PROGRESS REPORT for EPC-19-060

October, 2021

Recipient Project Manager: Sarah Kurtz

Commission Agreement Manager: Jeffrey Sunquist

What we planned to accomplish this period

1. We will prepare the materials for the November public workshop
2. We will assemble both solar and wind 8760 files for the inputs to RESOLVE
3. We will continue work on the multiple papers.
4. We will continue to meet with stakeholders and community representatives to gather inputs and request feedback
5. We will continue working with E3 to implement the first steps of a plan about the changes to RESOLVE
6. We have an opportunity to present posters at a meeting of the Global Climate Leadership Council (which is run by University of California Office of the President) as they are discussing how to meet the UC's goals to achieve Carbon Neutrality by 2025. This group will be meeting at UC Merced in mid-October. We plan to share five posters related to this project.

What we actually accomplished this period

1. Materials for November public workshop

The materials for the November public workshop were prepared in time for submission on November 2. The submitted files can be viewed at https://www.energy.ca.gov/event/workshop/2021-11/staff-workshop-strategies-model-long-duration-storage . We are not attaching them here to avoid big attachments in emails. The submitted files include a PowerPoint presentation and two draft reports.

2. Assembly of 8760 files for inputs to RESOLVE (and SWITCH):

RESOLVE currently uses 37 representative days selected from 2007, 2008, and 2009 as the basis for the optimization. E3 plans to make more data sets available, but E3 does not plan to provide full-year (8760-hours) files. We would like to be able to use the full-year data to have more confidence in our understanding of the potential for long-duration storage. We would also like to be able to run simulations for multiple years to explore the effects of variable weather patterns on the use of long-duration storage.

The process of assembling these files includes several steps.

For solar:

1. Identify the location (or set of locations)
2. Identify the year
3. Extract the irradiance data relevant to the location and year using satellite data available in the National Solar Radiation Database (NSRDB) and store in a file with both temperature and irradiance
4. Identify the orientation of installation
5. Calculate the hourly solar electrical generation profile based on the irradiance data, temperature data, and common solar panel properties for each selected orientation and system configuration (see below)
6. Define how to use the multiple locations into a representative “resource”
7. Calculate the generation file for each identified representative resource from the average of the generation profiles for that resource, weighted by the anticipated potential capacity for that specific location.
8. Verify confidence in the data by comparing to existing data sets

For wind:

1. Identify the location (or set of locations)
2. Identify the year
3. Identify the power curve
4. Identify the height of the turbine
5. Using the simulated wind-speed data from NREL’s Wind Toolkit and the selections from steps 1-4, calculate the hourly wind generation profile for each location in the set of locations.
6. Define how to use the multiple locations into a representative “resource”
7. Calculate the generation file for each identified representative resource from the average of the generation profiles for that resource, weighted by the anticipated potential capacity for that specific location.
8. Verify confidence in the data by comparing to existing data sets.

Toward implementing the above, as of October 31, we obtained the NSRDB irradiance data for all of California for the years 1998 through 2020, completing steps 1 through 3 for solar.

For step 4 for solar, we have selected four system designs:

1. One-axis-tracked horizontal-tilt with DC/AC=1.3. This duplicates the current design used by E3 in RESOLVE
2. South-facing latitude-fixed-tilt with DC/AC=1.3
3. One-axis-traced, south-facing latitude-tilt with DC/AC=1.3
4. South-facing latitude-fixed-tilt with DC/AC=1.5.

The reason for using the higher DC/AC ratio for the fixed system is that there are fewer hours per year when that system will be putting out full power, so the clipping will be less serious than for the others.

We have spent substantial time discussing the approach to defining the locations for each resource. This is a research project in and of itself. E3 has now shared with us the files that defined the locations they used for the various candidate sites. However, the file was created before some updates to the NREL data base, complicating the use of this file and the mapping of the data in the file to what has been historically used in RESOLVE is complicated as can be seen in Table 1. It appears that RESOLVE candidate resources were derived from this file by selecting only a subset of the total available sites that were documented. We will discuss the differences with E3 to see how they plan to handle this.

Table 1. Solar resources

CPUC Zone name from E3 file for new solar	**RESOLVE candidate resource name (with "Solar") "Can_build" = 1**	**RESOLVE Capacity limit (MW)**	**AC capacity in E3 file column F (MW)**
Central_Valley	Central_Valley_North_Los_Banos_Solar	12873	95457
	Distributed_Solar	26778	
Mountain Pass El Dorado	Mountain_Pass_El_Dorado_Solar	248	5761
Greater_Imperial	Greater_Imperial_Solar	35216	186818
	Carrizo_Solar	9907	
Greater_Carrizo	Kern_Greater_Carrizo_Solar	8329	130318
Kramer_Inyokern	Kramer_Inyokern_Ex_Solar	4508	157088
	Inyokern_North_Kramer_Solar	23653	
	North_Victor_Solar	4608	
Northern California	Northern_California_Ex_Solar	41532	948194
Riverside East Palm Spring	Riverside_Palm_Springs_Solar	57071	115383
	Sacramento_River_Solar	23484	
	SCADSNV_Solar	5608	
Solano	Solano_Solar	12025	187227
	Solano_subzone_Solar	0	
Southern_California_Desert	Southern_California_Desert_Ex_Solar	43713	73645
Southern_Nevada	Southern_Nevada_Solar	148600	743520
	Tehachapi_Ex_Solar	1488	
Tehachapi	Tehachapi_Solar	4801	121860
	Westlands_Ex_Solar	4404	
Westlands	Westlands_Solar	56151	262941
Arizona	Arizona_Solar	77080	385400
Total		**602077**	**3413612**

We will be continuing work on this task in November.

3. Continued work on multiple papers:

Updates on the multiple paper status are summarized in Table 2:

Table 2. Papers that are in progress. New developments are in **bold**.

Topic of paper	Targeted journal	Status	Lead author	Primary conclusion/impact
1a. Defining long-duration storage	Issues in Science and Technology	Published	All	Defining long-duration storage broadly will stimulate innovation
1b. Defining long-duration storage	Joule	**Published**	Noah Kittner	Defining long-duration storage broadly will stimulate innovation; define taxonomy
2. Seasonal challenges	PVSC conference proceedings	Published	Mahmoud Abido	Seasonal storage in a solar-driven grid will show minimum energy storage during the winter
3. Seasonal challenges	iScience	**Resubmitted**	Mahmoud Abido	Biggest challenges to resource adequacy will occur during the winter unless off-shore wind or a flat or dispatchable generator is added
4. Review of currently available storage technologies	Renewable and Sustainable Energy Reviews	Under review by journal	Rui Shan and Jeremiah Reagan	There are many storage options, some of which have the potential to replace existing fossil fuel plants
5a. Analysis of winter-dominant on-shore wind resource in California	Renewable and Sustainable Energy	**Under review by journal**	Zabir Mahmud	A small number of wind generators in California generate more electricity in the winter than in the summer. We are assembling data to assess how consistently this is seen and to assess what fraction of California could show winter-dominant wind generators.
5b. Analysis of storage applications and effect of off-shore wind	Joule	Data are being recalculated based on paper 5a and other results. Data are being organized for first draft	Zabir Mahmud	The amount of diurnal storage needed is about a quarter of a TWh. If the grid is solar dominated, the diurnal storage is used > 350 times/y. If wind is added, we still need the same amount of diurnal storage, but it will be used much less frequently…
6. Time sampling in modeling of storage	TBD	**Draft is almost finalized**	Pedro Sanchez	What is the effect of choosing different time periods on modeling long-duration storage?
7. Impact of load shifting	PVSC conference proceedings	Published	Ashling Leilaeioun	Impact on revenue when load shifting is used to move load from the head of the duck to the belly of the duck

Paper #1b: *Joule* published the paper – see attached.

