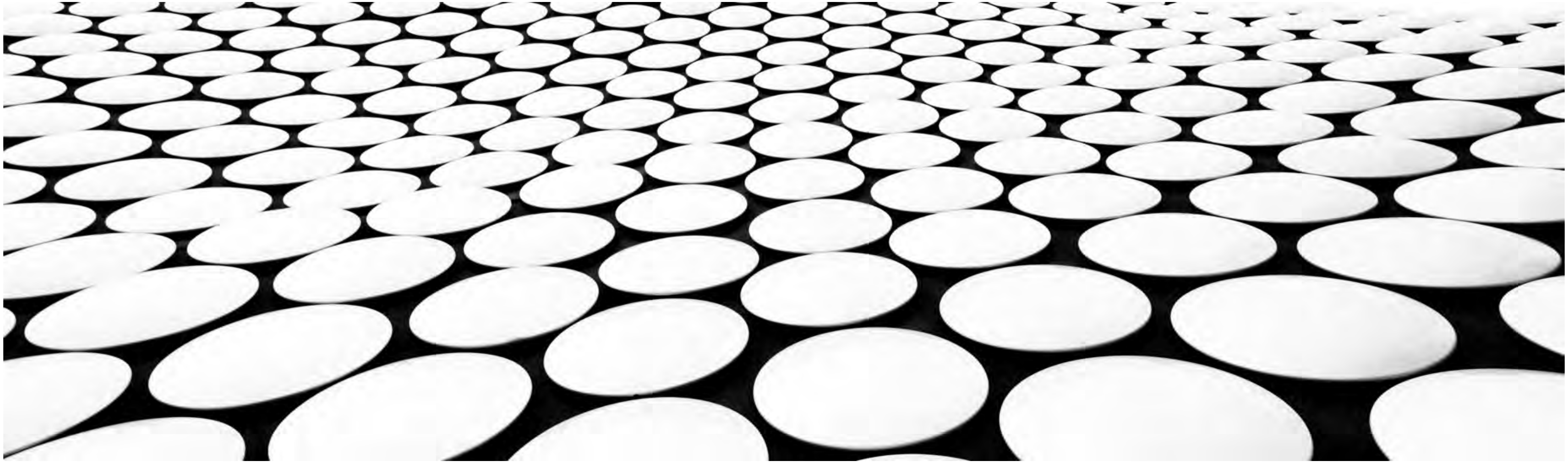
CALIFORNIA HYDROGEN BUSINESS COUNCIL

RENEWABLE GAS 360 WEBINAR – MAY 12, 2021



CALIFORNIA HYDROGEN BUSINESS COUNCIL

Hydrogen Means Business in California!

Platinum

Baker Botts, Ballard, Bay Area Air Quality Management District, BayoTech On-Site Hydrogen, Cummins, Mitsubishi Power, Ørsted, PG&E, Plug Power, SDG&E (A Sempra Energy utility), SoCalGas (A Sempra Energy utility)

Silver

AST Advanced Structural Technologies, Inc., Bennett, BMW, Black & Veatch, Burckhardt Compression, Chesterfield Special Cylinders, Chiyoda Corporation, CPI, ElDorado National - California, Energy Independence Now, Fastech, FIBA, Cashman Preload Cryogenics, Fiedlergroup, GM, Giner, GNA, GTA, GTM, Hexagon, Hofer, HydrogeNXT, HyET Hydrogen, Hydrogenious Technologies, Hypoint, Hyundai, Intertek, Iwatani Corporation of America, Johnson Matthey Fuel Cells, Kiewit, Kraft Powercon, Landi Renzo USA, Loop, Millennium Reign Energy, Mitsui & Co., Mpower, New Flyer of America, Nuvera, Nel Hydrogen, PDC Machines, The Port of Long Beach, Rio Hondo College, Ricardo North America, RIX, SAFCell, Sunline, Quantum Fuel Systems, Tom's, Trillium, True Zero, Worley, Worthington Industries, Swagelok, SMUD

Gold

A-C Transit, Bloomenergy, Chart (Cooler By Design), Dominion Energy, Element Markets, GreenbergTraurig, Parsons, IRD (IRD Fuel Cells LLC), nel, Nikola, PowerTap Hydrogen, South Coast AQMD, Linde, Sumitomo Electric, Toyota (Let's Go Places), US Gain, Sumitomo Corporation

Innovators

Anca Faur, BCC parts Corp., CHARM, CMB, Dash Energy, Daylight, Drive On, LLC, electro-active technologies, Fuel Solutions, Horizon, IVYS Energy Solutions, 122 West, EcoNavitas, Johnson Peltier, Noyes Law Corp., Planet Hydrogen Inc., PrimIDEA Building Solutions, RH2C, SA Strategic Analysis, T2M, M.R.S Enterprises, Terrella Energy Systems, Versallis Tech Services LLC, WaysH, Oberon Fuels, Inc., PNNL, Planetary Hydrogen, Resato, Sheldon Research & Consulting, Starworks, The Leighty Foundation, Yosemite Clean Energy, Zero Carbon Energy Solutions

Affiliates

Advanced Power & Energy Program, California Air Resources Board, California Fuel Cell Partnership, Calstart, CTE, CHFCA, Coalition for Clean Air, RHA Renewable Hydrogen Alliance

CALIFORNIA HYDROGEN BUSINESS COUNCIL

- OVER 125 MEMBERS

- RANGING FROM GLOBAL LEADERS TO START-UPS

CALIFORNIA HYDROGEN BUSINESS COUNCIL (CHBC)

VISION, MISSION, PRINCIPALS AND OBJECTIVES

- **Our Vision:**
  - CHBC is committed to advancing the commercialization of hydrogen and fuel cell technology in the energy and transportation sectors to achieve California's climate, air quality, and decarbonization goals.
- **Our Mission:**
  - Provide clear value to our members and serve as an indispensable and leading voice in promoting the use of hydrogen and fuel cell technology in the energy and transportation sectors in California and beyond.
- **Our Principals:**
  - Leadership, Integrity, Teamwork and Inclusion

California Hydrogen Business Council – CHBC – Hydrogen Means Business in California

CALIFORNIA HYDROGEN BUSINESS COUNCIL

Hydrogen Means Business in California!

CHBC ENGAGEMENT ON CALIFORNIA POLICY

TRANSPORTATION

- Vehicle and Infrastructure Incentives
- Cap and Trade
- Greenhouse Gas Reduction Fund (GGRF)
- Zero Emission Vehicle Regulations
- Low Carbon H2 Pathways for Transportation Fuel
- Optimizing the Low Carbon Fuel Standard (LCFS) for H2

GAS & ELECTRIC MARKET DESIGN

- Electric and Gas Grid Modelling
- Integration of Renewable H2 (RH2) into State Resource Planning
- RH2 Generation
- RH2 for Long-term Energy Storage
- Wholesale market access for RH2 production
- RH2 Pipeline Blending

DECARBONIZATION PLANNING

- Legislative Support for State Decarbonization Program Funding
- CEC Integrated Energy Policy Report
- Joint Agencies Low Carbon Power Plan (SB 100)
- CARB Scoping Plan for Point Sources, Vehicles and Infrastructure

CALIFORNIA HYDROGEN BUSINESS COUNCIL

Hydrogen Means Business in California!

Harnessing Renewable Hydrogen for Long Term Energy Storage

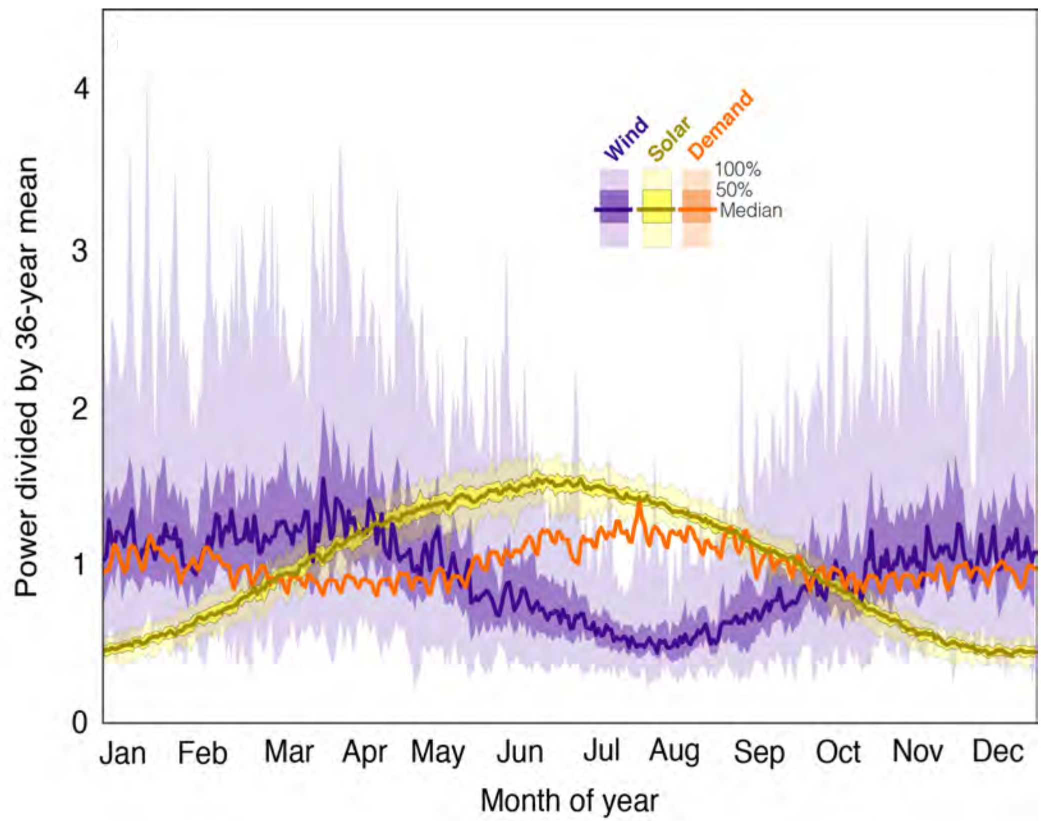
Nathan S. Lewis
Jacqueline A. Dowling
Katherine Z. Rinaldi

Division of Chemistry and Chemical Engineering
California Institute of Technology

Renewables for Power Generation

Geophysical reliability of solar/wind on continental scale?

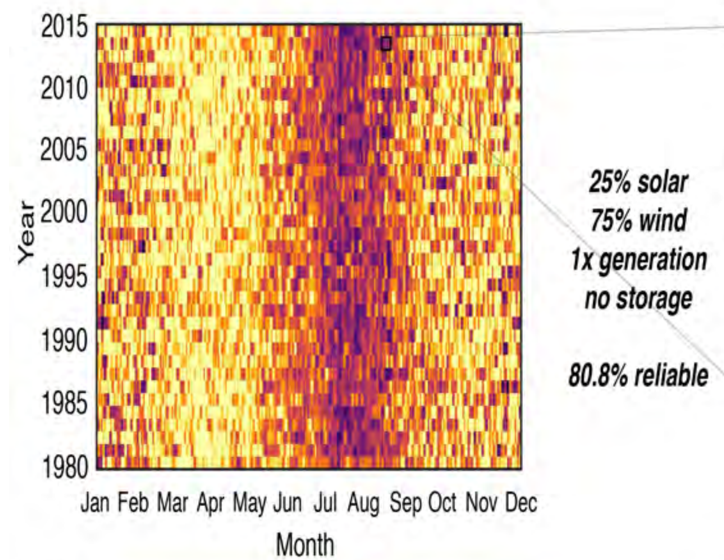
- Consideration / adoption of 80-100% renewable electricity mandates
- Claims workable using 100% wind, water (pumped hydro) and solar
- "Always windy somewhere or sun will be shining somewhere" ?

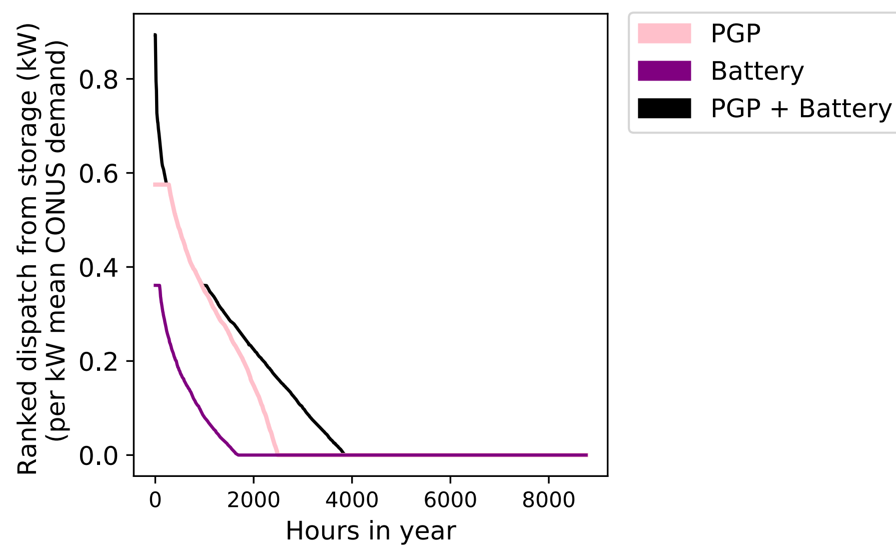


Source: M. Shaner, S. Davis, N. Lewis, K. Caldeira (2018). Energy & Environmental Science.

