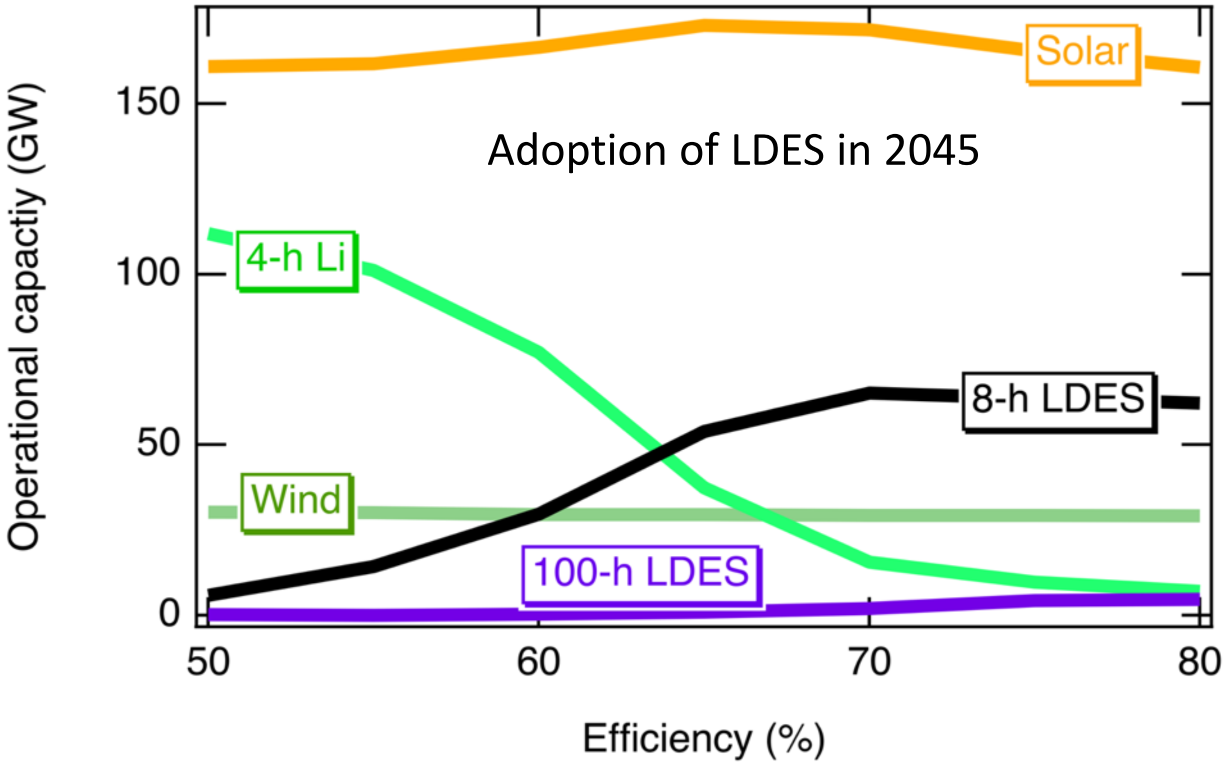

Use of LDES falls for efficiencies < 65% (unless costs are lower)

Duration	Vary cost, constant efficiency
4 hours	1 X Li power cost or 1 X Li energy cost; 85%
8 hours	**1.2** X Li power cost or **0.6** X Li energy cost; *X%*
12 hours	**1.4** X Li power cost or **0.47** X Li energy cost; *X%*
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Effect of more pumped hydro storage

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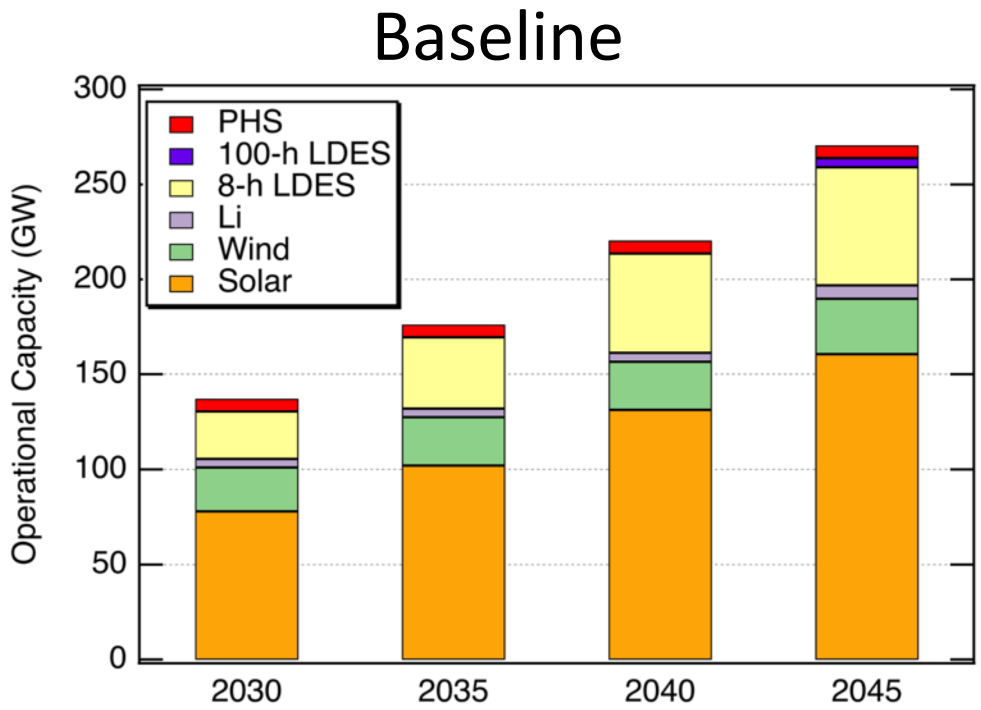

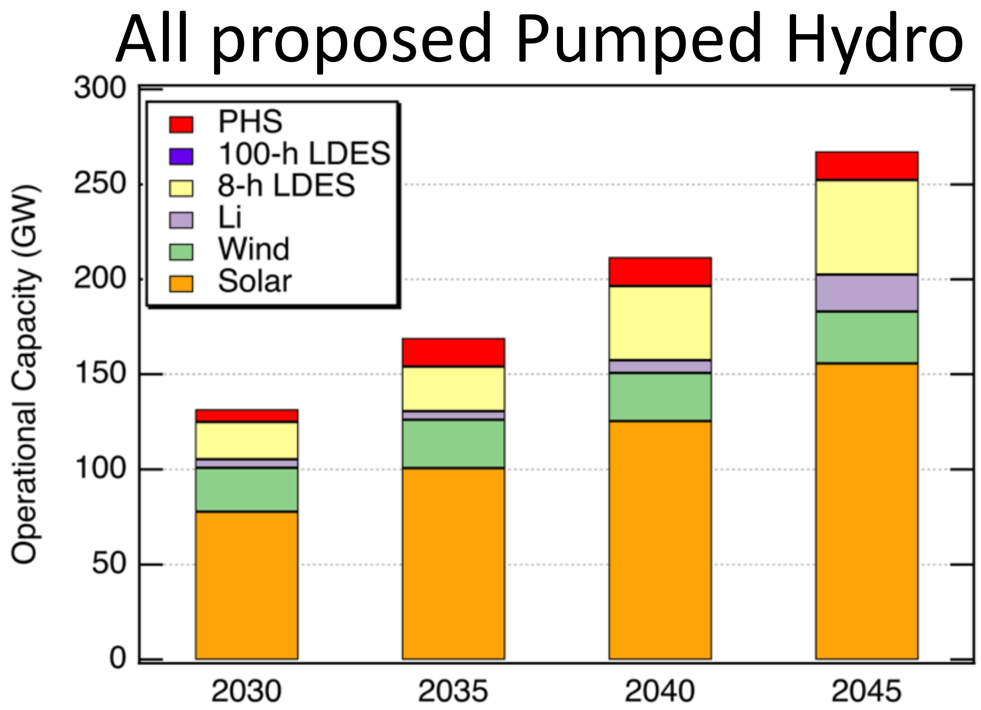

Building more pumped hydro storage reduces need for other LDES
New concepts for closed-loop PHS could become attractive (are included in IRA), enabling even more PHS than proposed today

Summary of Core Scenario analysis

- While a mixture of durations will be needed, to avoid overbuilding the power capacity or the energy capacity, the sweet spot is 8-12 hours for Core scenario
- The cost target follows the $/kWh of Li batteries for durations < 8 h (generally)
- The cost target becomes more challenging
  - for > 8 h durations
  - for lower efficiency (for broad market acceptance)
- For a small amount of storage, low-efficiency 100-h storage may be competitive without a lot of cost reduction
- When multiple LDES are offered
  - If the LDES is > 65% efficient, 8-h captures significant market share from Li
  - 100-h may be adopted in small amounts in 2045

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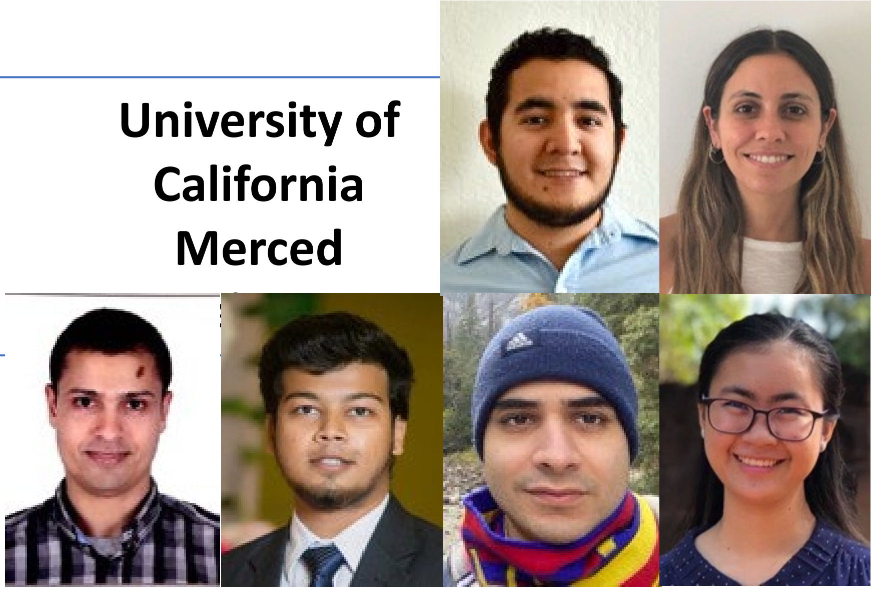
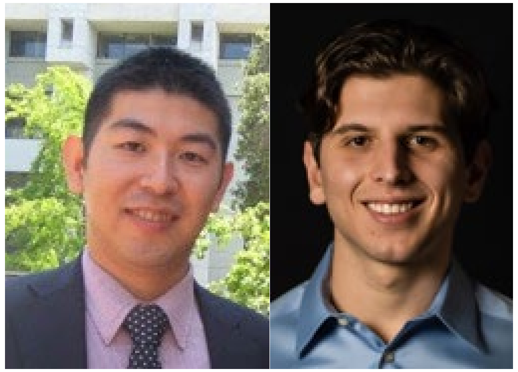
Summarize key conclusions for CEC and LDES companies/customers

Thanks to a great research team

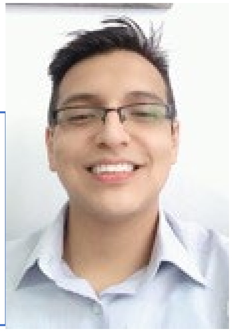
University of California Merced



University of California Berkeley
Dan Kammen
Sergio Castellanos



University of California San Diego
Patricia Hidalgo-Gonzalez



University of North Carolina Chapel Hill
Noah Kittner

Note: Pedro, Kenji, and Tyler have graduated and moved on to other jobs. (Pedro joined NREL's modeling team)

Effect of EV charging on need for LDES

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- How might EV charging choices affect the need for storage?
- This section presented by Farzan ZareAfifi

Overview of EV charging study

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- **Motivation:** what is the value of daytime charging?
- **Inputs**:
  - Three *profiles* for charging light-duty Zero Electric Vehicles (ZEVs)
  - *Energy demand* forecast of ZEVs
- **Results:**
  - Daytime charging requires less storage.
  - How much could be saved?
- **Practicality:**
  - What is net cost savings?
  - Is savings for storage bigger than cost of required charging infrastructure?

Effect of EV charging on storage

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How will EV charging load affect the need for storage?
What is the value of daytime charging?

Unconstrained (no incentive) light-duty ZEVs charging profile

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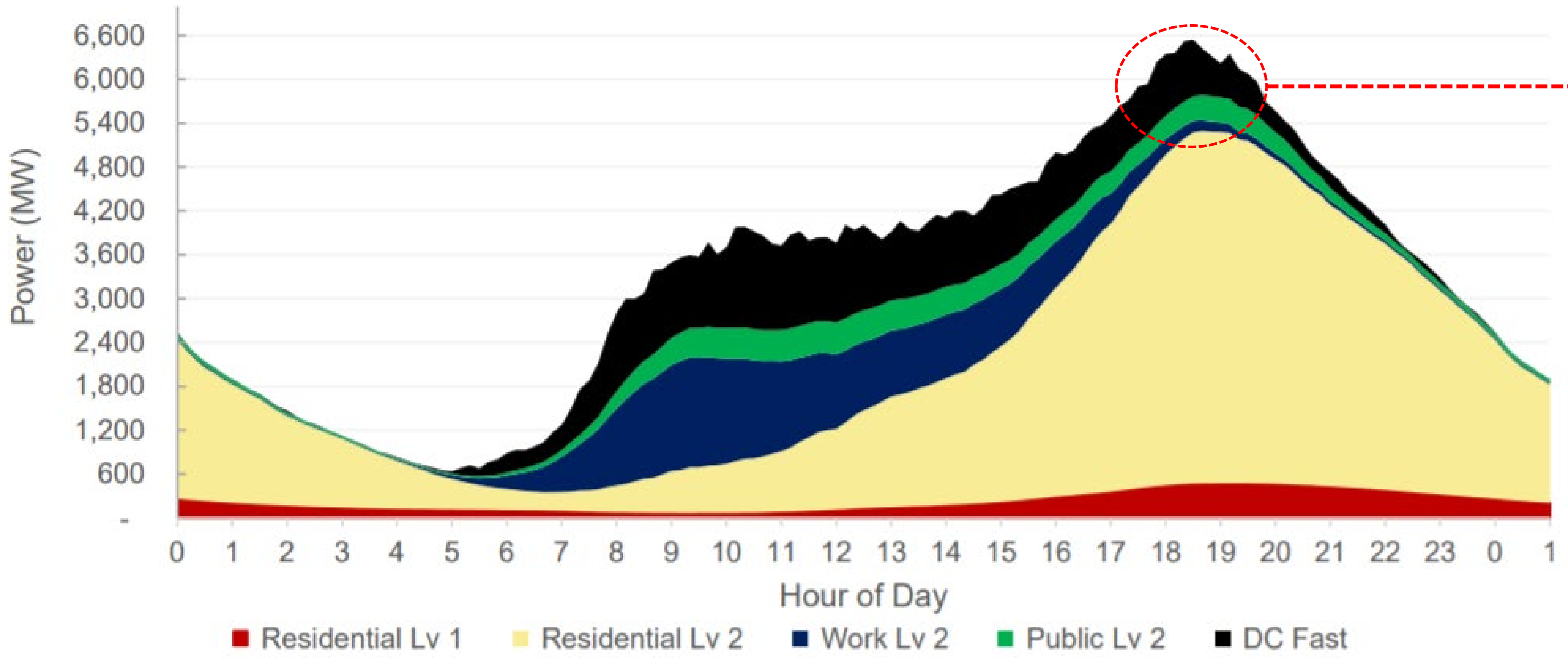
According to the CEC assessment of the AB 2127:

Unconstrained Charging Alternative Future; Weekday Load Profiles

Figure D-1: Projected 2030 Weekday Load Curve for the Unconstrained Alternative Future



Peak load happens when people come back to their homes; NO policy

https://www.energy.ca.gov/programs-and-topics/programs/electric-vehicle-charging-infrastructure-assessment-ab-2127

Nighttime (current TOU) light-duty ZEVs charging profile

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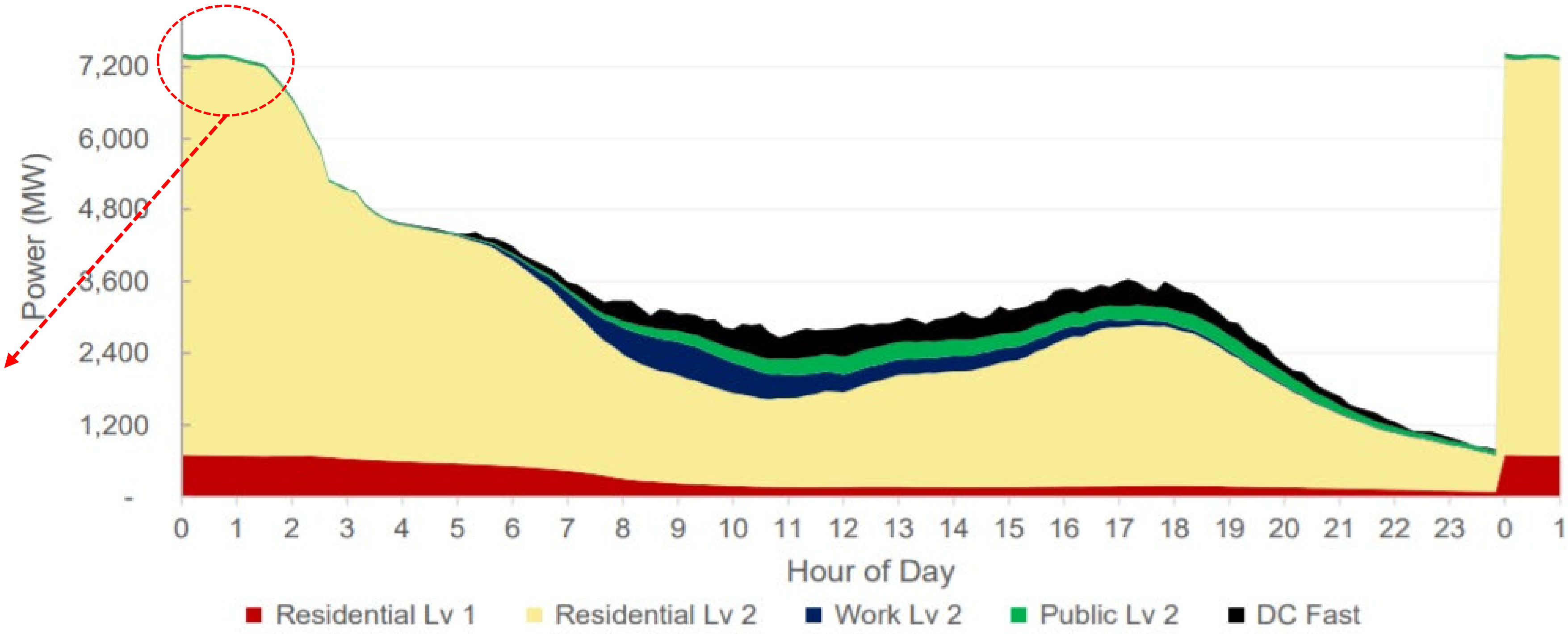
According to the CEC assessment of the AB 2127:

Nighttime Charging Alternative Future; Weekday Load Profiles

Current incentive program: lower electricity rates for charging EVs



https://www.energy.ca.gov/programs-and-topics/programs/electric-vehicle-charging-infrastructure-assessment-ab-2127

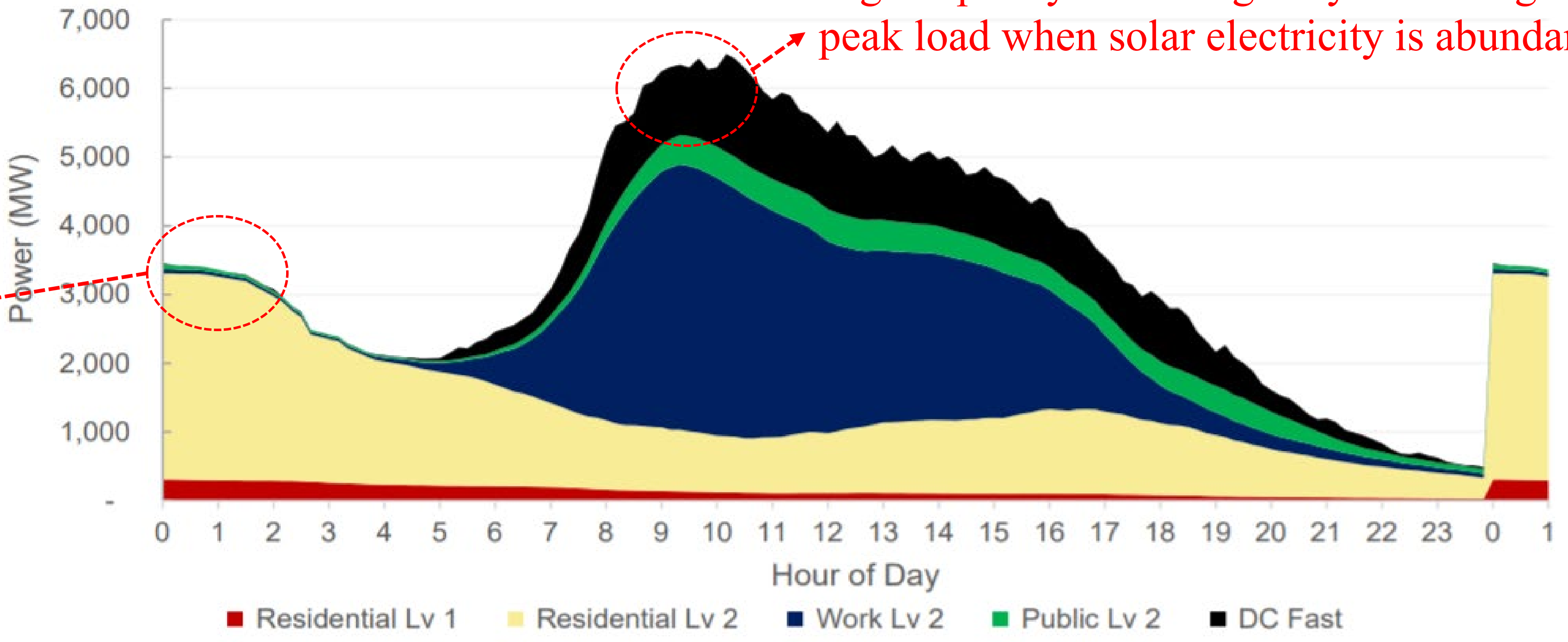
Daytime (e.g. workplace) light-duty ZEVs charging profile

According to the CEC assessment of the AB 2127:

Daytime Charging Alternative Future; Weekday Load Profiles

Logical policy: encourage daytime charging; peak load when solar electricity is abundant

Current incentive program: lower electricity rates for charging EVs



https://www.energy.ca.gov/programs-and-topics/programs/electric-vehicle-charging-infrastructure-assessment-ab-2127

Energy demand forecast for 2045:

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IEPR 2021[1]

- **Projected energy demand using in RESOLVE: 55,000 GWh/y**
- **15M ZEVs**
- **46% ZEVs penetration**
- **40 miles/day/vehicle on average**

[1] https://www.energy.ca.gov/data-reports/reports/integrated-energy-policy-report/2021-integrated-energy-policy-report

Three profiles scaled for energy demand (2045)

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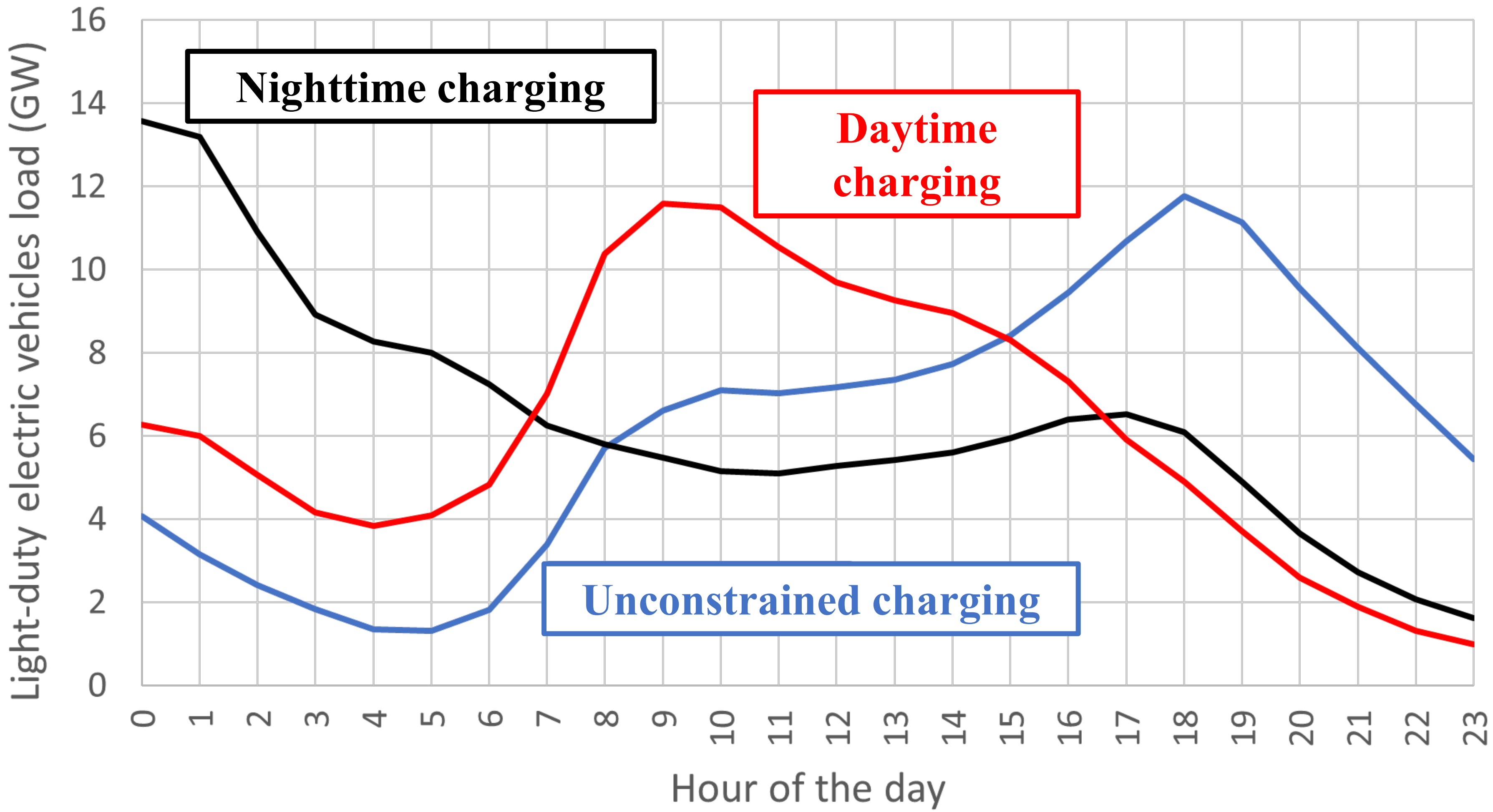

Direct use of solar power is maximum for the daytime charging profile

Effect of daytime charging on storage

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How much does the daytime charging reduce the need for storage?