Paper #3: Seasonal changes: The review was completed by *iScience*. We have revised the manuscript and resubmitted.

Paper #5a: Winter-dominant wind: We are awaiting review by Renewable and Sustainable Energy.

Paper #5b: *Statistical analysis of storage needed as a function of mix of generation*: We found that, in response to comments from reviewers of the other articles, we should model the storage as being less than 100% efficient. We needed to revise the various parts of the code to account for the less than 100% efficient. This was not as straightforward as was initially expected and has required a revision to the approach we were using for these calculations.

*Paper #6: Time sampling for capacity expansion plannin*g: A first draft of this paper is nearing completion. We plan to submit it in November.

With the multiple publications being finished, *we have updated the website* at https://sites.ucmerced.edu/ldstorage/publications%20version%202.

We have also updated the Knowledge Transfer Plan and will attach it to this monthly report.

4. Stakeholder and collaborator meetings: During the month of October, we met with:

- Roderick Go at E3
- Julia Prochnik of Long Duration Energy Storage Association of California
- Greg Rosen and Eshhar Chetsrony of Augwind
- David Bierman of Antora Energy
- Emailed with Priya Sreedharan of Gridlab, Ron Sinton of Sinton Instruments and several storage companies (Malta, Quidnet, Clear Creek, 24/7, etc.) to get their input on the draft reports that were submitted.
- Hosted presentation by Jeff Reed of the University of California Irvine on his studies of how hydrogen could be adopted if it can be used in natural gas type pipelines

5. Continue work with E3 to develop a plan about the changes to RESOLVE

E3 shared the files that define the locations for the various resources for RESOLVE. We are beginning to use those.

E3 is progressing rapidly on their code development now. Once the workshop summary is completed, we anticipate moving faster on the code.

6. We presented five posters at the Global Climate Leadership Council (which is run by University of California Office of the President) meeting on October 14-15, 2021.

We prepared and presented five posters On Oct. 14-15. These are attached for reference.

“Seasonal Challenges for a California Renewable-Energy-Driven Grid” Mahmoud Abido, et al

"Geographical Variability of Summer- and Winter-dominant Onshore Wind” Zabir Mahmud, et al

“Evaluating emerging long-duration energy storage technologies” Jeremiah Reagan, et al

"Time sampling strategies for studying the value of long-duration storage" Pedro Sanchez, et al

"Utilization of Energy Storage in California's Electrical Grid" Daniel Baerwaldt, Socheata Hour, Yi Hao Xie, Sarah Kurtz

How we are doing compared to our plan

The creation of the full-year generation profiles for the multiple candidate solar and wind resources is taking longer than we expected. Once the public workshop is completed in November, this will be our primary focus. Otherwise, things have not changed from last month.

Significant problems or changes

No change from last month.

What we expect to accomplish during the next period

1. We will submit the materials for the November public workshop
2. We will participate in the November public workshop and write a summary of the workshop
3. We will continue work on the multiple papers.
4. We will continue to meet with stakeholders and community representatives to gather inputs and request feedback
5. We will continue working with E3 to implement the first steps of a plan about the changes to RESOLVE

Status of Milestones and Products.

Task #	Task	Deliverable	Due date	Status
1.2	Kick-off meeting	Updated budget	9/18/2020	Complete
1.3	CPR Meeting #1	CPR Report	TBD	
	CPR Meeting #1	CPR Meeting #1	TBD	
1.4	Final meeting	Final Meeting	11/11/22	
		Schedule for closeout	11/18/22	
		Draft and Final Written Products	11/18/22	
1.5	Progress Reports & Invoices	Progress Reports	Monthly	Ongoing
		Invoices	Monthly	Ongoing
1.6	Final Report	Draft Outline	6/30/22	
		Final Outline	TBD	
		Draft Report	8/30/22	
		Final Report	10/31/22	

		Written Responses to Comments on Draft Report	9/15/22	
1.7	Match funds	Status letter	9/9/20	Revision submitted
1.9	Subcontracts	Final subcontracts	TBD	Awaiting CEC approval of revised budget
1.10	TAC	List of potential members	9/9/20	Completed
		List of TAC members	TBD	Completed
		Documentation of TAC member commitment	TBD	Completed
1.11	TAC Meetings	Draft TAC meeting schedule	10/1/20	Completed
		TAC meeting 1	11/4/20	Completed
		TAC meeting 2	8/5/21	Completed
		TAC meeting 3	2/3/22	
		TAC meeting 4	11/2/22	
		Note, each meeting need multiple actions		
		Final TAC meeting schedule	TBD	Completed
		Draft TAC meeting agenda	TBD	First one completed
		Backup materials	TBD	First one completed
		Final TAC Meeting agenda	TBD	First one completed
		TAC meeting summaries	TBD	First one completed
2.1	Data assembly	Draft baseline description	2/4/21	Completed
		Final baseline description	2/25/21	Completed
2.2	Confirmation of baseline data and approach	Draft modeling approach description	2/4/21	Completed
		Final modeling approach description	2/25/21	Completed
2.3	Implementation of baseline data into models to create initial baseline scenario	Summary of baseline model results	3/23/21	Completed
		CPR Report #1	15 days prior	Completed

3.1	Evaluate and document future energy storage technology alternatives	Draft storage Technology summary	7/2/21	Completed
		Final storage technology summary	8/12/22	
3.2	Define representative future energy storage technology alternatives	Draft proposed storage scenarios summary	4/1/22	
		Final	8/12/22	
3.3	Evaluate and document future energy electricity generation technology alternatives	Draft electricity generation technology summary	8/2/21	Completed
		Final	8/12/22	
3.4	Define representative future electricity generation technology alternatives	Draft proposed electricity generation scenarios summary	4/1/22	
		Final	8/12/22	
4.1	Multi-day model optimization	Summary of multi-day baseline model results	9/2/21	Completed
		CPR #2	**Summer**	
4.2	Grid scenario selection	Draft grid scenario summary	10/11/21	Requires RESOLVE to be functioning
		Final	12/13/21	
5.1	Preliminary Scenario Analysis	Draft preliminary analysis summary	2/11/22	
		Final	4/15/22	
5.2	Final scenario analysis	Draft final analysis summary	6/10/22	
		Final	8/12/22	
6.1	Initial public meetings	Opening workshop presentation materials	11/17/20	Completed
		Northern CA workshop	12/3/20	Completed
		Southern CA workshop	12/3/20	Completed
		Opening workshop summary	1/8/21	Completed
6.2	Public workshop for grid scenario selection	Agenda	11/2/21	In progress
		Presentation materials	11/2/21	In progress
	Public workshop with CEC and TAC to present proposed scenarios		11/16/21	Scheduled for 11/17/21
		Workshop summary	11/23/21	