Geophysical Resource Data-Driven Assessment of Gaps Between Supply and Demand

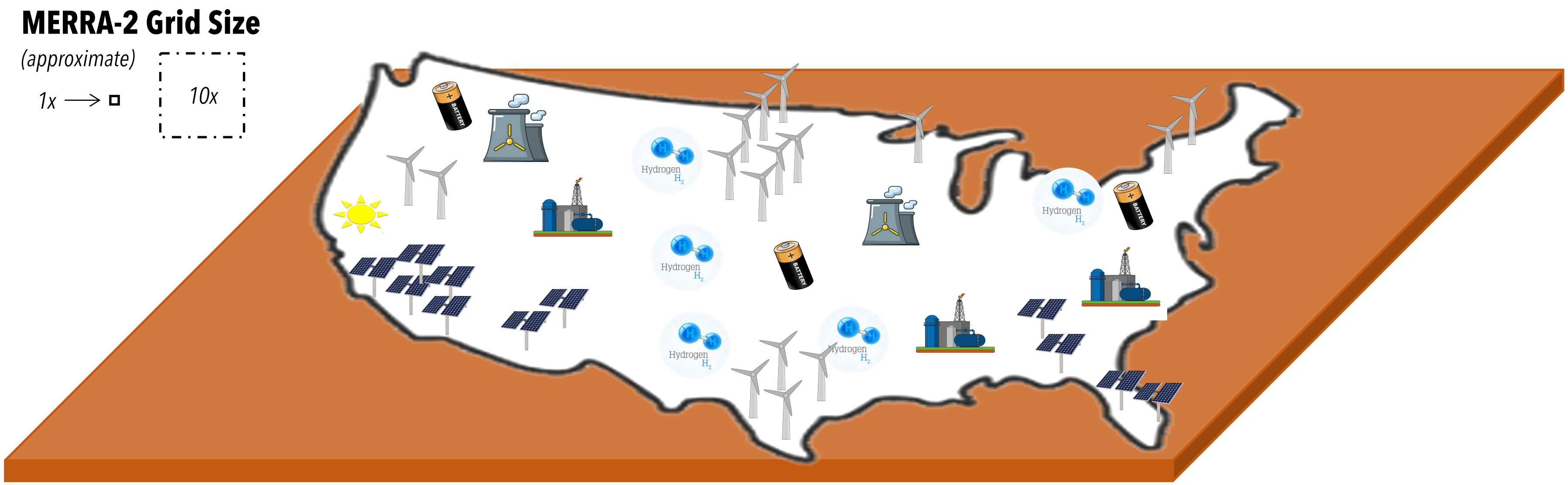
- Wind and Solar Generation over contiguous U.S.
- >99.99% resource adequacy is a blackout for <1 hour per decade
- Infrastructure lifetime of grid is ~40 years
- Assessment requires wind/solar co-variability over 30-40 year periods
- Ideal, lossless transmission over contiguous U.S. between all generation and load
- Generation based on 39 years of hourly ~50 km reanalysis (weather) data
- Demand based on hourly EIA data (for 2015-2018)





Source: M. Shaner, S. Davis, N. Lewis, K. Caldeira (2018). Energy & Environmental Science.

Macro Energy Model (MEM)



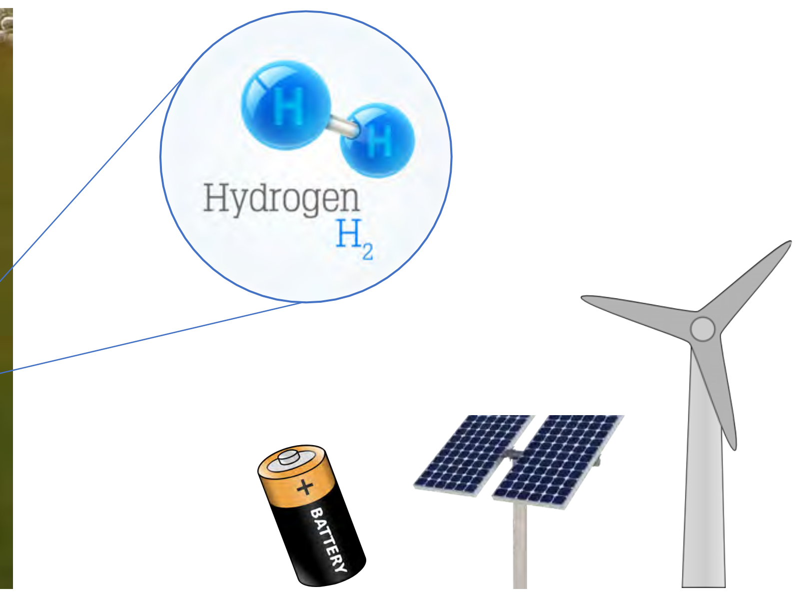
- Function is to minimize overall system costs
- Solves for installed capacities and hourly use of a 100% renewable, 100% reliable end state
- The system is built overnight using current costs, electricity demand from EIA, and wind and solar availability from MERRA-2

Role of Long-Duration Energy Storage in Variable Renewable Electricity Systems

Power-to-Gas-to-Power (PGP) with Hydrogen

Hydrogen split from water provides fuel for long-duration energy storage.

We find that long-duration energy storage (e.g., power-to-gas-to-power with hydrogen) can make reliable wind-solar-battery electricity systems more affordable.

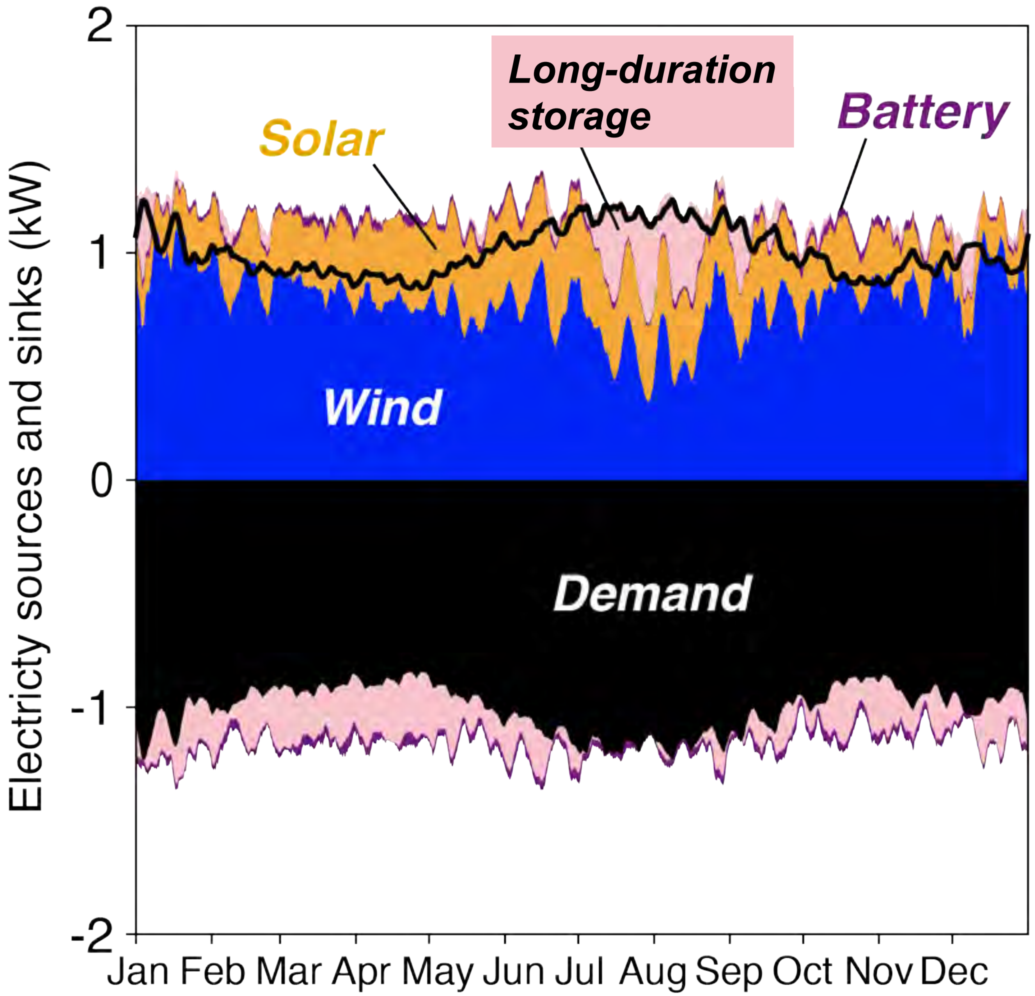


Dowling, J. A.; Rinaldi, K. Z.; Ruggles, T. H.; Davis, S. J.; Yuan, M.; Tong, F.; Lewis, N. S.; Caldeira, K. *Joule* **2020**. 41907.

Key Questions

- What **storage technologies will cost-effectively fill the gaps** between wind and solar supply and electricity demand?
- What is the **role of long-duration energy storage** in wind- and solar-based electricity systems?

Role of long-duration energy storage like Power-to-Gas-to-Power (PGP) with hydrogen

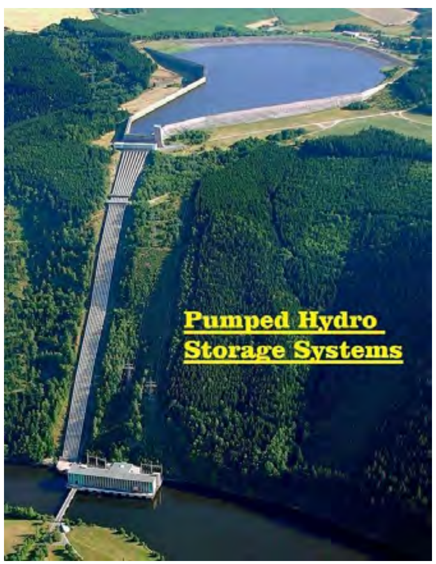


Long-duration storage:

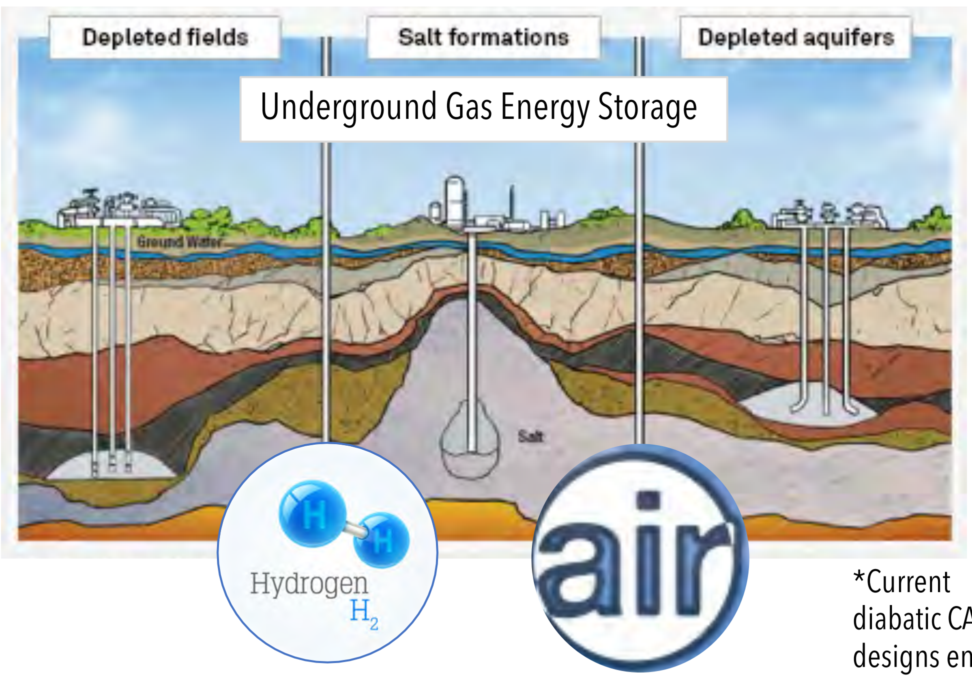
- ***can reduce costs of wind-solar-battery systems at current technology costs***
- ***fills seasonal and multi-year storage functional roles***
- ***could further reduce system costs with future cost improvements***

Examples of long-duration energy storage

- **Long-term, large-capacity energy storage** may ease reliability and affordability challenges of systems based on naturally variable generation resources.
- **PGP** is the base case long-duration storage technology used herein.



Pumped Hydro Storage (**PHS**)

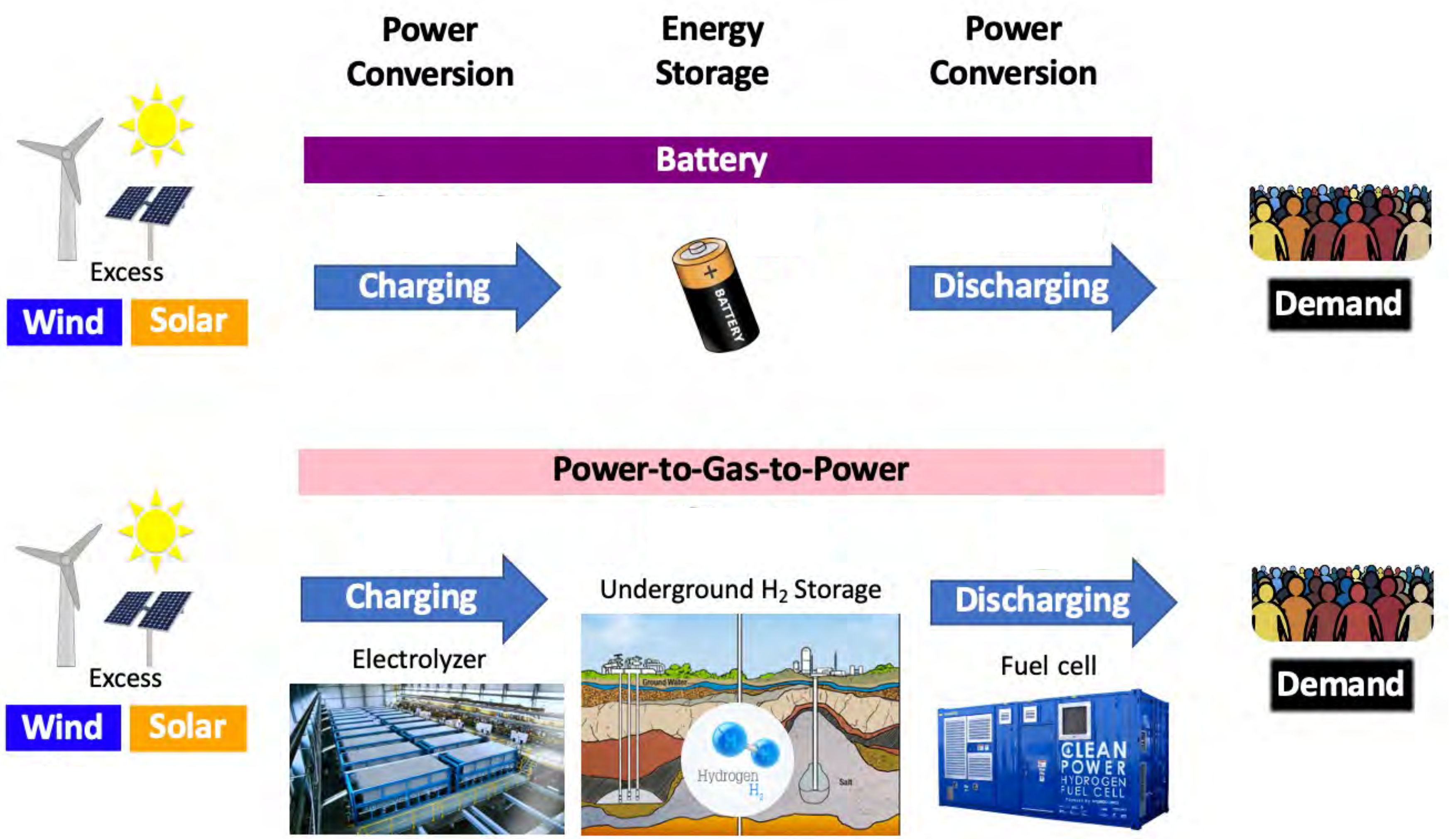


Power-to-Gas-to-Power (**PGP**, with hydrogen fuel)