Comparison of the operational capacities for the three profiles

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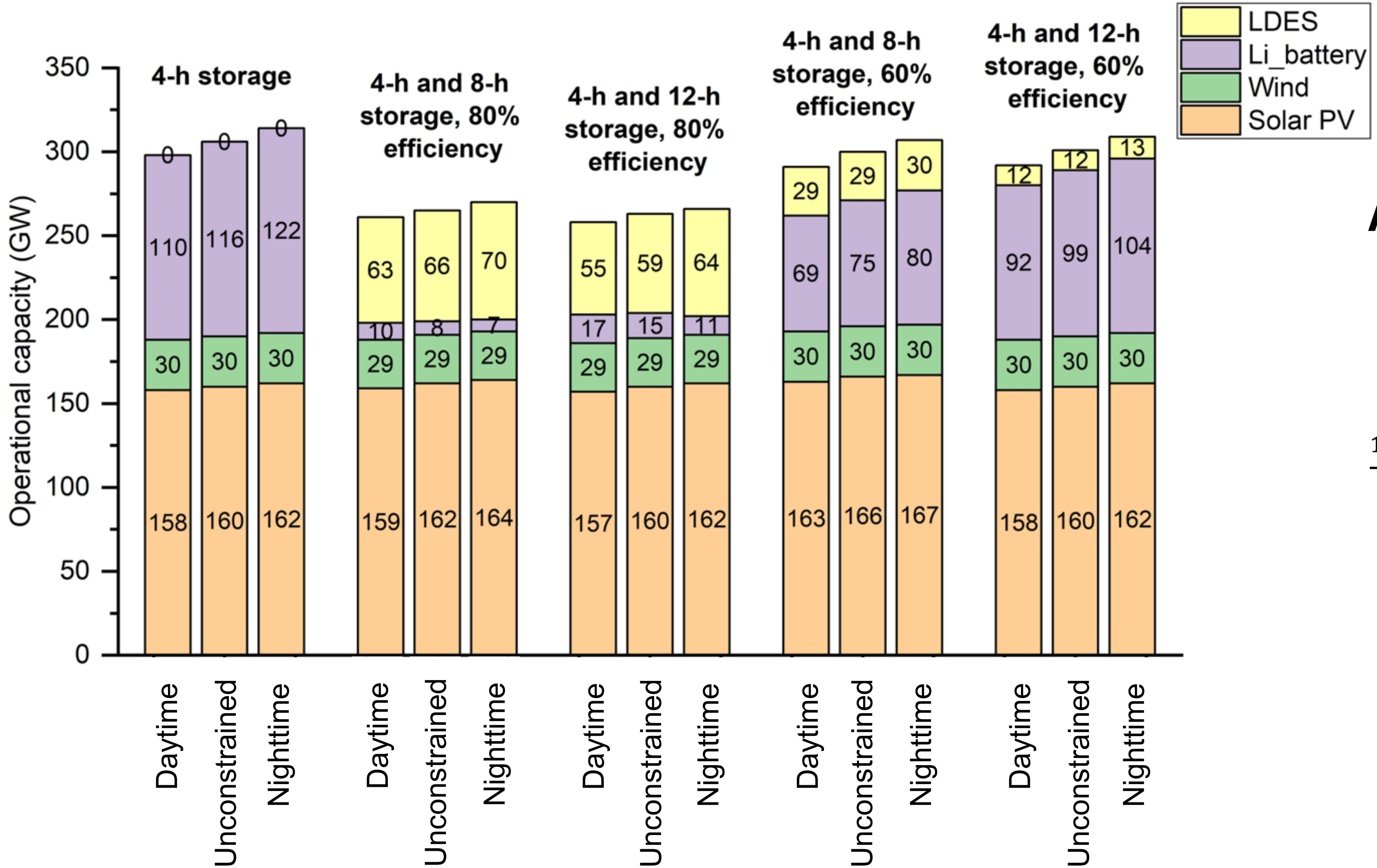

Assumption:

$$\frac{8\text{−}h\ storage\ cost\ (\frac{\$}{kW})}{4\text{−}h\ storage\ cost\ (\frac{\$}{kW})} = 1.2$$

$$\frac{12\text{−}h\ storage\ cost\ (\frac{\$}{kW})}{4\text{−}h\ storage\ cost\ (\frac{\$}{kW})} = 1.4$$

Daytime charging reduces the total operational capacity for storage

Storage capital cost

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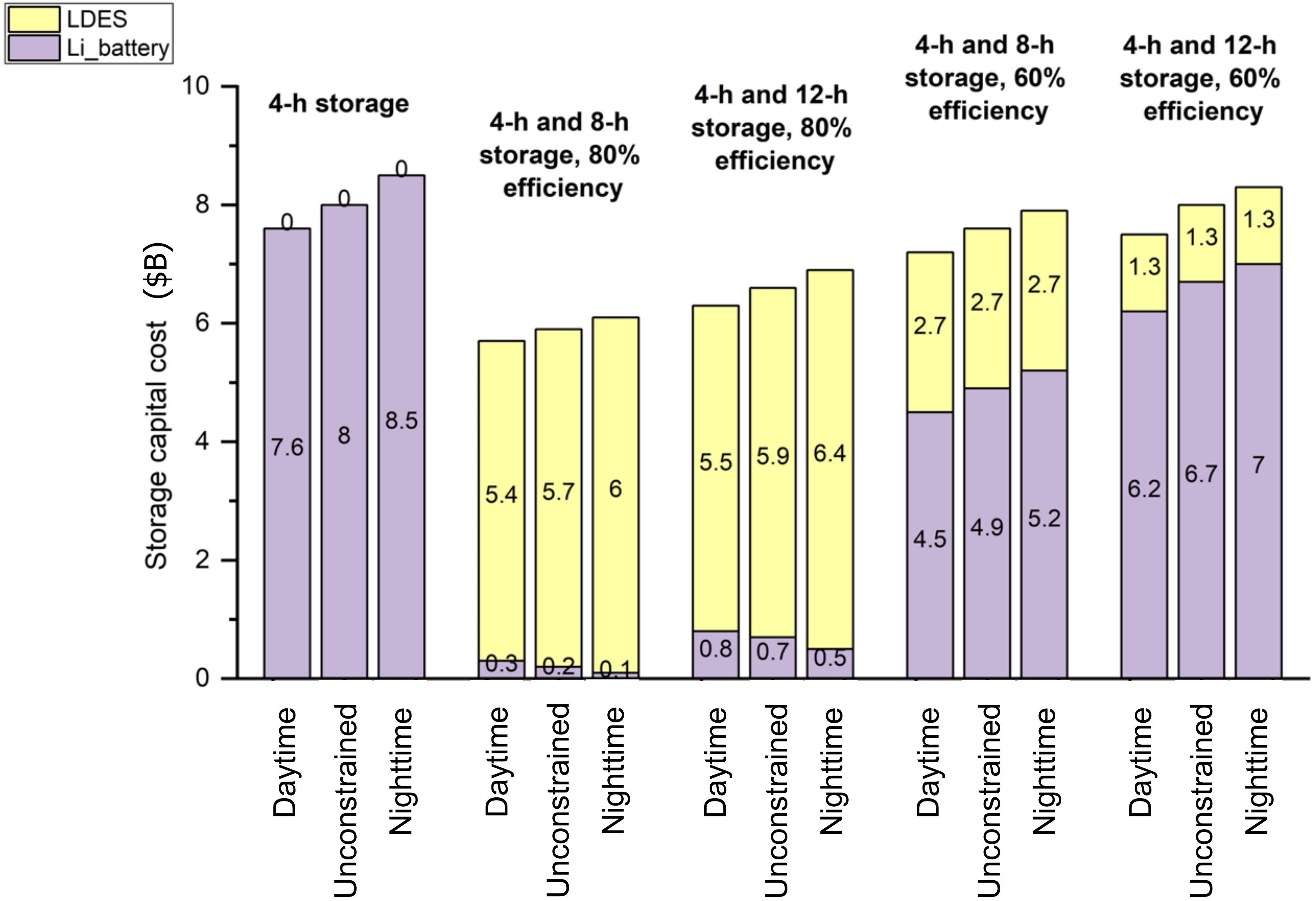

Assumption:

$$\frac{8\text{–}h\ storage\ cost\ (\frac{\$}{kW})}{4\text{–}h\ storage\ cost\ (\frac{\$}{kW})} = \mathbf{1.2}$$

$$\frac{12\text{–}h\ storage\ cost\ (\frac{\$}{kW})}{4\text{–}h\ storage\ cost\ (\frac{\$}{kW})} = \mathbf{1.4}$$

Cost differences of storage could be ~ \$ billion

Is this significant compared to the infrastructure cost?

Daytime charging requires more non-residential charging infrastructure. How much is this added cost?

- It is unclear if tomorrow's charging infrastructure will look like today's as it is still evolving fast.

- An example of the reported innovations:
  Installing RV outlets everywhere to charge EVs[1]:

[1] https://heatmap.news/electric-vehicles/nema-14-50-mobile-charger-lucid-air

Solar-covered parking lots

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Is it practical to charge California's ZEVs with solar-covered parking lots?

Mounting solar panels over the parking lots

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Two studies estimating parking lots area in California:

- A press release by Senator Becker estimated approximately 400 square miles of parking lots in the state, equivalent to 26 GW of solar canopies[1].

- The research by the U.S. Geological Survey estimates that parking lots cover 0.47% of the U.S.' total contiguous land area, corresponding to around 800 square miles of parking lots in California, equivalent to 52 GW of solar canopies[2].

➢ ***Is 26-52 GW sufficient to meet the daytime charging?***

[1] https://pv-magazine-usa.com/2023/04/12/california-senate-transport-committee-passes-solar-parking-canopy-and-highwayside-law/
[2] https://www.usgs.gov/news/estimates-areal-extent-us-parking-lots-now-available

Can we meet the ZEVs load with 26-52 GW solar canopies?

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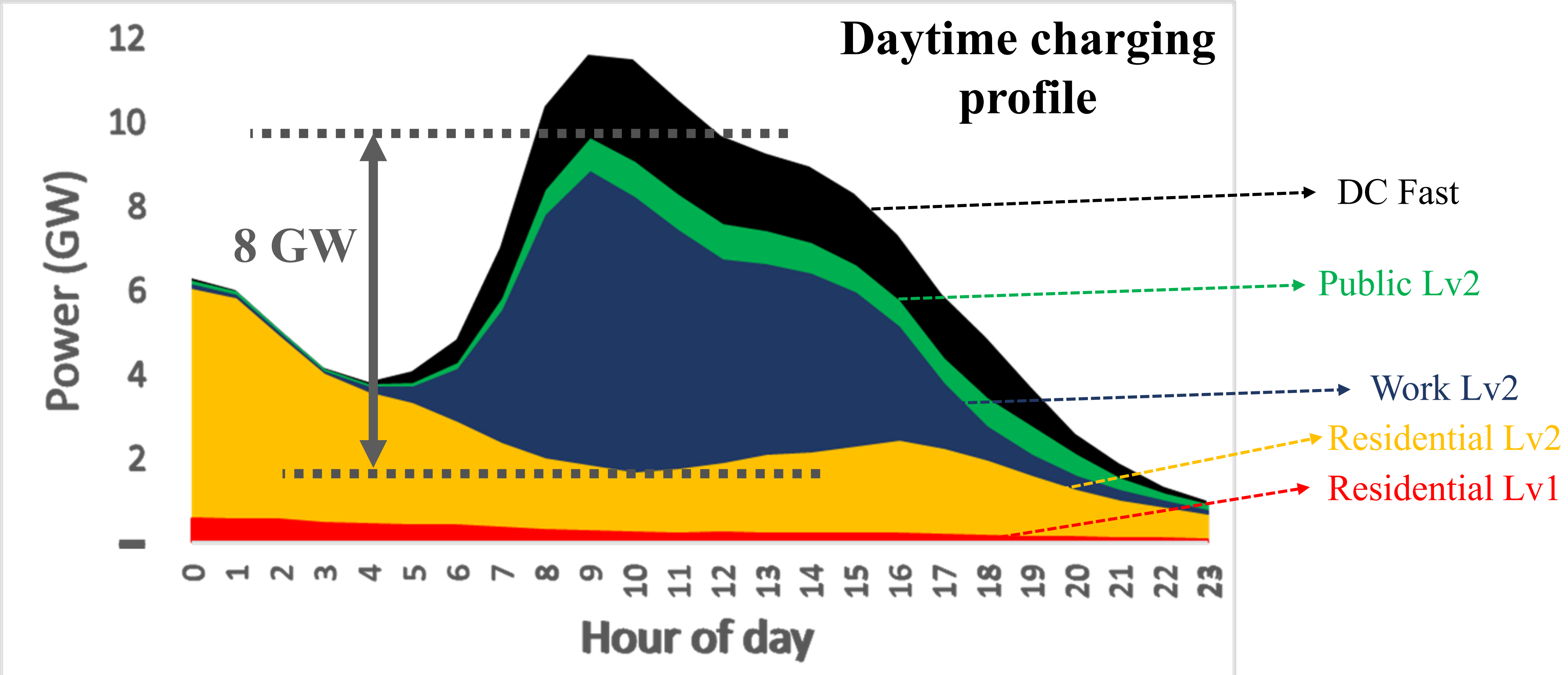

- ✓ **By using 15-30% of the parking lots, the peak load of 8 GW for work and public charging could be met.**
- ✓ **1000 hours generation/y →26-52 TWh energy generation < 55 TWh projected energy demand → energy for chargers other than workplace and public ones should come from somewhere else.**

Takeaways

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✓**Daytime charging** of light-duty ZEVs decreases the storage cost ~ $ billion, motivating investment in daytime charging infrastructure.

✓The cost of charging infrastructure using today's technology would be ~ $ billion, motivating innovations in charging infrastructure technology.

✓15% - 30% of California's parking lots, if covered with solar, could meet the daytime charging demand.

Effect of generation on need for LDES

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- How could more solar and wind generation in the winter affect the need for storage?
- This section presented by Zabir Mahmud

Overview of solar and wind study

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Objective:

- Understanding the value of
  - different solar mountings
  - winter-dominant onshore wind
  - 25GW offshore wind by 2045

Introduction:

- Different solar and wind generation profiles

Results:

- Effect of different solar panel mountings on
  - Annual solar curtailment
  - LDES cost target = *f* (*duration*, *efficiency*)
- Impact of offshore and winter-dominant onshore wind resources on storage needs

Motivation

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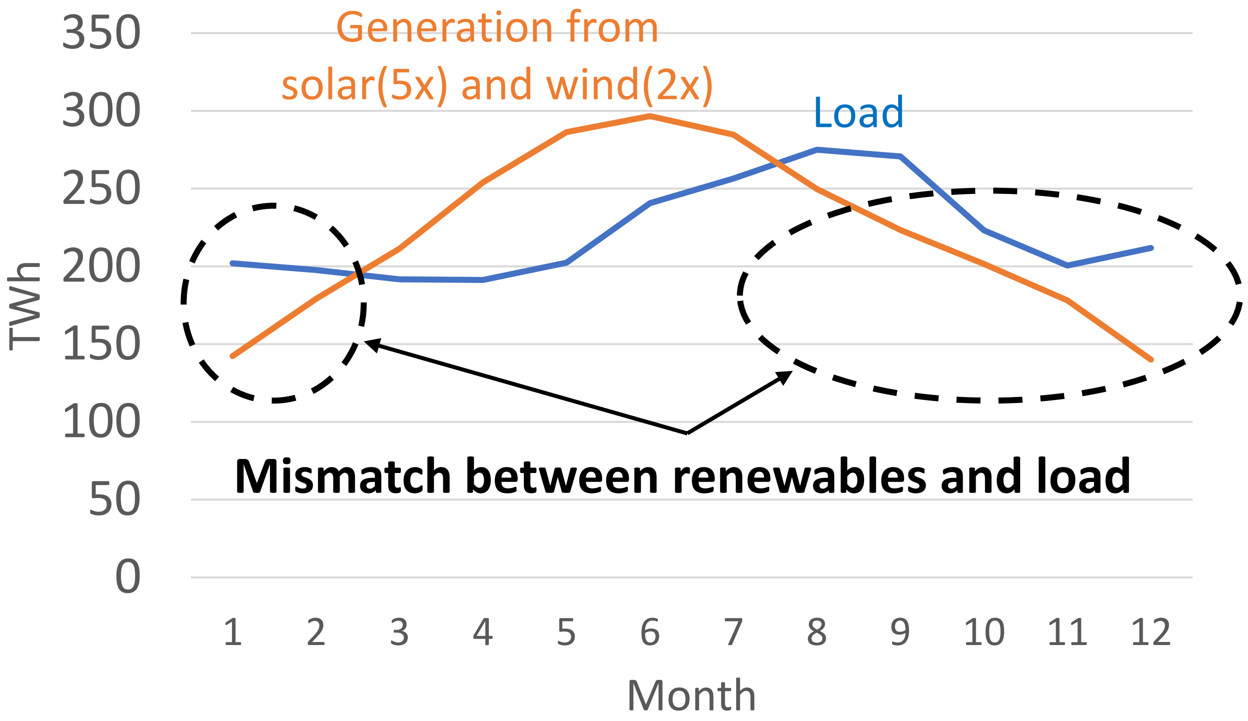
- For California, renewable generation and load experience seasonal mismatches



Winter-dominant generators could be helpful

Motivation

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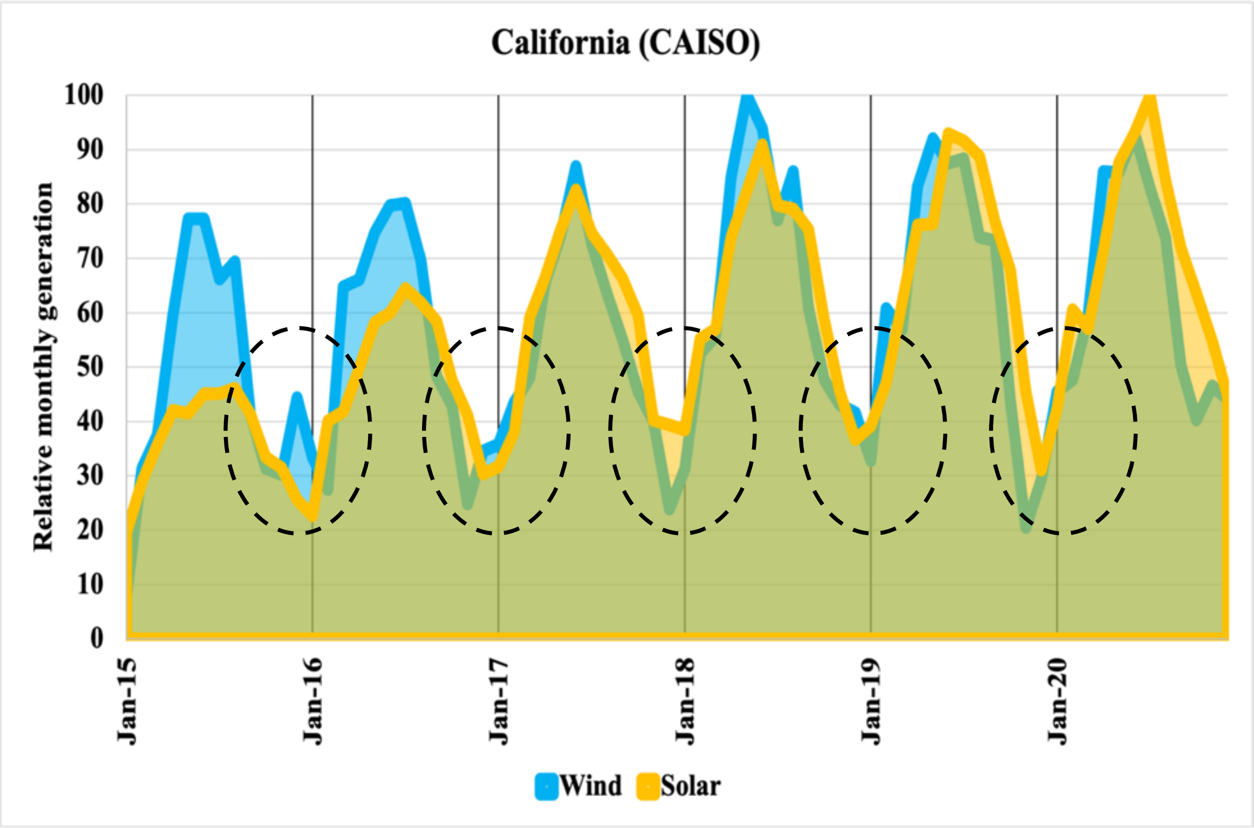

For California, both solar and wind generation increases in the summer and drops during the winter

* https://ww2.energy.ca.gov/almanac/electricity_data/web_qfer/index_cms.php
* https://www.eia.gov/electricity/data/eia860/
* https://www.eia.gov/electricity/data/eia923/

Introduction to different solar mountings

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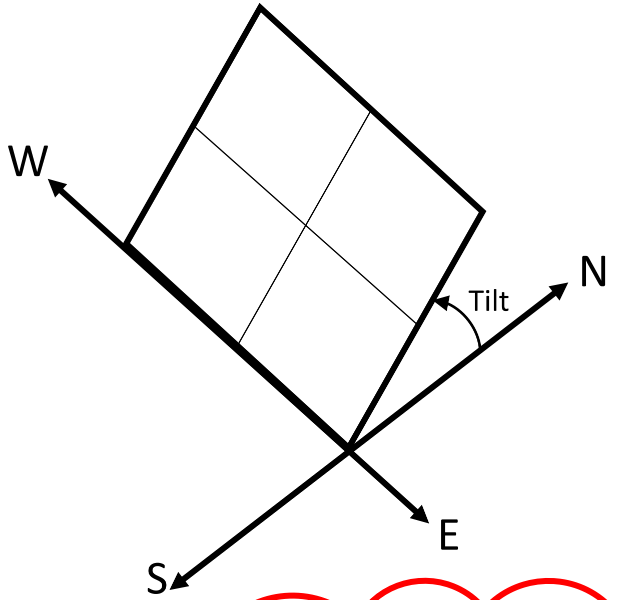
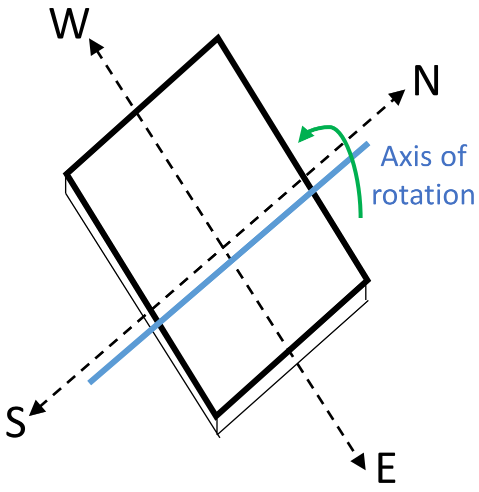
- While modeling a future renewables-driven grid for California, we have the opportunity to choose the solar panel mounting configuration
- We implemented three types of mounting configurations

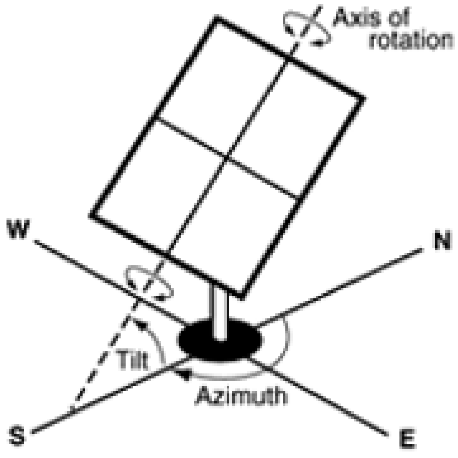
Introduction to different solar mountings

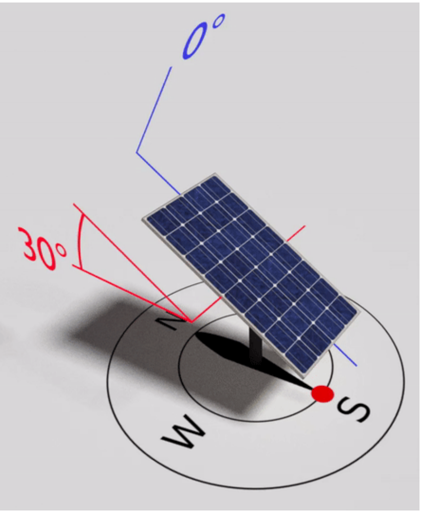


Fixed
South-facing tilt
(Fixed Tilt)



Horizontal
1-axis tracked
(Tracked No Tilt)





South-facing tilt
1-axis tracked
(Tracked Tilt)

Introduction to different solar mountings

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Which of these most commonly wins today?

Tracked no tilt

About 90% of newly installed utility-scale PV capacity

Tracked tilt

Remaining 10% of utility scale

Fixed tilt

Majority for rooftop (though tilt varies)

Comparison of solar profiles

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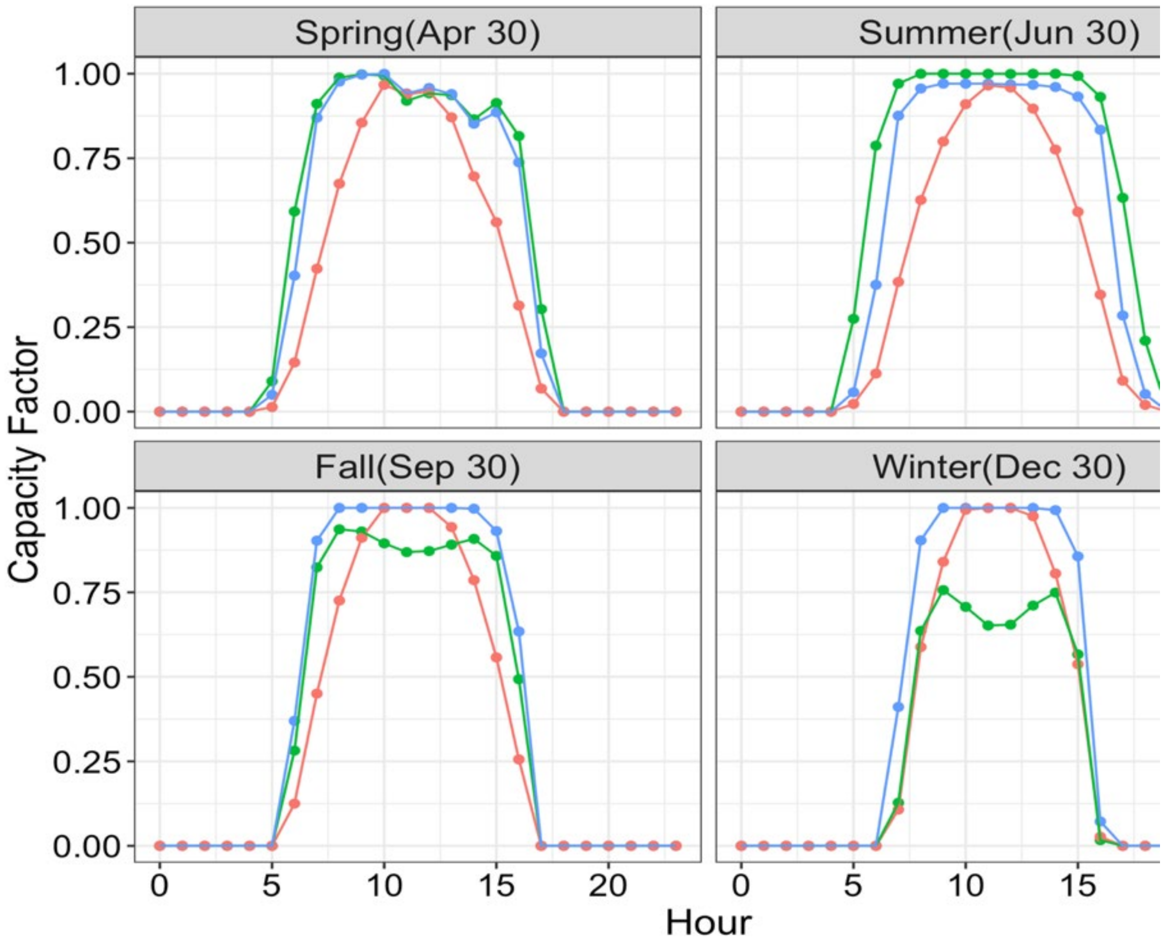

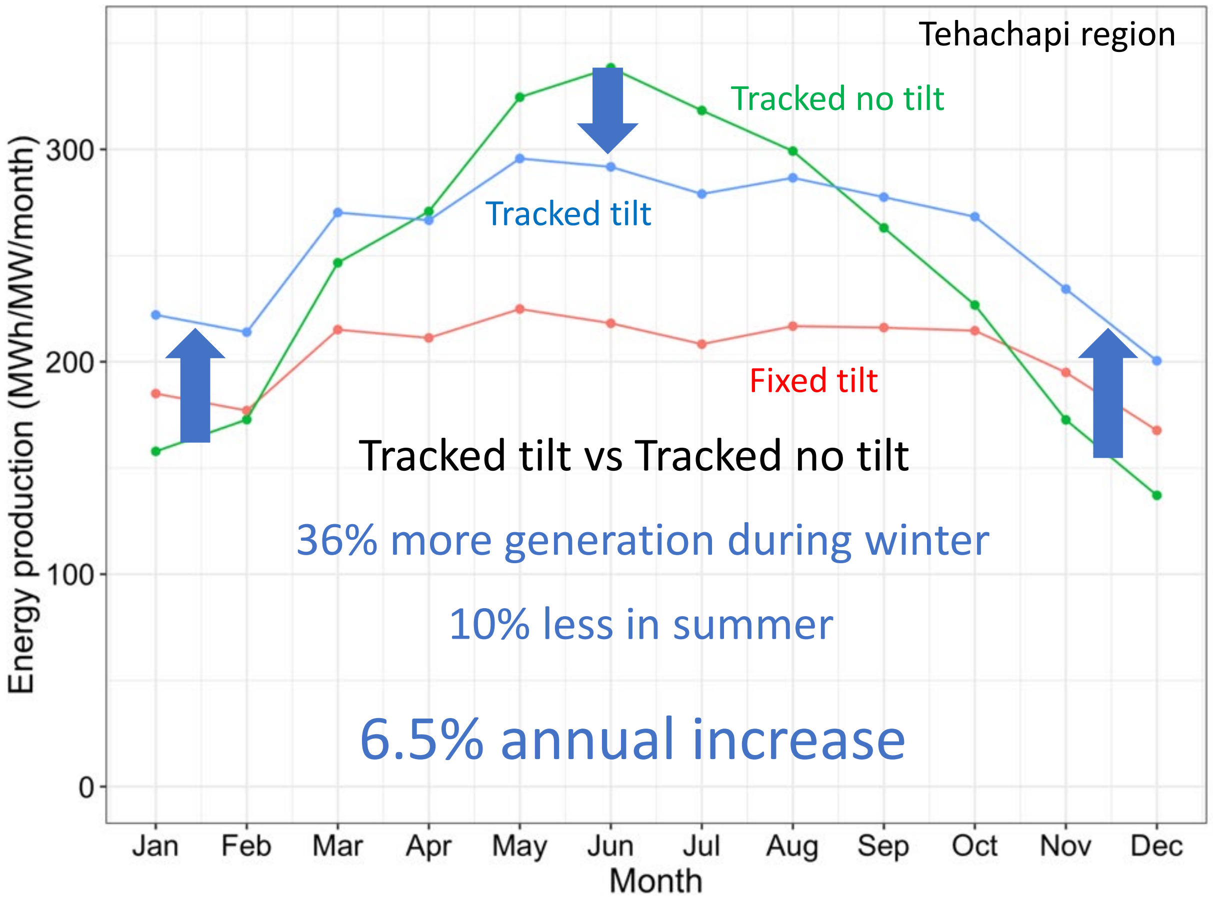

Tracking with tilt can capture more solar energy

Effect of mountings on solar curtailment

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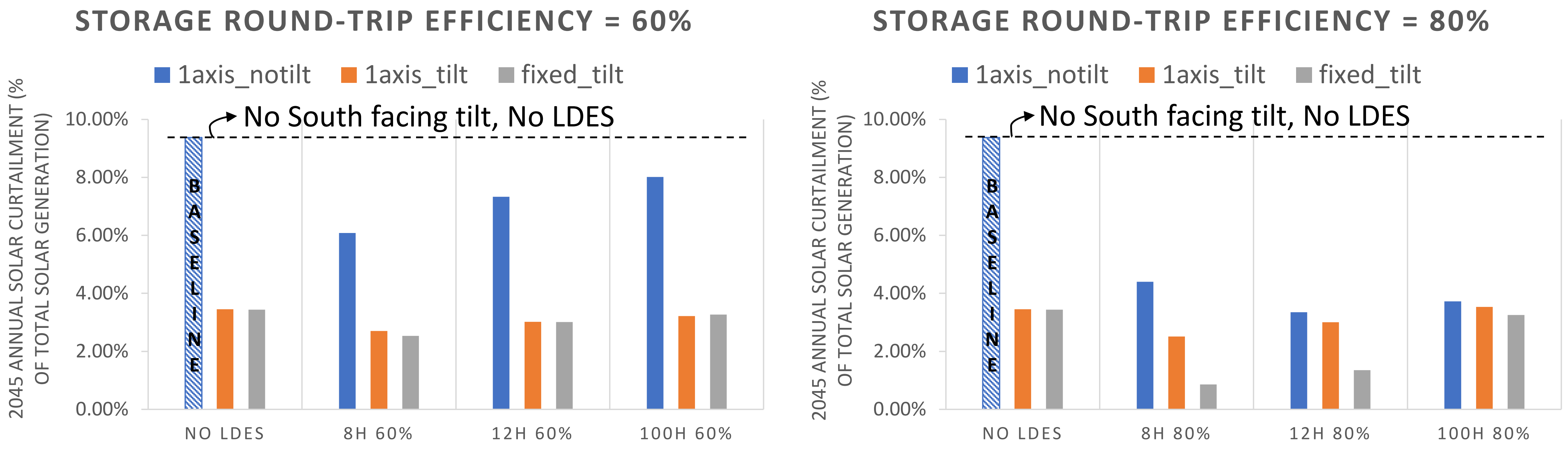

For baseline, we do not include south-facing tilt and LDES. Dashed horizontal line shows 9.4% curtailment for baseline scenario.