6.3	Public workshop for preliminary scenario analysis	Agenda	3/3/22	
		Presentation materials	3/3/22	
	Public Workshop with CEC and TAC to present preliminary analysis		3/18/22	
		Workshop summary	3/25/22	
6.4	Public Workshop for Final Scenario Analysis	Agenda	7/1/22	
		Presentation materials	7/1/22	
	Public workshop with CEC and TAC to present final analysis		7/15/22	
		Workshop summary	7/22/22	
7	Evaluation of Project Benefits	Kick-off meeting benefits questionnaire	9/18/20	Completed
		Final meeting benefits questionnaire	10/14/22	
8	Knowledge transfer activities	Draft initial fact sheet	7/23/20	Completed
		Final initial fact sheet	7/30/20	Completed
		Draft final project fact sheet	7/21/22	
		Final project fact sheet	7/28/22	
		Draft knowledge transfer plan	12/31/20	Completed
		Final knowledge transfer plan	2/26/21	Completed
		Draft knowledge transfer report	8/30/22	
		Final knowledge transfer report	10/31/22	

KNOWLEDGE TRANSFER PLAN for EPC-19-060

Draft January 12, 2021

Updated November 2021

Recipient Project Manager: Sarah Kurtz

Commission Agreement Manager: Jeffrey Sunquist

Objectives

We define a Knowledge Transfer Plan that enables both

- Communication of our results
- Gathering of information and feedback from the community

Elements of Communication plan

In the following sections we describe the following elements of the communication plan:

- CEC-hosted public workshops
- Social media: Twitter
- Websites
- Publications – technical audiences
- Publications – general audiences
- Webinars
- Conference presentations
- Private meetings

Knowledge Transfer coordination with E3

Project EPC-19-060 executed by UC Merced and partners will coordinate Knowledge Transfer activities in partnership with the companion project, managed by E3, who is a fellow recipient of grant funds for GFO-19-308. UC Merced will be pleased to share results and stimulating discussions, while maintaining independence in the assumptions and approaches taken. We hope to benefit from the resulting synergy while maintaining the independence that will enable us to obtain unique results.

Table of timeline for planned elements

Communication element	Planned completion date	Status
Public workshop #1 – Introduction to project	Dec. 3, 2020	Completed
Public workshop #2 – Grid scenario selection	Fall 2021	

Public workshop #3 – Preliminary scenario analysis	Summer 2022	
Public workshop #4 – Final scenario analysis	Fall 2022	
LinkedIn site set up	Spring 2021	Completed
Website @ UCMerced live	Spring 2021	Completed
Publication – Defining how we talk about long-duration storage	Spring 2021	Completed
Publication – Developing intuition about when resource adequacy will be most problematic in a zero-carbon world	Summer 2021	Completed
Publication – Technology overview of self-contained long-duration storage technologies	Fall 2021	Submitted
Publication – Comparison of modeling results for SWITCH and RESOLVE – where are the biggest differences?	Winter 2021-22	
Publication – How much difference could EV charging strategy make for long-duration storage?	Spring 2022	
Publication – Geographical distribution: does it matter where we put the storage resources?	Summer 2022	
Publication – Cross-sector opportunities: what are the best options for making use of variable cheap electricity	Fall 2022	
Publication – What technologies will be available when according to the learning curve analysis?	Winter 2022-23	
Publication – In the final analysis, what cost targets would each duration/efficiency of long-duration storage need to hit to be useful?	Spring 2023	
Webinar participation – Long-duration storage	Spring 2021	
Webinar participation – Resource adequacy for a zero-carbon grid	Fall 2021	
Webinar participation – Effects of EV charging on needed long-duration storage	Spring 2022	
Webinar participation – Actions CEC can take that will make a difference	Fall 2022	
Webinar participation – What will be the most important roles of long-duration storage in a range of scenarios?	Spring 2023	
Conference presentation – Seasonal challenges of resilience for a zero-carbon grid?	Summer 2021	
Conference presentation – Self-contained long duration storage options	Fall 2021	
Conference presentation – Optimal geographical placement of storage assets	Summer 2022	
Conference presentation – Types of long-duration storage assets needed as a function of time	Fall 2022	

CEC-hosted public workshops

Dec. 3, 2020 – First public workshop was held

3. French, S. (2020). Low-Carbon Hydrogen Production. In H2FC Supergen Hydrogen Research Conference 2020.

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Commentary

Cross-sector storage and modeling needed for deep decarbonization

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Sarah Kurtz is a Professor at the University of California Merced. She spent more than 30 years at the National Renewable Energy Laboratory studying multi-junction III-V solar cells, reliability of photovoltaic modules and systems, and other solar-related projects. She is now leading a study of the value of long-duration storage, funded by the California Energy Commission.

As many researchers work to achieve a decarbonized grid, there is a general appreciation that we need to model the total energy system, but that doing so is difficult, if not impractical. Studies may focus on one piece of the grid and reach a conclusion whether a particular approach will or won't work. Including cross-sector storage in modeling provides opportunities to enable solutions that are otherwise impossible to identify and that may become the key to reaching a lowest-cost, lowest-carbon energy system.

The dramatic decline in cost of wind and solar electricity generating technologies illustrates this point, with wind and solar well-positioned to replace high-carbon energy sources. Due to their variability, wind and solar require enabling technologies to maximize their potential as part of a decarbonized energy system. Enabling technologies that could help achieve rapid decarbonization and integration across sectors include—but aren't limited to—long-duration energy storage, electric vehicles, distributed energy resources (DERs), heat pumps, thermal storage, net-zero hydrogen production, and negative emission technologies. These technologies differ in terms of their role and function in the electricity grid and reach across sectors. A focus on a single technology could lead to narrow solutions. This commentary provides a structure to articulate the role of different enabling technologies and cross-sector options to achieve energy system decarbonization and background to help readers assess whether a modeling study is likely to have missed opportunities that could limit the applicability of the conclusions. Today, energy storage is rapidly increasing in performance and decreasing in cost.[1]

The integration of energy storage and renewables into the grid demands new models that focus on novel approaches to explore and manage their optimal operation and least-cost solutions. These types of systems models are already evident in analyses considering electrification of transportation, space heating, and cooking. Typically, in the electric sector, there has been a focus on short-duration, electric energy storage to assist with the variability of wind and solar–think lithium-ion batteries for a Powerwall or utility-scale installations such as the Tesla Megapack in South Australia. Lithium-ion batteries are dominant for electric vehicles and in new grid-scale storage models. In the transportation sector, emerging research considering vehicle-to-grid applications of lithium-ion batteries is at the state-of-the-art. A cross-sector approach could be even more informative. With renewed interest in green hydrogen, produced by excess electricity from solar and wind, there could be a scaling effect in the demand for hydrogen affecting transportation electricity trajectories and power sector load profiles. A shift toward hydrogen has multiple implications that we need to understand more clearly, not just in the electricity sector, but also for transportation, agricultural, and industrial applications.