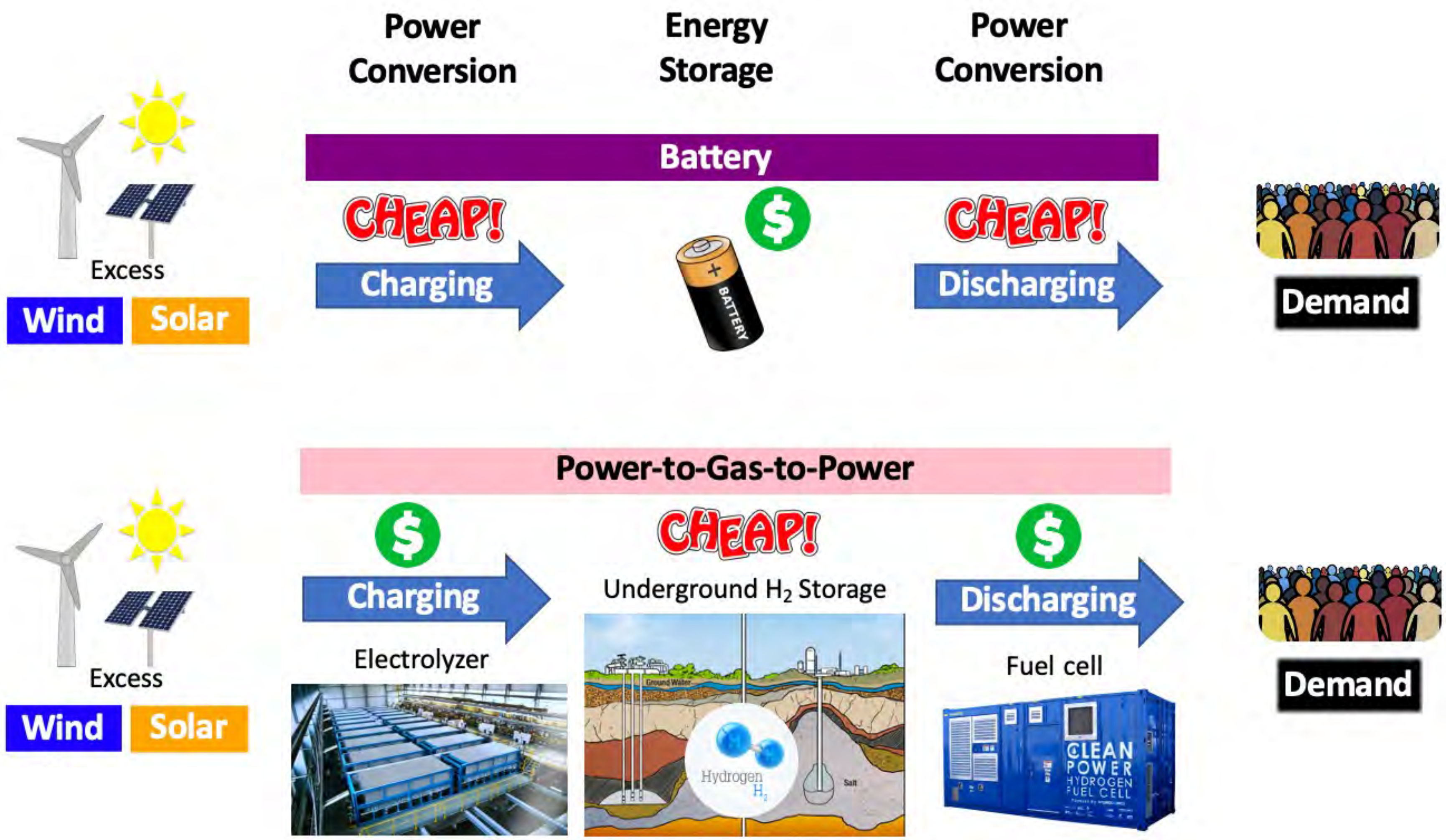
*Compressed Air Energy Storage (**CAES**)

*Current diabatic CAES designs emit carbon

Storage technologies fill the gaps between supply and demand



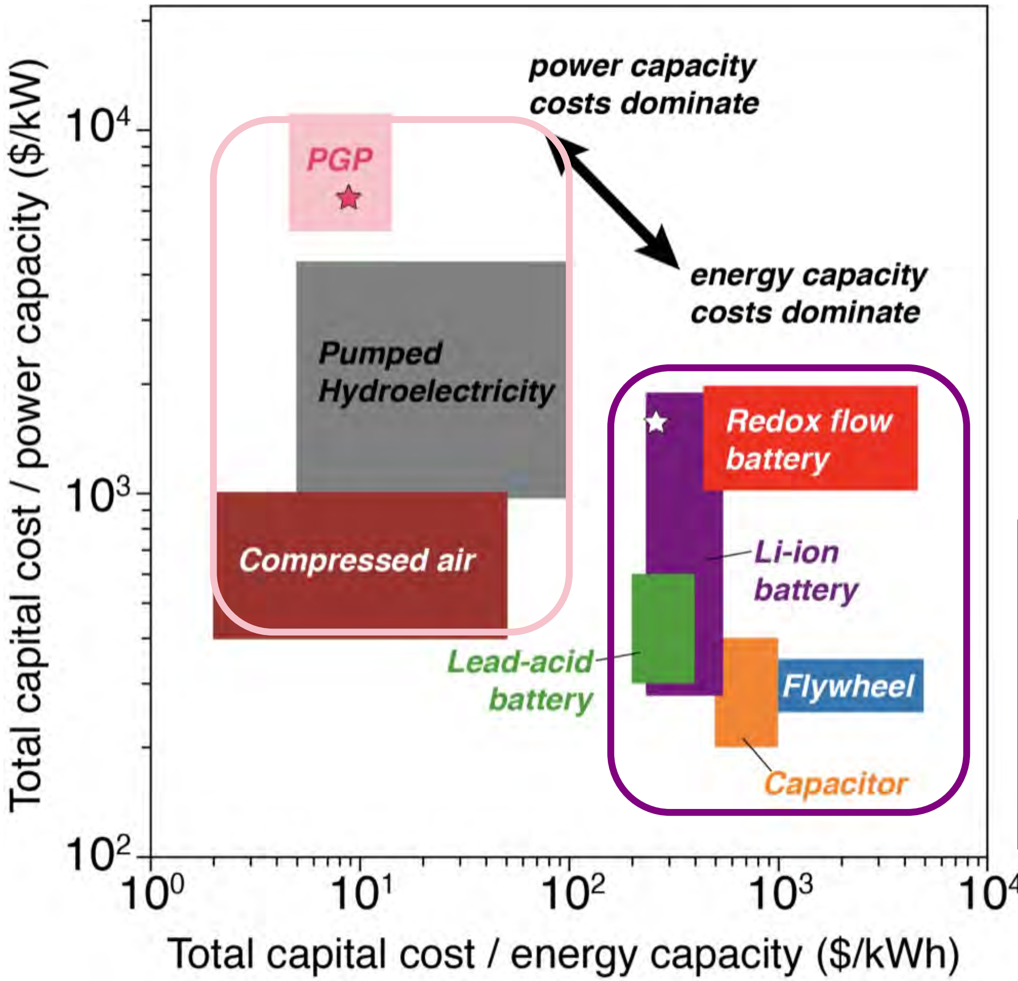
Power and energy costs impact model results



PGP is a long-duration storage technology

- Long-duration storage technologies (10 hours or greater) have very different cost structures compared with Li-ion battery storage.

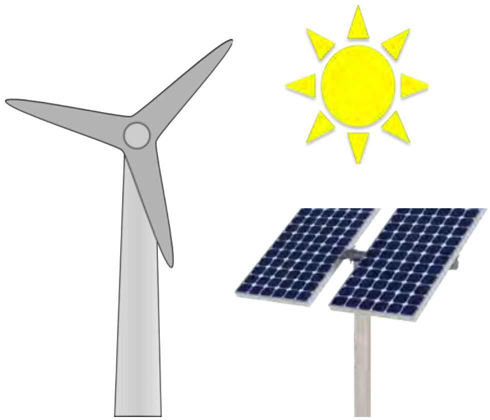
Long-duration storage options



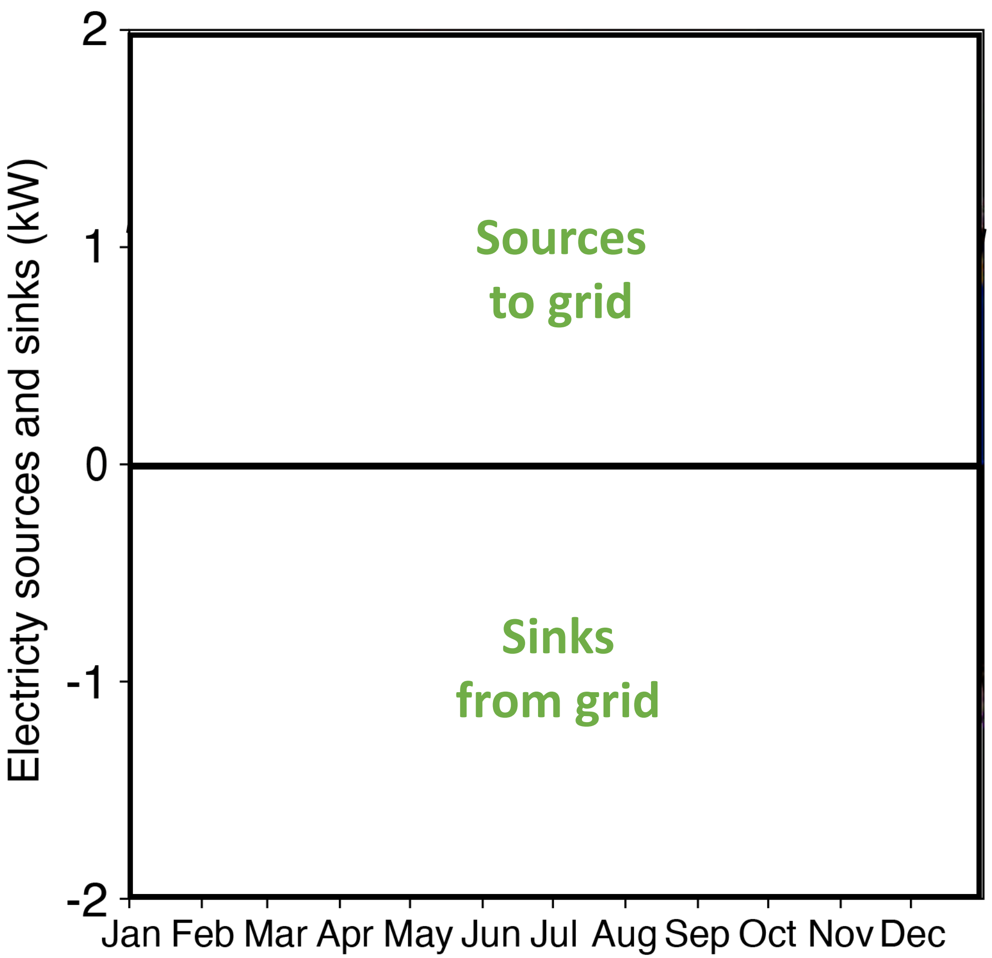
Short-duration storage options

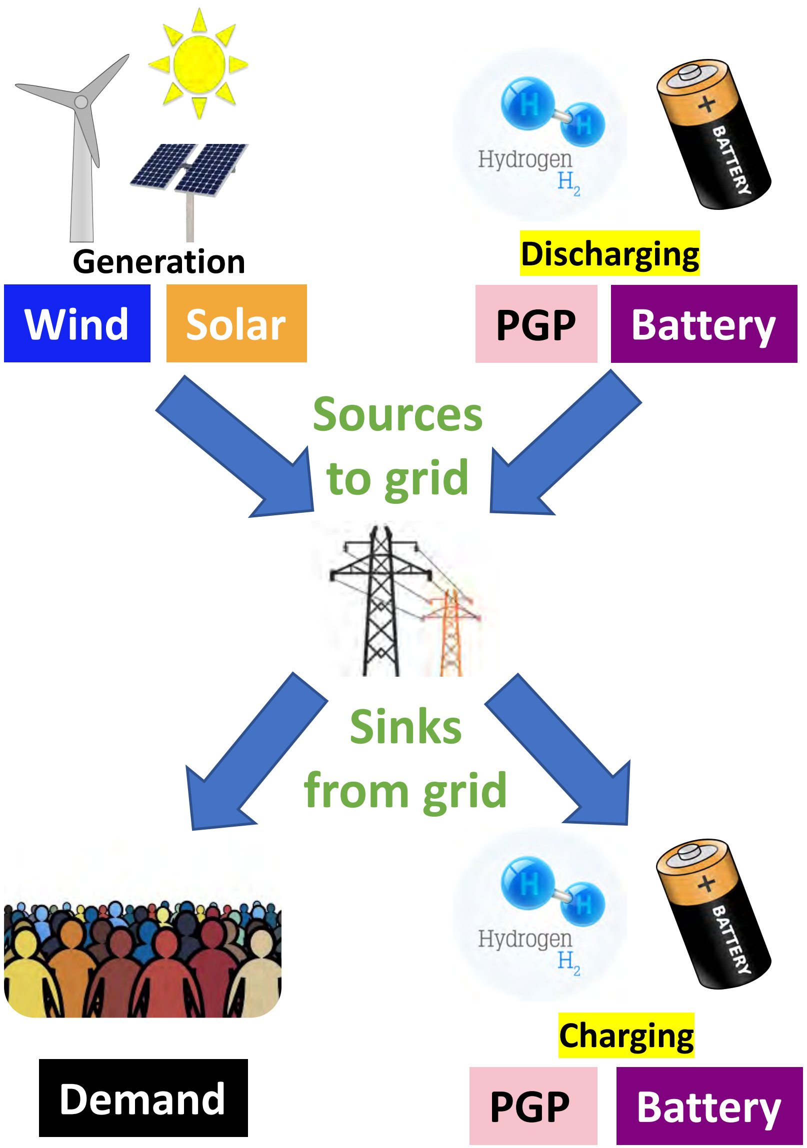
Macro Electricity Model (MEM)