For other cases, we use south-facing tilt or LDES or both and it leads to a lower annual solar curtailment by 2045 though the amount of decrease varies

Effect of mountings on solar curtailment

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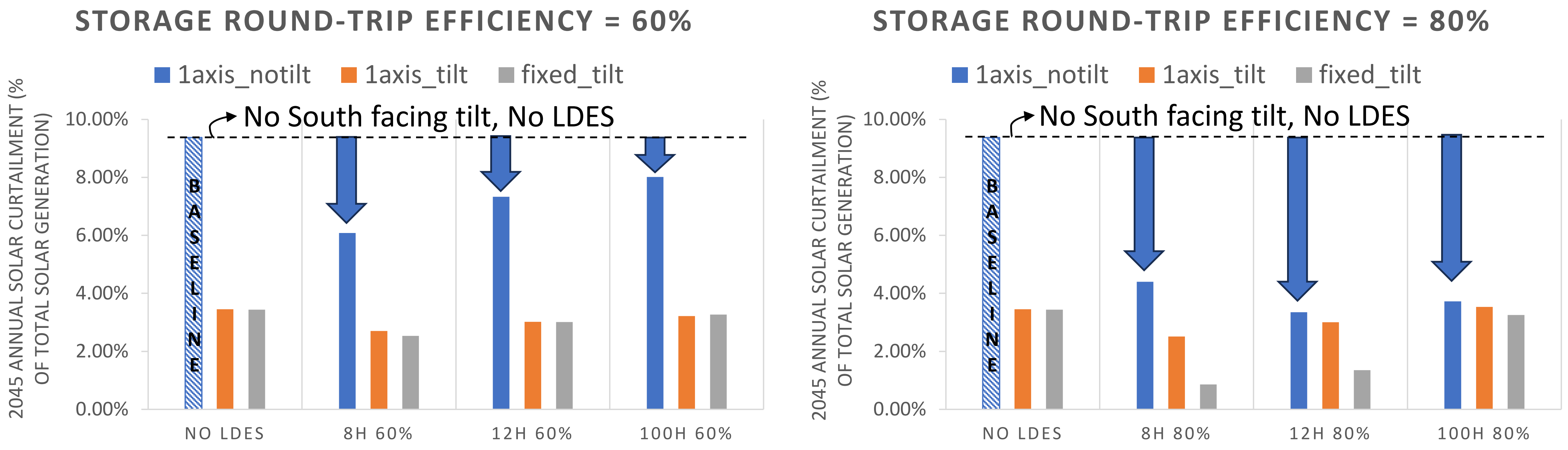
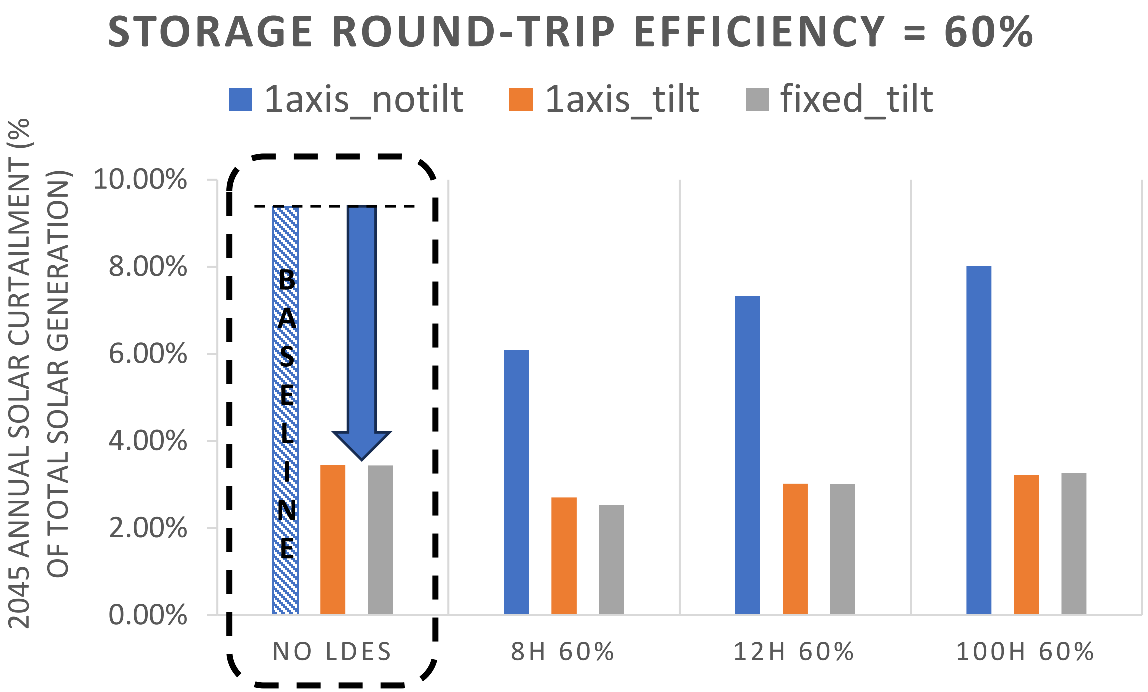
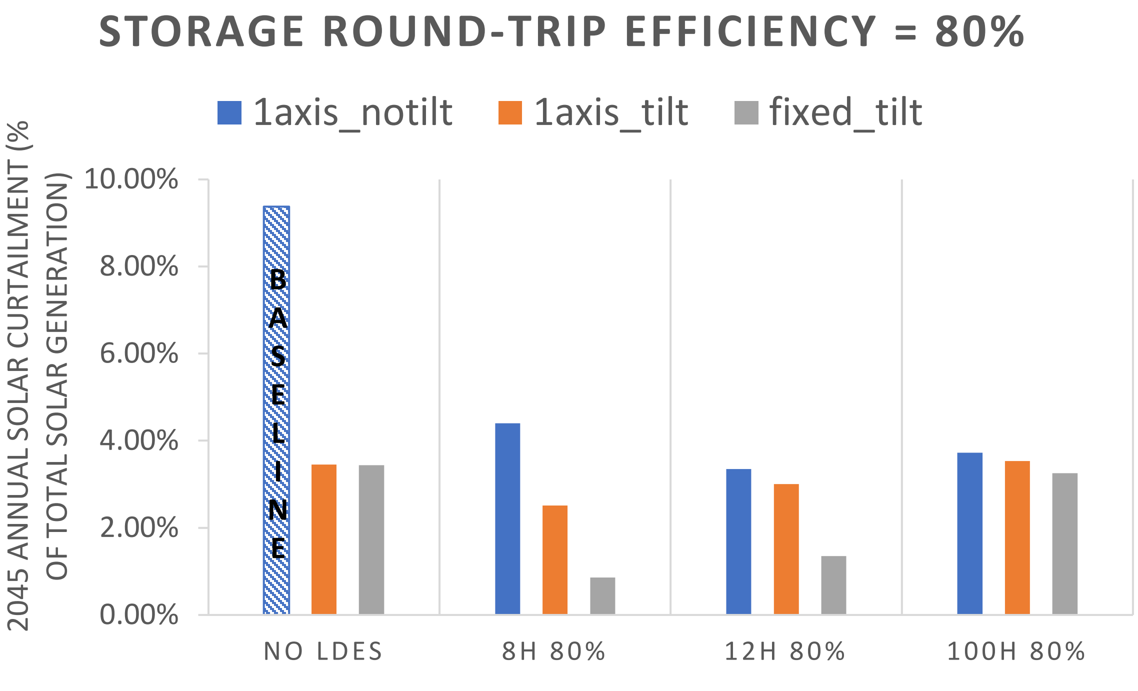


Adding LDES reduces the curtailment for horizontal single-axis tracking

- 60% round trip efficiency is helpful though depends on duration
- 80% reduces curtailment more

Effect of mountings on solar curtailment





Using south-facing tilt can reduce the curtailment even if we do not use LDES

The annual solar curtailment drops to 3.5% from 9.4% as a fraction of total solar generation

Effect of mountings on solar curtailment

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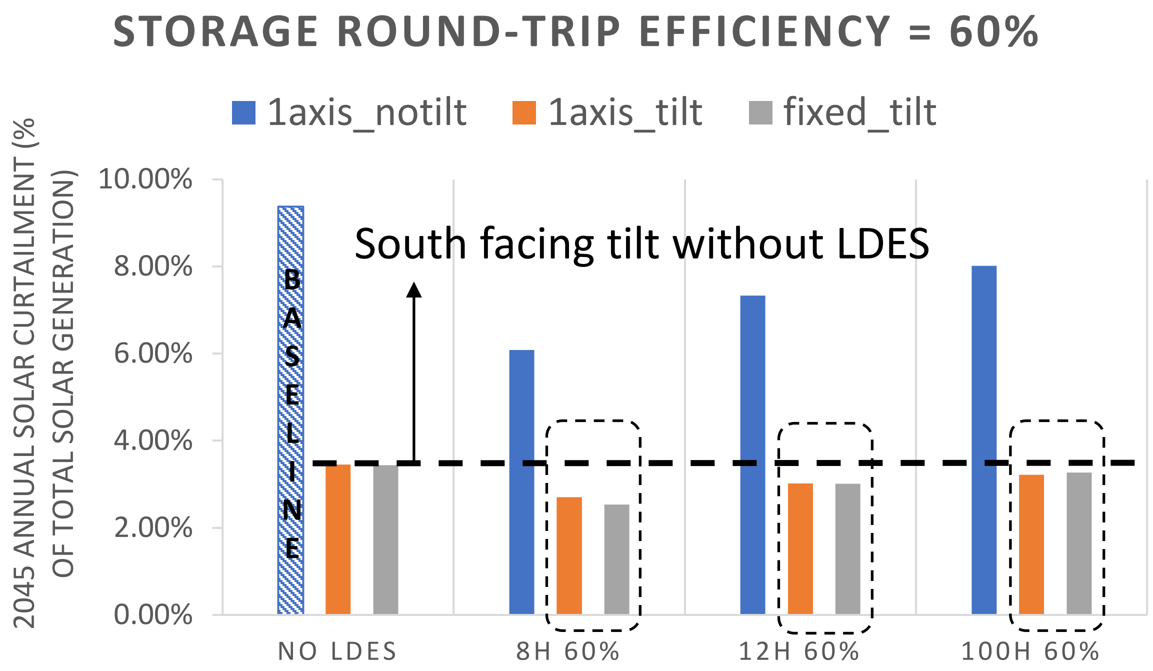

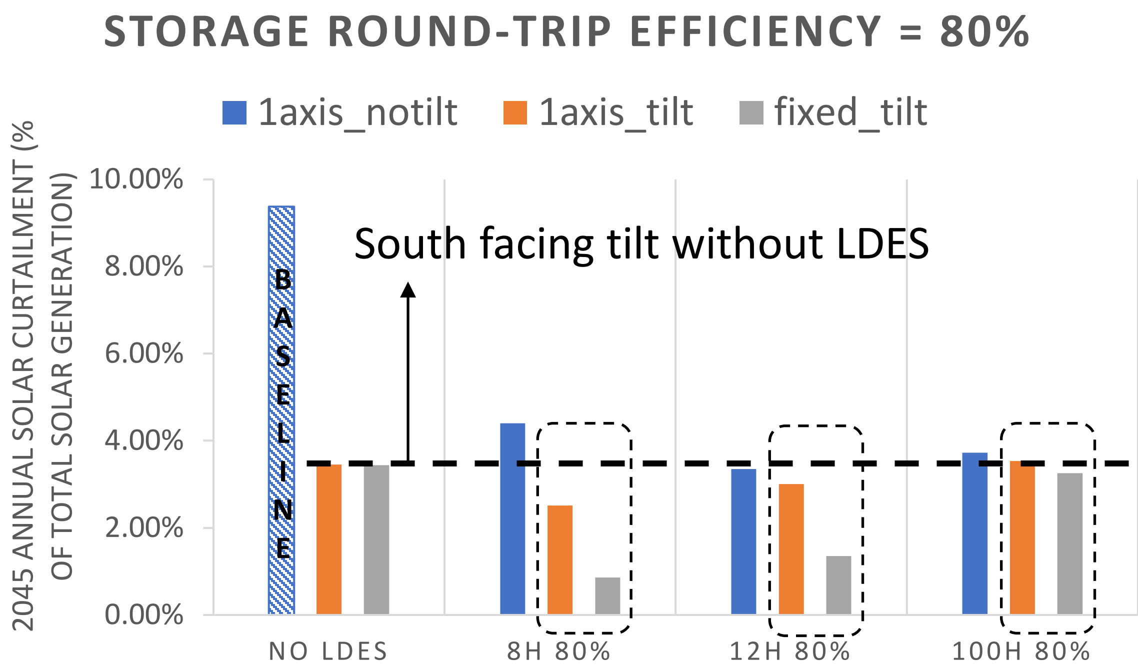

LDES and south-facing tilt together are most effective

Effect of mountings on LDES cost target as a function of storage duration

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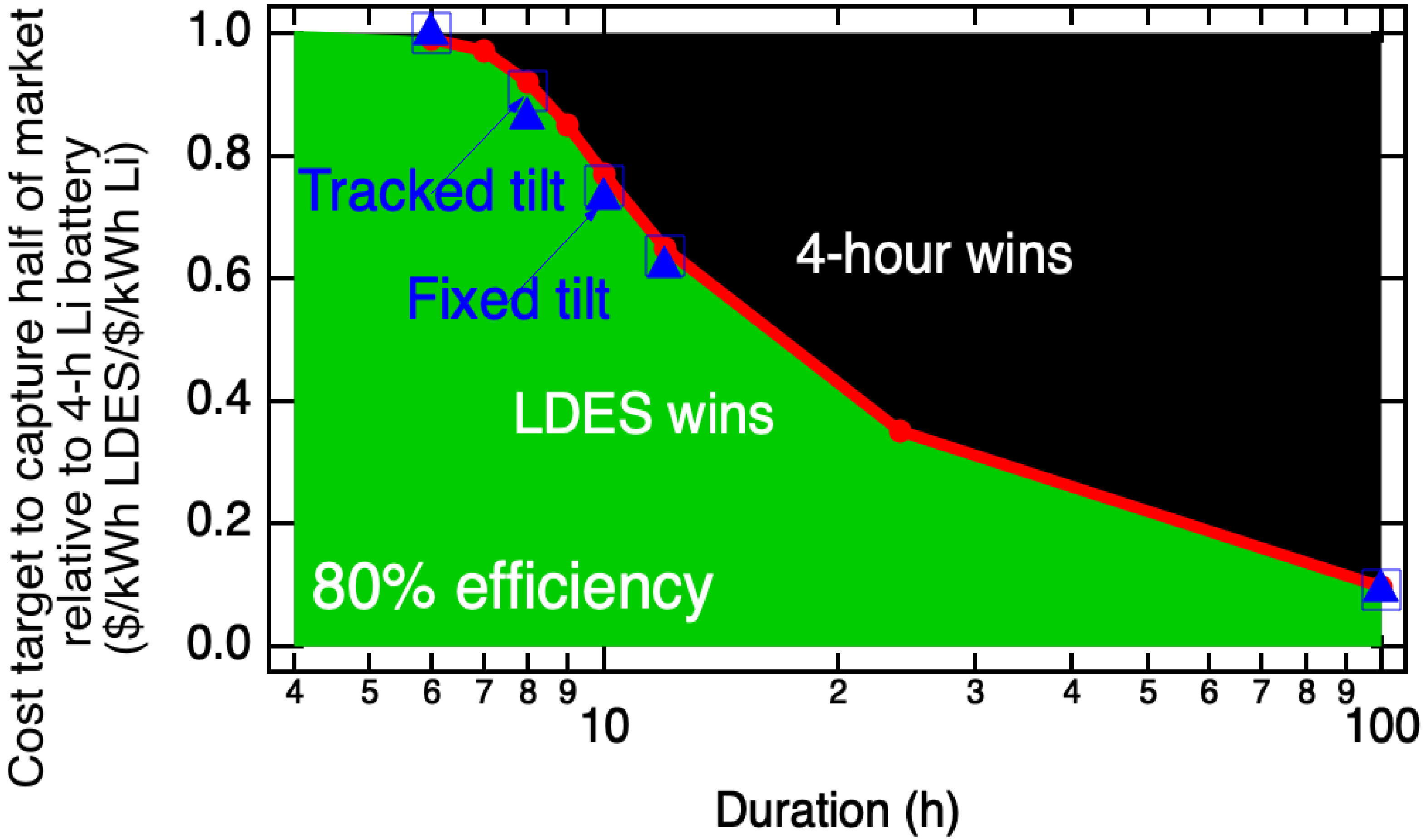

Competition between 4-h and LDES as a function of duration is not strongly influenced by solar mounting configuration

Effect of mountings on LDES cost target as a function of storage efficiency

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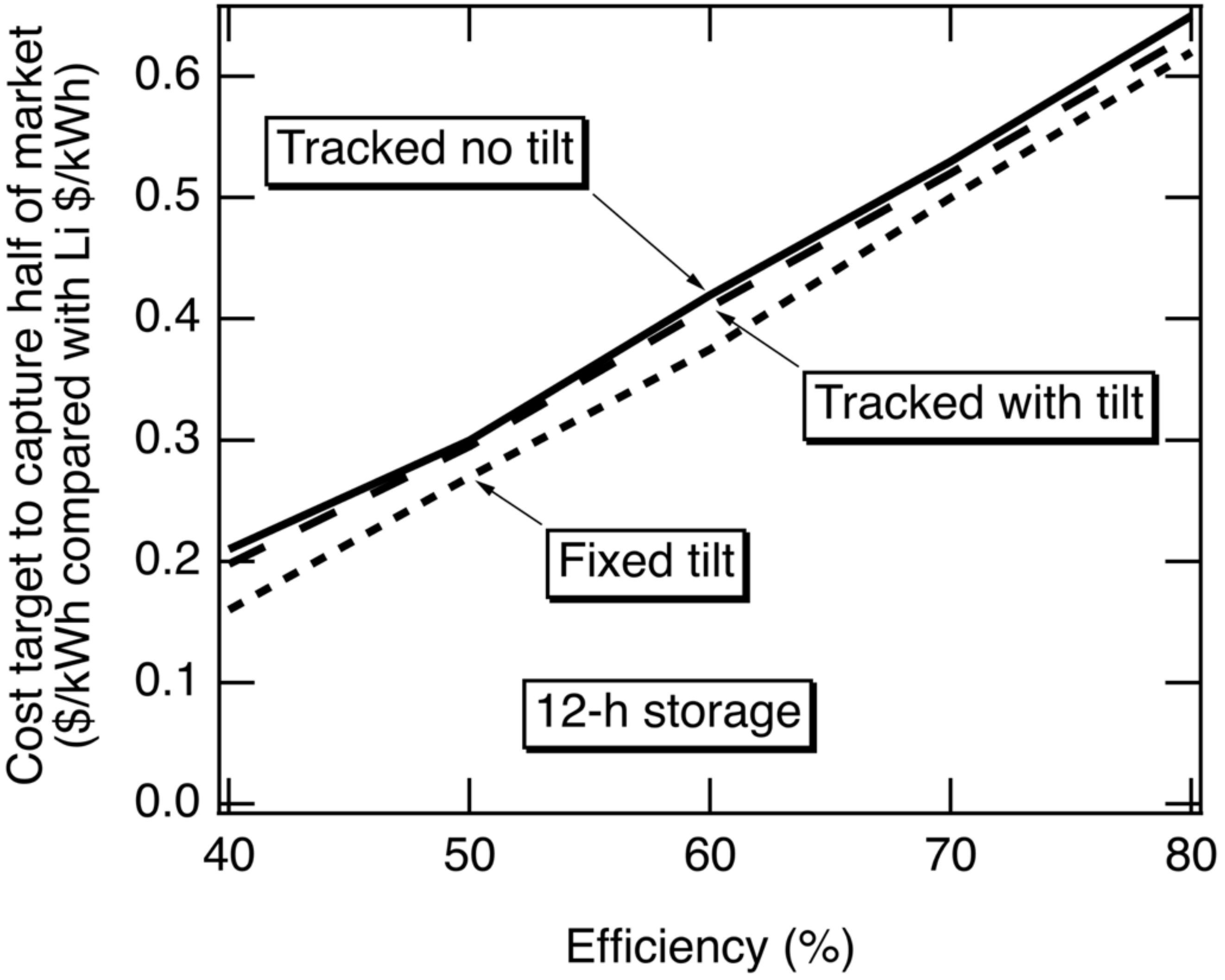

Storage efficiency has similar significance on LDES cost target for these three solar panel mounting configurations

Effect of wind on storage needs

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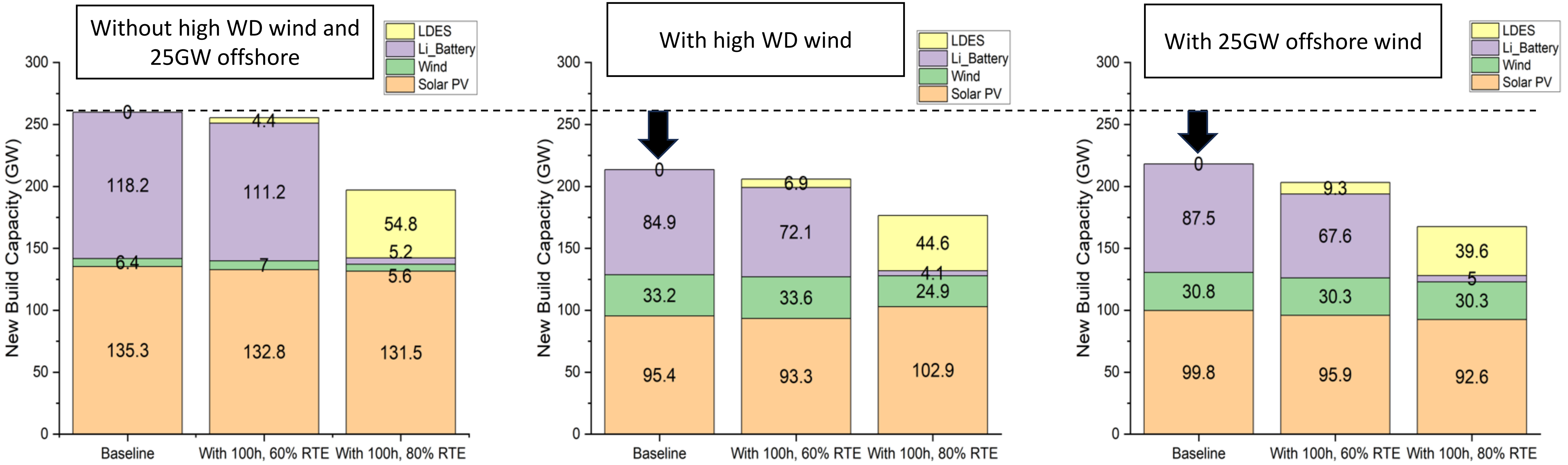

While using no LDES, adding 25 GW of winter dominant (WD) or offshore wind decreases solar by 35-40 GW and storage by 30 GW, resulting in net decrease in capacity expansion.

Effect of wind on storage needs

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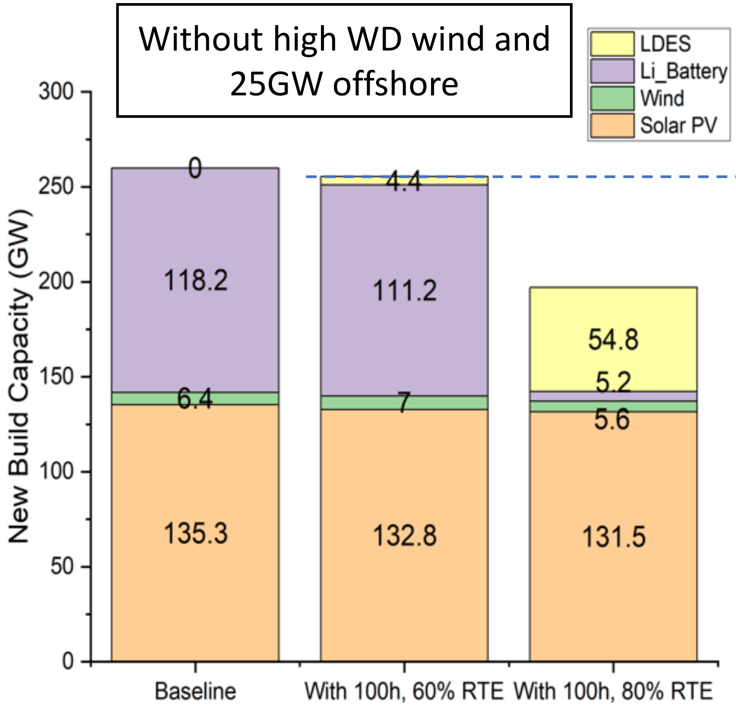
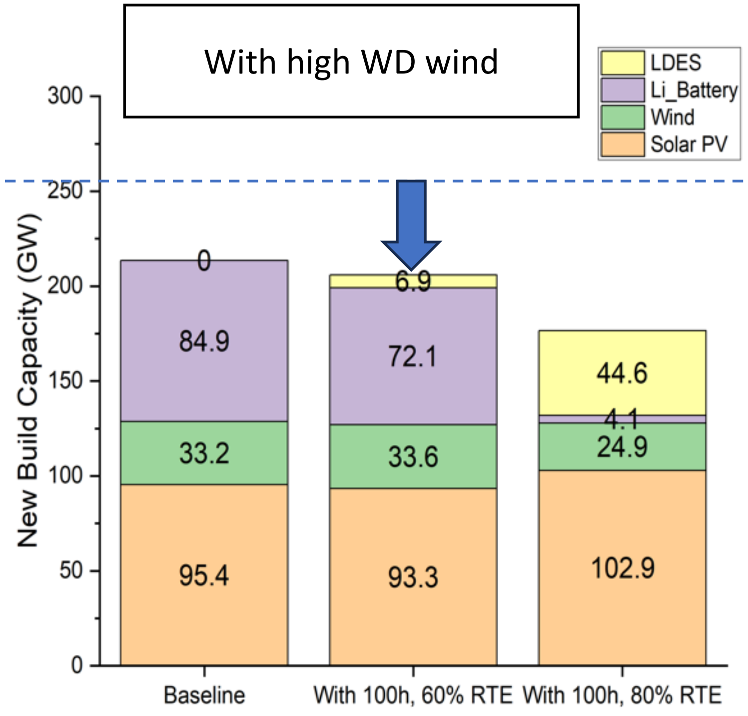
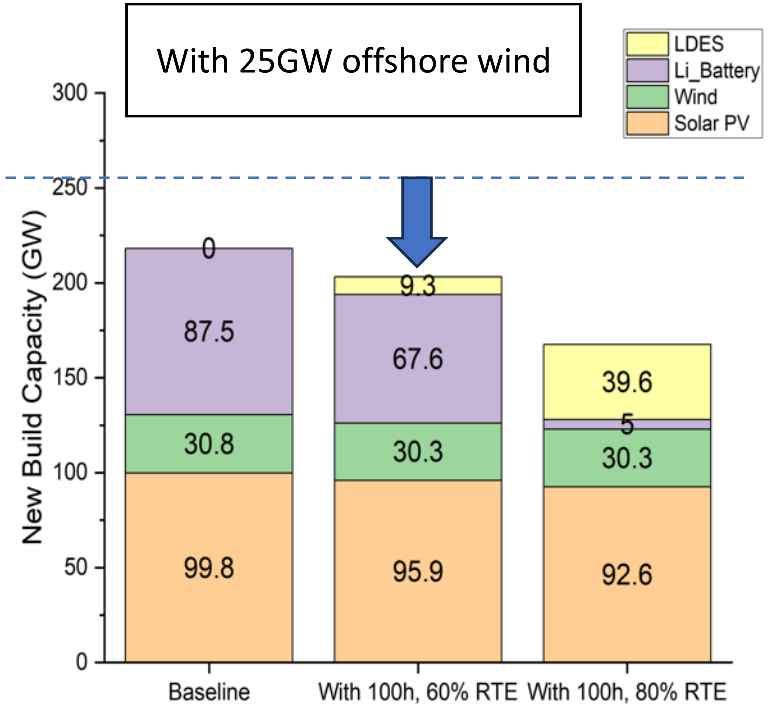
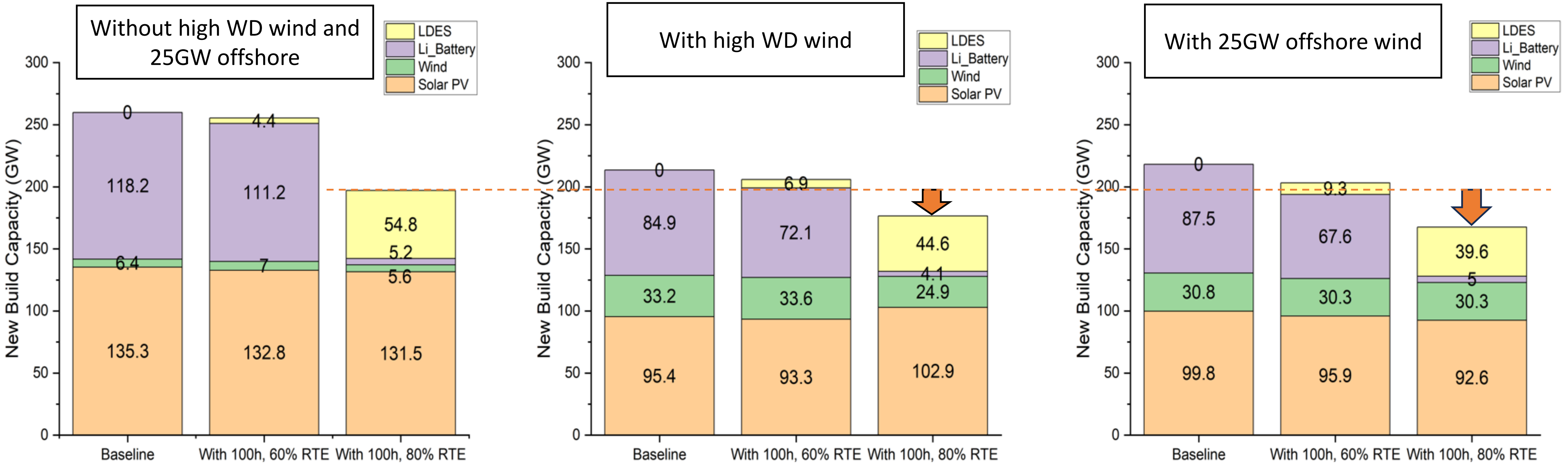






With 100h LDES of 60% efficiency, adding 25 GW of winter dominant (WD) or offshore wind decreases solar by 35-40 GW and storage by 35-40 GW, resulting in net decrease in capacity expansion.