Whereas decarbonization efforts have focused on identifying sector-specific interventions—such as the reduction of CO_2 intensity in a coal-fired power plant or the adoption of energy efficient appliances—new classes of tools are needed to consider cross-sector, cross-day aspects of energy choices. Transforming variable solar and wind electricity into reliable generation sources places a greater emphasis on forecasting the timing of energy supply and demand. For instance, will increased reliance on solar and wind demand a strategic hydrogen reserve similar to current stocks of natural gas production? If we move to a decarbonized future that heavily emphasizes electrification, how much more supply will we need to produce? To some extent, cross-sector models have been implemented and are interrogated by different groups–these include NEMS, GCAM, and TIMES/MARKAL.[2–4] Yet some of these models have not yet fully integrated the temporal and operational implications of solar and wind-dominated transition—from short-term supply fluctuations to seasonal changes in resource availability. For instance, recent work highlights how important duration and temporal resolution becomes when thinking about deep decarbonization of electricity.[5] A cross-sector solution would identify complementary technologies across multiple durations and locations in the energy system. The electric sector demand from transportation, heating, cooling, and power-to-gas may completely shift because of a decarbonized energy system and change our needs during different months and hours. Therefore, cross-sector storage may be quite important in solving both diurnal challenges and seasonal fluctuations. Simply lumping all energy storage into single categories such as short-term, seasonal, and cross-day durations may fall short of our needs though as there are technologies that fulfill multiple purposes and can adapt based on geography-specific energy system requirements.

Some studies have explored, from a decarbonization standpoint, the role of solar thermal, electric, and gas water/space heating in integrating renewable energy to the grid.[6,7] Other studies begin to analyze the implications of a cross-sector shift in heating demand from gas-based fuels to electricity.[8] Yet more work of this nature is needed to understand the size, scale, and scope of technology interventions that cross sectors and the resulting implications for total energy system decarbonization.

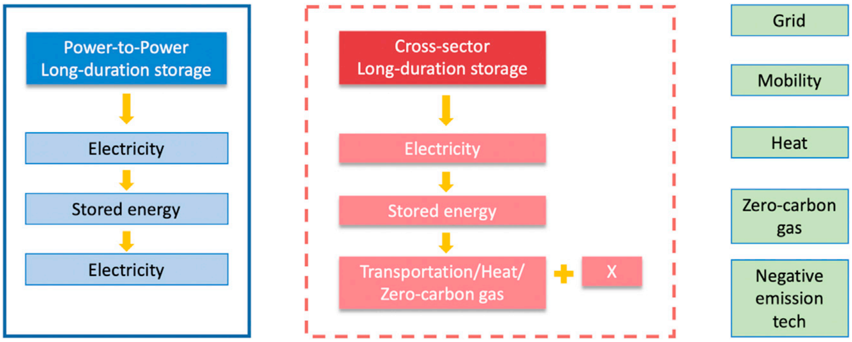

Figure 1. An example of self-contained Power-to-Power storage (blue), cross-sector storage (red), and different categories of input and end-use sectors (green) that could benefit from different energy forms such as electricity, heat, and hydrogen

Negative emission technologies are also becoming a topic of important research and debate convergent with energy storage. How much energy should we divert toward implementing negative emission technologies, such as carbon capture and storage, direct air capture of CO_2, and innovative processes such as the CO_2-to-liquid fuels for use across different energy sectors? Direct air capture, such as systems developed by Climeworks, to directly convert ambient CO_2 in the air using heat and electricity into stored or re-usable CO_2 that feeds agricultural greenhouses and useful products is emerging as a potential consumer of heat and electricity as a flexible load. Existing plants capture up to 4,000 tons of CO_2/year, but as costs decline to below \$750/ton, these facilities could increase to hundreds of millions of tons of CO_2 removed from the air.[9,10] They could offer flexibility in the timing of operation – yet this scale-up would also require increasing amounts of electricity and (ideally waste) heat.

With all these technologies emerging as potential storage options, it could help to map out different applications and use-cases of energy storage. For instance, biogas, which is typically viewed as a generation technology, could be used as a way to balance the grid regardless of its categorization as generation or storage. One way to represent opportunities across sectors is to consider the time-scale or duration of storage and second, the input and end-use form of energy.

Input and end-use storage categories

Storage can occur within and across sectors. For example, hydrogen can be used as storage within the power sector or can be used to couple the power sector with different sectors such as transportation, industrial, or agriculture. Distinguishing between power-to-power storage and cross-sector storage is crucial for better modeling approaches and policy decisions. Rather than treating storage as one monolith with similar properties – including some categorizing features of input and output energy forms would be helpful to develop more integrated pathways toward deep decarbonization.

A long-established challenge of integrating higher shares of variable solar and wind electricity on the grid is modeling storage. Inevitably, there are periods where a system may generate a surplus of electricity and not enough during times of high demand such as at night when the sun does not shine or when the wind is not available either. Having flexibility on what to do with that electricity becomes increasingly important.

We could store electricity into different energy carriers or vectors and then transform them into electricity, gas, heat, hydrogen, or use it to capture CO_2. Each of these options carries its own pros and cons and depends geographically on needs. Figure 1 displays a few configurations of input and end-use storage options. The blue displays a self-contained, power-to-power form of storage. In the middle, in red, we see there are other potential forms of cross-sector storage that can be used with electricity. Alternately, there is a list of services on the right side in green that can take different forms of energy–electricity, heat, hydrogen gas, or other energy that are important areas for decarbonization research.

The form of energy flowing in and out of an energy reservoir such as electricity, heat, and hydrogen and the form of the final energy demand served from storage could be represented as one way to classify different types of decarbonization strategies. This has been referred to as Power-to-X but can be expanded when electric power is not the input category. For instance, waste heat from thermal generation could be stored as thermal storage and then converted into electricity for use when the sun is not shining. If that was not an ideal or efficient use of the thermal energy, it could be used to contribute to other heat applications, gasification, or use in a negative emission technology such as direct air capture.

Many storage technologies can address different sectors or different storage applications across durations. In models that focus on deep decarbonization, with an end goal of zero or near-zero emissions across sectors, the desired goals should focus on the function of the storage to meet the major objective rather than compartmentalizing each storage technology into a reduced-function form–where batteries either provide ancillary services or longer-duration resilience needs. Under a changing climate, resilience needs may arise as extra redundancies in storage may allow us to adapt and cope with extreme wildfires, heat events, and flooding that are increasingly experienced.