- Input data:
  - U.S. wind and solar availability
  - U.S. electricity demand
  - Fixed and variable costs of wind, solar, PGP, batteries
  - Technology performance metrics
- Constraint:
  - 100% reliable (no unmet demand)
- Objective function:
  - Minimize overall system cost
  - Solve for capacity and hourly use of each technology
  - No use-models are assumed

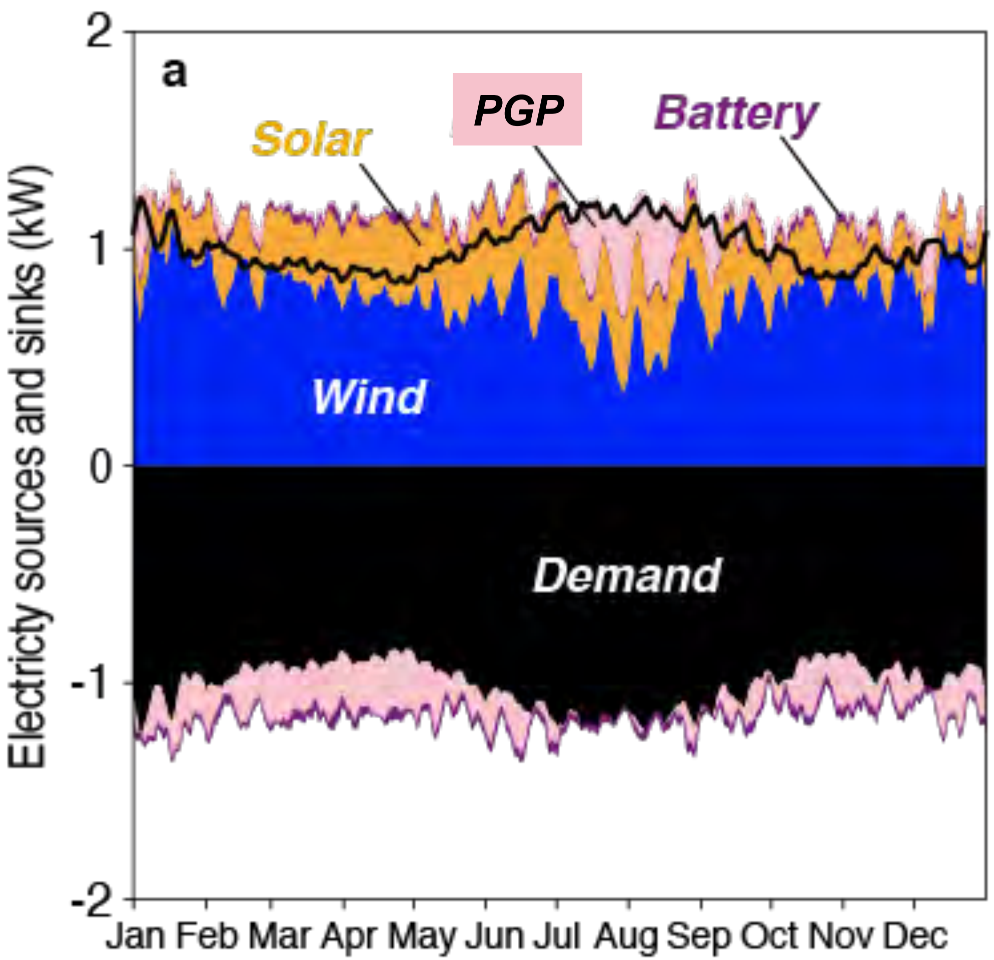


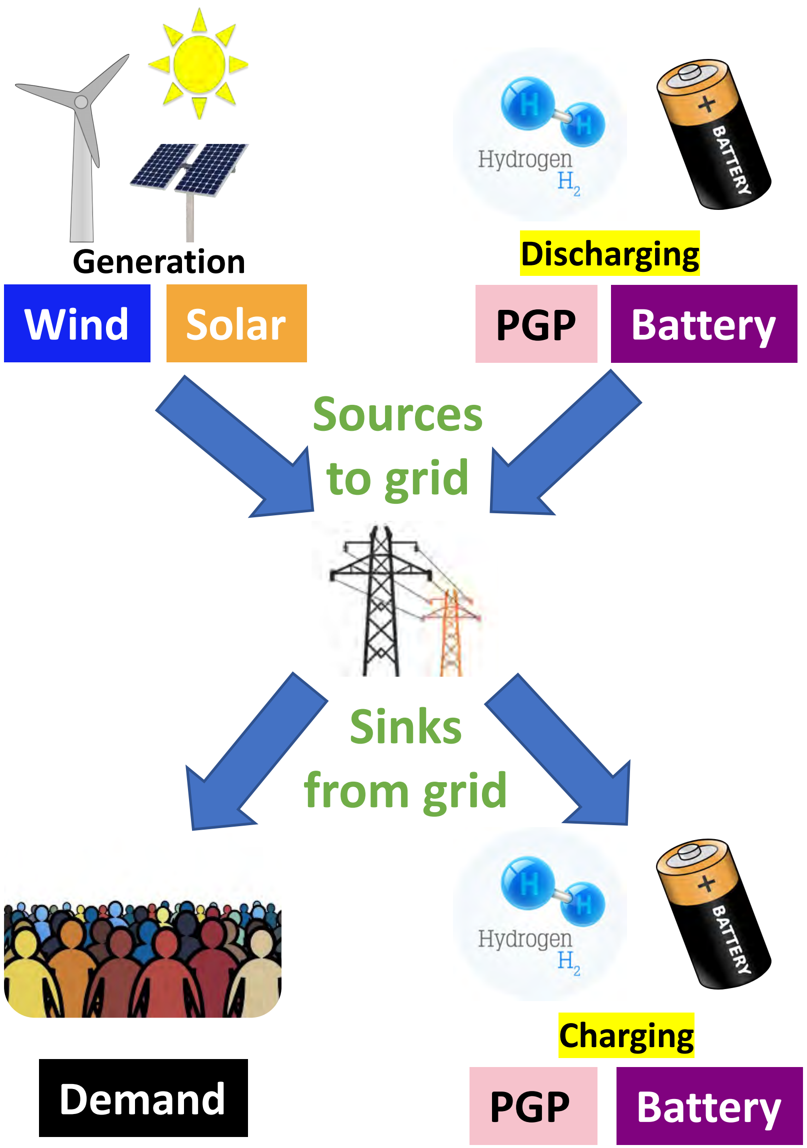
Electricity sources and sinks



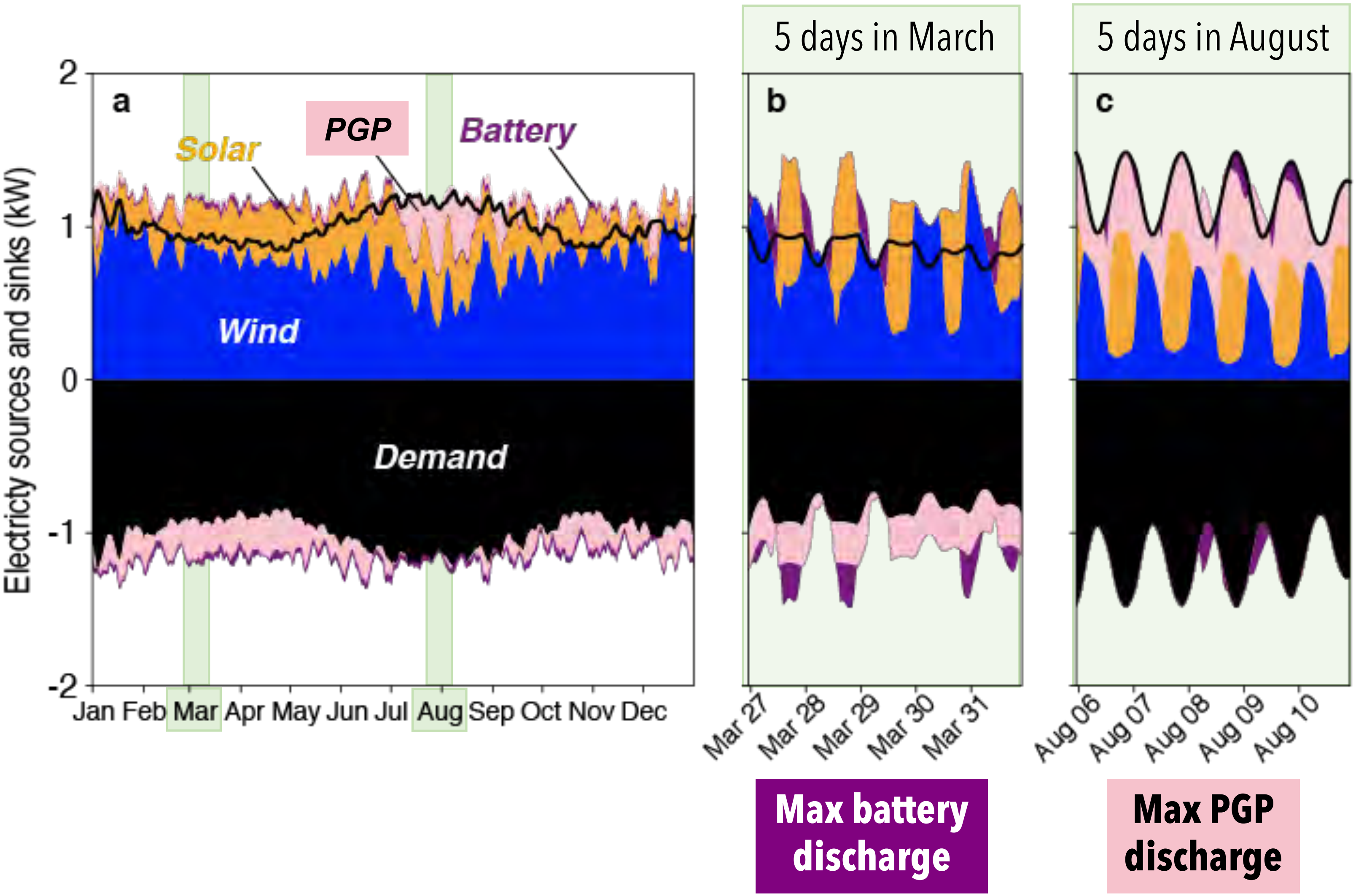


Currently available PGP technology can cost-effectively fill gaps between supply and demand





PGP meets summertime demand and complements daily battery storage



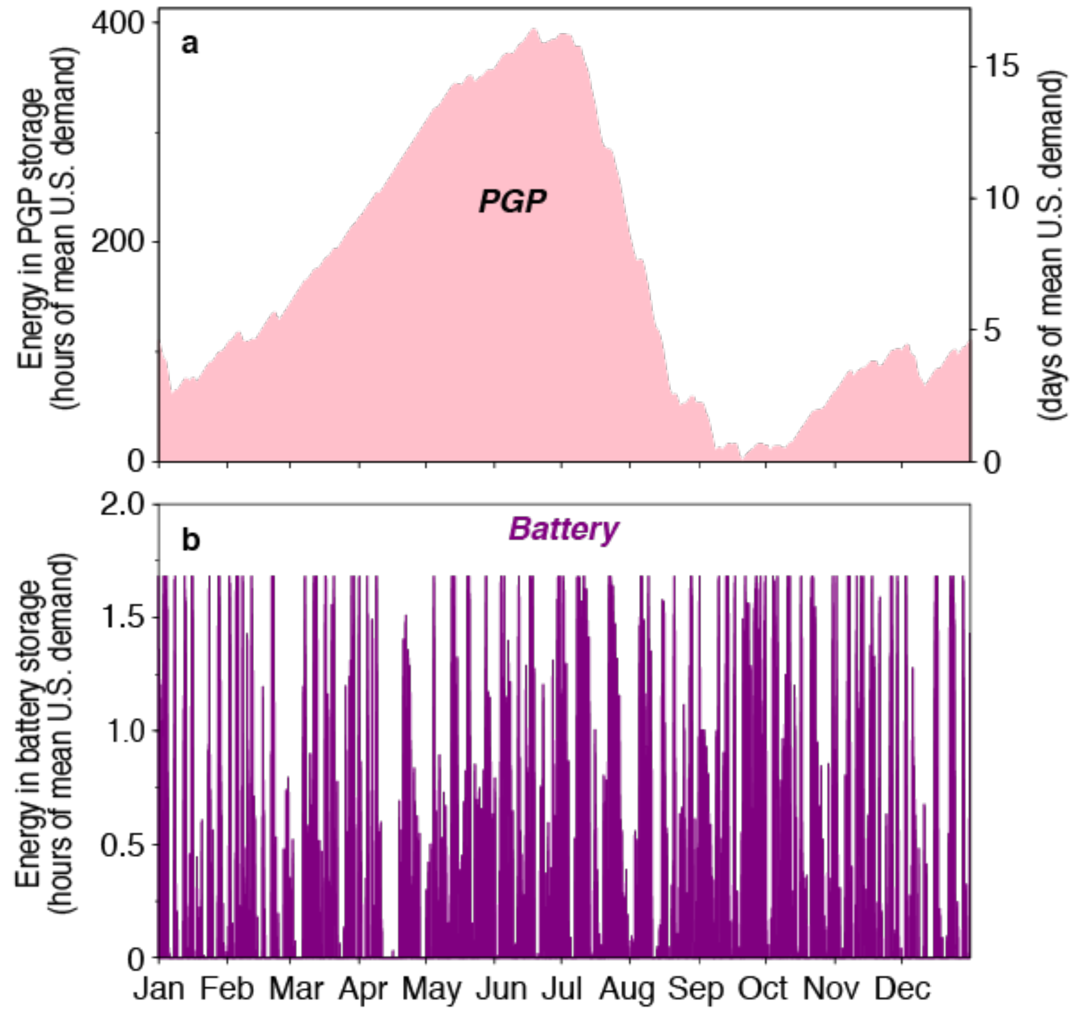
Seasonal and daily storage functional roles