Effect of wind on storage needs



With 100h LDES of 80% efficiency, adding 25 GW of winter dominant (WD) or offshore wind decreases solar by 30-40 GW and storage by 10-15 GW, resulting in net decrease in capacity expansion.

Optimal LDES duration for high wind?

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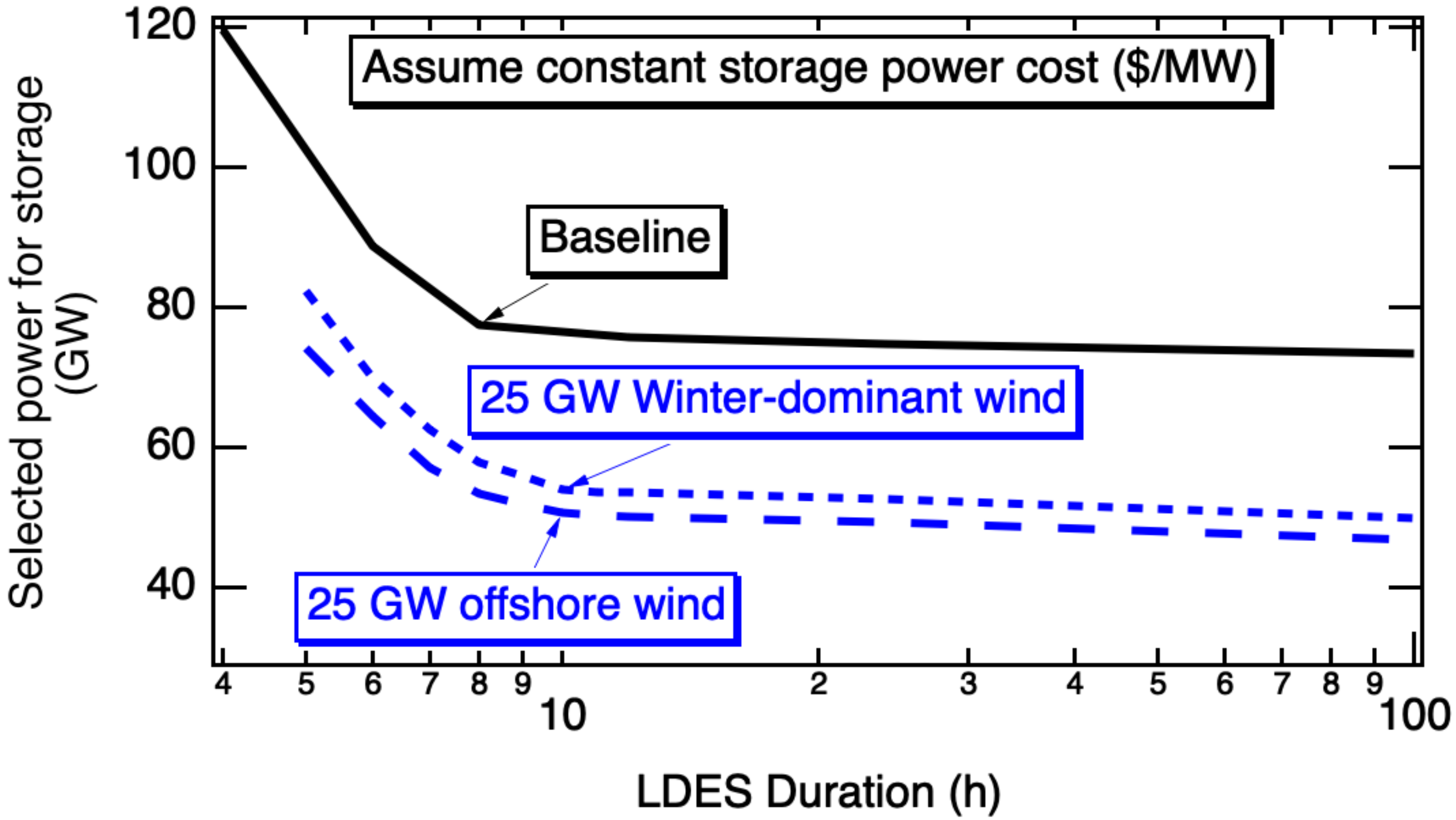

Storage built for 2045 baseline scenario:
Power is overbuilt for LDES < 8 h for baseline
Power is overbuilt for LDES < 10 h for high wind scenarios

Conclusions

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- Higher curtailment is observed for systems with no south-facing tilt
- Mounting configuration has little effect on needed storage type (duration and efficiency)
- In 2045, the optimal configuration may be a south-facing tilt. Details will depend on innovations to reduce costs of tilted systems
- Offshore and winter wind reduce the total capacity expansion, particularly need for solar and storage

Effect of oxy-combustion on need for LDES

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- How could a closed-loop (no flue gas) oxy-combustion process (Allam cycle) affect the need for storage?
- This section presented by Mariela Colombo

Overview of oxy-combustion study

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- Introduction to oxy-combustion
- Modeling assumptions
- Results
  - Addition of LDES and oxy-combustion to baseline
  - Oxy-combustion dispatchability
- Practical implications
- Conclusions

Introduction to oxy-combustion

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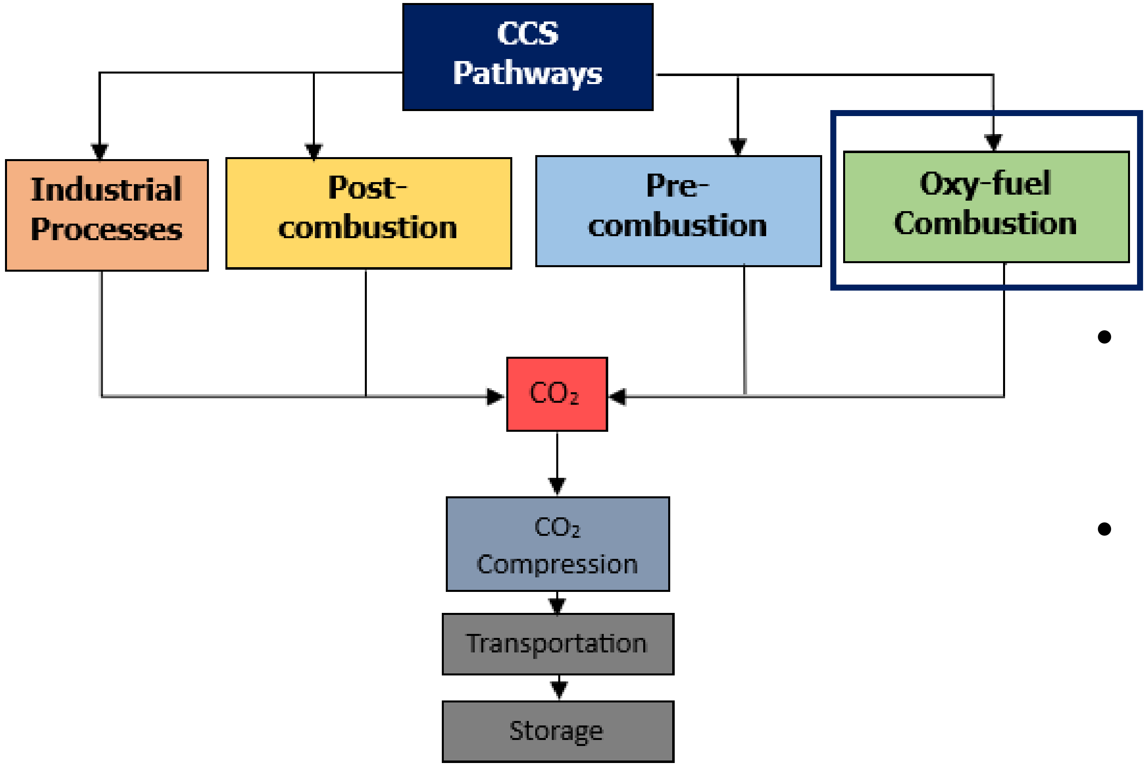
- **Firm low-carbon resources**, such as natural gas with carbon capture and sequestration (CCS), could reduce **power sector decarbonization cost**
- **Uncertainty** on technological and economic parameters



- **Oxy-combustion** = Combustion with **O_2**, *instead of air*.
- **Simplified carbon capture**: High-purity CO_2 stream obtained

Introduction to oxy-combustion

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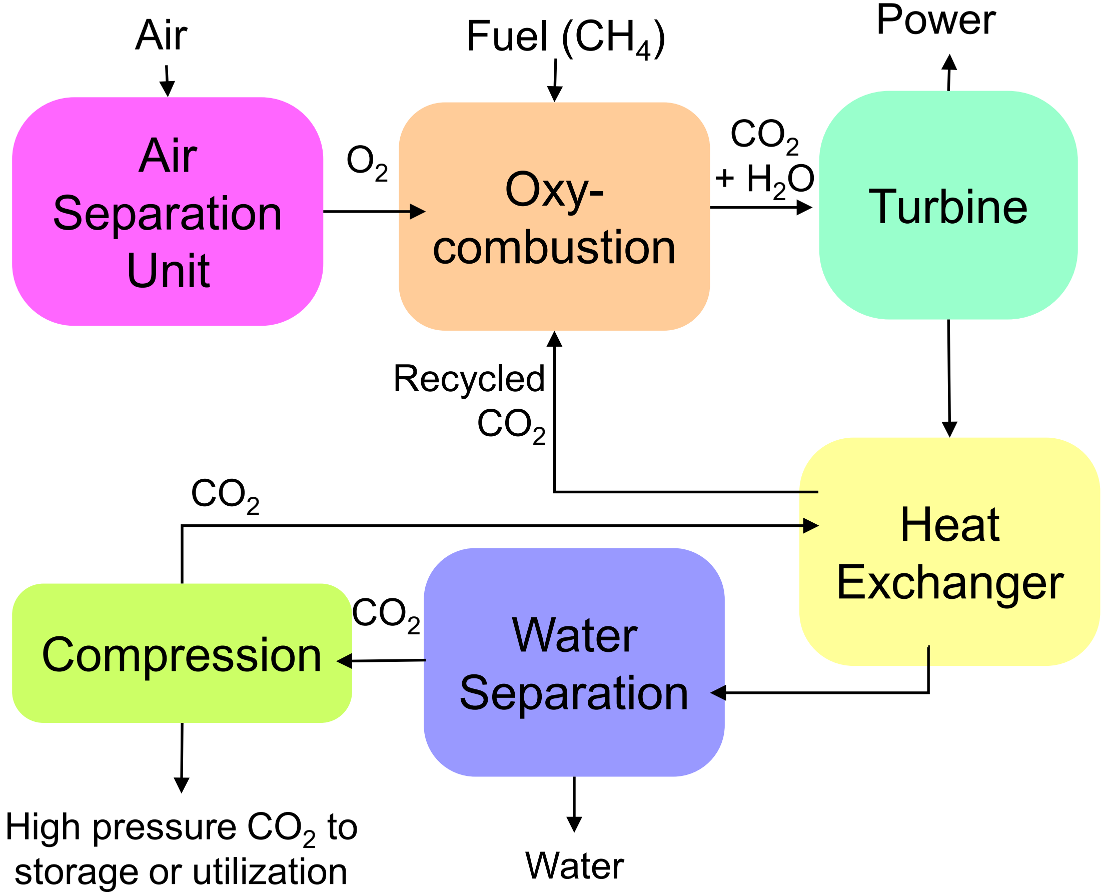
One approach: Allam Cycle by NET Power

- High-pressure CO_2 is working fluid in a **closed-loop cycle**, avoiding all emissions by design (e.g., CO_2, NO_x)
- First utility-scale project of **300 MWe** operational in **2026**, in **Texas** (NET Power, 2023)
- **Efficiency** comparable to CCGT: 59% LHV for gas (Allam R. et al, 2016)

Simplified diagram of the process



Modeling assumptions

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Oxy-combustion:

- Estimated potential in California due to infrastructure requirements:

Model year	Maximum operational capacity (GW)
2030	0.5
2035	1
2040	2
2045	4

- Capital cost 1 to 2.5 times CCGT cost

Baseline:

- No LDES or oxy-combustion available

LDES:

- In this section, we will focus on the results with **100-h LDES**

	60% Efficient	80% Efficient
100 hours	**1.8 X Li power cost; 0.072 X Li energy cost**	**1.8 X Li power cost; 0.072 X Li energy cost**

Selection of oxy-combustion in baseline

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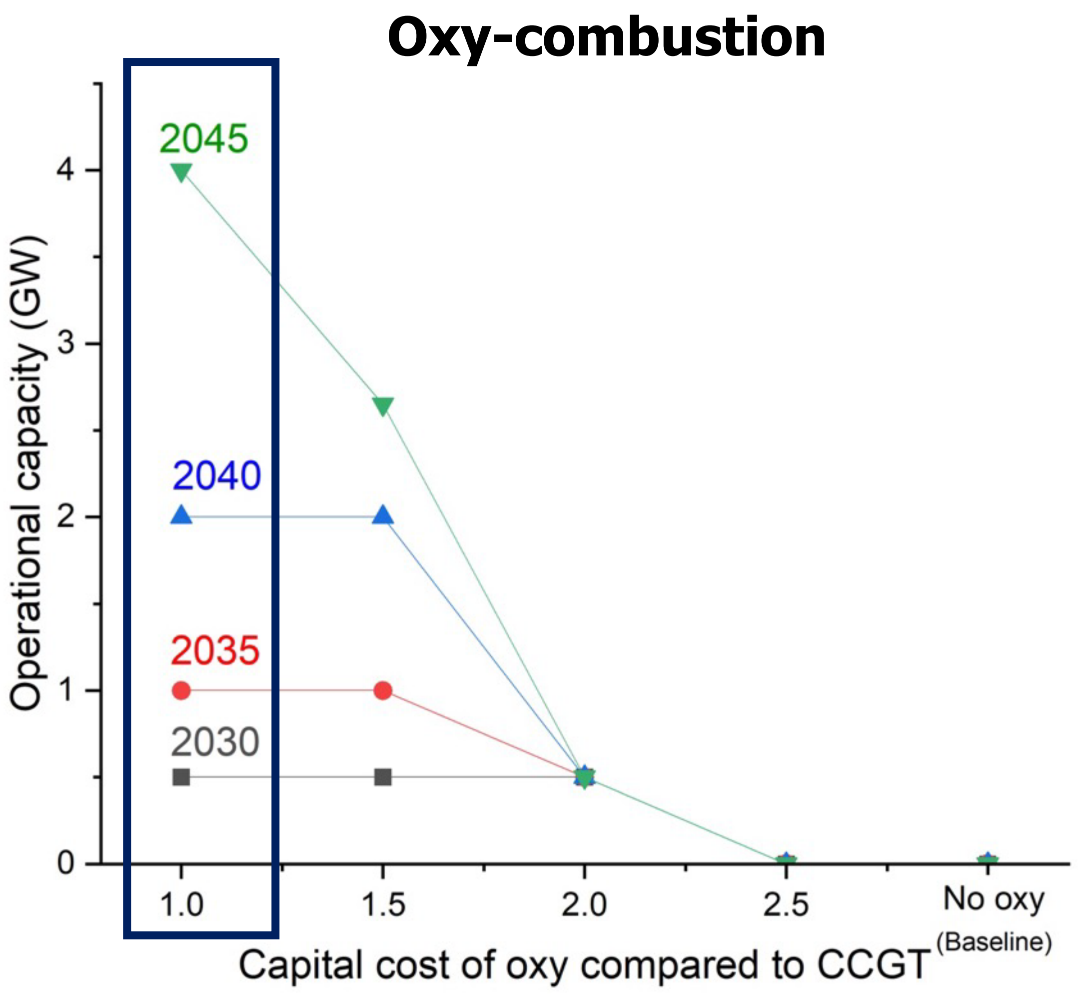

- Maximum operational capacity obtained only when the cost is equal to CCGT
- Selection limited to costs ≤ 2 times CCGT

Effect of oxy-combustion on need for 100-h LDES

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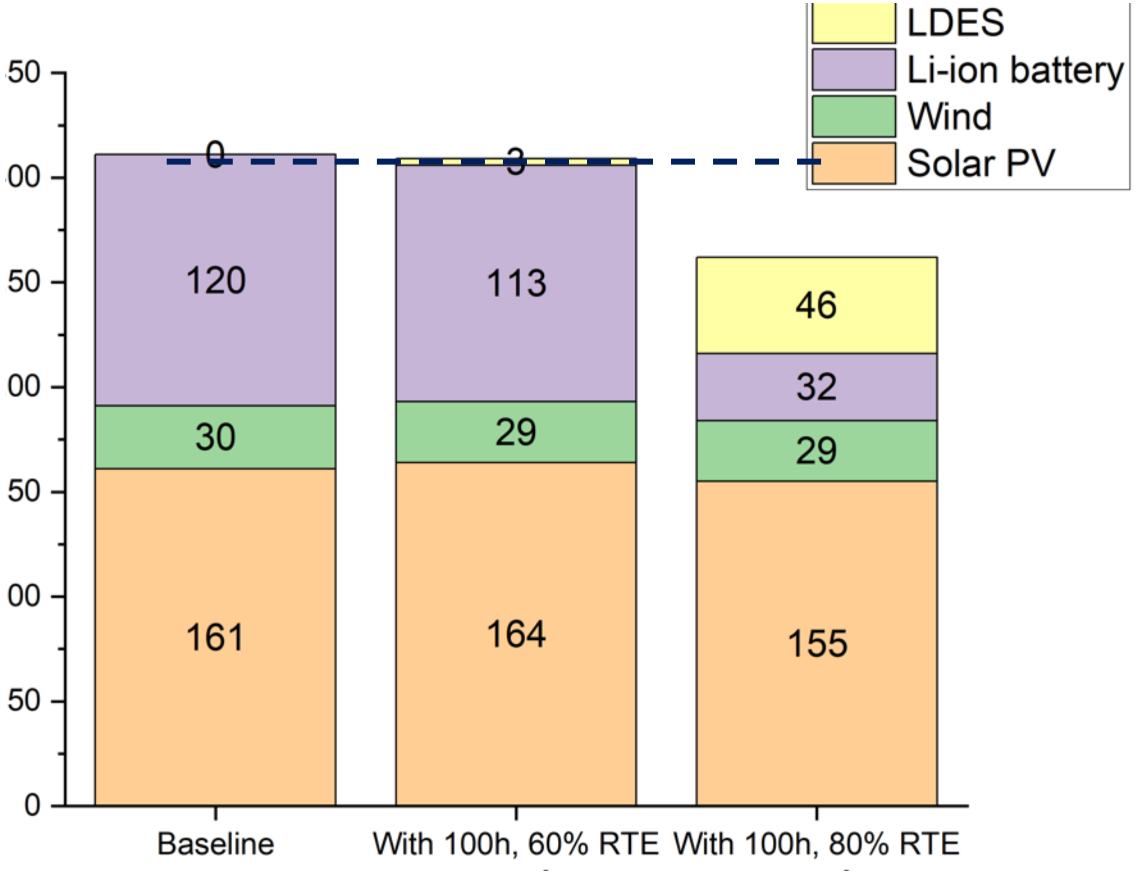
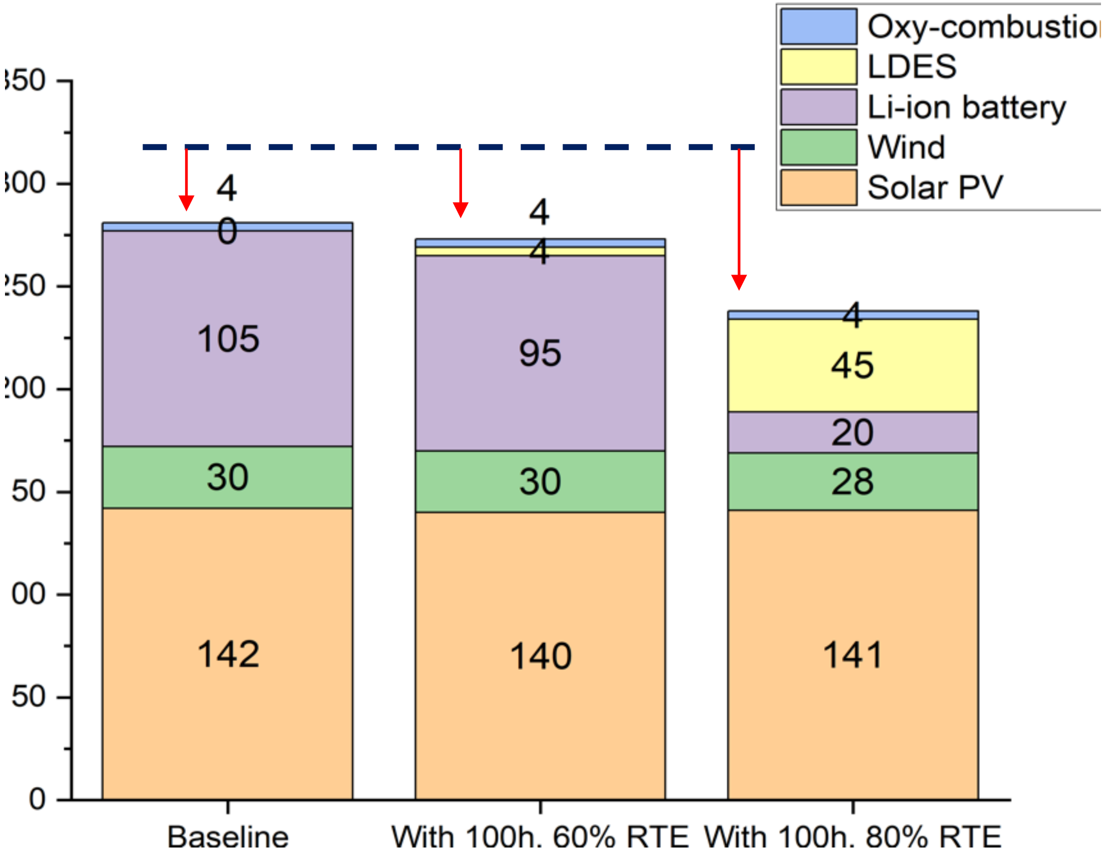
Without oxy-combustion



With oxy-combustion



- With oxy-combustion, the operational capacity **of solar PV and storage is reduced**

Effect of oxy-combustion on need for 100-h LDES

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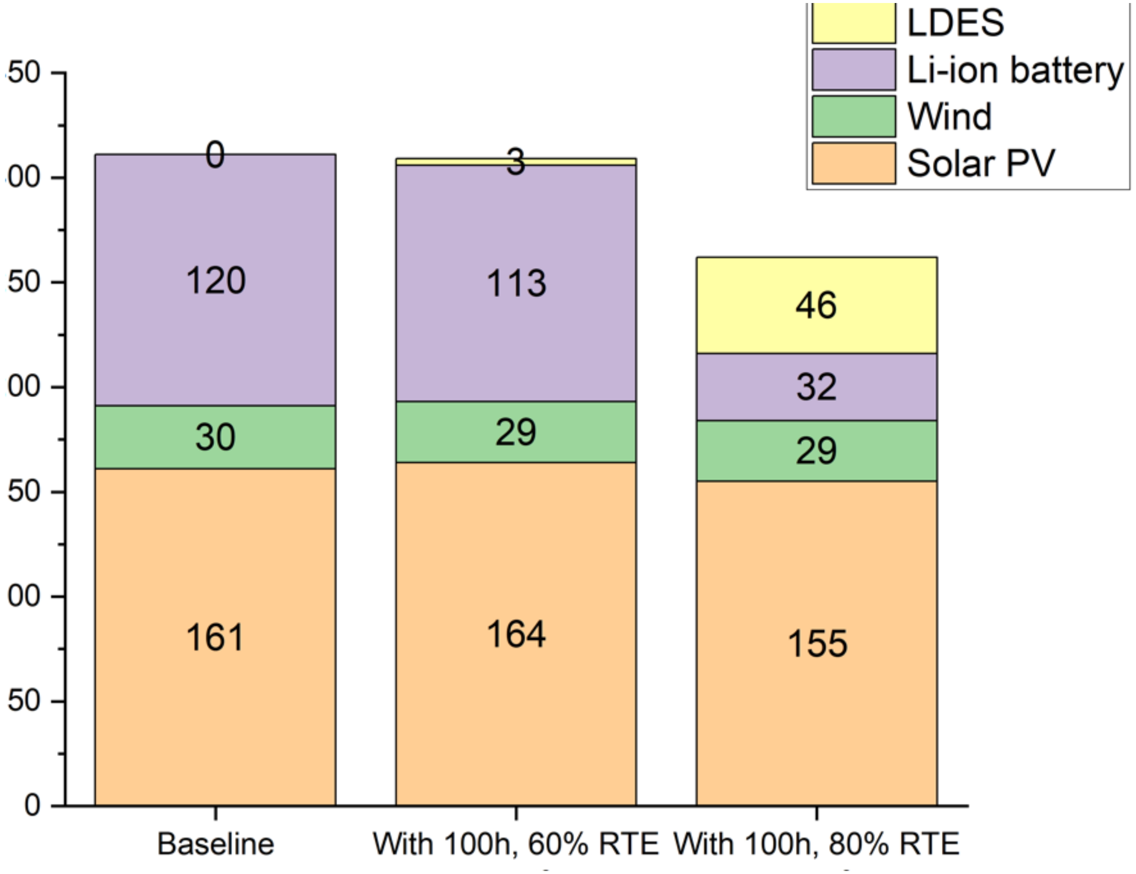
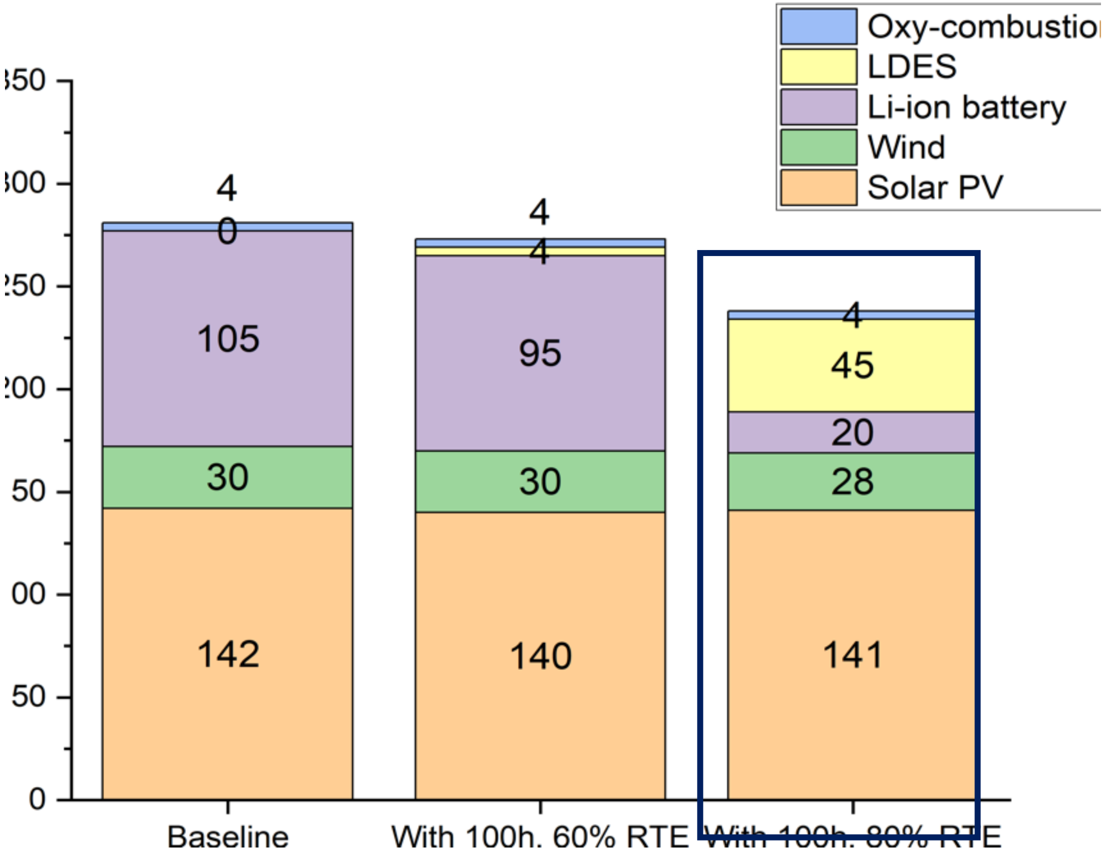
Without oxy-combustion



With oxy-combustion



- 100h, 80% RTE **LDES** + **oxy-combustion**: **Smallest capacity expansion** needed for meeting 2045 energy demand

When is oxy-combustion dispatched?

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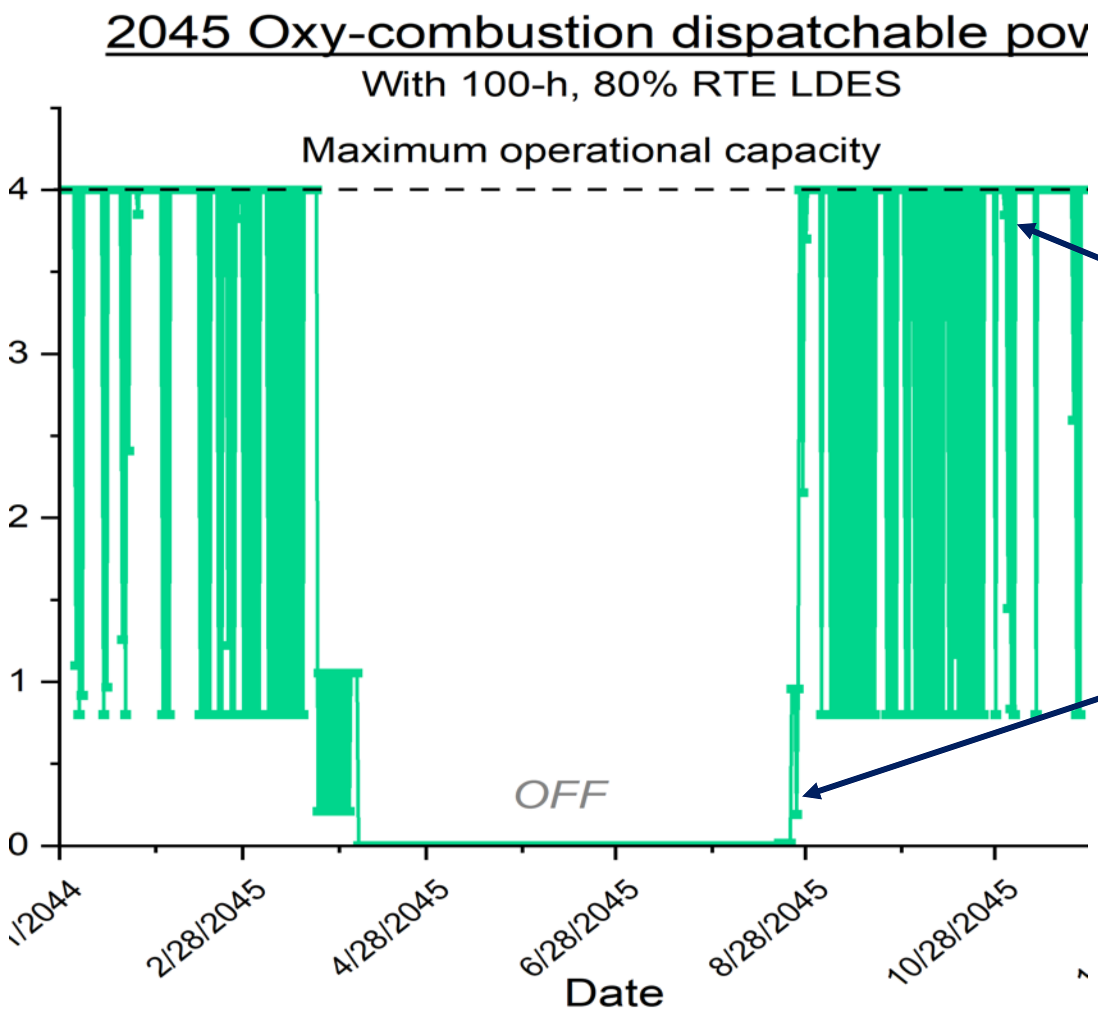

- Oxy-combustion is selected to operate mainly in **winter months**.
- In **spring/summer** months is **OFF**.