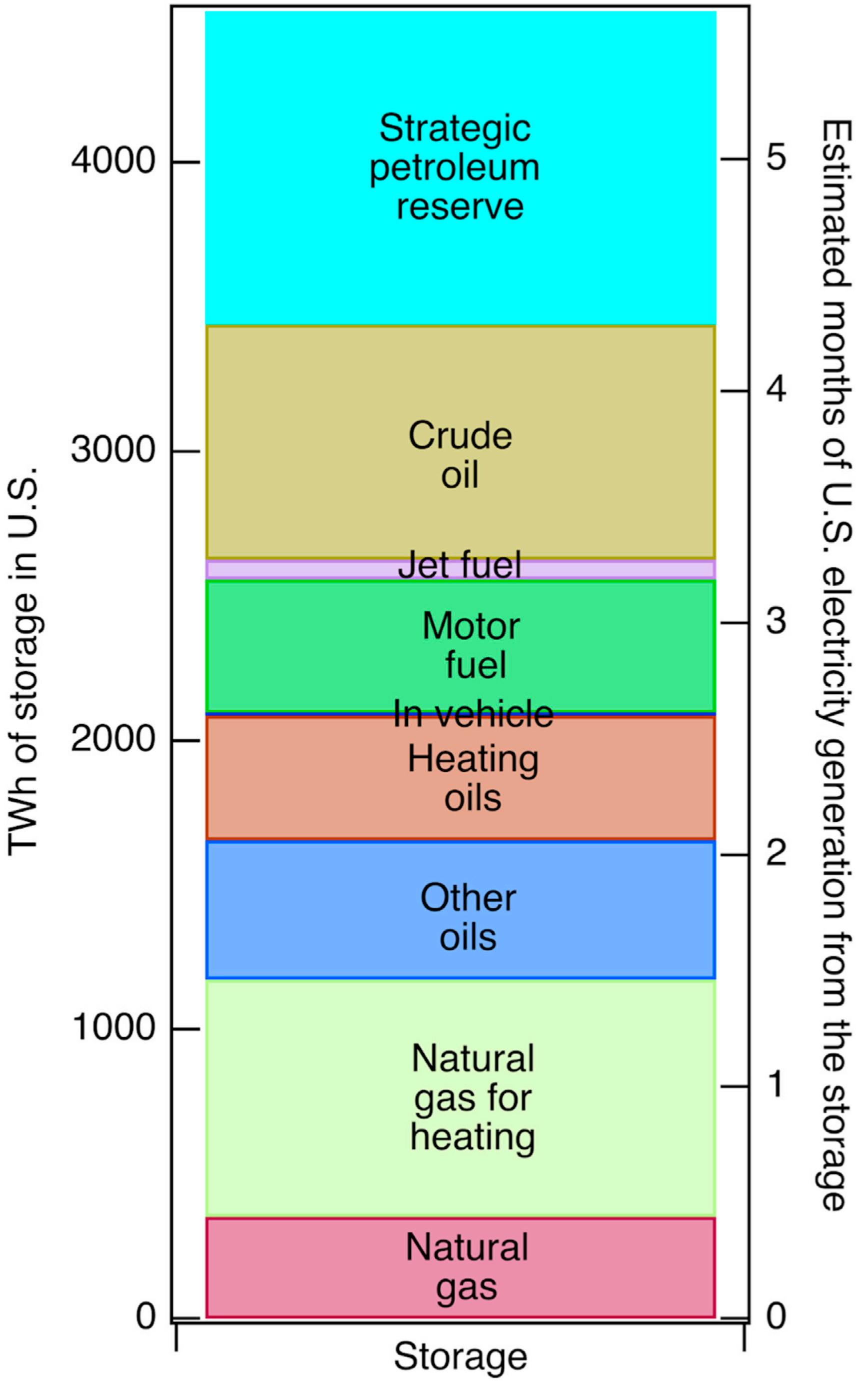

Figure 2. Approximate chemical energy storage used to supply the transportation, heating, power, and chemical sectors today

The TWh of chemical energy on the left axis is translated into estimated months of electricity generation assuming 40% efficiency and U.S. use of 3800 TWh of electricity in 2020. The natural gas stored for heating applications was estimated from the depletion of the stored natural gas during the heating season. The 350 TWh "Natural gas" may be used for power generation, heating, or other uses. The "In vehicle" estimate assumed 300 million vehicles with 30 kWh of storage in each. Data from EIA.[11–13]

Large-scale, long-duration energy storage

In this vein of resilience and providing a backup for power balancing, energy storage may also strategically provide security for a household, company, or country seeking to ensure their likelihood of having energy services available during a time of crisis. For instance, the United States currently maintains a strategic petroleum reserve to use—as a result of the 1973 Oil Crisis—and continues to pursue large storage reserves. These stocks are maintained as a way to hedge against extreme crisis–such as during the COVID-19 pandemic, wildfire season, or natural disaster disruptions that can affect the ability to produce energy resources.

Figure 2 shows how the United States maintains its Strategic Petroleum Reserve as well as chemical energy storage for transportation, heating, electricity, and other sectors. This concept demonstrates there is a cross-sector opportunity to provide energy security for a grid that has high penetrations of wind and solar electricity yet may remain vulnerable to outside threats.

In a deeply decarbonized US, there are many ways that a Strategic Energy Reserve could take shape. Having a cross-sector approach would build resilience, yet much of the chemical energy stores could shift across different energy sectors. For instance, for those who view electrification of end-use sectors as a critical pathway toward meeting aggressive climate reduction targets, having a Strategic Electricity Reserve could come in handy–particularly during natural disasters such as the California wildfires, Texas winter cold spells, or extreme heat waves that are likely to occur over the next half-century as global warming continues. This Strategic Energy Reserve for Electricity could take multiple forms serving as an example of a cross-sector opportunity. The reserve would allow for a resilient response to threats such as climate change, cybersecurity breaches, or resource scarcity. It could be a multipronged strategy that contains long-duration energy storage, zero-carbon generation sources, and distributed infrastructure that can operate independent of the larger electric grid.

With increased attention toward electrifying transportation, a cross-sector approach may suggest that vehicles need strategically located DC-fast chargers to provide short bursts of power rather than long duration energy storage devices that serve multiple days. Yet, for more remote areas that are heavily reliant on one or two primary high voltage transmission lines, there may be significant value in siting more flexible technologies such as flow batteries, gravity storage, or liquid-air type energy storage plants that could provide such a Strategic Electricity Reserve.

Currently, balancing authorities are responsible for matching electricity supply and demand within a specific region. In the United States, there are 74 different balancing authorities. These interconnections govern the transmission of power and are responsible for power grid reliability in real time. Multiple months of distributed and centralized electricity reserves could be coordinated across balancing authorities with an accounting of both transmission and utility-scale storage resources to improve interconnectivity and resilience in case of emergency. This would also benefit utilities during a cybersecurity threat or attack even if the physical amount of chemical storage is decreased, going beyond the capabilities of capacity markets.

The volume of the Strategic Petroleum Reserve in energy will likely decrease in an electrified future. However, as estimated on the right-hand side of Figure 2, it's likely that a Strategic Energy Reserve for Electricity would be useful that lasts up to six months, if not more. For instance, this storage volume could be simultaneously considered across energy sectors, for electricity, transportation, industry, and chemicals. When coupled with renewable energy such as solar and wind plants, the reserve would consist of the necessary enabling technologies to recharge the grid and maximize the availability of the solar and wind that could reconnect in an emergency. This energy reserve could focus on the availability of longer-duration storage, expanded transmission, or zero-carbon generation options in the event of a significant catastrophe, where one would need to not only utilize solar and wind for real-time loads, but also recharge storage devices to ensure against a cloudy or windless day. The reserve does not need to consist of all chemical storage, a diverse range of sectors would build resilience and opportunities to recover from outages or security threats and ensure the availability of energy for conversion to electricity.

A deeply electrified and decarbonized energy system dramatically changes the timing and intermittency of generation. Domestic renewable energy fluctuates, yet potentially builds resilience by having many more generators—both centralized and distributed—than a system that historically is reliant on large-scale (> 300 MW) thermal generators and nuclear power stations for electricity. The geographic distribution of variability offers some benefits that could reduce need for a Strategic Energy Reserve. Short-duration forms of power support for reliability in a low-inertia power system would be critical–areas where batteries, flywheels, and supercapacitors shine. For vehicular and building resources, more dense and distributed charging stations for batteries and other gas supplies such as hydrogen vendors would also reduce the need for conventional chemical storage. Depending on the energy input type and the energy output type, the security afforded by large stocks of petroleum and oil resources could be replaced. In a new system, security could be defined by the ability to produce electricity, heat, or hydrogen gas at a moment's notice, with the accompanying generation source. It could be a literal store of these energy types. In a system focused on electricity that could include greater electricity storage such as long-duration gravity or hydro-based systems. With opportunities to store energy as hydrogen gas or liquid hydrogen, this low carbon fuel could provide stable seasonal storage to balance demands and offer flexibility across electricity, transportation, agricultural, and industrial sectors, as needed.