PGP 16 days

Inter-seasonal storage

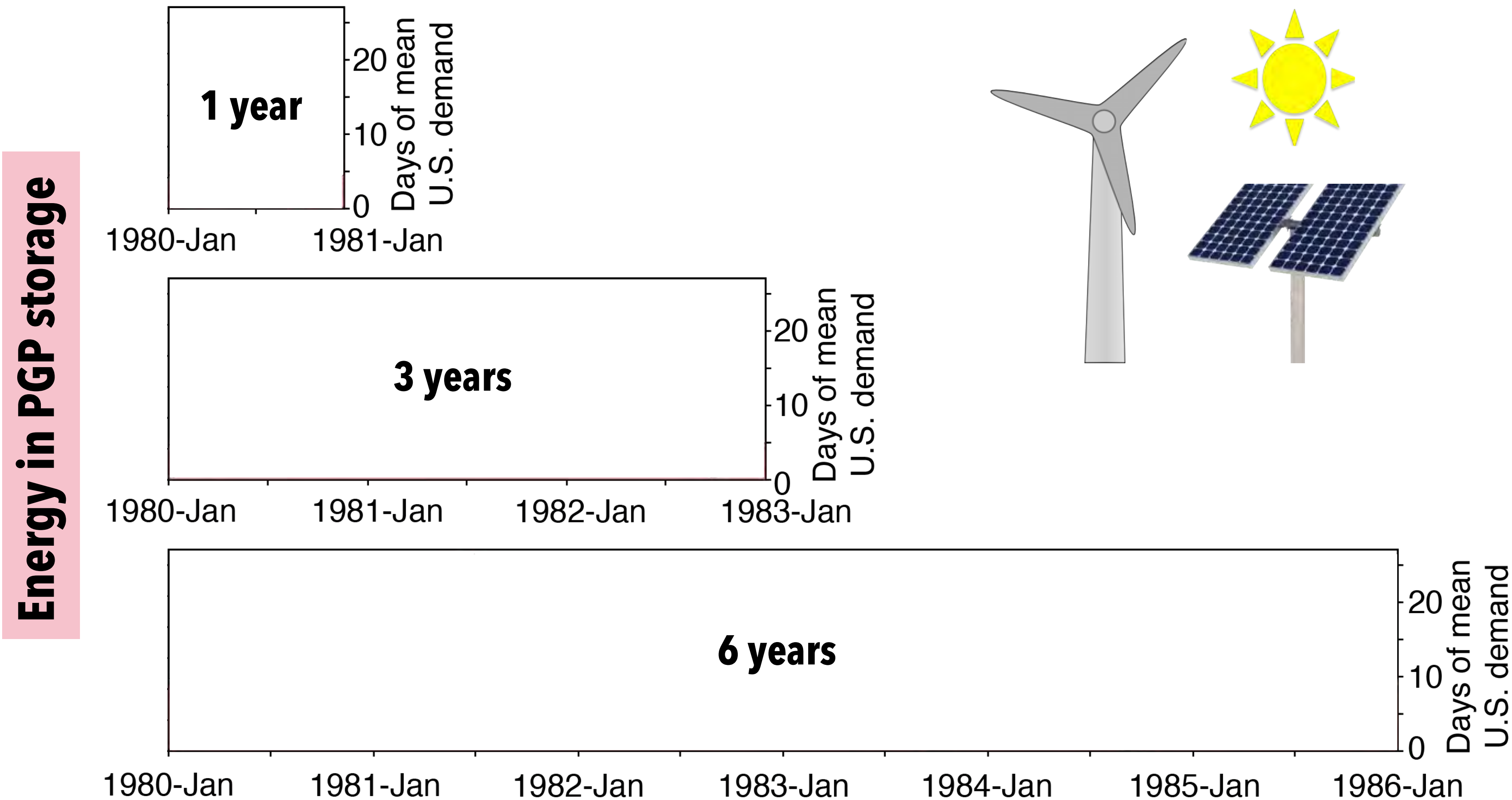
Battery 1.7 hours

Intra-daily storage

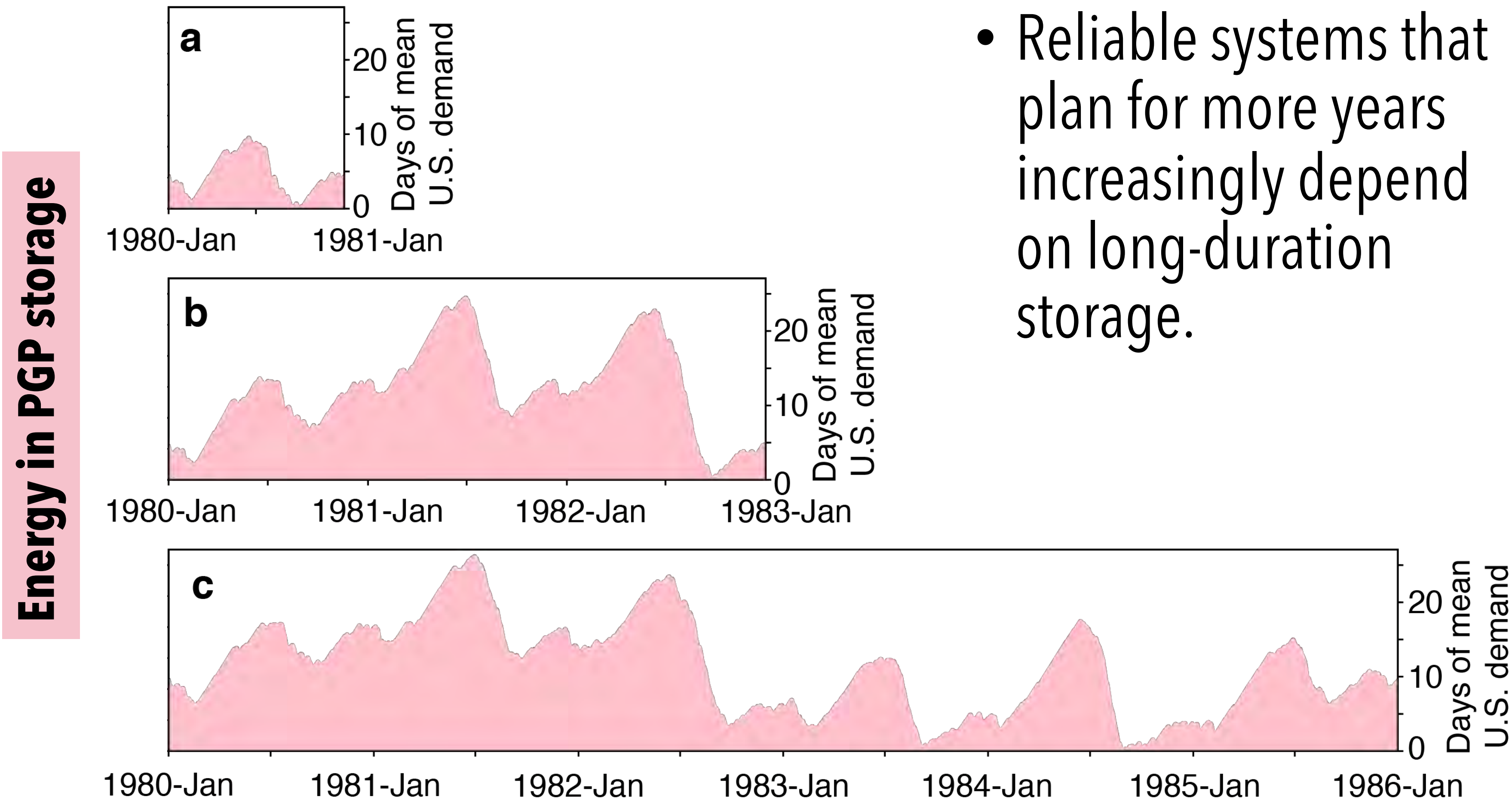


- Batteries are not cost-effective for seasonal energy storage.

Long-term weather datasets capture the role and value of long-duration storage like PGP

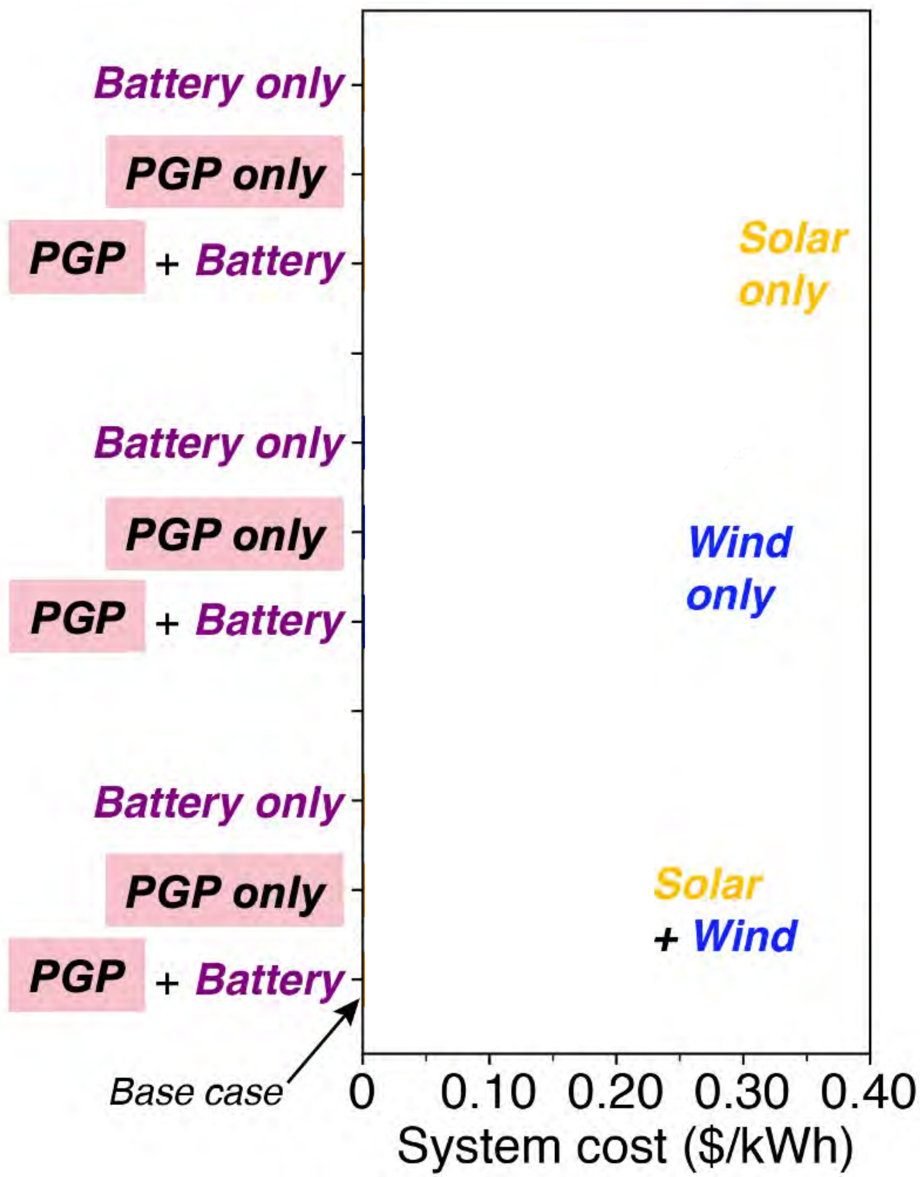


Multi-year PGP energy storage is cost-effective

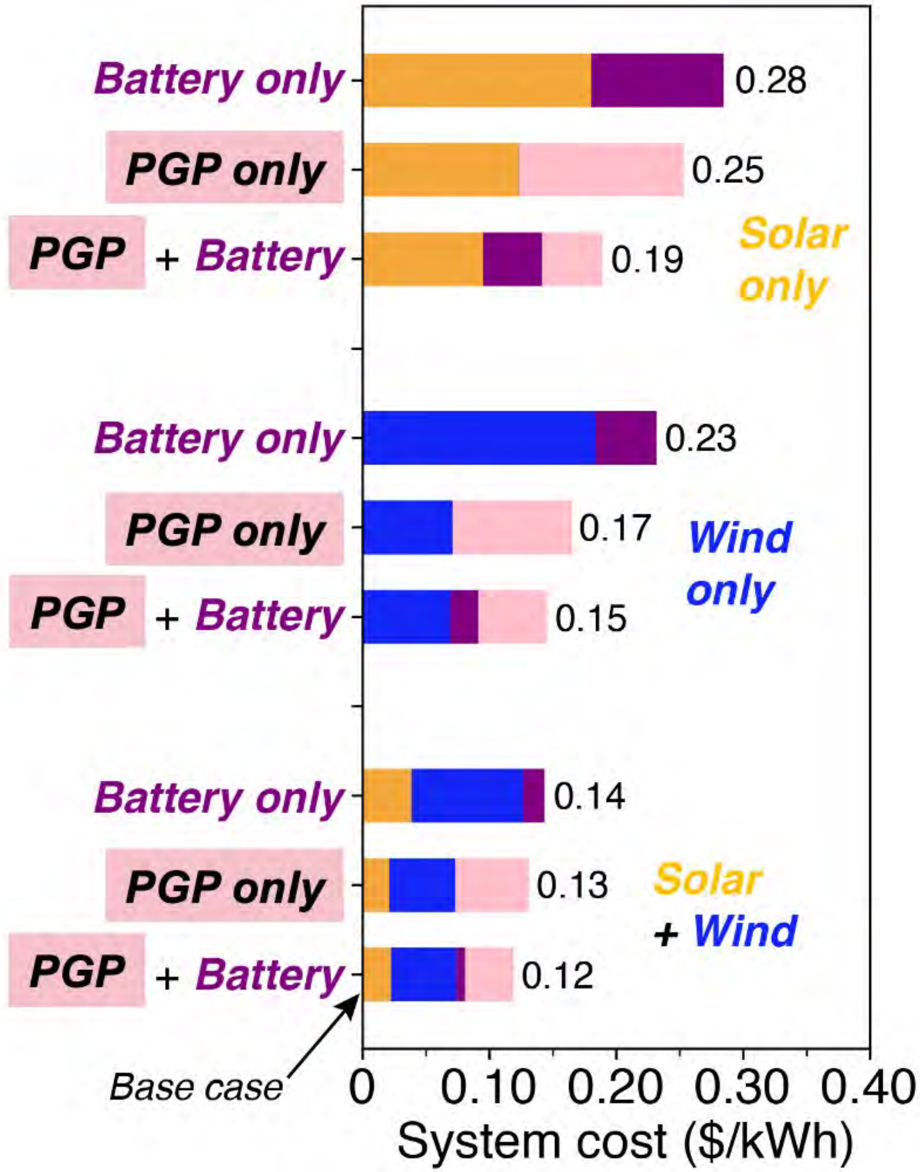


- Reliable systems that plan for more years increasingly depend on long-duration storage.