Effect of oxy-combustion on need for LDES

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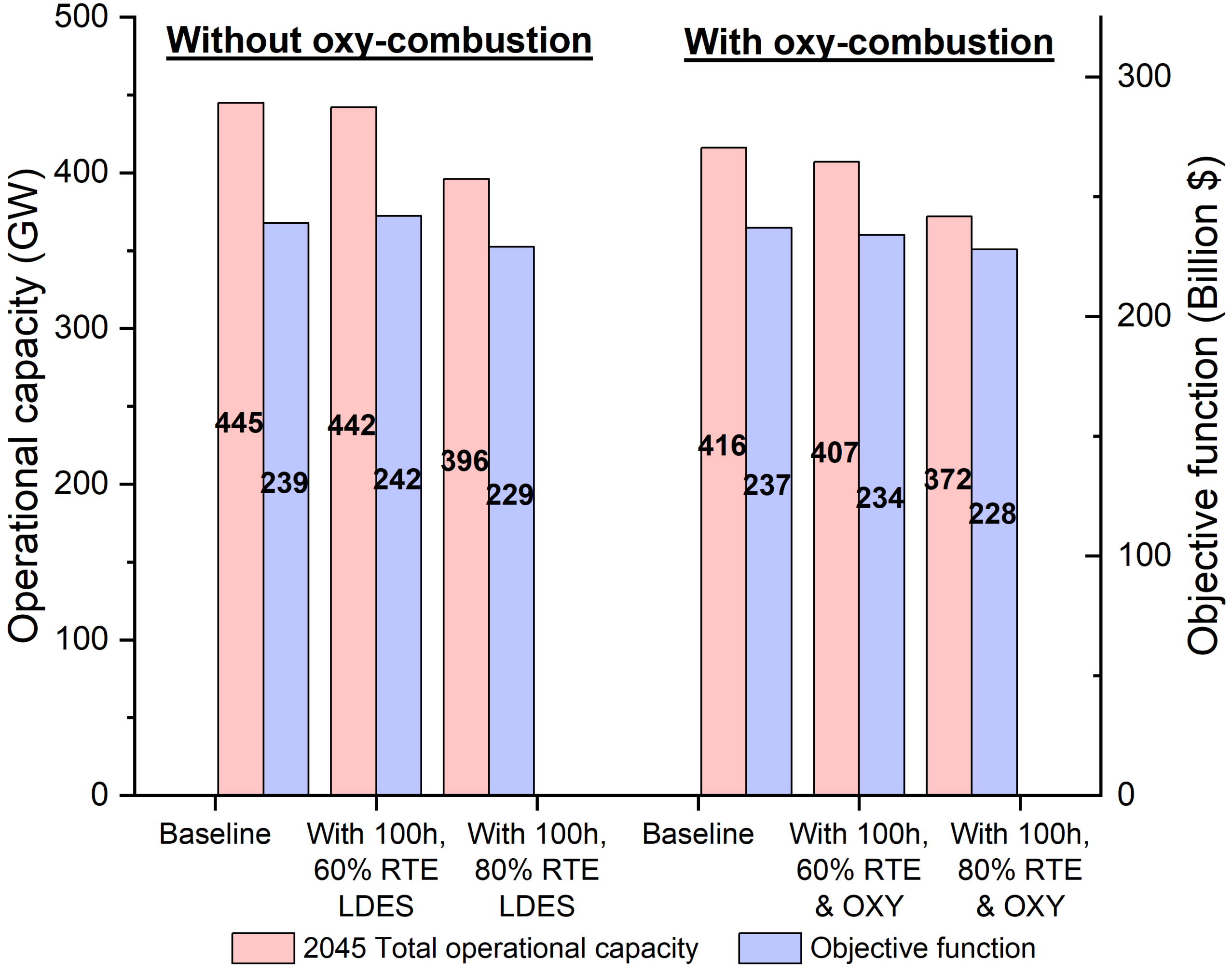

- Oxy-combustion could facilitate a **smoother decarbonization** of the power sector

But what are the practical implications?

Practical implications: Storage

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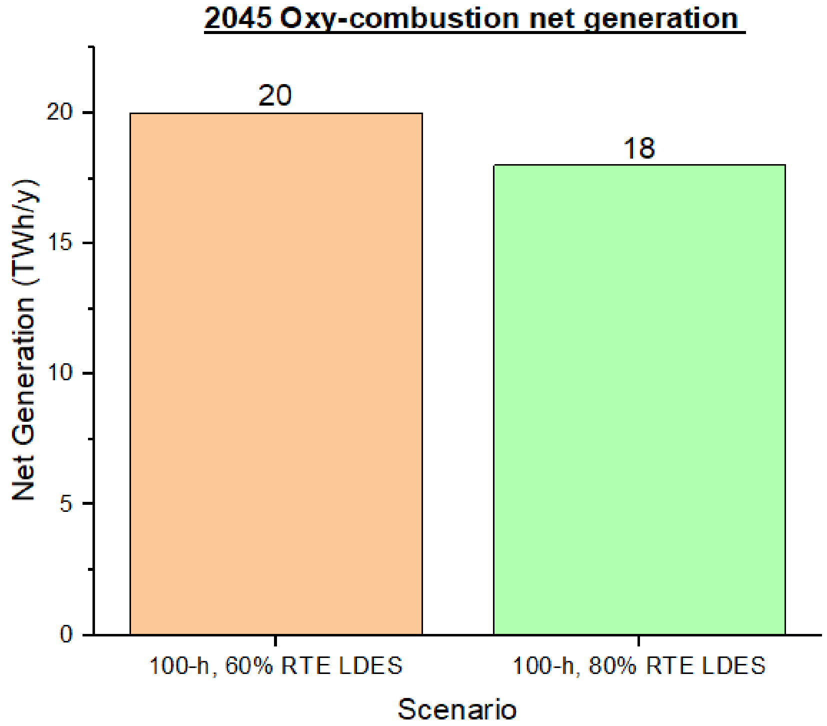
Challenges include:

- Technology **not mature** *yet*
- Infrastructure for **transportation** and **storage**
- **Regulatory framework**
- **Public acceptance**

Storage

Based on Stanford Center for Carbon Storage[1] assessment, **CA could store 70 GT or 60 MMt/y of CO_2 for more than 1000 years.**



2045, 4 GW of oxy-combustion:

- Net generation: 20 TWh/y
- CO_2 captured: **6.7 MMt/y** *(assuming 100% capture eff)*

The modeled CO_2 emissions would be easily accommodated

[1] https://sccs.stanford.edu/california-projects/opportunities-and-challenges-for-CCS-in-California

Practical implications: Infrastructure requirements

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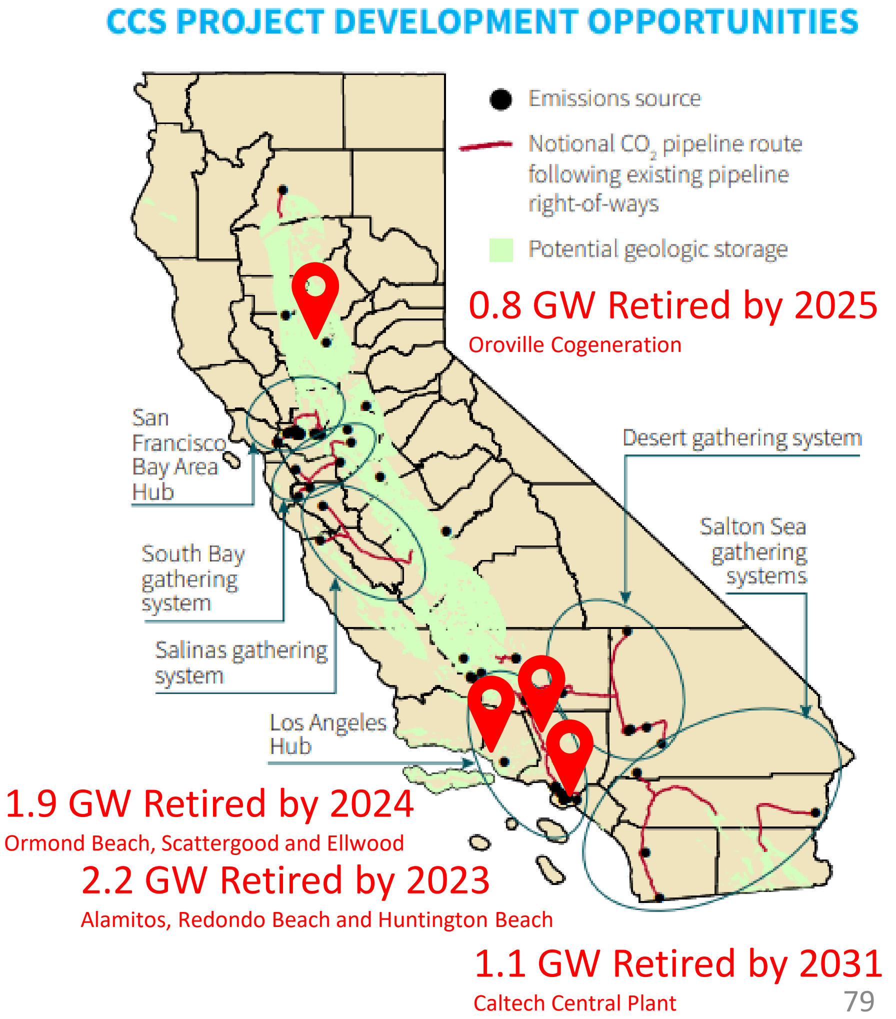
- Locations with good **storage quality** + **CO_2 hubs** + **pipelines** are preferred for CCS projects.

- (New) Allam cycle power plants could be installed at retiring NG facilities for **more efficient infrastructure design**

Source: Stanford Center for Carbon Storage, 2021 and Form EIA-860, 2021.



Practical implications: Public acceptance

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- **Closed-loop process:** also avoids criteria pollutant emissions by design.

- CCS with natural gas **does not mitigate upstream emissions** or other environmental consequences **associated with the extraction and transportation of natural gas.**

- Allam cycle could be applied to **biogas** and gasified solid fuels such as **biomass**.

Conclusions

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- Closed-loop oxy combustion could **reduce** the **need of storage**, **capacity expansion and system costs** for decarbonization

- **Uncertainty** regarding how fast it can scale up and costs go down

- **Infrastructure, regulatory and social challenges** will need to be addressed

Effect of electrolyzers on need for LDES

- How hydrogen electrolyzers affect the need for storage?
- This section presented by Mariela Colombo

Overview of electrolyzer study

- Introduction to hydrogen electrolysis as a flexible load
- Modeling assumptions
- Results
  - Effect of electrolyzers as a flexible load on storage and load balancing
- Conclusions

Introduction to hydrogen electrolysis

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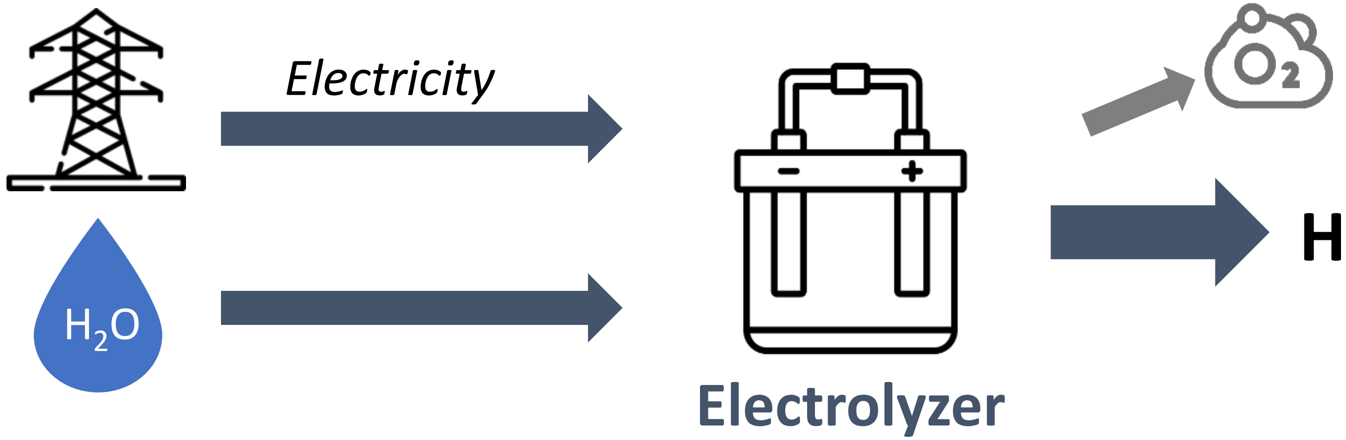
- Electrolysis is the process of using **electricity** to split **water** into **hydrogen** and **oxygen**
- This reaction takes place in a unit called an **electrolyzer**



Hydrogen

- Energy generation
- Industrial processes
- Transportation

1 MW of solar PV (\$/y) + 1 MW of electrolyzer (\$/y)

\+ CF of solar PV = CF electrolyzer ≈ 0.3

Electrolyzer conversion efficiency = 50 kWh/kgH_2

≈ 53 ton H_2/year

=

Modeled H_2 production cost*

$$\frac{\text{Cost of solar PV + electrolyzer (\$/y)}}{\text{Hydrogen production (kg/y)}} \approx 2\ \$/\text{kg}$$

Not including storage and transportation costs

Modeling assumptions

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- **Electrolyzer upfront cost** considered ranged from **600$/kW in 2030** to **450$/kW in 2045.**
- **H_2 selling price** was considered **99%** of the **lowest modeled production cost**.
- The **effect of the electrolyzers** was studied when **multiple LDES** are offered, at the *same cost per kW, but different efficiencies.*

Duration	Vary efficiency, constant power cost
4 h Li	1 X Li power cost or 1 X Li energy cost; 85%
8 hours	1 X Li power cost or 0.5 X Li energy cost; **75%**
12 hours	1 X Li power cost or 0.33 X Li energy cost; **70%**
24 hours	1 X Li power cost or 0.17 X Li energy cost; **60%**
100 hours	1 X Li power cost or 0.04 X Li energy cost; **50%**

Effect of electrolyzers on need for LDES

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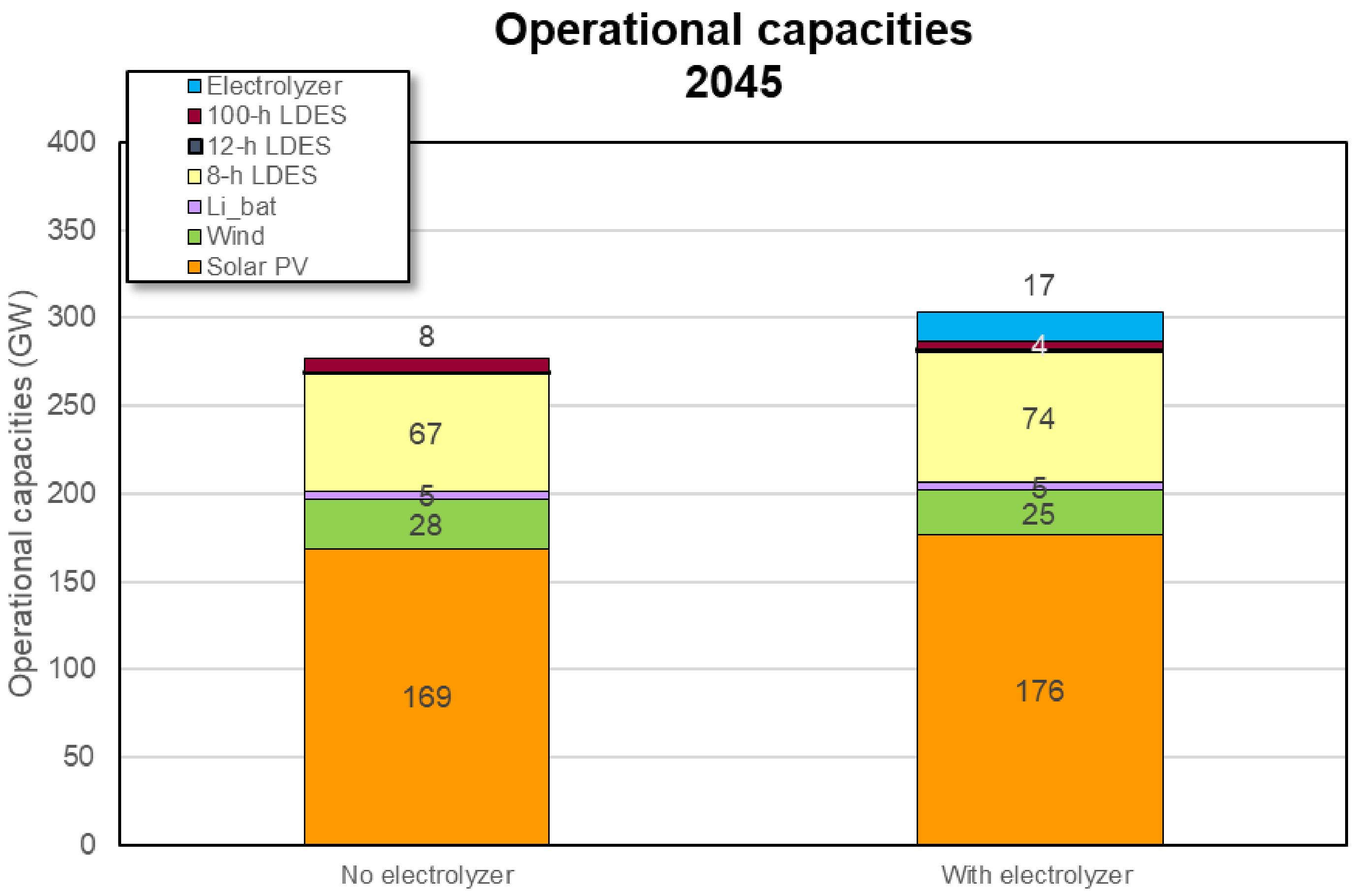
H_2 selling price = 99% modeled production cost



- Even at H_2 selling prices considered, **electrolyzers are being built**.
- **Solar PV and LDES** capacity is *slightly higher*.

Effect of electrolyzers on the grid

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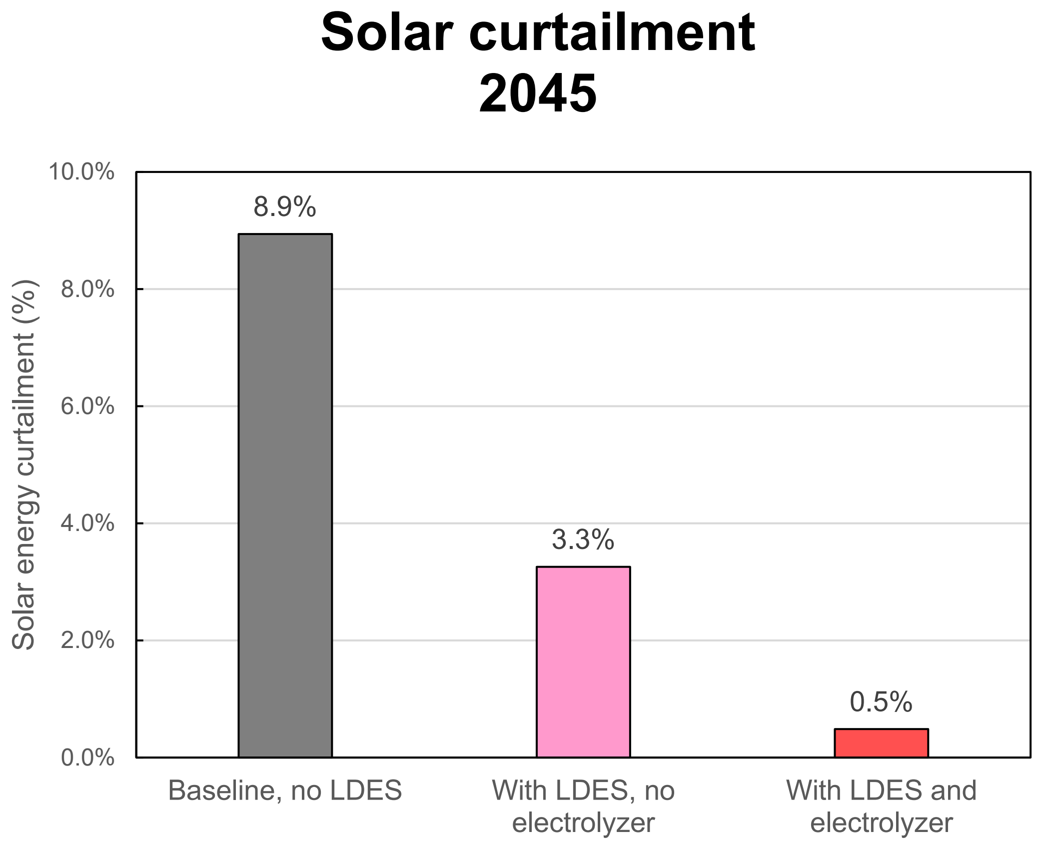

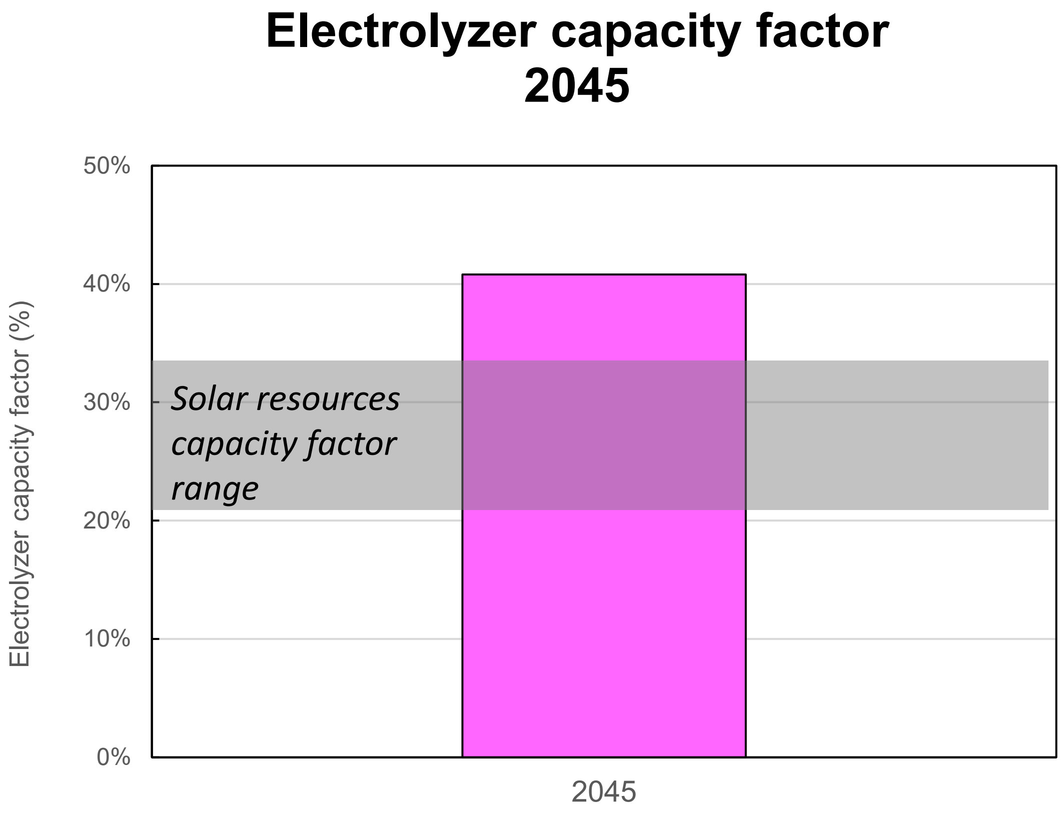

- **Electrolyzers reduce solar curtailment.**
- Even at low H_2 selling prices, **capacity factor** is **above 30%**.

Electrolyzers as flexible load

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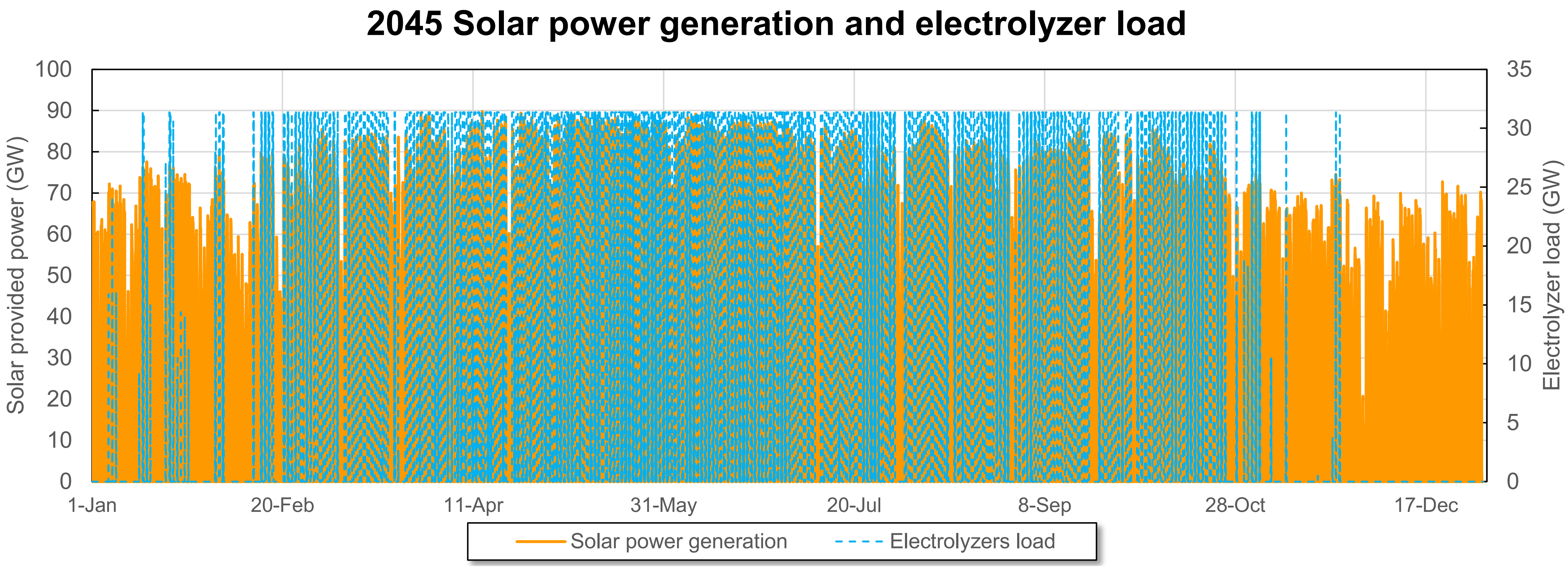

- During **winter**, electrolyzers are **mostly OFF**.
- During **summer and full sun days**, electrolyzers operate at **full power**.