The role of gaseous fuels in an electrified world

The role of gas in a deeply decarbonized electrified world remains uncertain. Some proponents suggest carbon capture and storage technology will decrease in cost to become more competitive than alternative and expensive storage. Other potential gas alternatives such as hydrogen could provide low-carbon substitutes into existing pipeline and infrastructure networks. Gas is typically considered an available, on-demand resource that can meet electricity, transportation, and other versatile needs. That's why either liquid hydrogen or hydrogen gas attracts enough attention for a $1/kg Energy Earthshot, as low-cost renewable hydrogen could replace existing natural gas systems with a decarbonized alternative. For existing natural gas and biogas systems, there are potential synergies that utilize the Allam cycle to generate heat and capture CO_2 and water. Carbon capture and storage coupled with power generation makes sense for some places that have legally mandated net-zero emission energy systems. Yet, there may be challenges ahead—one is the impact on air quality from upstream extraction—particulate matter emissions and nitrous oxides may still be present in such systems that can concern public health.[14]

On the other hand, hydrogen presents an interesting opportunity to utilize cross-sector storage in a way that could be mutually beneficial and more efficient to achieve deep decarbonization. Zero-carbon hydrogen gas can be used in a variety of industrial applications where electricity is expensive or inefficient. Zero-carbon hydrogen could facilitate further electrification of end-use sectors and allow for reconversion to electricity through fuel cells as back-up to individual buildings or communities. There could also be the inclusion of hydrogen in steel-making and industrial process heat. If electric heat pumps, vehicles, and induction cooking stoves become more pervasive, there will be less need for natural gas.

Cross-sector approaches can enable commercialization of seasonal storage

A forward-looking modeling and policy approach would analyze cross-sector decarbonization from a systems perspective. Though it is tempting to investigate individual sectors and their responses—better, more holistic, and realistic solutions will likely emerge. Additionally, while technological synergies can be captured that are often neglected, such as the example if hydrogen demand surges, there could be unintended effects of diverted solar and wind electricity to the hydrogen sector when electricity is scarce and expensive. Vehicle-to-grid based electric vehicle interactions could allow for substantial benefits for both the electricity sector and the transportation sector by offering different value streams and making electric vehicles more affordable for large fleets of vehicles, which today consume diesel and natural gas.

By identifying the input and end-use energy types for classifying storage technologies and other generation, one can move beyond labels and confusion arising from short-duration and long-duration classifications of storage. The functional purpose of energy systems can be used in a cross-sector way to solve broader system challenges of decarbonization. Cross-sector thinking can improve overall energy security. Then, modelers and policymakers can identify better technologies suitable toward overall societal goals such as deep decarbonization and rapidly make the changes needed to achieve our ambitions.

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DECLARATION OF INTERESTS

The authors declare no competing interests. This document was prepared as a result of work sponsored by the California Energy Commission. It does not necessarily represent the views of the Energy Commission, its employees, or the State of California. The Energy Commission, the State of California, its employees, contractors, and subcontractors make no warranty, express or implied, and assume no legal liability for the information in this document; nor does any party represent that the use of this information will not infringe upon privately owned rights. This report has not been approved or disapproved by the Energy Commission nor has the Energy Commission passed upon the accuracy of the information in this report.

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Nov. 17, 2021 – Second public workshop

Spring or summer 2022 – Preliminary scenario analysis workshop

Fall 2022 – Final scenario analysis workshop

These workshops will be advertised by CEC to facilitate greater participation. Additional public workshops may be held if there appears to be benefit. The format of the workshops (in-person, virtual, or hybrid) will depend on the status of the pandemic and will be designed to be most effective.

Social media: Twitter

Dan Kammen has a Twitter account with more than 18,000 followers. We will use this as our primary means for communicating:

- Results
- Upcoming events
- Requests for feedback

Other team members also have Twitter accounts. We will take care that the most important results are shared by Dan Kammen who has the widest following.

Social media: LinkedIn

We will create a group on LinkedIn and post information about the project there.

Websites

We will create a website at UC Merced to post information about the project. The websites at each of the partner institutions will provide a link to the main webpage. Specifically, we will arrange to have links from:

- https://coolclimate.org/

We will use our website to attract sharing of information from storage companies.

Publications – technical audiences

Results of the project will be published in peer-reviewed journals to establish the scientific accuracy of the publications. Journals we have used in the past include:

- Applied Energy
- Energy Policy
- Energy Strategy Reviews
- Environmental Research Letters

- Environmental Science & Technology
- Issues in Science and Technology (policy audience)
- Joule
- Nature Climate Change
- Nature Energy
- Science
- Utilities Policy

Publications – general audiences

After publication of studies in peer-reviewed journals, we will capture key conclusions for a general audience. We will identify appropriate trade journals or websites for publication of such reports. For example, Dan Kammen is an advisor for https://www.next10.org/. Next 10 has a program to study Clean Energy and will partner with us on writing and sharing reports written for more general audiences.

Examples of journals read by more general audiences include:

- The Electricity Journal
- Scientific American

Webinars and other Panels, etc.

The Long-Duration Energy Storage of California (https://www.storeenergyca.org) has already approached us (along with GridLab) to participate in a Webinar. We plan to participate in a Webinar with them in 2021 (probably March) and a second in 2022.

We will discuss with Emily Kirsch whether PowerHouse would like to host a focus session on long-duration storage.

Once the Pandemic is under better control, we anticipate the possibility of returning to in-person meetings and participating on panels or in workshops.

We are hosting a set of webinars with limited audiences. So far, we have hosted:

- Keith Parks of Xcel Energy
- Taylor McNair of Grid Lab
- Julio Friedmann of Columbia University (Center on Global Energy Policy)
- Erin Childs of Strategen and CESA
- Jennifer Dowdell of TURN
- Jeff Reed of the University of California Irvine
- Sergio Duenas of Strategen and CESA

Conference presentations

We will present our work at technical conferences including:

- Photovoltaic Specialists’ Conference
- American Geophysical Union
- Informs: Institute for Operations Research and the Management Sciences

Private meetings

We are meeting with individual companies to gather information about their technologies. We have already met with the following:

- Harvard University (Flow batteries)
- Quidnet Energy (Geomechanical storage)
- NREL (High-temperature energy storage)
- Antora Energy (High-temperature energy conversion with thermophotovoltaics)
- Energy Vault (Gravity storage)
- Erin Childs of Strategen and CESA
- Julia Prochnik of Long-Duration Energy Storage of California
- Highview (Liquid air)
- Malta Inc. (Thermal storage)
- ETES (Thermal storage)
- Cat Creek Energy (Solar/Wind/Pumped hydro)

We anticipate that our other outreach efforts will enable us to identify more companies to meet with and that we will use these meetings to collect information and inform our studies as well as share our plans and results to obtain feedback.

Feedback

GridLab is willing to provide feedback as we develop materials.

Results

The publications are listed at

https://sites.ucmerced.edu/ldstorage/publications%20version%202

News items can be found at

https://sites.ucmerced.edu/ldstorage/news-events

- Informational Hearing for the Assembly Select Committee on California’s Clean Energy Economy, organized on Aug. 18 by CCST

Utilization of Energy Storage in California's Electrical Grid

A Quantitative Analysis of Batteries in California

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Background

California has experienced massive growth in the energy storage capacity available to the state. In particular, electric batteries have become an integral part of the future of sustainability and efforts to address blackouts, unplanned shortages, and growing energy demands.