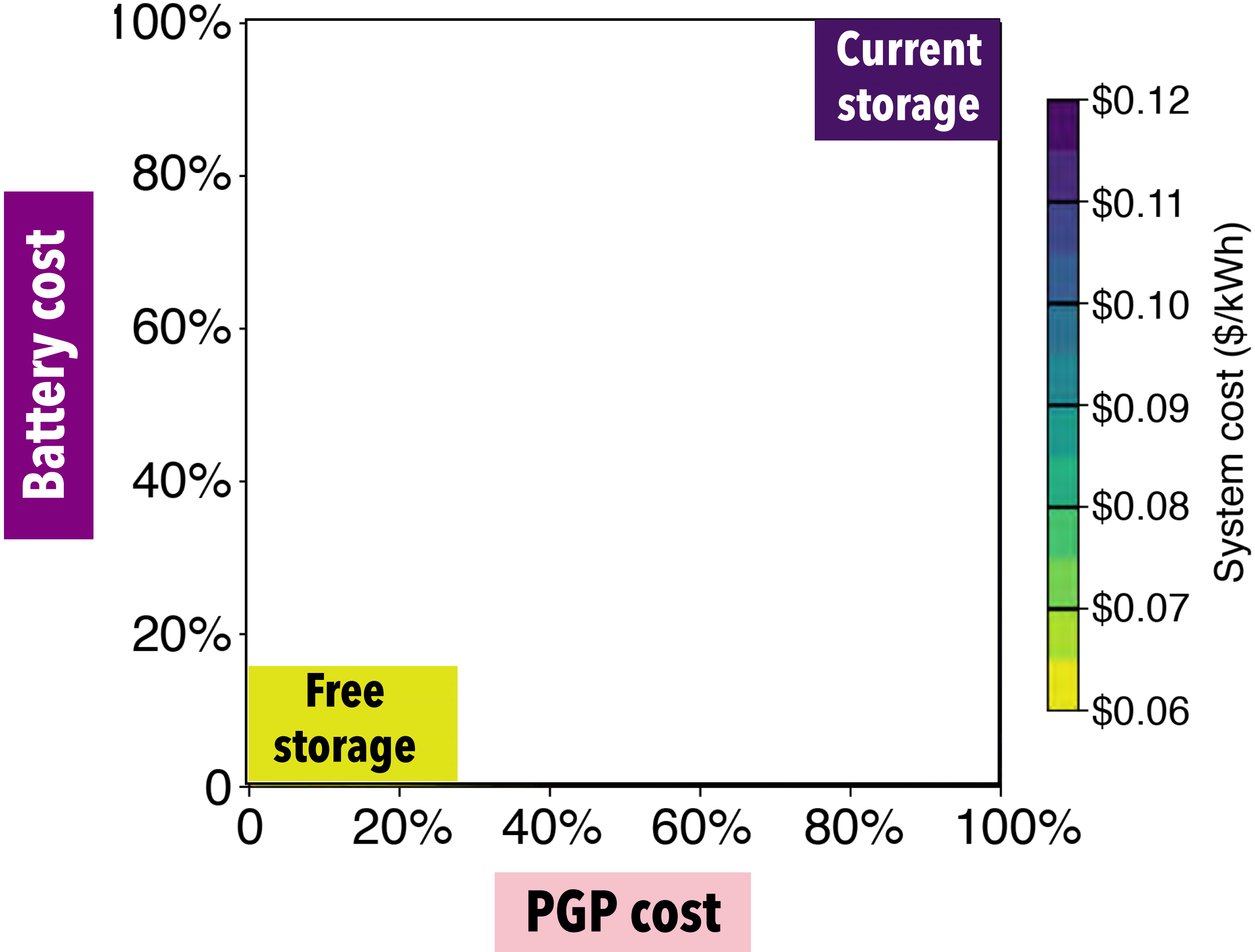
What is the value of including PGP in the system?



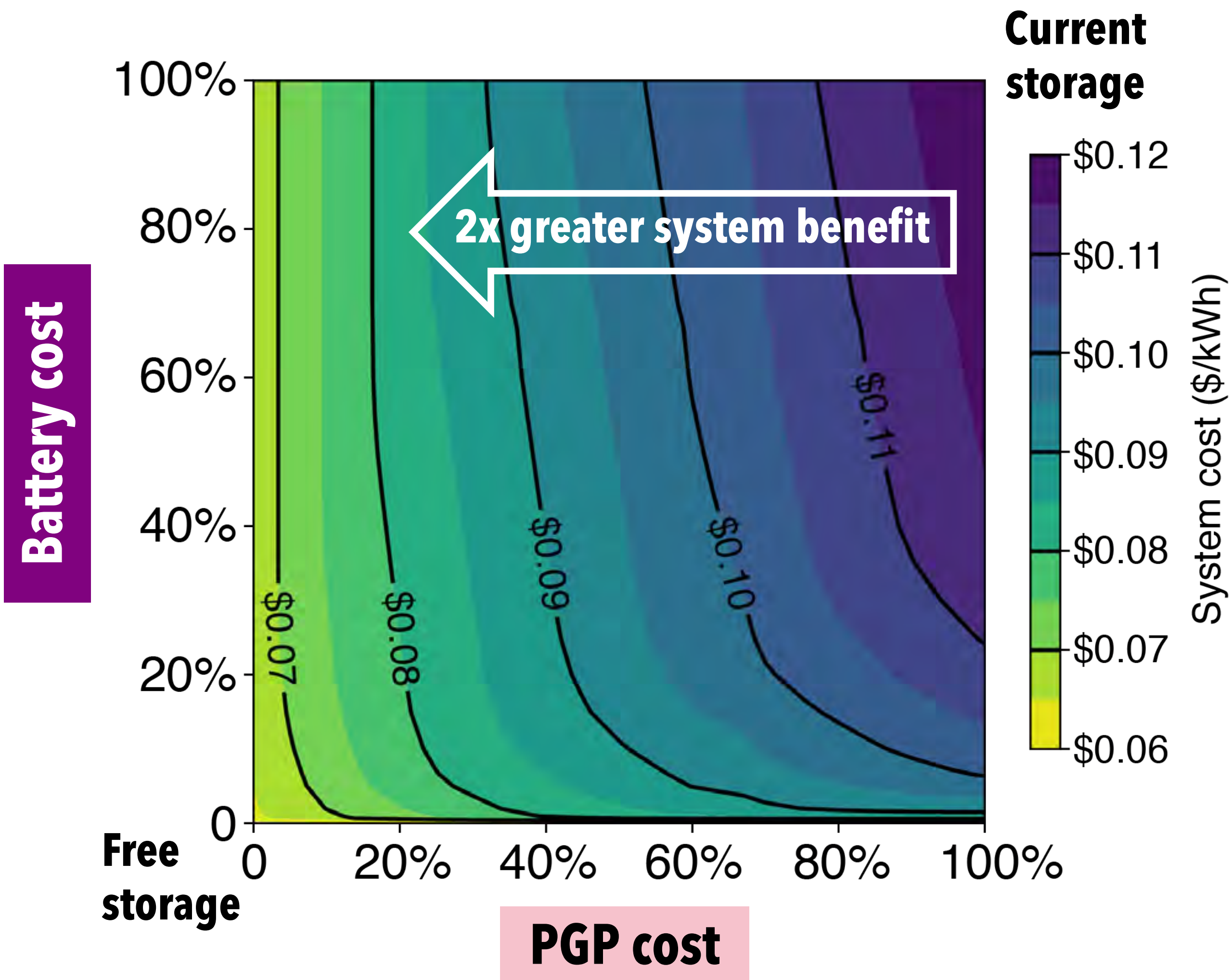
Addition of PGP reduces costs in all cases considered



What about future innovations (cost-reductions) in storage technology?

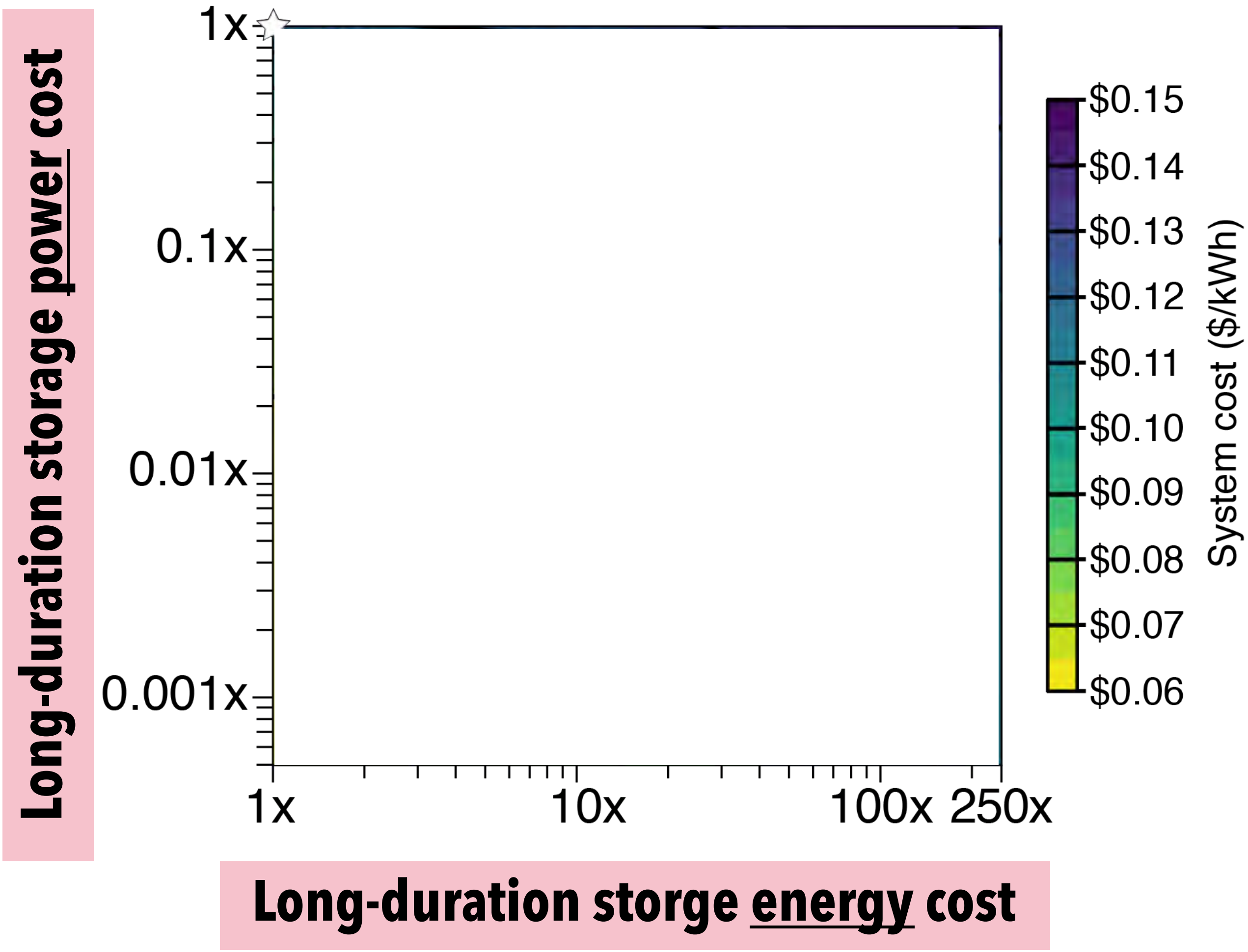


Electricity costs are much more sensitive to reductions in PGP costs than they are to reductions in battery costs