Electrolyzers as flexible load

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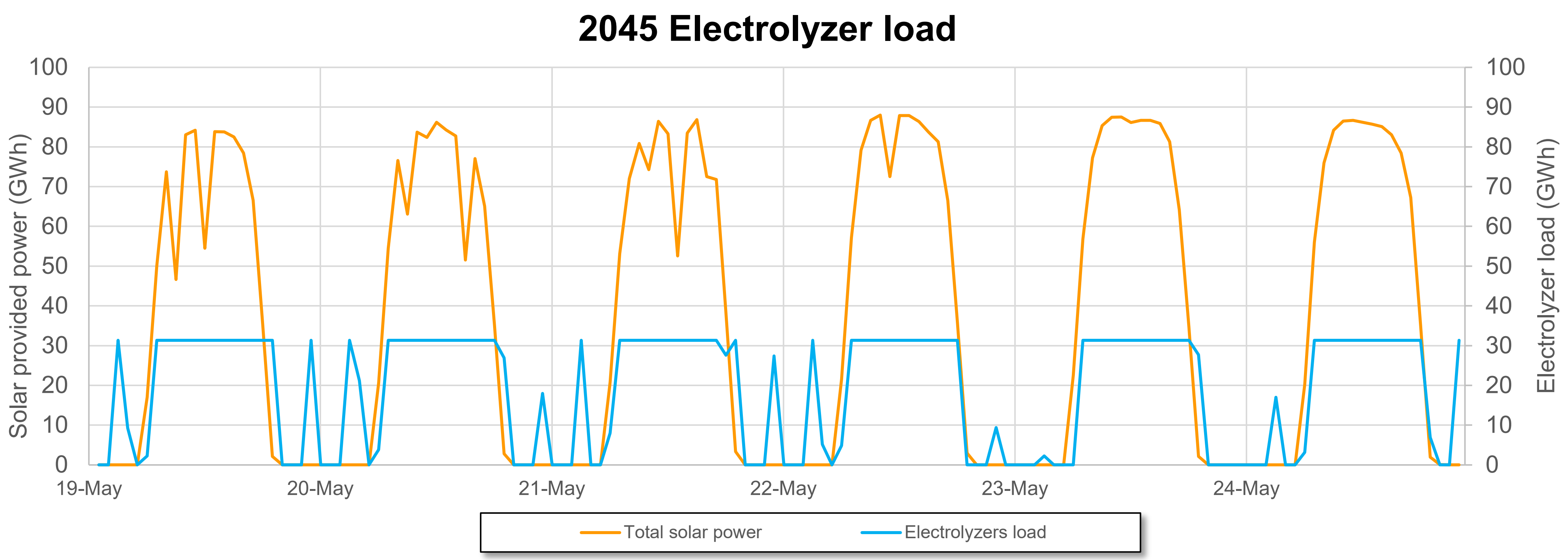
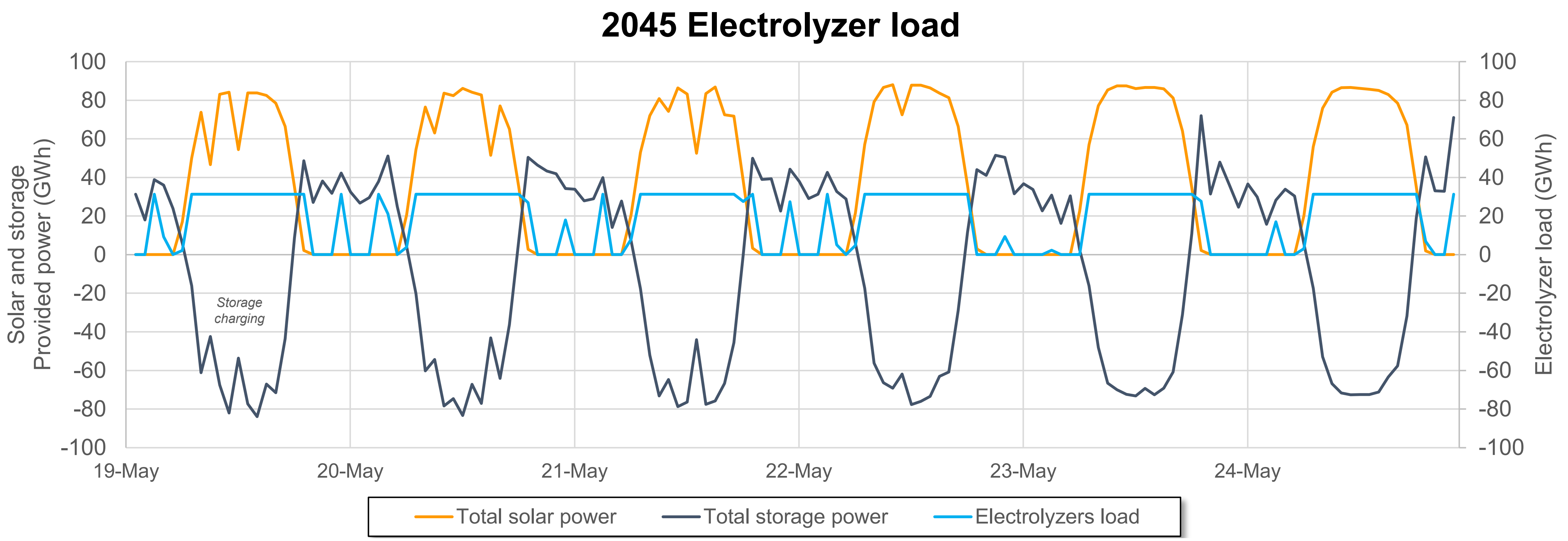


- In general, electrolyzers load **follows solar generation profile**.
- During *some days in spring and summer*, they also **operate at night.**

Electrolyzers as flexible load



- In general, electrolyzers load **follows solar generation profile**.
- During *some days in spring and summer*, they also **operate at night**.
- When **storage exceeds demand**, it is used for hydrogen production, increasing the value of the storage to the system.

Conclusions

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- **Electrolyzers can use “free” electricity** (that would otherwise be curtailed) even when an isolated solar-electrolyzer plant is not economical

- **Electrolyzers act as a flexible load** turning off during the winter and on cloudy days

- **Electrolyzers also improve use of storage** by being able to operate during the nights when storage exceeds the demand

- **Practical implementation:** As demand for green hydrogen grows, the addition of this large, flexible load will **help to stabilize the grid**, possibly reducing the need for storage, while making the installed storage more valuable

Summary

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- For Core scenario, 8- to 12-hour storage minimizes overbuild of storage power and energy
- Lower-efficiency, 100-h storage may be competitive for a small portion of the market even without extreme cost reductions
- Daytime charging in workplace and public parking lots could decrease cost of total system by more than cost of infrastructure, but the infrastructure strategy should be studied
- South-facing solar will reduce solar curtailment
- Adding offshore or winter-dominant wind reduces storage needs
- Closed-loop oxy-combustion (Allam cycle) could reduce need for storage, but use may be limited by infrastructure development
- Electrolyzers can serve as flexible load balancing both summer-winter and other times, while increasing the value of storage

Papers and reports available

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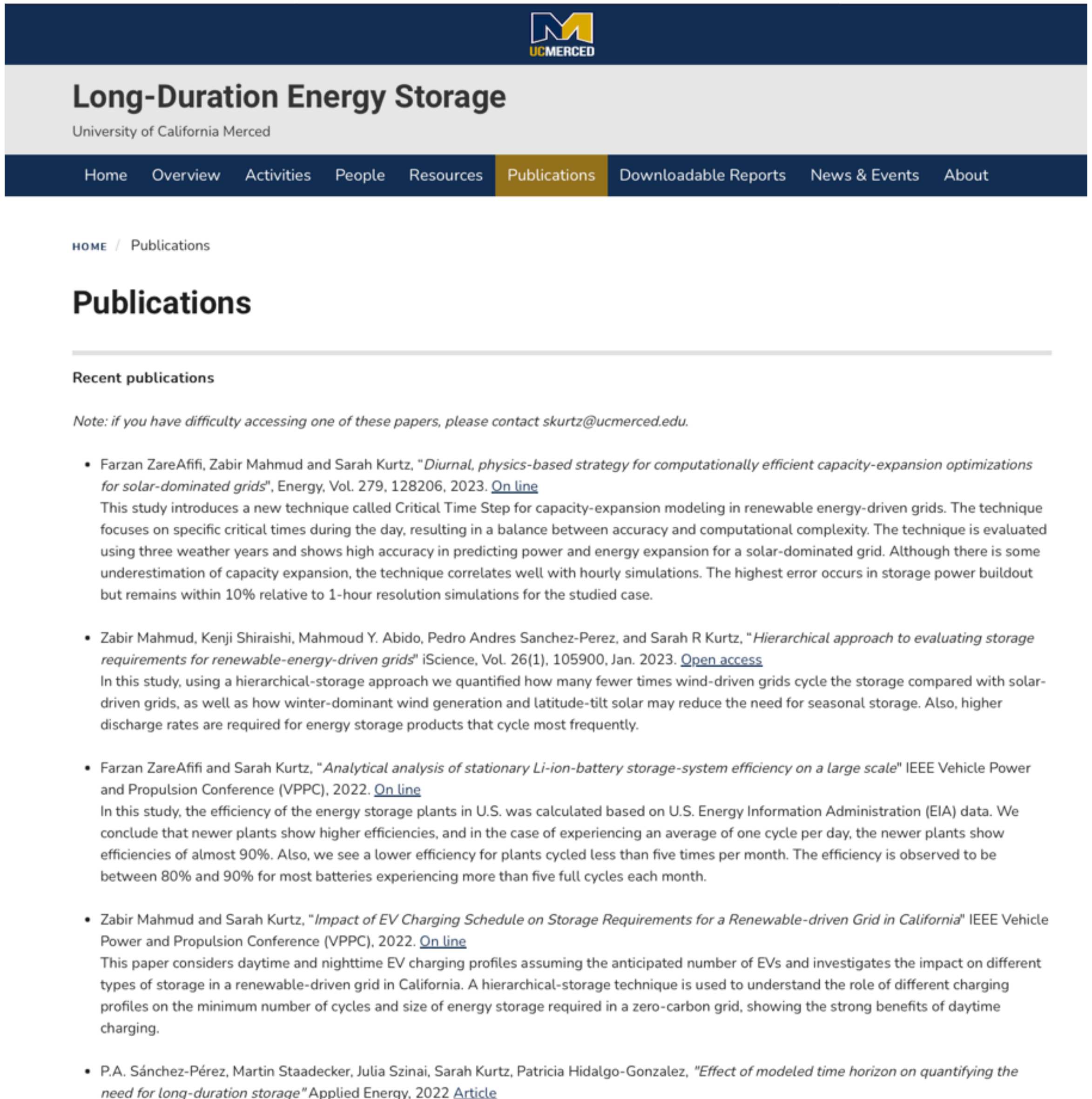
- We’ve shown here a fraction of our studies
- See https://sites.ucmerced.edu/ldstorage/publications%20version%202 to access our complete list of papers and reports



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Long-Duration Energy Storage

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Publications

Recent publications

Note: if you have difficulty accessing one of these papers, please contact skurtz@ucmerced.edu.

- Farzan ZareAfifi, Zabir Mahmud and Sarah Kurtz, "*Diurnal, physics-based strategy for computationally efficient capacity-expansion optimizations for solar-dominated grids*", Energy, Vol. 279, 128206, 2023. On line
  This study introduces a new technique called Critical Time Step for capacity-expansion modeling in renewable energy-driven grids. The technique focuses on specific critical times during the day, resulting in a balance between accuracy and computational complexity. The technique is evaluated using three weather years and shows high accuracy in predicting power and energy expansion for a solar-dominated grid. Although there is some underestimation of capacity expansion, the technique correlates well with hourly simulations. The highest error occurs in storage power buildout but remains within 10% relative to 1-hour resolution simulations for the studied case.
- Zabir Mahmud, Kenji Shiraishi, Mahmoud Y. Abido, Pedro Andres Sanchez-Perez, and Sarah R Kurtz, "*Hierarchical approach to evaluating storage requirements for renewable-energy-driven grids*" iScience, Vol. 26(1), 105900, Jan. 2023. Open access
  In this study, using a hierarchical-storage approach we quantified how many fewer times wind-driven grids cycle the storage compared with solar-driven grids, as well as how winter-dominant wind generation and latitude-tilt solar may reduce the need for seasonal storage. Also, higher discharge rates are required for energy storage products that cycle most frequently.
- Farzan ZareAfifi and Sarah Kurtz, "*Analytical analysis of stationary Li-ion-battery storage-system efficiency on a large scale*" IEEE Vehicle Power and Propulsion Conference (VPPC), 2022. On line
  In this study, the efficiency of the energy storage plants in U.S. was calculated based on U.S. Energy Information Administration (EIA) data. We conclude that newer plants show higher efficiencies, and in the case of experiencing an average of one cycle per day, the newer plants show efficiencies of almost 90%. Also, we see a lower efficiency for plants cycled less than five times per month. The efficiency is observed to be between 80% and 90% for most batteries experiencing more than five full cycles each month.
- Zabir Mahmud and Sarah Kurtz, "*Impact of EV Charging Schedule on Storage Requirements for a Renewable-driven Grid in California*" IEEE Vehicle Power and Propulsion Conference (VPPC), 2022. On line
  This paper considers daytime and nighttime EV charging profiles assuming the anticipated number of EVs and investigates the impact on different types of storage in a renewable-driven grid in California. A hierarchical-storage technique is used to understand the role of different charging profiles on the minimum number of cycles and size of energy storage required in a zero-carbon grid, showing the strong benefits of daytime charging.
- P.A. Sánchez-Pérez, Martin Staadecker, Julia Szinai, Sarah Kurtz, Patricia Hidalgo-Gonzalez, *"Effect of modeled time horizon on quantifying the need for long-duration storage"* Applied Energy, 2022 Article

WECC study of transmission-storage synergies

- UC San Diego studies will be introduced by Dr. Patricia Hidalgo-Gonzalez

The Impact of Storage Costs on the need and use of transmission in the WECC and California

California Energy Commission Final Public Workshop

Paul Serna-Torre + Prof. Sarah Kurtz + Prof. Patricia Hidalgo-Gonzalez

UC San Diego
JACOBS SCHOOL OF ENGINEERING

Monday, Oct 9th, 2023

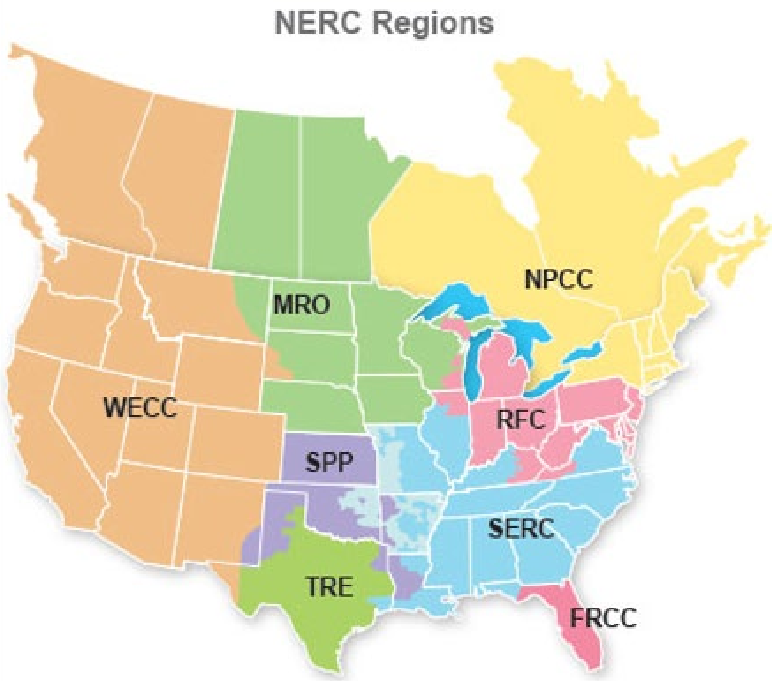
Outline

- Recap
  - Methodology: SWITCH WECC
  - Previous findings
- The impact of storage costs on need and use of transmission for the WECC and California

Recap

Methodology: SWITCH WECC model[1]

- Capacity expansion deterministic linear program
- Minimizes total cost of the power system:
  - Generation investment and operation
  - Transmission investment and operation
- Geographic:
  - Western Electricity Coordinating Council
  - 50 load areas, 7,000+ candidate projects
- Temporal:
  - Investment period: 2050
  - Time resolution: sampling every 4 hours, for all 365 days
  - Dispatch simulated simultaneously with investment decisions



[1] https://github.com/REAM-lab/switch/

Methodology: SWITCH WECC model[1]

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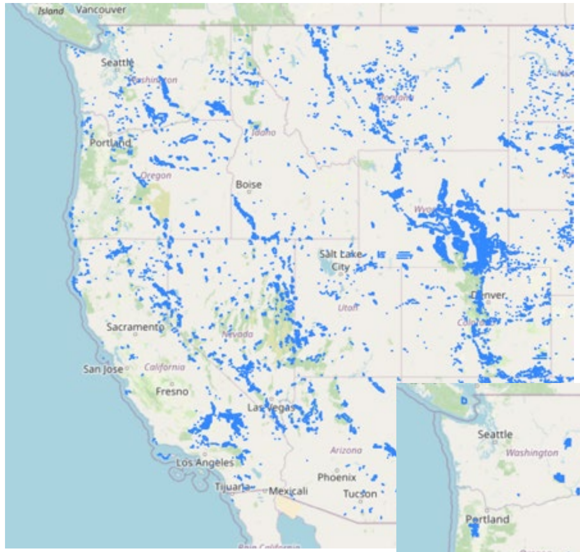
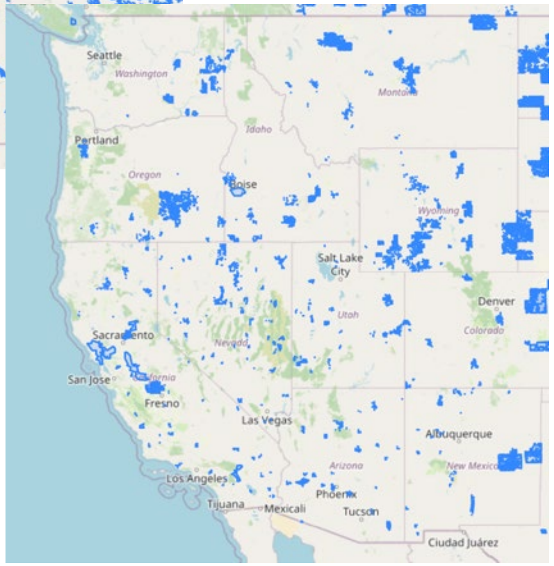


Wind candidates



Solar candidates

[1] https://github.com/REAM-lab/switch/

Projects' findings

P. Sanchez-Perez et al., "Effect of modeled time horizon on quantifying the need for long-duration storage" in Applied Energy, 2022.

- We must model continuous 365 days otherwise the deployment of LDES is not properly characterized

M. Staadecker et al., "The Value of Long-Duration Energy Storage and its Interaction with a Zero-Emissions Electricity Grid" (under review)

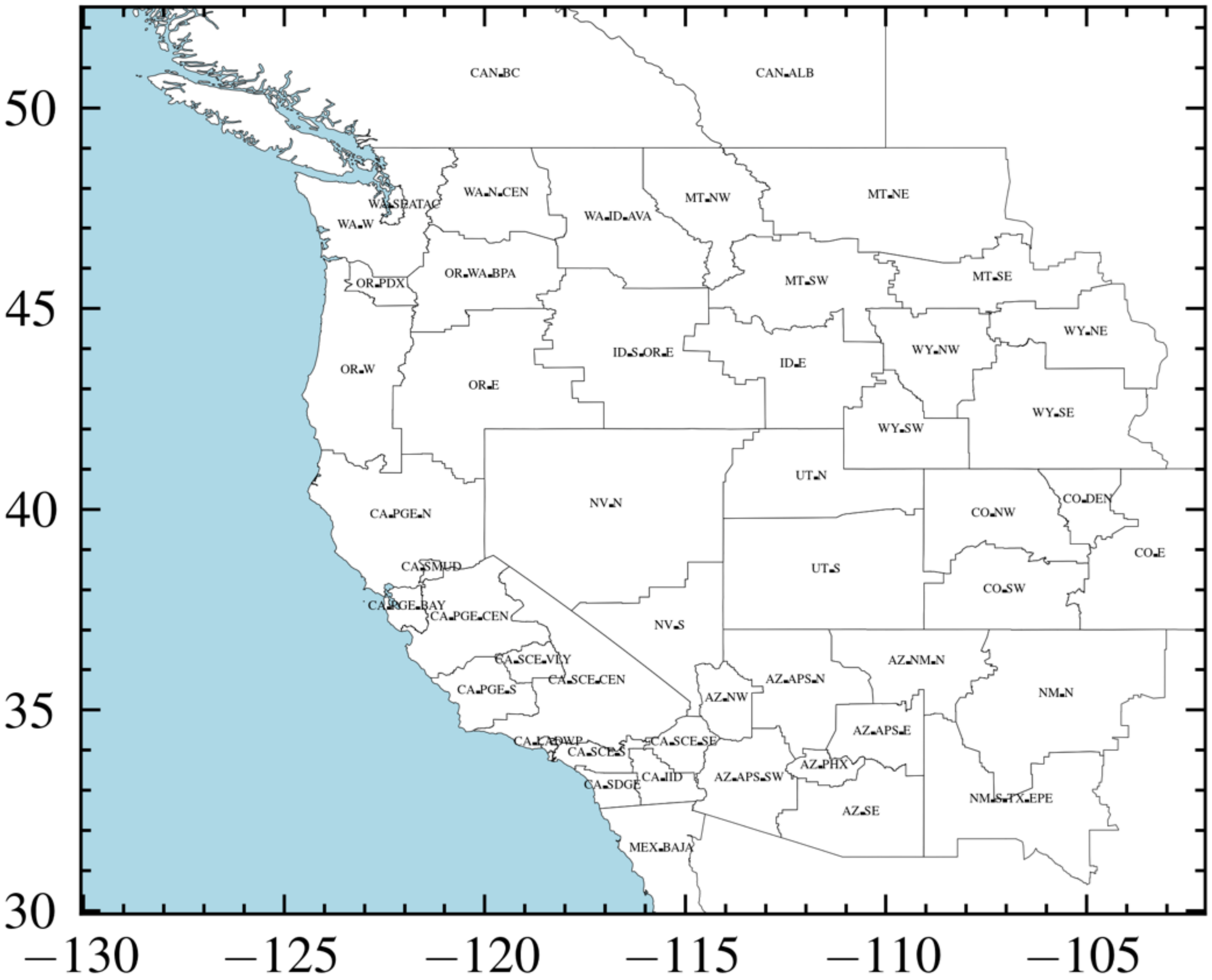
- Quantification of the benefits in electricity pricing of federal/state mandates for LDES deployment.
- How does the deployment of LDES change depending on:
  1. the ratio of solar/wind deployed
  2. The costs of long-duration storage
  3. Hydropower availability

P. Serna-Torre et al., "The Impact of Storage Costs on the need and use of transmission in the WECC and California" (in prep.). TODAY!

The Impact of Storage Costs on the need and use of transmission in the WECC and California

How is the Western Interconnection modeled in the SWITCH model?

- 11 states disaggregated into 50 load zones.
- Each load zone has a demand and generation portfolio.



Parameters to consider in the scenarios under analysis

Input parameters

Carbon emissions

Total emissions (tCO_2) of the generation fleet deployed WECC-wide

Storage power capacity cost

Cost ($/kW) of the power-related components of the candidate storage projects

Storage energy capacity cost

Cost ($/kWh) of the energy-related components of the candidate storage projects

Transmission capacity cost

Total transmission capacity (GW) deployed in the WECC ≤ Transmission cap

Scenarios under analysis

Input parameters

Scenario	Carbon emissions	Storage power capacity cost	Storage energy capacity cost	Transmission capacity cap
1 2 3 4 5 6	Zero	325 $/kW	170 $/kWh	*No cap* 75% 50% 25% 10% 5%
7 8 9 10 11 12	Zero	140 $/kW	170 $/kWh	*No cap* 75% 50% 25% 10% 5%
13 14 15 16 17 18	Zero	10 $/kW	10 $/kWh	*No cap* 75% 50% 25% 10% 5%

"High storage cost scenarios"

"Mid storage cost scenarios"

"Low storage cost scenarios"

Highlights

- As **storage costs decline**, Arizona and New Mexico **deploy more solar power and storage energy capacity** that support the rest of the WECC.

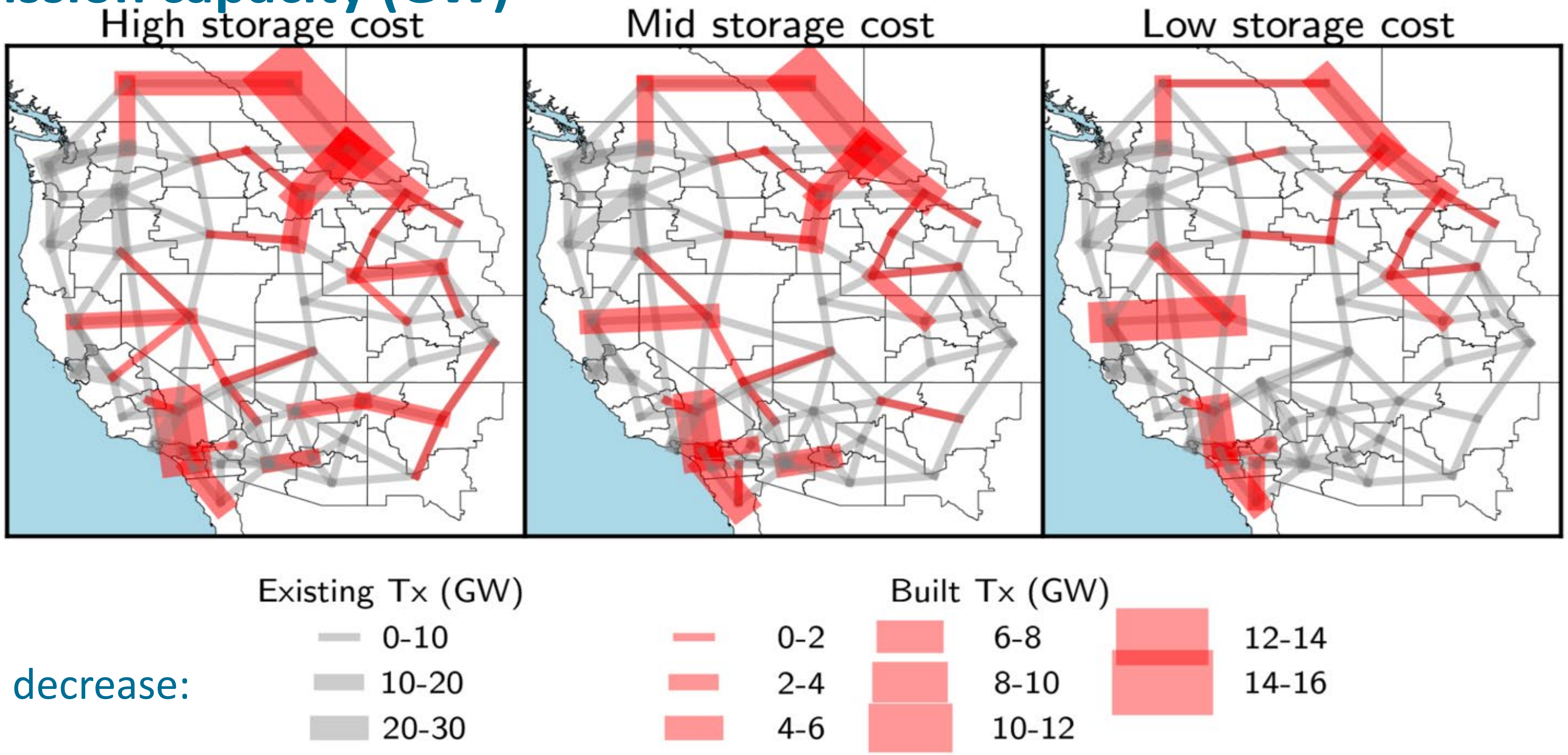
- Storage costs decline results in
    - less transmission in the WECC and
    - higher loading for existing transmission lines.

- Storage costs decline results in
    - less in-state transmission in California and
    - **building more transmission between California and its neighbors**.

- When the **transmission capacity is the most constrained**, **California's storage duration** increases up to **11.3 h** (compared to 7 h in the baseline).

What are the implication of storage costs declines on the expansion and loading of the transmission lines?

Built transmission capacity (GW)



As storage costs decrease:

1. California requires more intertie transmission.
2. California requires less in-state transmission.
3. The WECC requires less transmission.

Transmission capacity	High storage cost scenario	Mid storage cost scenario	Low storage cost scenario
CA intertie	42.9 GW	45.7 GW	50.7 GW
CA in-state	117.0 GW	116.5 GW	114.7 GW
WECC-wide	480.7 GW	475.5 GW	455 GW

Analysis of the use of transmission lines

We employ the **loading** of the transmission lines that is defined by:

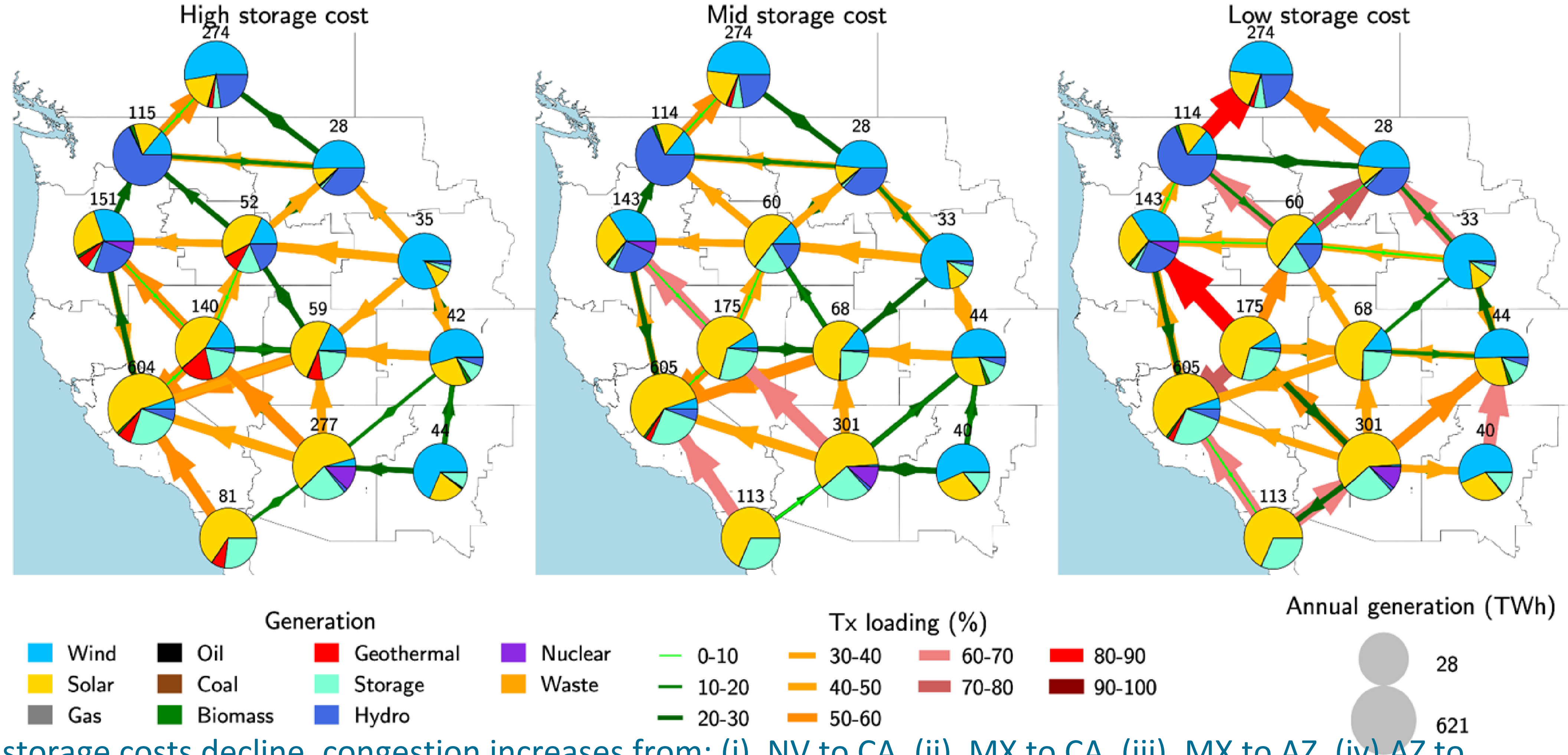
$$\textit{Loading of transmission line} = \frac{\text{Power flow (MW)}}{\text{Capacity (MW)}}$$

Three cases under analysis:

1. Average loading of transmission lines for 2050
2. Loading of transmission lines during the peak California demand (July 25, 2050 ~8:00 pm)
3. Loading of transmission lines during the California highest imports (April 4-5, 2050 ~3:00 am)

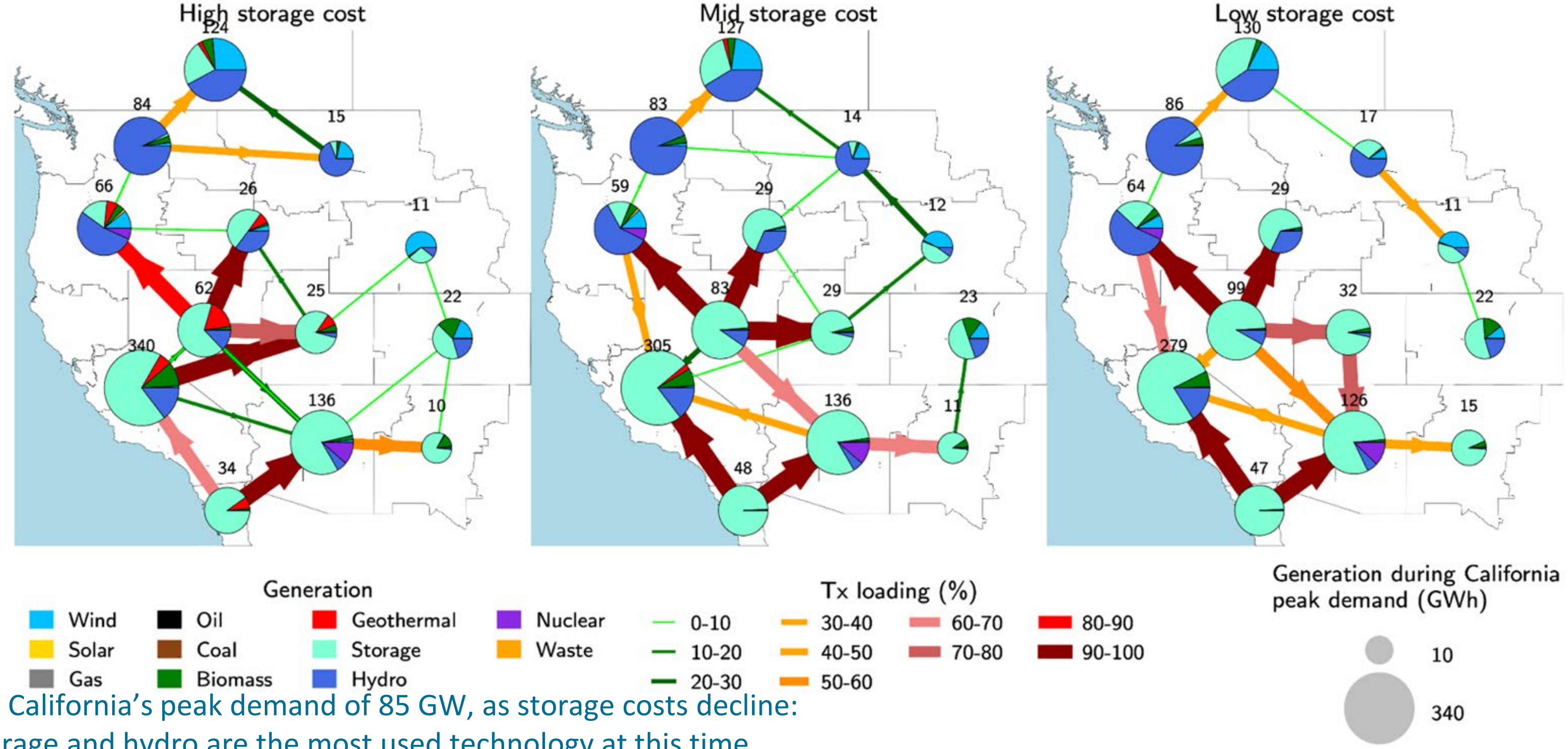
The extreme cases

Average loading of transmission lines for 2050



- As storage costs decline, congestion increases from: (i) NV to CA, (ii) MX to CA, (iii). MX to AZ, (iv) AZ to neighboring states.
- High dependence of CA and the WECC on solar resources in AZ and NV.