Objective

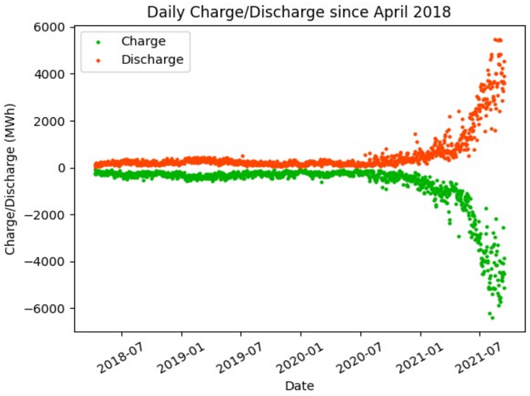
Quantify the extent of the utilization of Electrochemical Battery Storage by California's electrical grid.

Methods

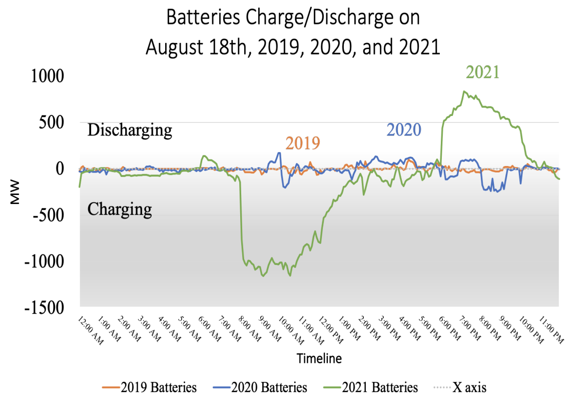
Analyze public data from the California Independent System Operator (CAISO) to observe trends from batteries over the past few years.

Data Analysis

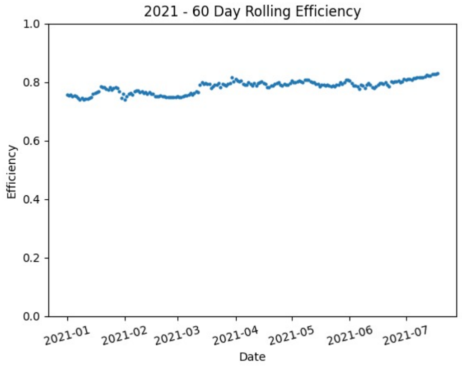
Between 2018 and 2020 there has been a massive growth in the use of batteries in the state of California. Particularly, we have observed a notable increase in the 4th quarter of 2020 into the 1st quarter of 2021 where the daily total power usage grew exponentially.



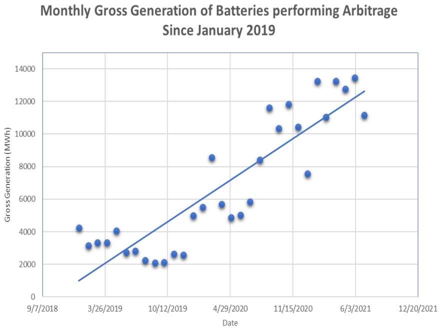
Calculated charge/discharge state of batteries by day between 2018 and 2021, showing the impressive increase in 2021.



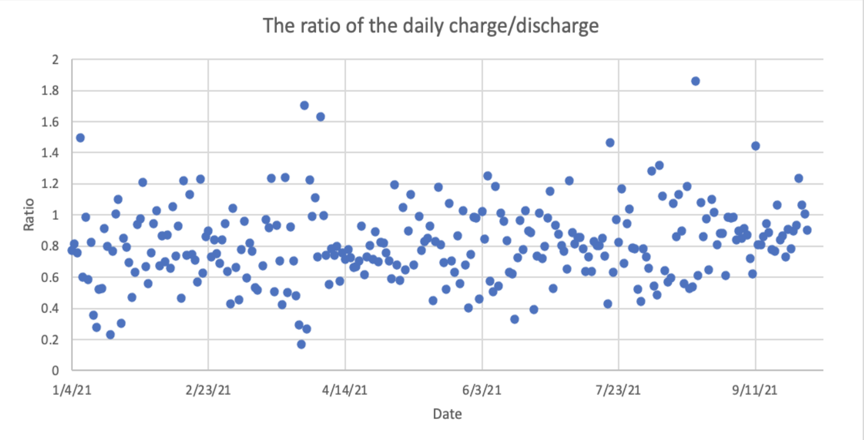
The extent to which batteries are utilized between 2019 and 2021 has seen extraordinary growth. Note that in 2021 the batteries are charging and discharging in 4-hour increments.



Batteries in California have exhibited an efficiency around 80% in 2021.



A general trend is growing Arbitrage activity with Battery Storage, over three times the Gross Generation has been observed in 2021 compared to 2019.



Effective daily efficiency calculated from the ratio of the charge and discharge showing the large daily variability, which translates on average to the 80% efficiency shown above.

Conclusion

- Utilization of batteries in California has increased from about 0.3 GWh/day in 2019 to about 5 GWh/day in 2021
- Usage pattern has changed from spontaneous bursts to systematic charging when the sun rises and discharging as the sun sets
- The battery efficiency is averaging about 80%

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Seasonal Challenges for a California Renewable-Energy-Driven Grid

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DOWNLOAD THE POSTER

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Background

Decarbonizing the electricity grid is a long-term target for a growing number of countries. The continuous development in the solar and wind electricity during the previous decades make them a reliable key sources of electricity especially if connected to a battery storage system.

Objective

- How can 100% renewable energy grid be achieved in California?
- When will be the resource adequacy challenge in a 100% renewable energy grid?
- What is the effect of different renewable energy scenarios on the required storage size?

Methods

A high-level energy balance approach [1] is used as in Eq. (1), in which a balance between the supply and demand is applied while considering an energy storage is connected to the grid.

$$Generation \pm Storage = Load + Surplus \qquad \text{Eq.(1)}$$

Data Analysis

The effect of the size of the solar buildout on the calculated state of charge is shown in Fig. 1. The historical thermal generation, nuclear generation and imports were replaced with additional solar. This six-year analysis clearly shows that for each year the time of the biggest challenge is around February. Similar calculations for 2015-2020 in Fig. 2, showed that the minimum state of charge in the reservoir is always observed during the winter. Fig. 3 shows the storage state of charge while scaling up the solar, onshore wind, offshore wind and a flat generation separately. The needed storage size is increased while adding onshore wind generation and decreased while adding offshore wind or flat generation. The minimum state of charge occurs in winter for all except flat generation. A similar conclusion can be extracted from Fig. 4 for more scenarios. Fig. 5 shows how the surplus electricity increases, and the storage size decreases with the annual generation as the solar generation is increased while having an almost fixed <10% losses due to the storage round trip efficiency.