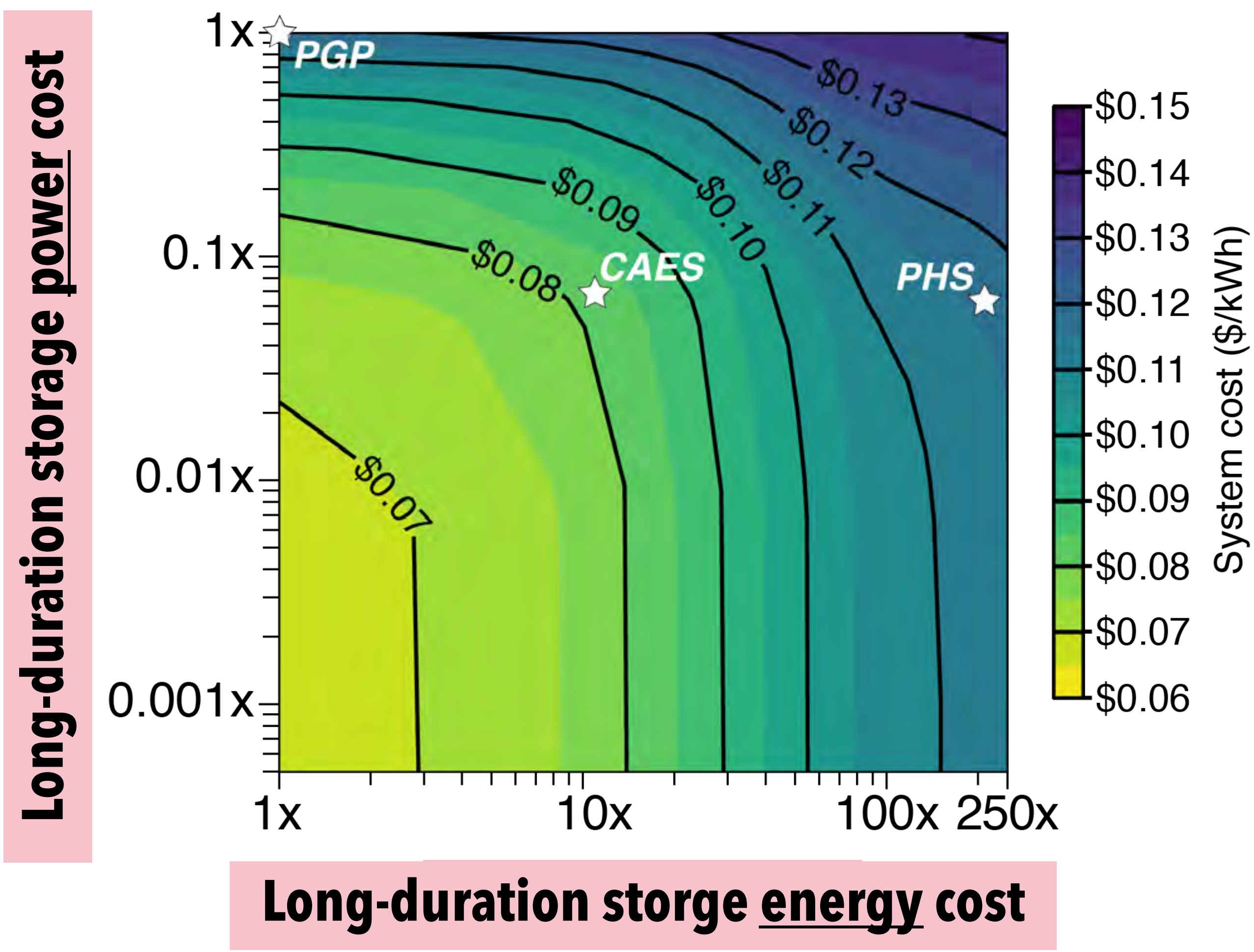


- A 10% reduction in PGP costs would reduce system costs 2x more than a 10% reduction in battery costs.

What type of innovations (cost-reductions) would benefit long-duration storage like PGP?



PGP would benefit greatly from continued innovations in fuel cells, H2 combustion turbines, electrolyzers, and other power conversion devices



PGP:
Utility-scale projects are expanding

CAES:
Current diabatic designs emit carbon

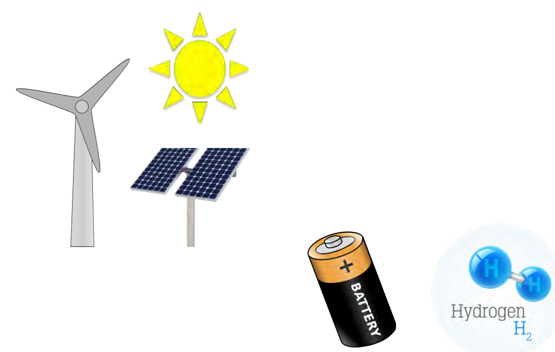
PHS:
Mature technology, major future cost reductions are unlikely

Conclusions

- **To make 100% renewable reliable electricity more affordable, include currently available long-duration storage technology.**
  - Long-duration storage would reduce costs of reliable solar and/or wind systems with or without battery storage.
- **Long-duration storage plays unique roles, such as seasonal and multi-year storage, that increase the affordability of electricity from variable renewable energy.**
  - Long-duration storage meets demand during summertime lulls in wind power and fills in for interannual variations in wind and solar power. Reliable systems that plan for more years increasingly depend on long-duration storage.
- **Variable renewable electricity costs are more sensitive to reductions in long-duration storage costs than they are to reductions in battery costs.**
  - Technology innovations and future cost improvements in long-duration storage could further reduce the cost of renewable, reliable electricity.

California Case Study

Wind and solar resource droughts in California highlight the benefits of long-term storage and integration with the Western Interconnect



Rinaldi, K. Z., Dowling, J. A., Ruggles, T. H., Caldeira, K., & Lewis, N. S. (2021). Environmental Science & Technology.

Key Questions

- How do these results change when restricting resources to **smaller regions**, such as the state of **California**?
- Are there periods when there is **minimal sunshine and wind over the whole state**?

Key points for decision-making

- California experiences **multi-day calm and cloudy periods over the whole state** each year that will strictly limit renewable electricity generation at those times

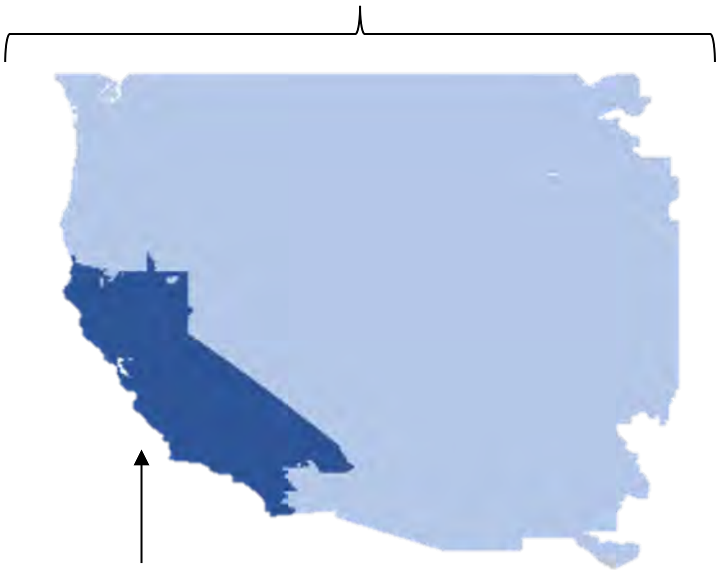
- To make 100% renewable, reliable electricity in California more affordable, **include long-duration storage** and/or **incorporate wind and solar generation from the Western Interconnect**

A data-driven analysis of weather-related variability

- 39-years of reanalysis weather data from 1980-2018, evaluate the variability and availability of wind and solar resources over the state of California and the Western Interconnect

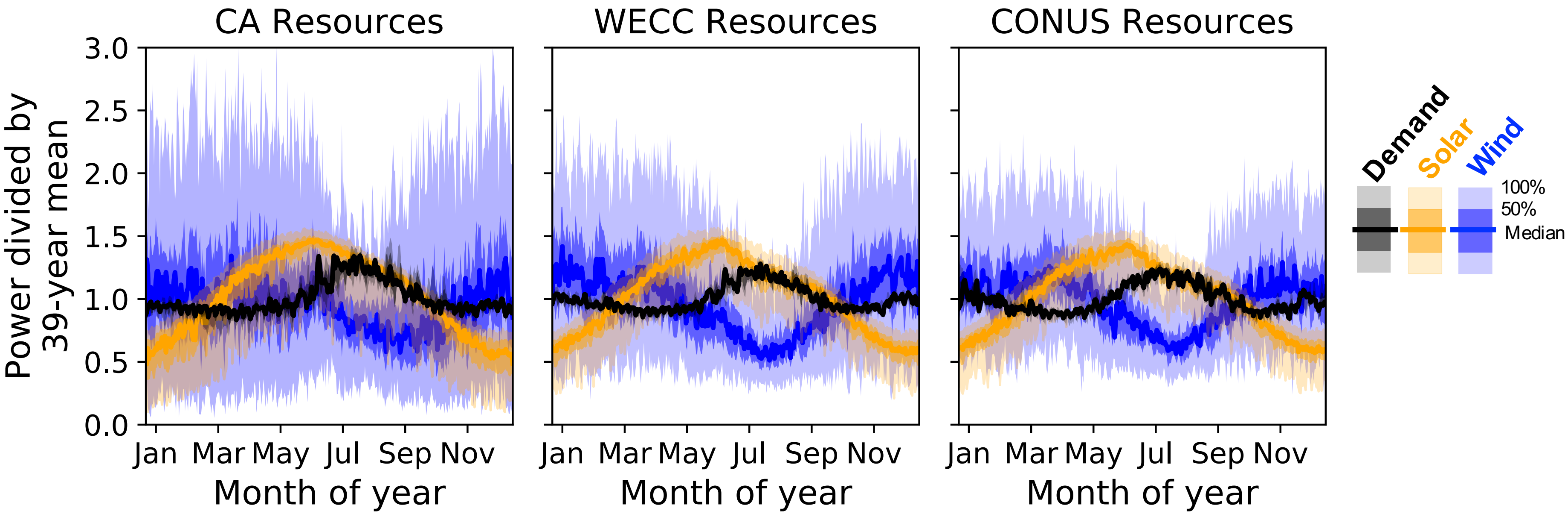
- This data-driven approach allows us to directly quantify periods of resource droughts that would limit renewable energy dispatch

Western Interconnect (WECC)
One of the three major AC power grids in the US transmission grid

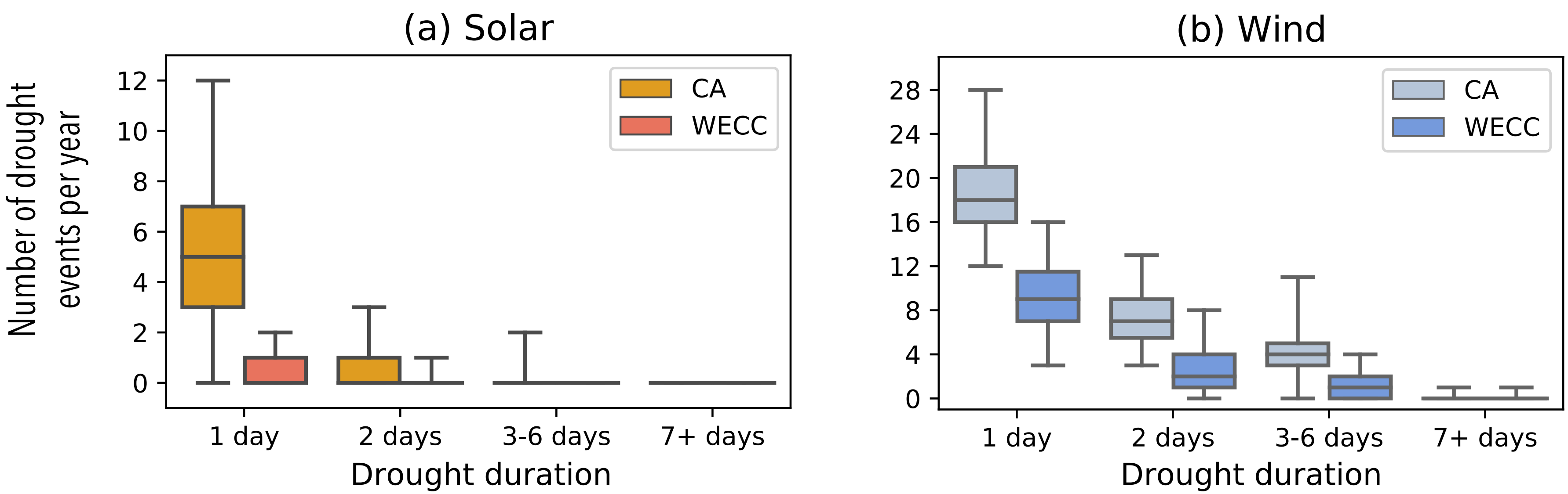


California
CAMX region which includes balancing authorities of all the major cities (SF, LA, SD)

Tightening geographical constraints increases resource variability



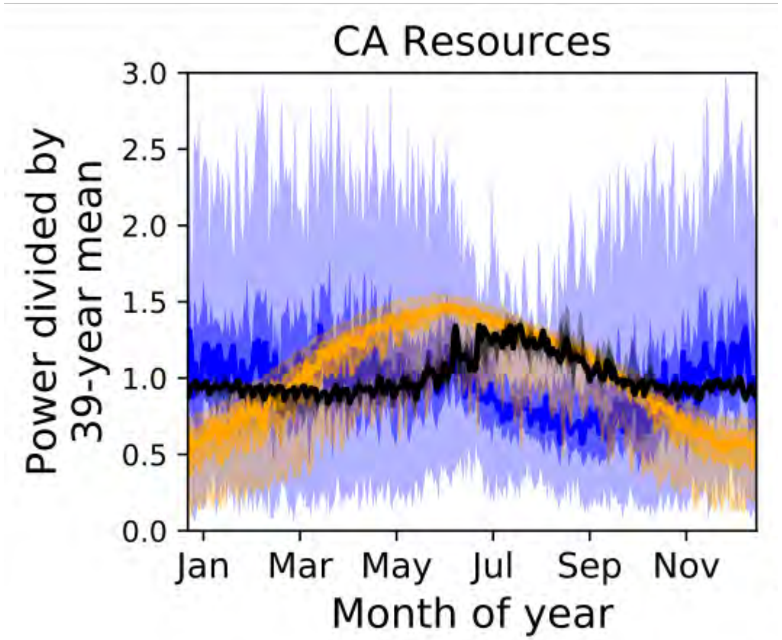
California experienced prolonged periods of resource drought