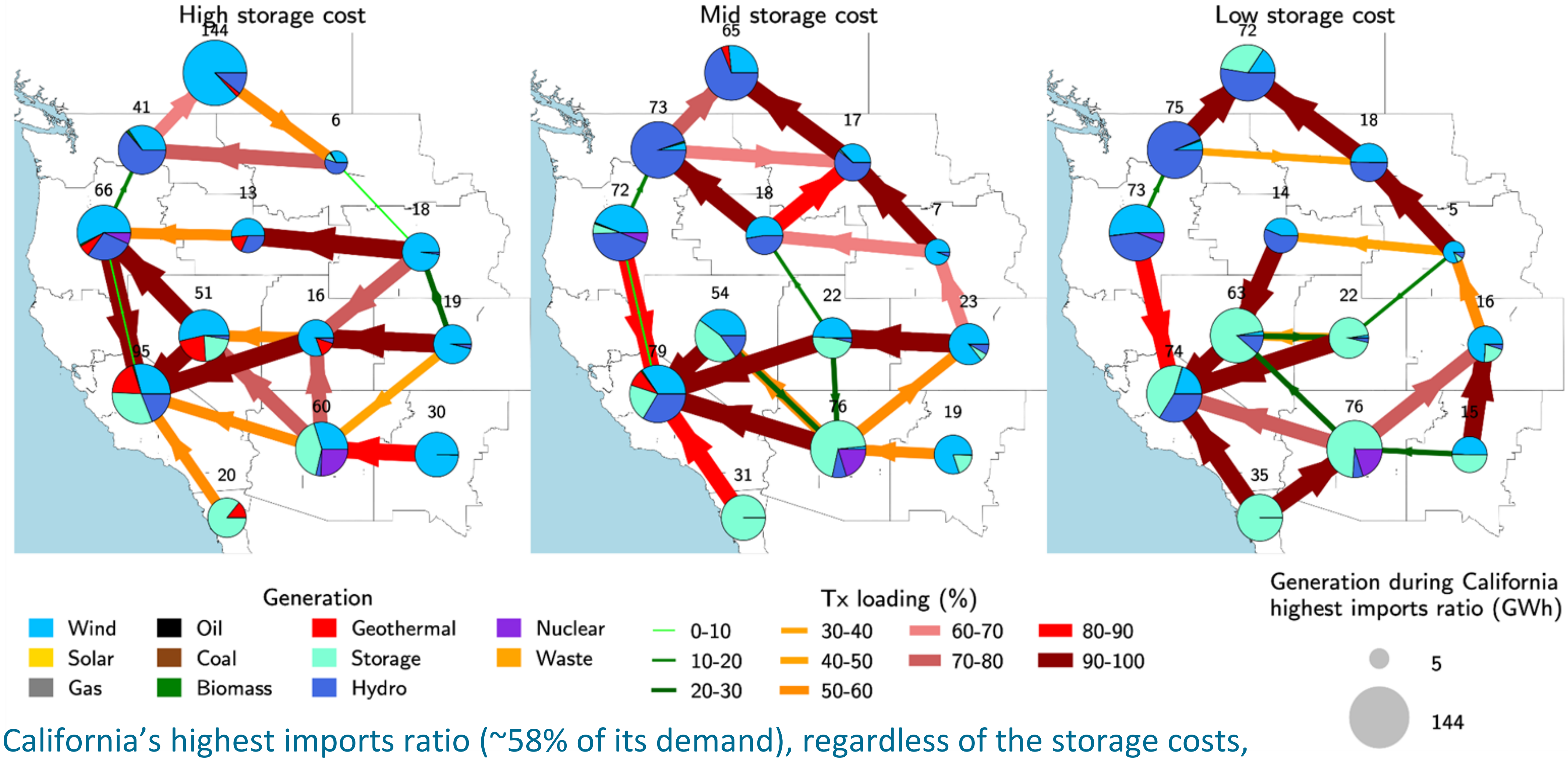
Loading of transmission lines during the California peak demand (July 25, 2050 ~8:00 p.m.)



During the California's peak demand of 85 GW, as storage costs decline:

- Storage and hydro are the most used technology at this time.
- The loading of CA - NV increases in direction to CA.
- The loading of OR - CA increases in direction to CA.
- The loading of CA - AZ increases in direction to CA.

Loading of transmission lines during the California highest imports ratio (April 4-5, 2050 ~3:00 a.m.)

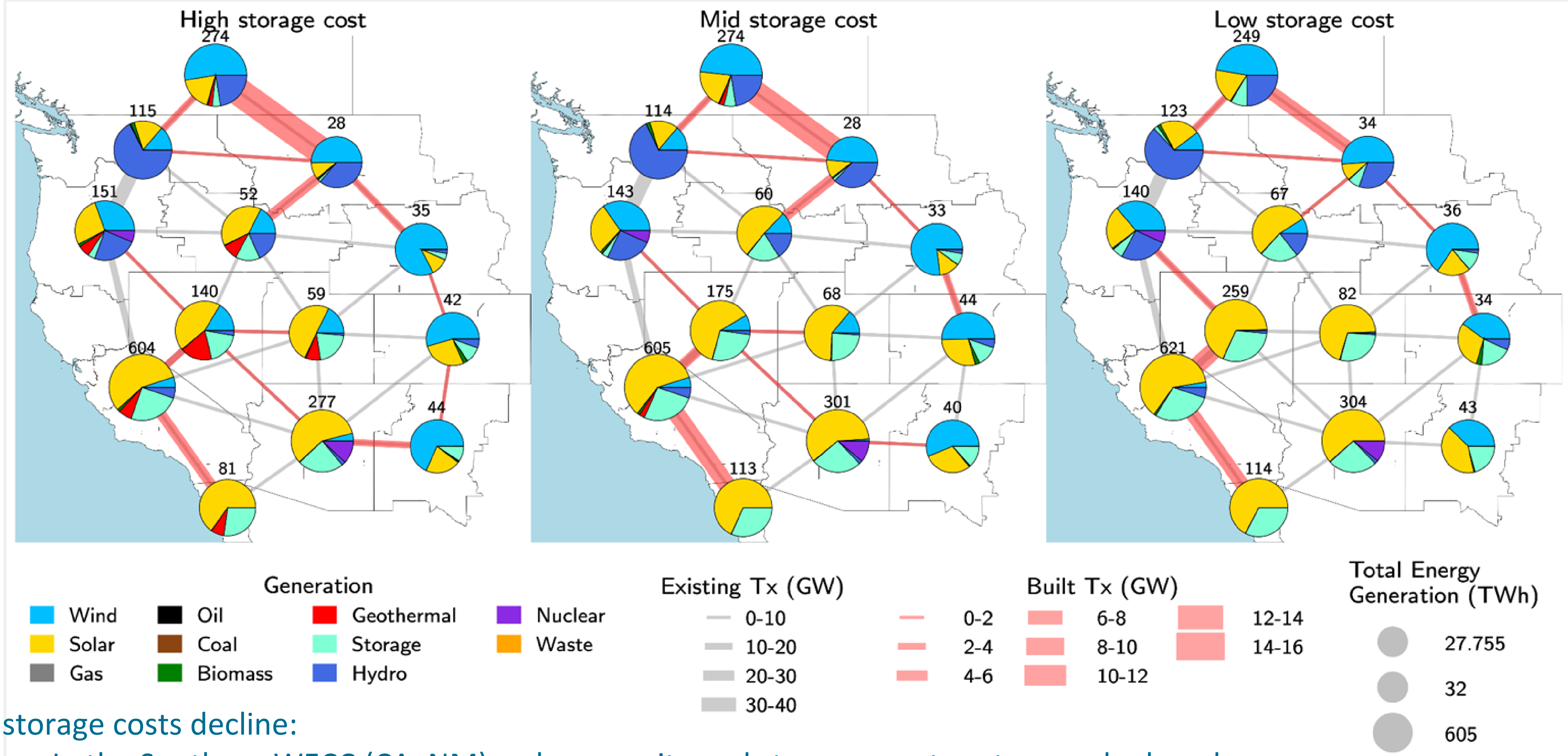


During California's highest imports ratio (~58% of its demand), regardless of the storage costs,

- CA heavily relies on NV (90-100% loading). NV also brings energy from ID and other eastern states.
- In second place, CA brings energy from OR and AZ.

Storage costs declines and generation portfolios and transmission capacity

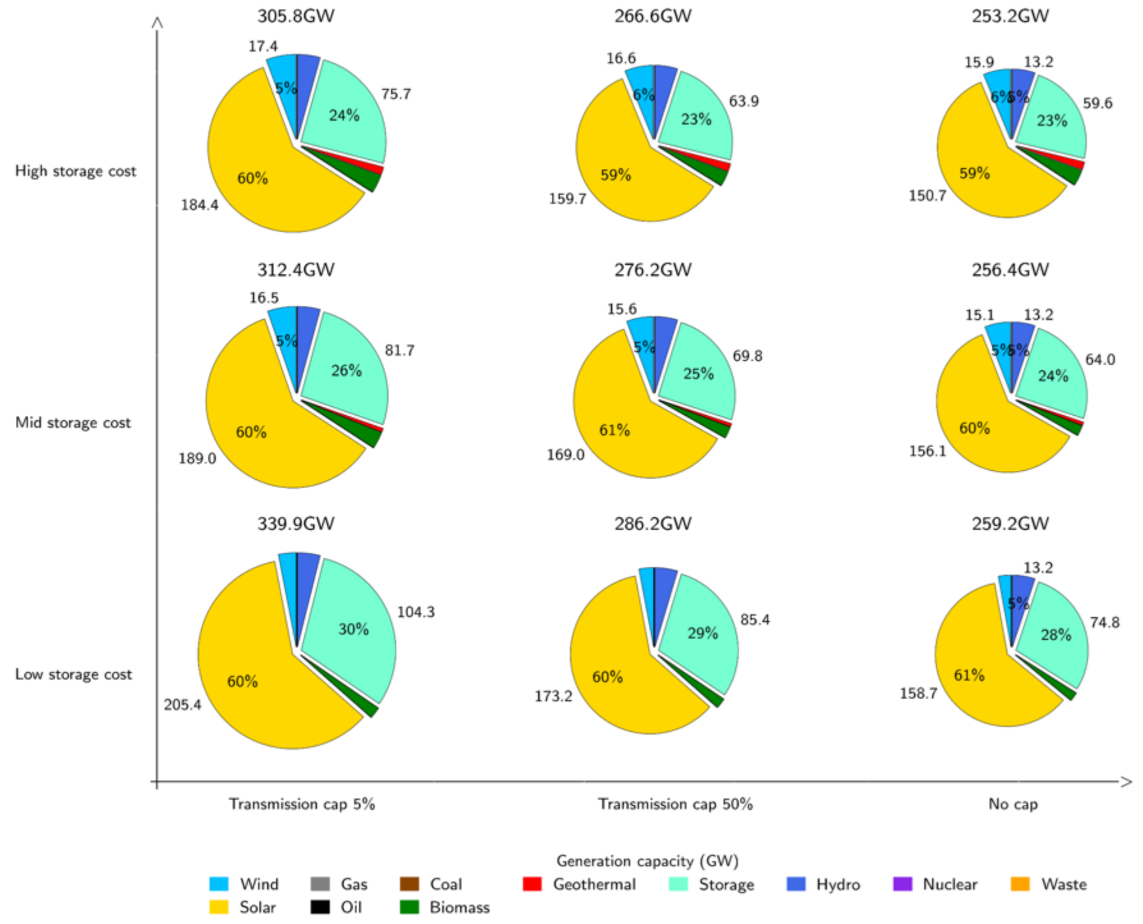
Annual generation by technology (TWh) and transmission capacity (GW)

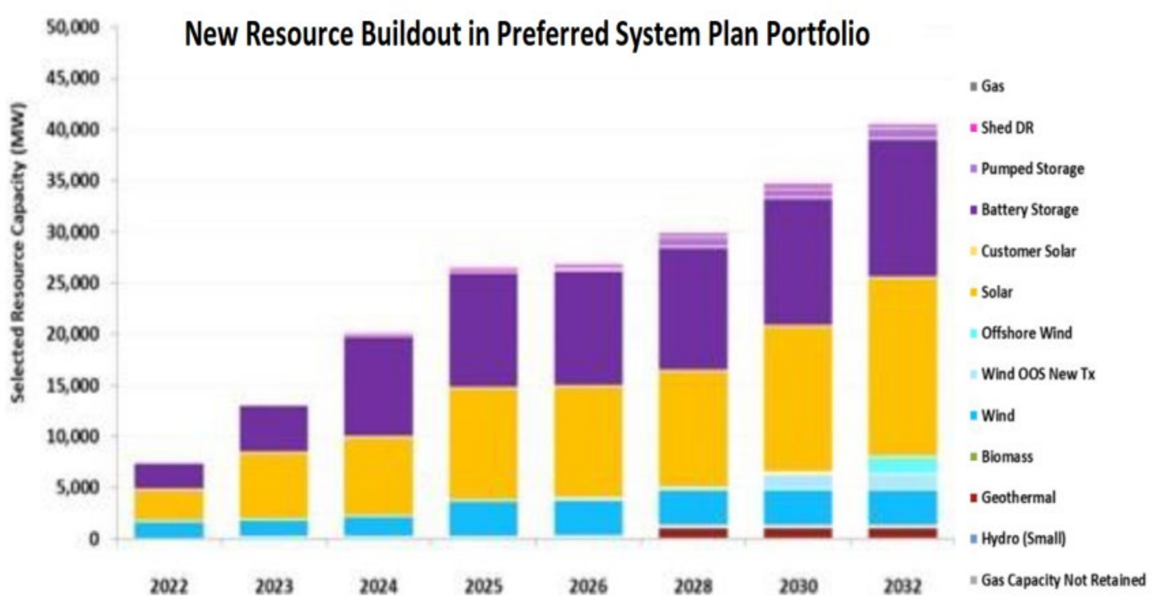


As storage costs decline:

- In the Southern WECC (CA, NM), solar capacity and storage assets get more deployed.
- In the Eastern WECC (CO, WY), wind capacity gets less deployed.

Installed generation capacity (GW) in California in 2050



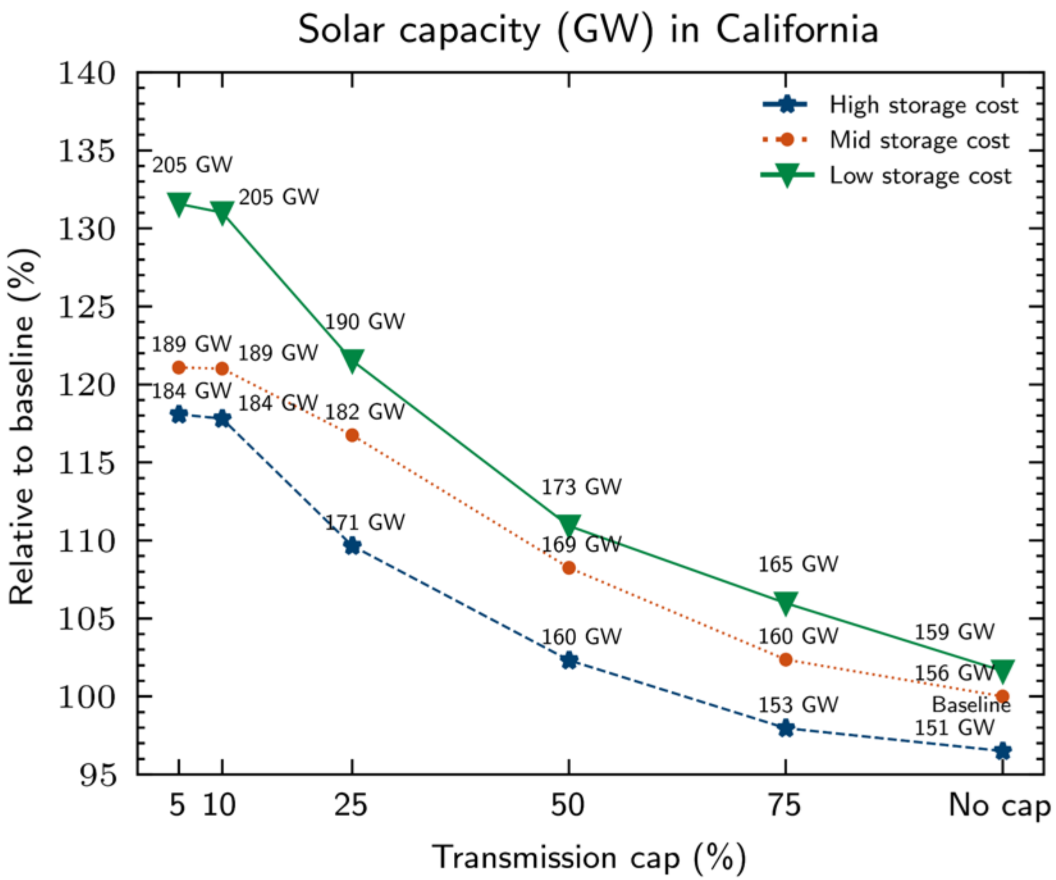


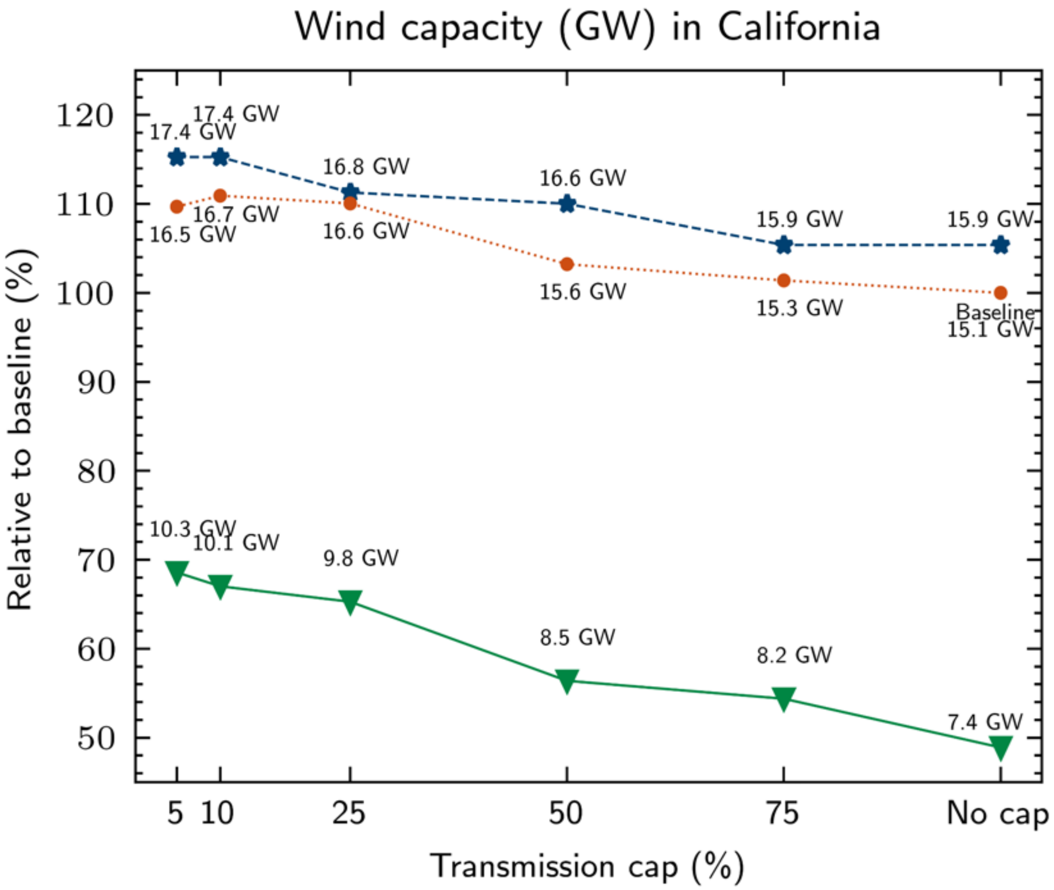
2021 CPUC IRP PSP[1]

CPUC's IRP shows ~39% of solar capacity in 2032, while SWITCH results show ~61% in 2050.
CPUC's IRP shows ~36% of storage power capacity in 2032, while SWITCH results show ~28% in 2050.

[1] California Public Utilities Commission, Fact Sheet: Decision Adopting 2021 Preferred System Plan

Deployment of solar and wind capacity in California

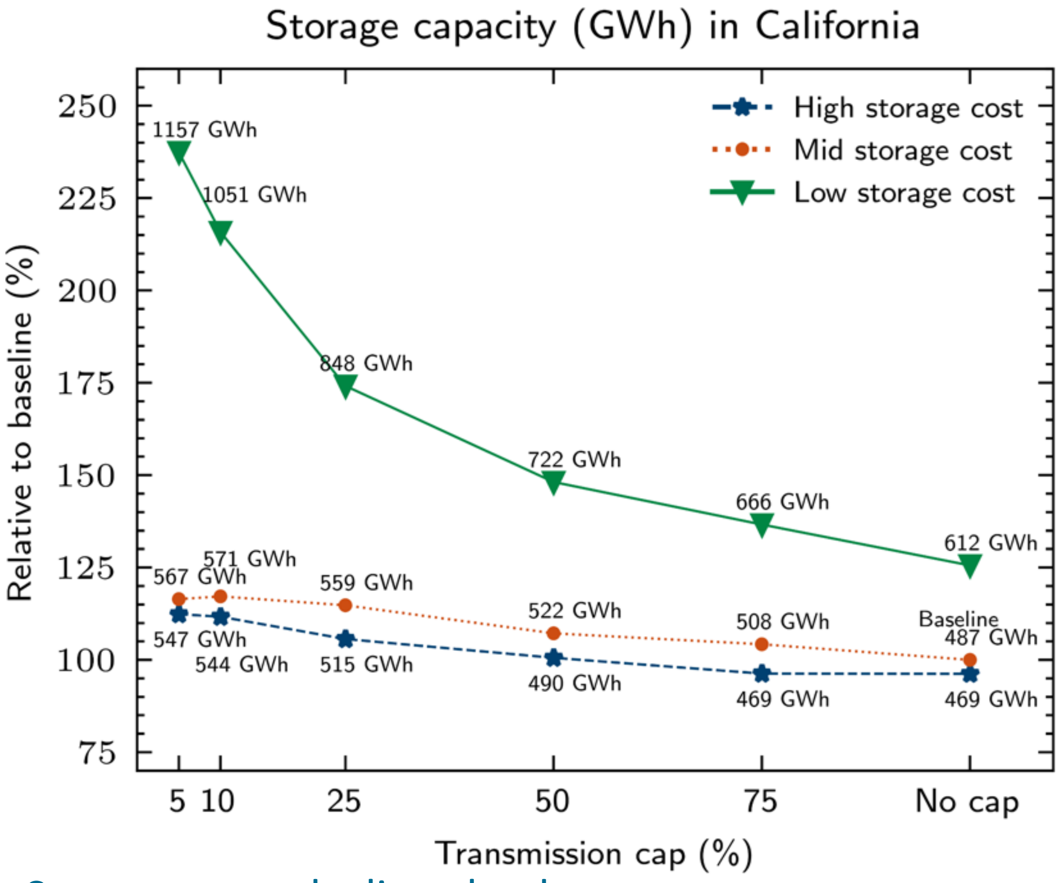


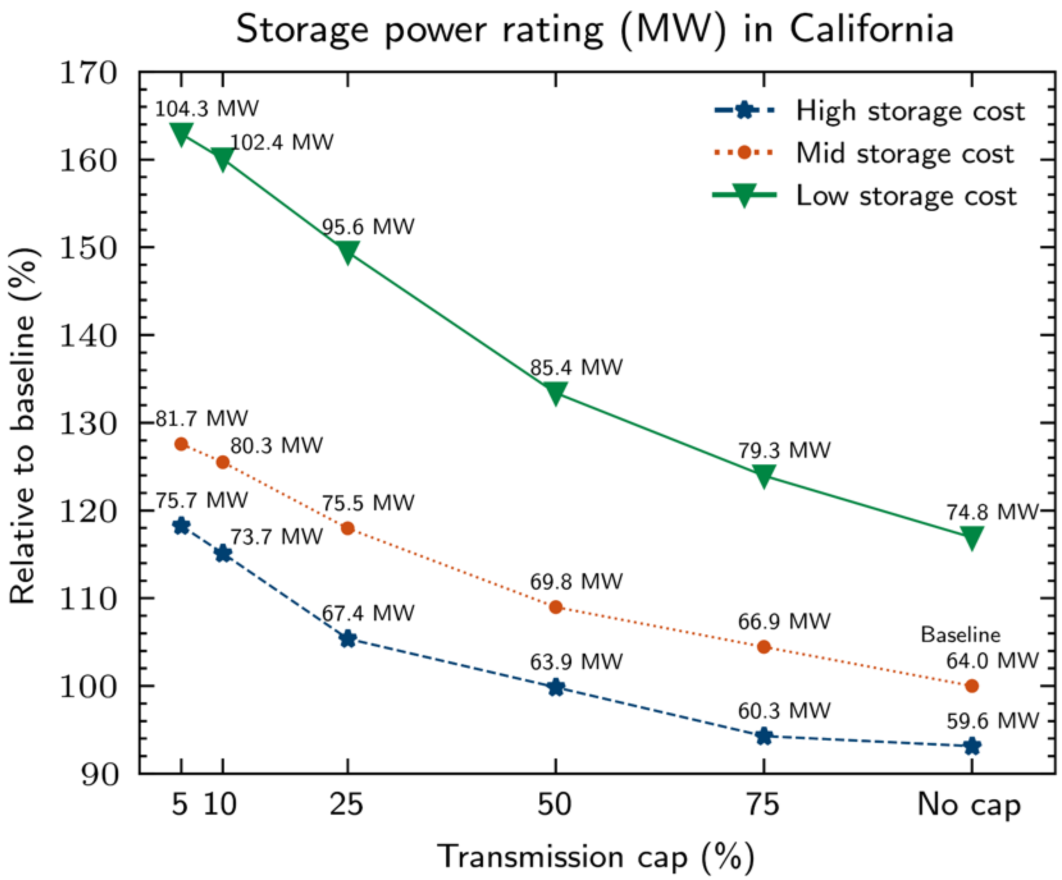


- Storage costs declines lead to an increase of up to 15% in solar capacity deployed in CA.
- The reduction in transmission capacity deployed WECC-wide results in an increase of up to 30% in solar capacity in CA

- Storage costs declines lead to a decrease of up to 60% in the wind capacity deployed in CA. **This is opposite to the trend shown in solar.**
- The reduction in transmission capacity deployed WECC-wide results in an increase of up to 20% in wind capacity deployed in CA