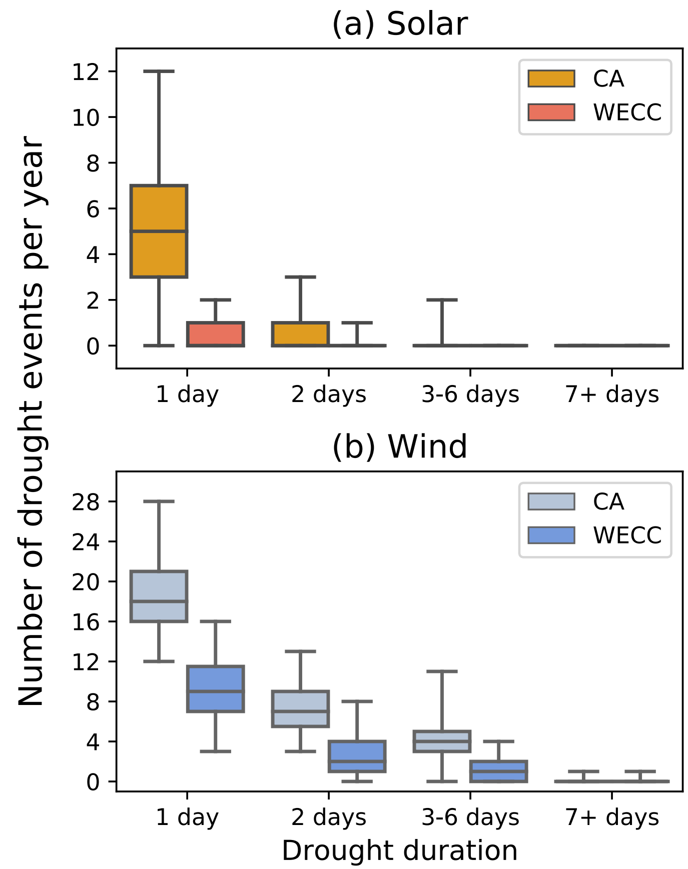
- For both the wind and solar resources, aggregating resources over WECC instead of California reduces the frequency and duration of these resource droughts but does not eliminate them
- These events are rare, but severe. If you only use a few years of data you could miss them
- Climate change related effects could worsen this issue

Data-driven quantification of resources

Variability



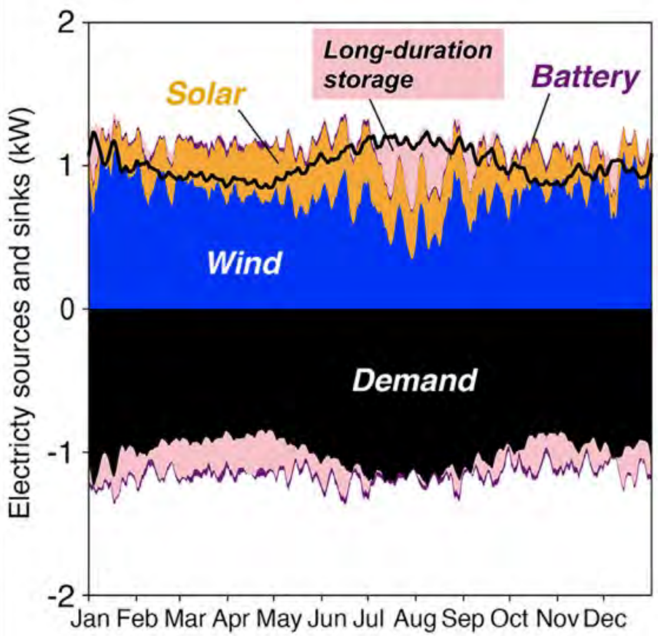
Availability



Options to compensate for inherent resource variability

Aggregation of Wind and Solar Resources

Addition of Long-duration Storage



Dowling, Jacqueline A., et al. "Role of long-duration energy storage in variable renewable electricity systems." *Joule* 4.9 (2020): 1907-1928.

Defining Scenarios

CA as an island

California demand
California wind and solar

CA with WECC resources

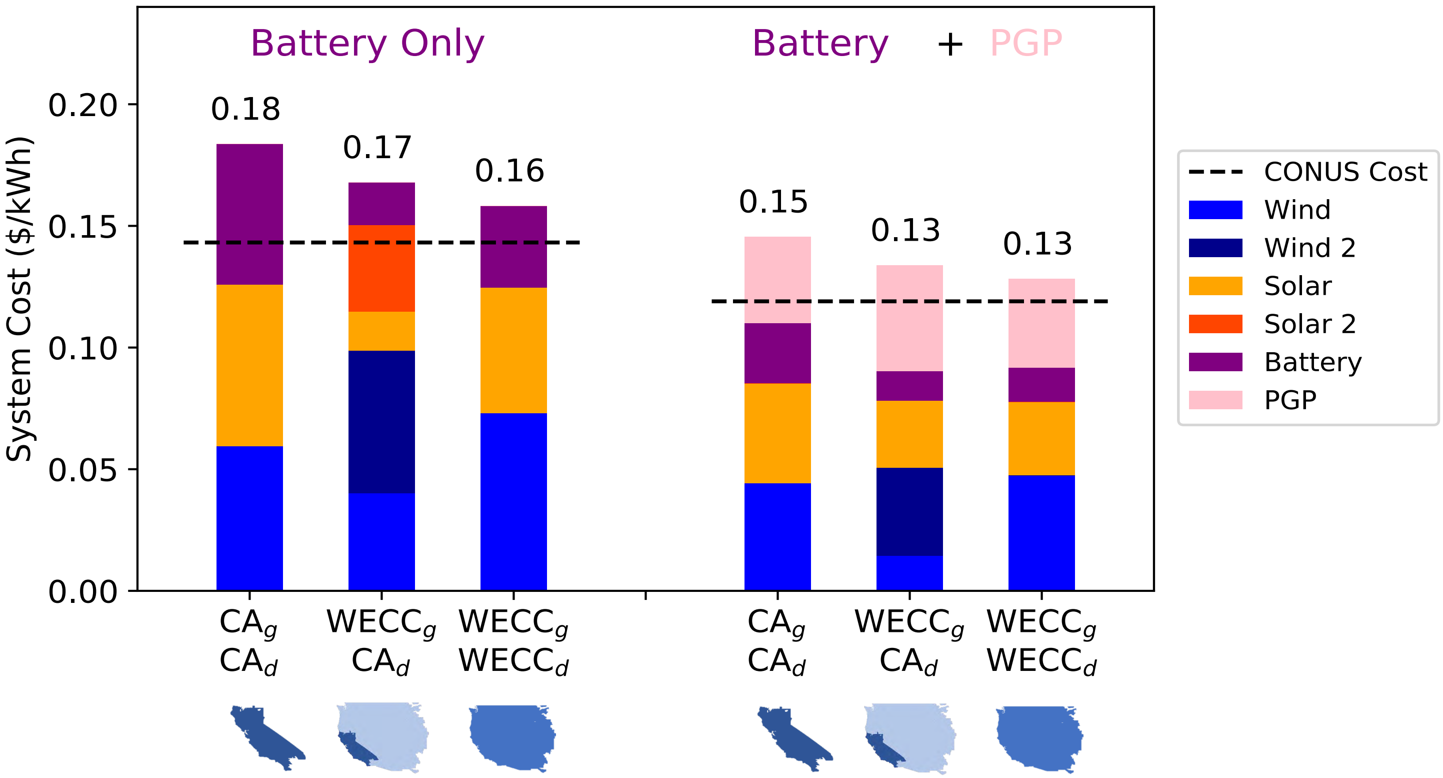
California demand
CA + WECC wind and solar

WECC as an island

WECC demand
WECC wind and solar

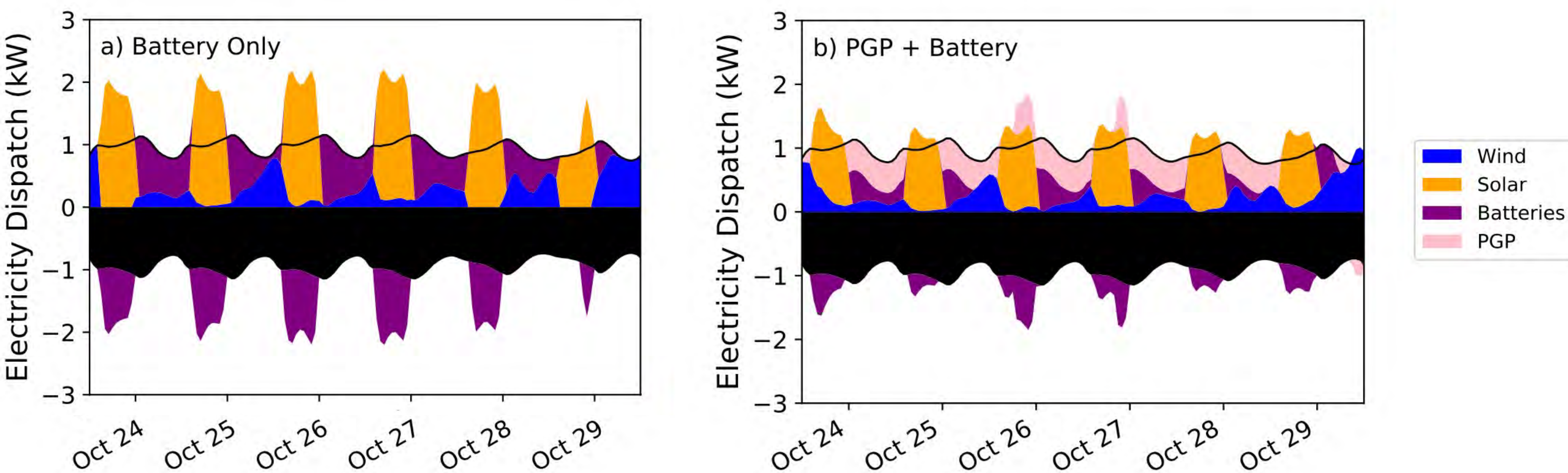
Each of these scenarios is modeled with and without long term energy storage (PGP)

Overall Modeling Results



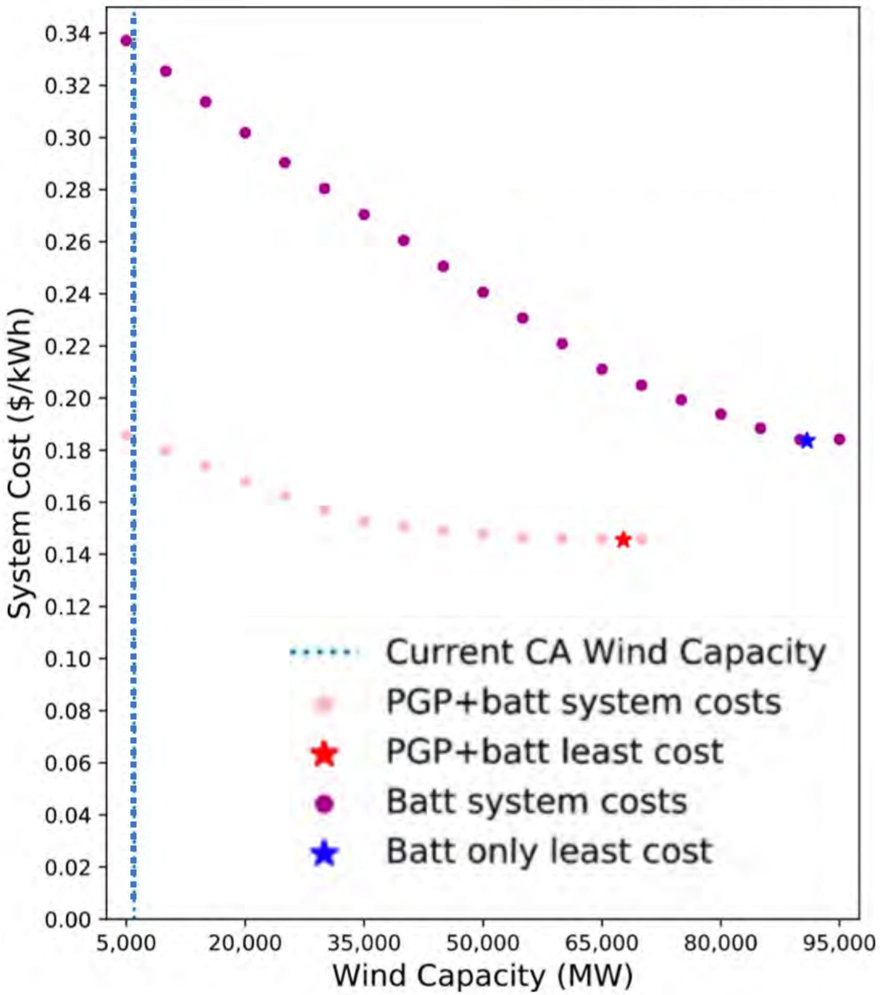
- For wind-solar-battery electricity systems, meeting CA demand with generation resources from WECC reduces costs by 9% compared to constraining resources entirely to CA
- Adding long-duration storage to systems that use California generation resources to meet California demand lowers costs by 21%

Long-duration storage fills the gaps during periods of resource drought



- Hourly dispatch over a wind drought lasting from October 24 to October 29
- In a battery only system, excess solar is used to charge batteries to meet demand
- When included, PGP fills the gaps instead.

Specifying Wind Capacity



Long-duration storage further reduces costs relative to battery only systems when wind capacity is restricted

Conclusions

- **Data-driven, multi-year analysis demonstrates the inherent issues of variability and availability for wind and solar resources in California**
  - Over a period of 39-years, California experiences multi-day cloudy and calm periods over the whole state. These rare but severe weather-related events lasted up to six days in the solar resource and up to ten days in the wind resource

- **Aggregating resources over larger areas like WECC reduces the frequency and duration of these events and can reduce costs in 100% reliable, renewable electricity systems**

- **Long-duration storage can cost-effectively compensate for these periods of prolonged resource drought.**
  - It also makes it more cost-effective for California to meet its own electricity needs without relying heavily on out-of-state infrastructure

Acknowledgements

Nathan Lewis

nsl@caltech.edu

Ken Caldeira

kcaldeira@carnegiescience.edu

Jacqueline Dowling

jdowling@caltech.edu

Katherine Rinaldi

kat@caltech.edu

We also acknowledge the contributions of our co-authors:
Prof. Steve Davis, Dr. Mengyao Yuan, Dr. Fan Tong, and Dr. Tyler Ruggles

RESNICK INSTITUTE
science + energy + sustainability
Caltech
CARNEGIE SCIENCE
SoCalGas
A Sempra Energy utility
Gates Ventures