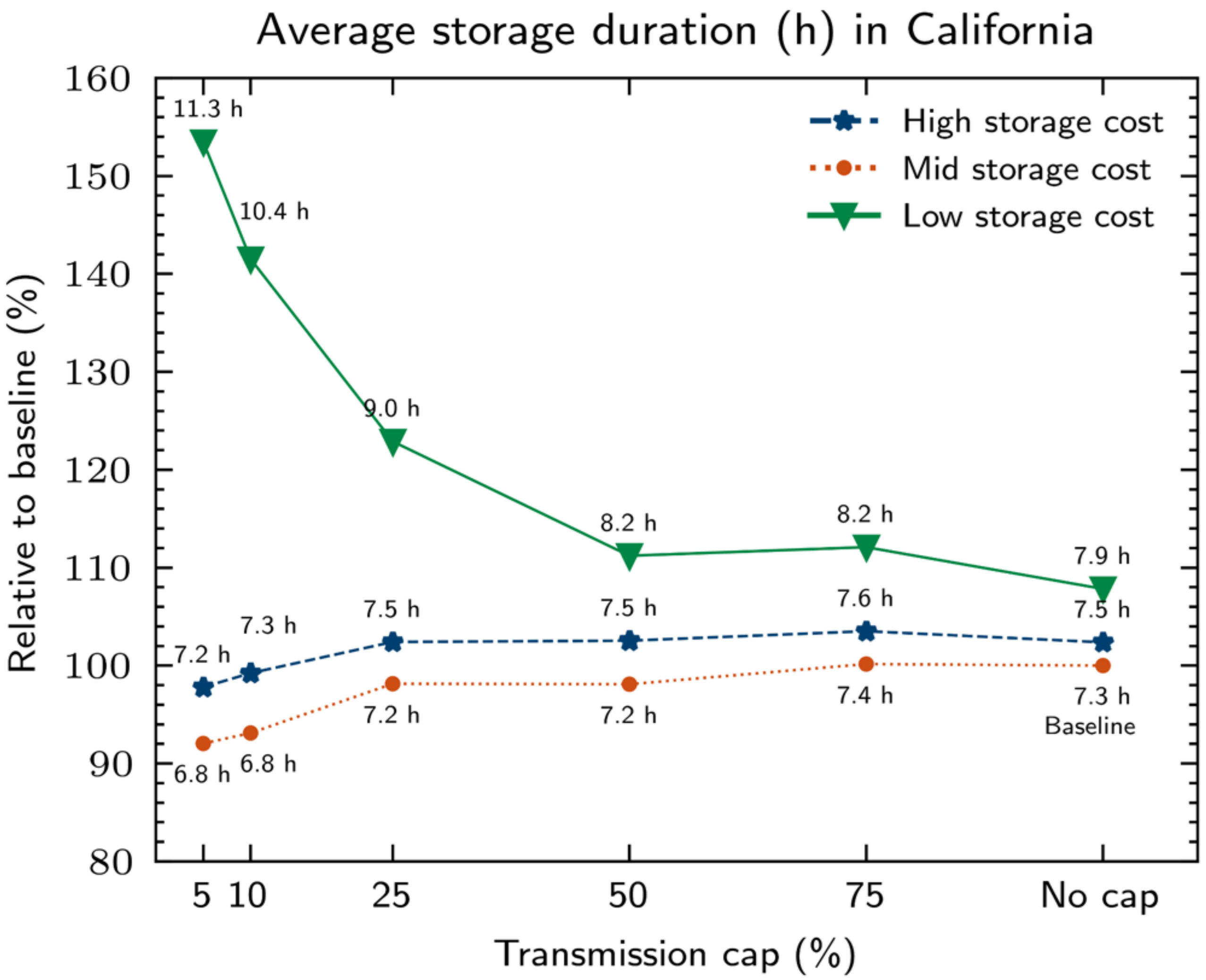
Deployment of storage in California





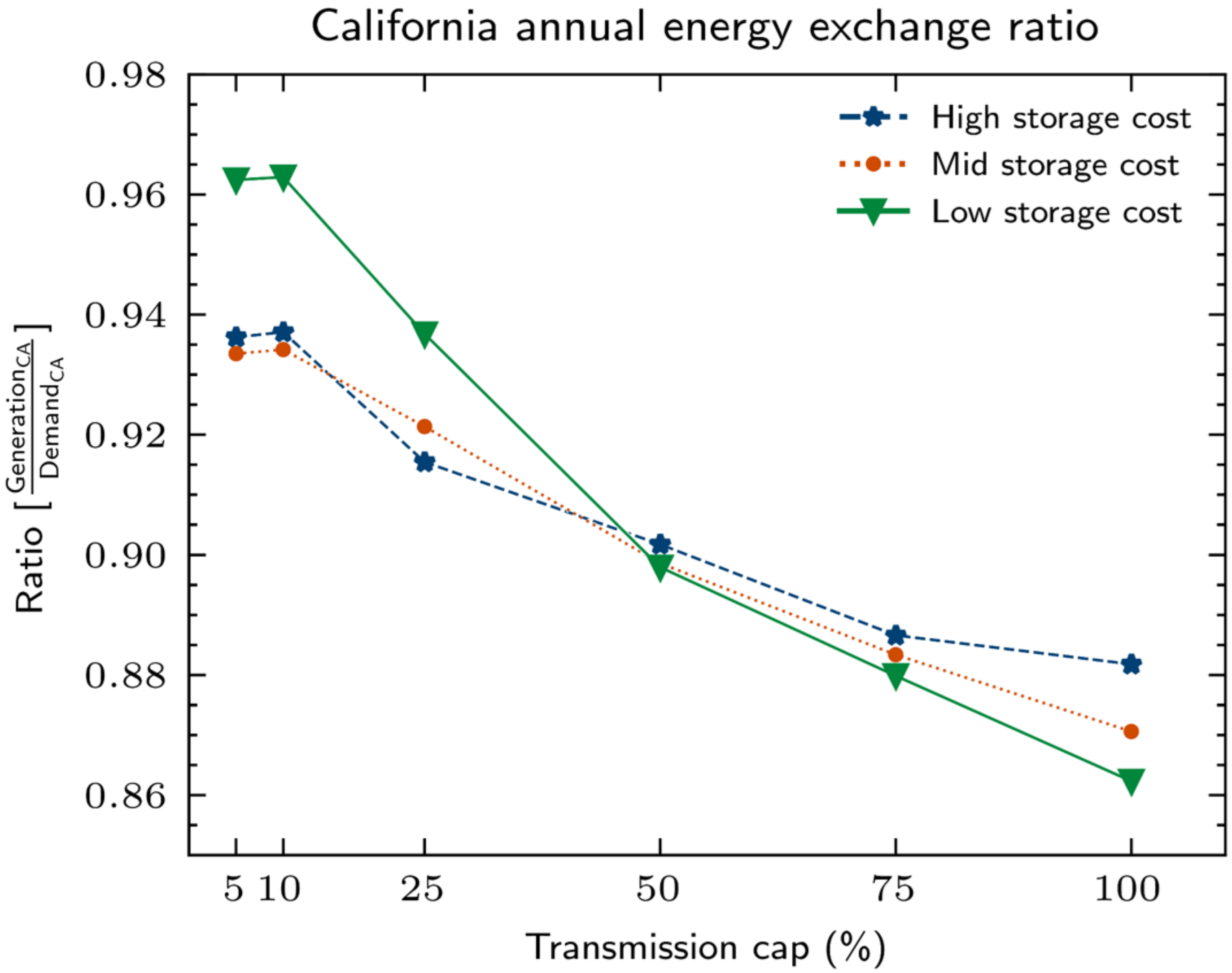
- Storage costs declines lead to:
  (Left panel) California's storage energy capacity increases up to 150%
  (Right panel) California's storage power capacity increases up to 50%.
- At low storage costs, the reduction in transmission deployed WECC-wide lead to increase total storage energy capacity in CA.

Deployment of storage in California



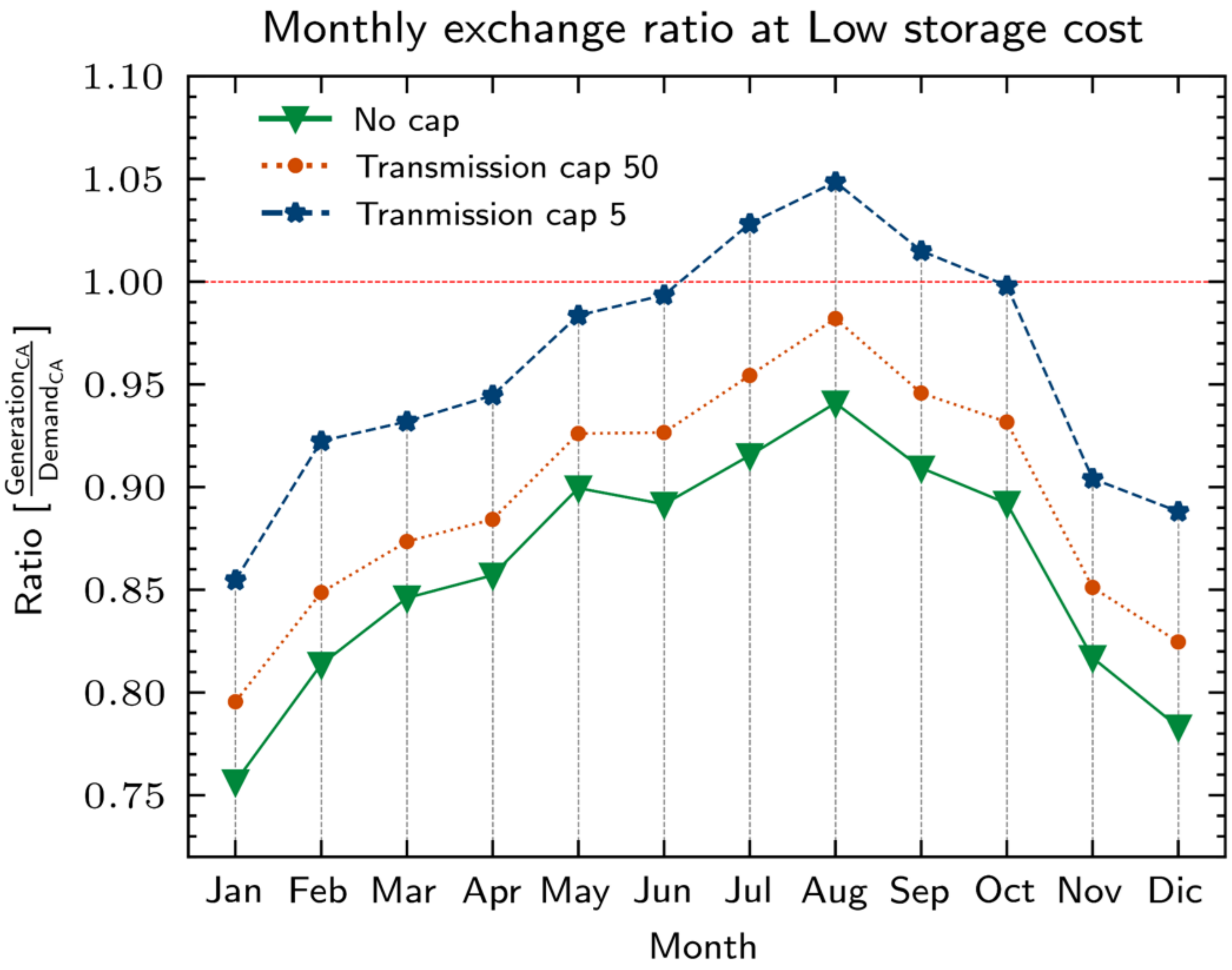
- Middle/high storage costs: the transmission cap **does not affect the storage duration**.
- Low storage costs: up to **60% longer storage durations (i.e., 11 h)**.
- Low storage costs: steepest storage duration increase between 25% to 10% of transmission cap.

Energy exchange ratio of California



- Stronger transmission caps result in **higher generation in-state.**
- Nevertheless, **California is still a net importer** in 2050.
- **Low storage costs** (green line): **Highest in-state generation** (~0.96 ratio).

Monthly energy exchange ratio of California



For low storage costs:

- **California is a monthly net importer** except when the transmission cap is the most restrictive (5%, blue line).

Highlights

- As **storage costs decline**, Arizona and New Mexico **deploy solar power and storage energy capacity** that support the rest of the WECC.

- Storage costs declines results in:
    - less transmission in the WECC and
    - higher loading for existing transmission lines.

- Storage costs declines results
    - less in-state transmission in California, and
    - **building more transmission between California and its neighbors**.

- When the **transmission cap is the most constrained**, **California's storage duration** increases up to **11.3 h** (compared to 7 h in the baseline).

Questions and comments?

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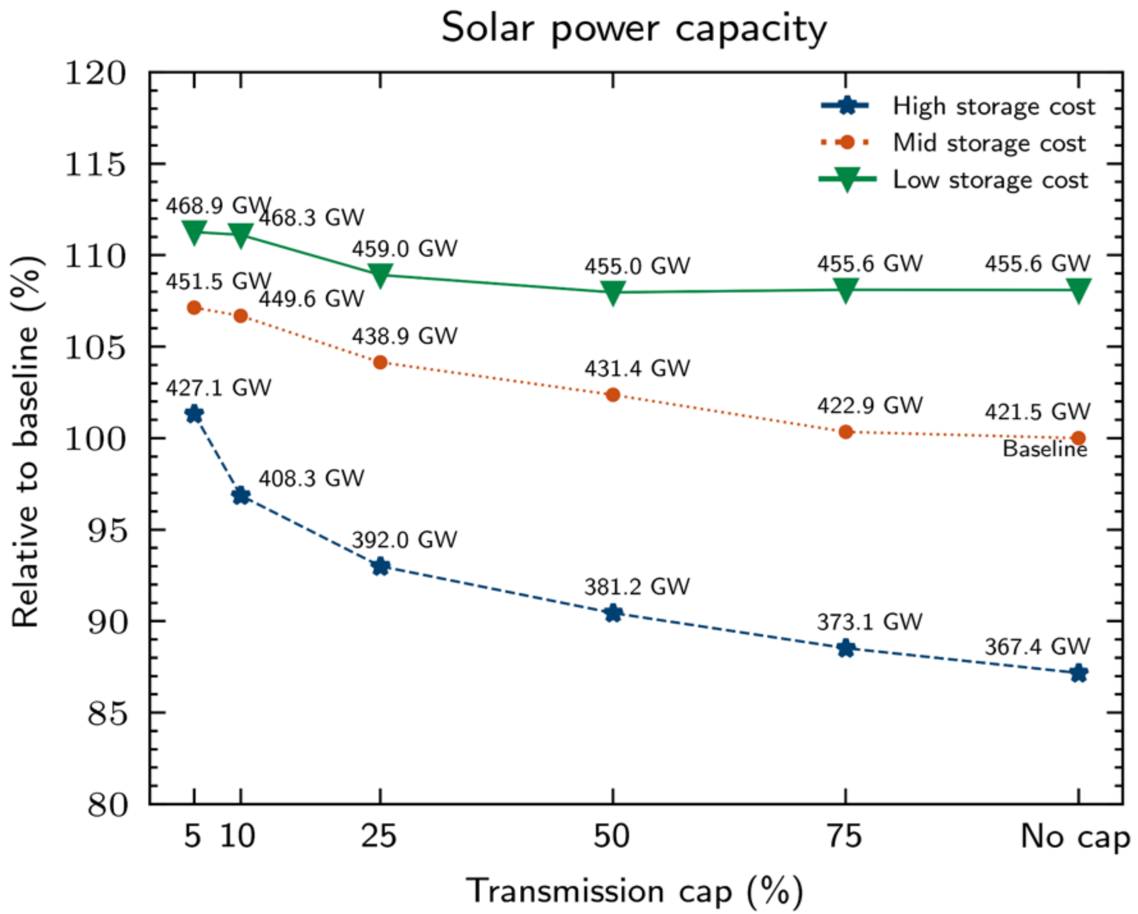
Monday, Oct 9th, 2023

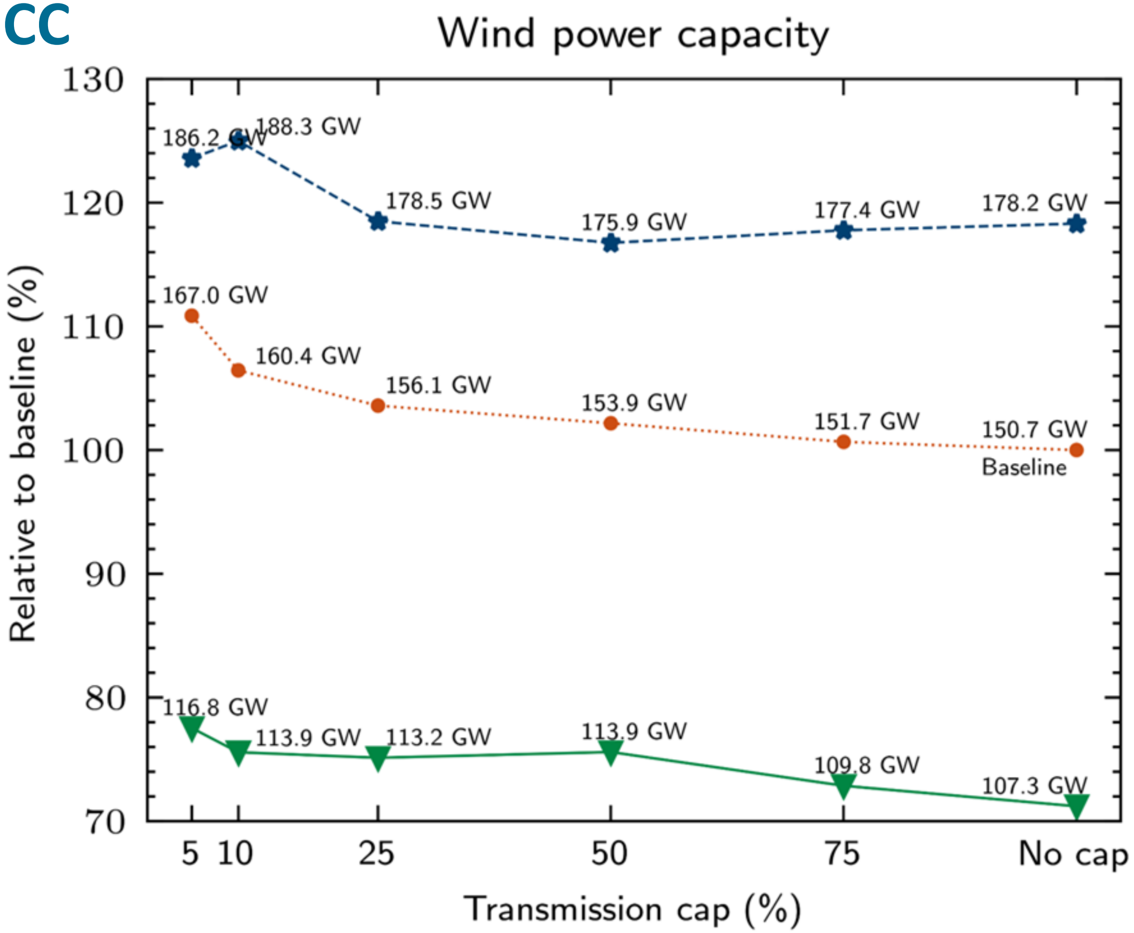
Appendix

Highlights

- As storage costs decline, the WECC is increasingly reliant upon solar resources. In this decline of storage costs, the southern WECC (Arizona, New Mexico) deploys more solar capacity and storage energy capacity, and becomes the main energy provider for the WECC.
- Storage costs declines result in the WECC: (i) building less transmission capacity, and (ii) having higher loading levels for existing transmission lines.
- Storage costs declines result in California: (i) building less in-state transmission capacity, and **(ii) building more intertie transmission capacity**.
- A reduction in transmission capacity deployed WECC-wide leads to the deployment of more solar capacity and more storage energy capacity. In addition, if storage costs decline, the storage duration increases.

Deployment of solar and wind capacity in the WECC





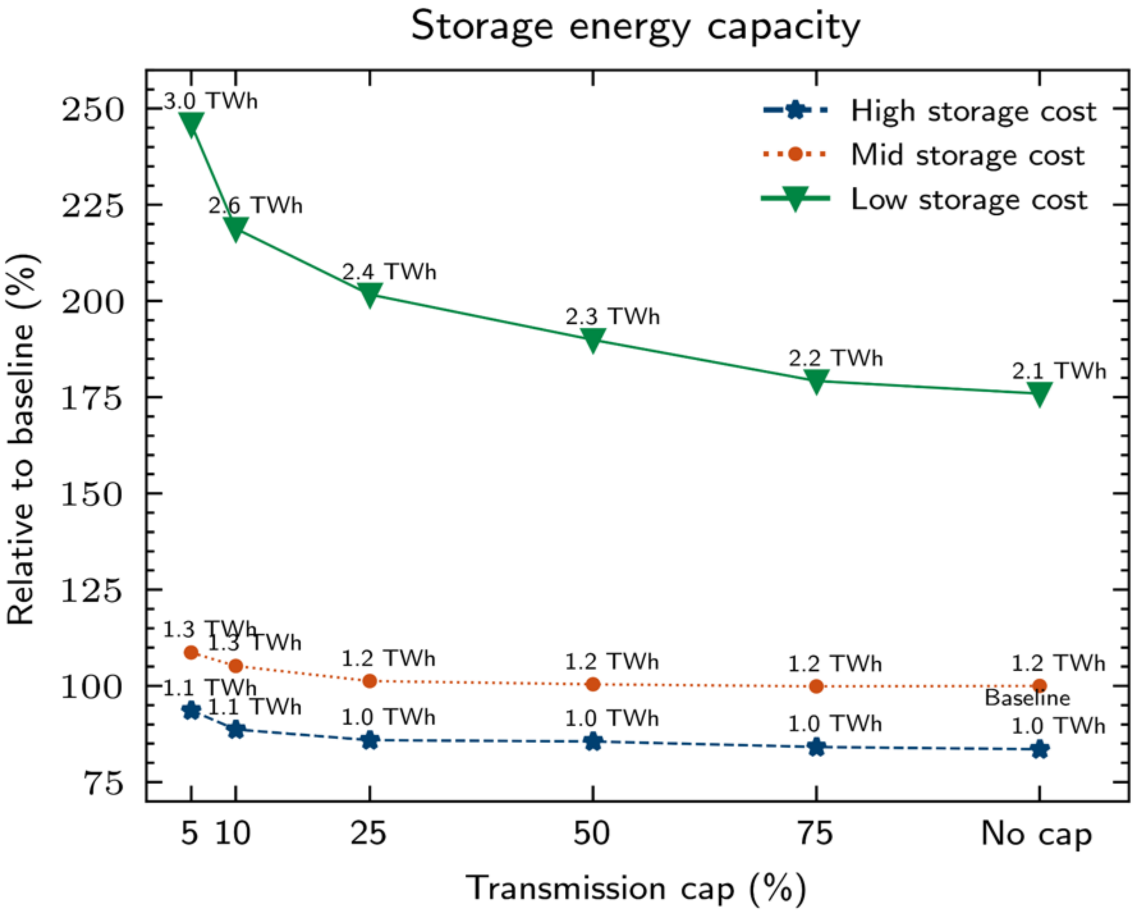
1. As the storage costs decrease (blue curve up to green curve), at any transmission cap the deployment of solar power capacity increases by up to 20%.

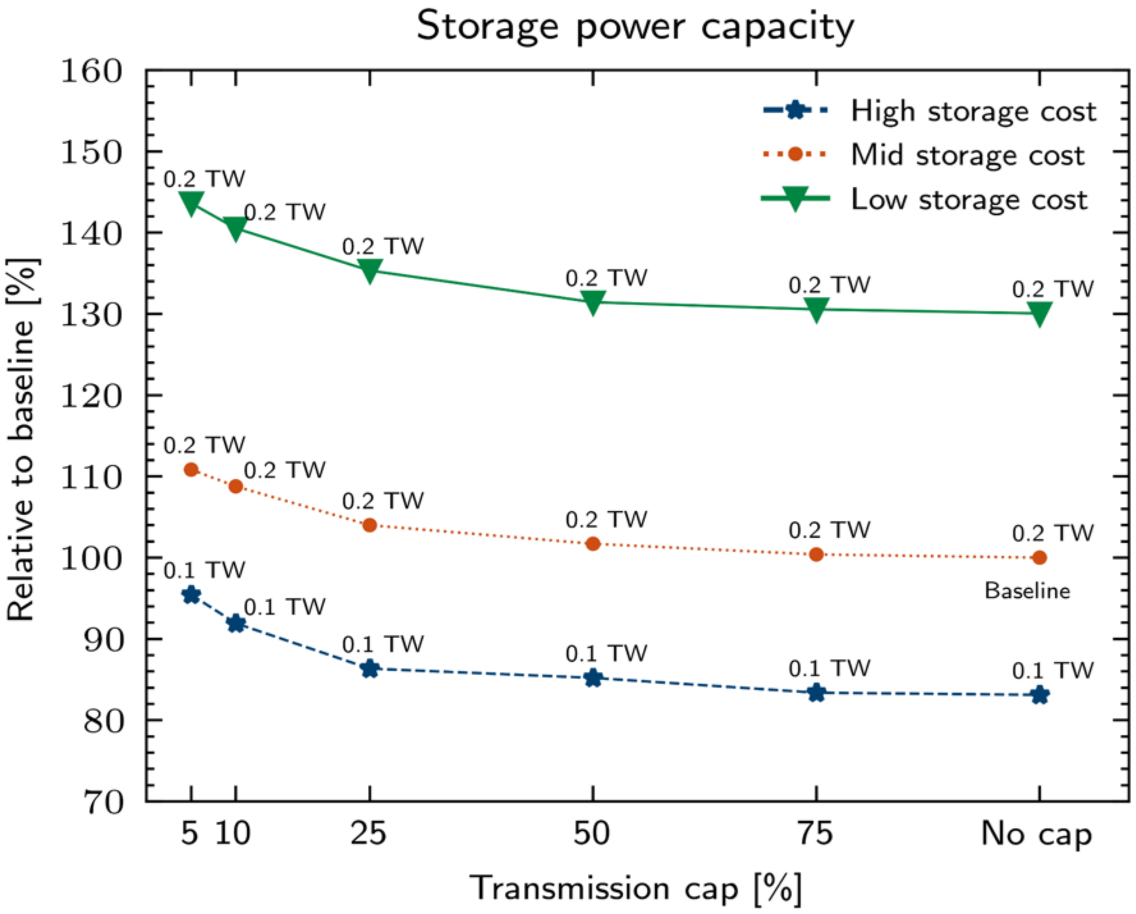
2. At any of the three levels of storage costs, as transmission cap reduces, the solar power capacity increases by up to 10%.

4. As the storage costs decrease (blue curve down to green curve), at any transmission cap the deployment of wind resources decreases by up to 50%.

5. At any of the three levels of storage costs, as transmission cap reduces, the wind power capacity increases by up to 10%.

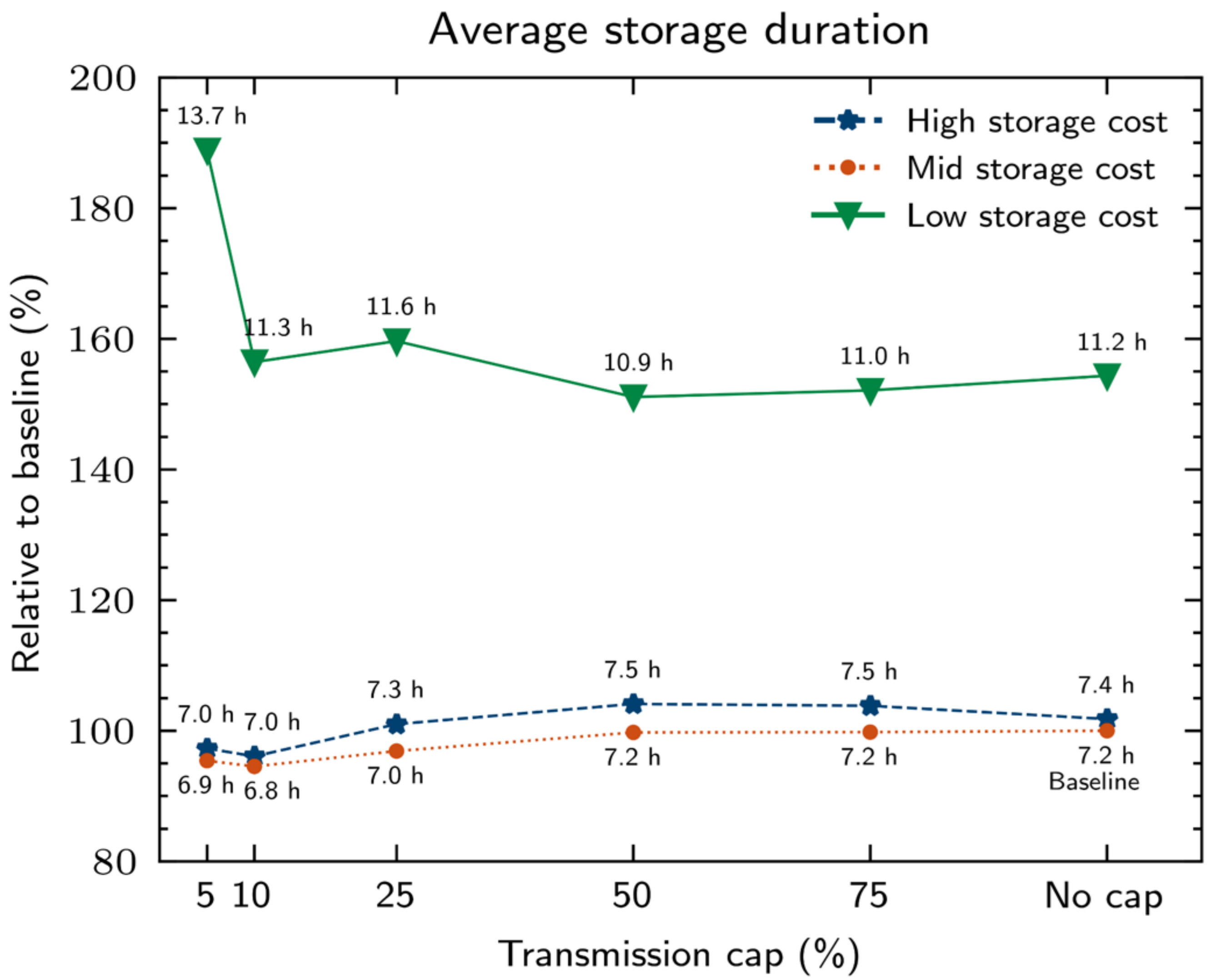
Deployment of storage in the WECC





1. As the storage costs decrease (blue curve up to green curve):
Left panel: the deployment of storage energy capacity increases by up to 150%
Right panel: the deployment of storage power capacity increases by up to 50%.
2. As transmission cap reduces, the deployment storage energy capacity increases, especially in low storage costs.

Deployment of storage technologies in the WECC



1. At any transmission cap, middle and high storage costs do not affect the storage duration significantly.

2. At any transmission cap, low storage costs show more storage durations. These durations are 60 - 90 % greater than the durations in the high and middle storage cost.

3. For low storage costs, when the transmission cap decreases from 10% to 5%, we see the largest increase in storage duration which is ~20%.