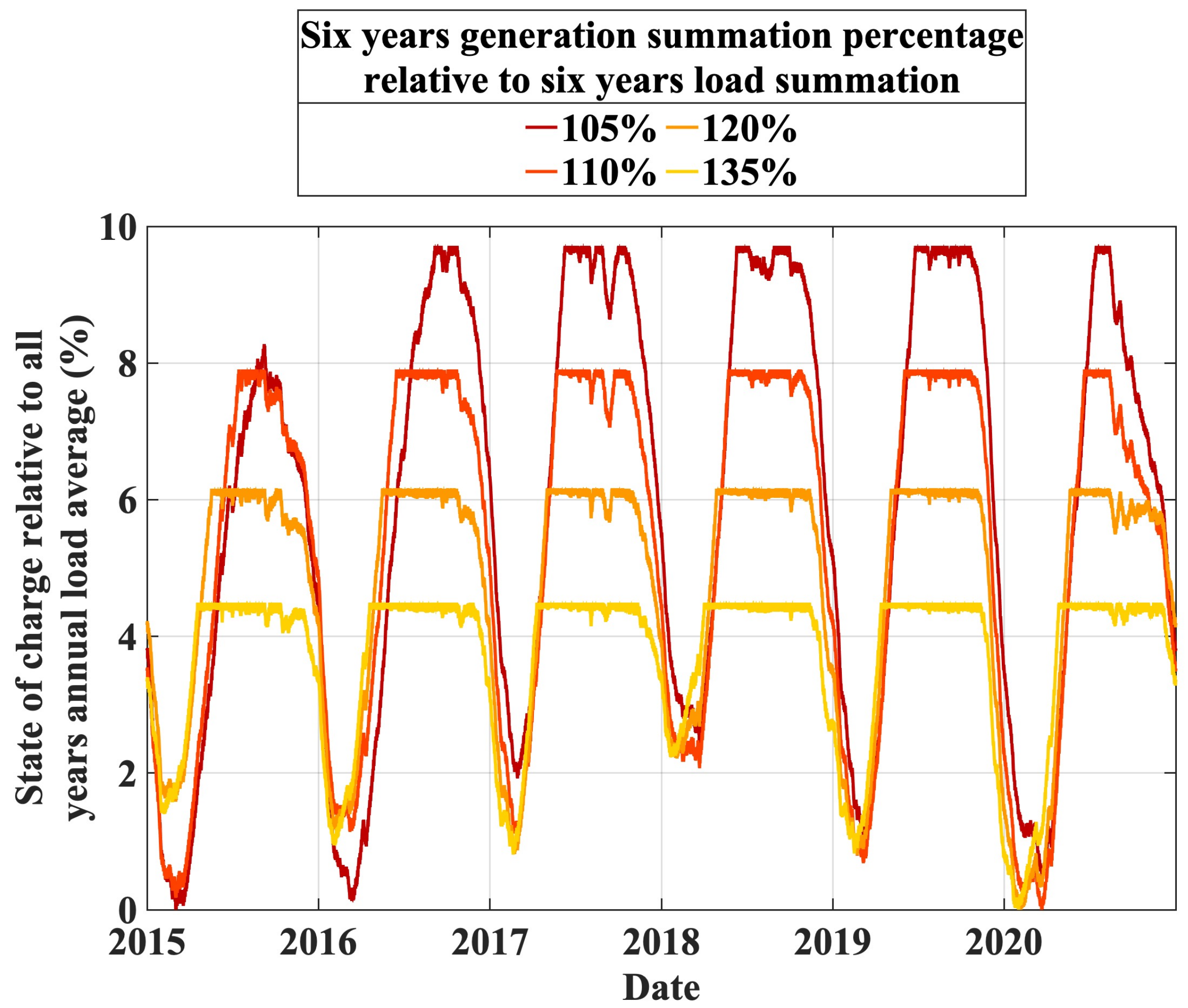

Fig. 1: Calculated storage state of charge using 2015 - 2020 generation and load data.

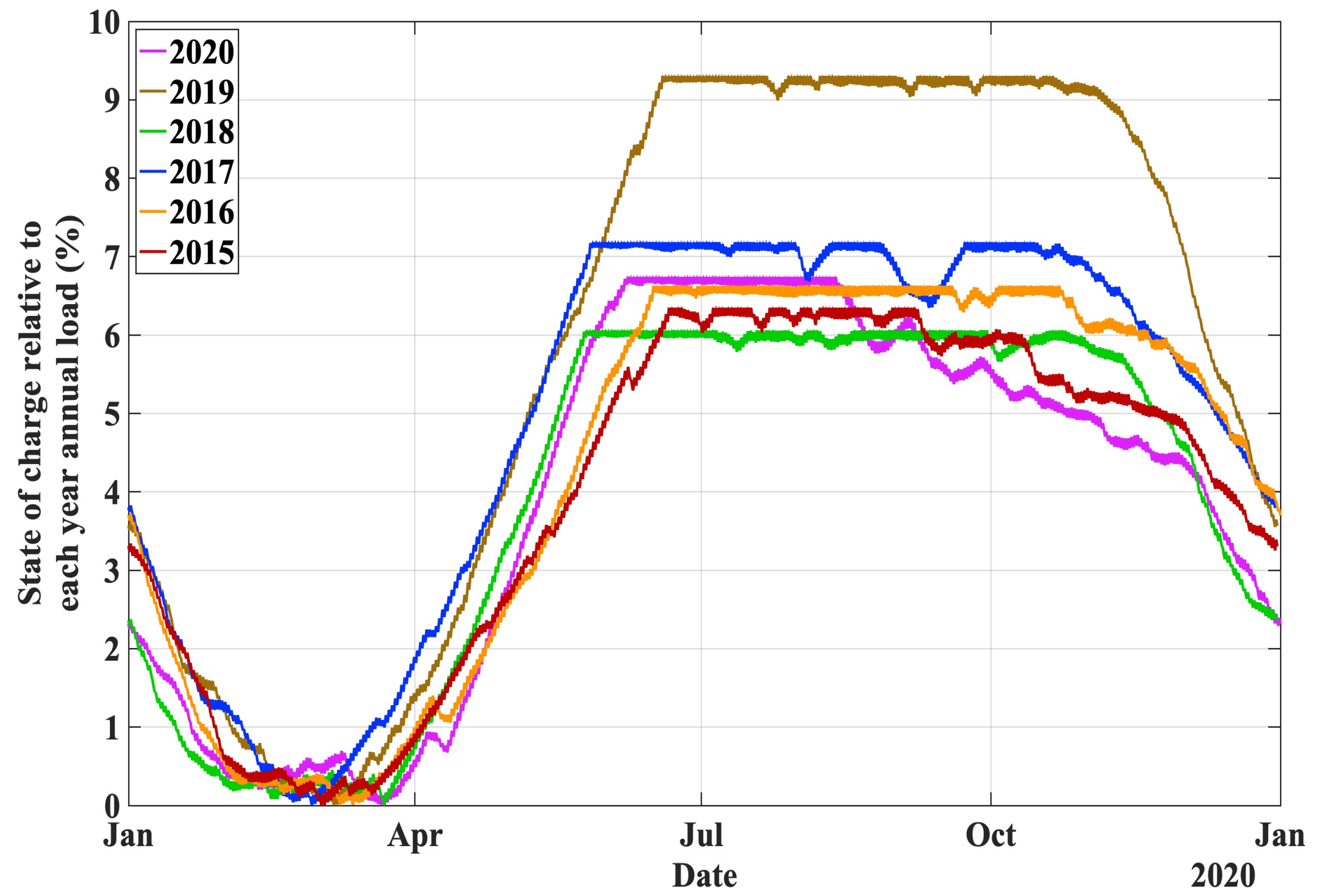

Fig. 2. Calculated storage state of charge using data from 2015-2020, showing only the total annual generation = 110% of annual load case for each year.

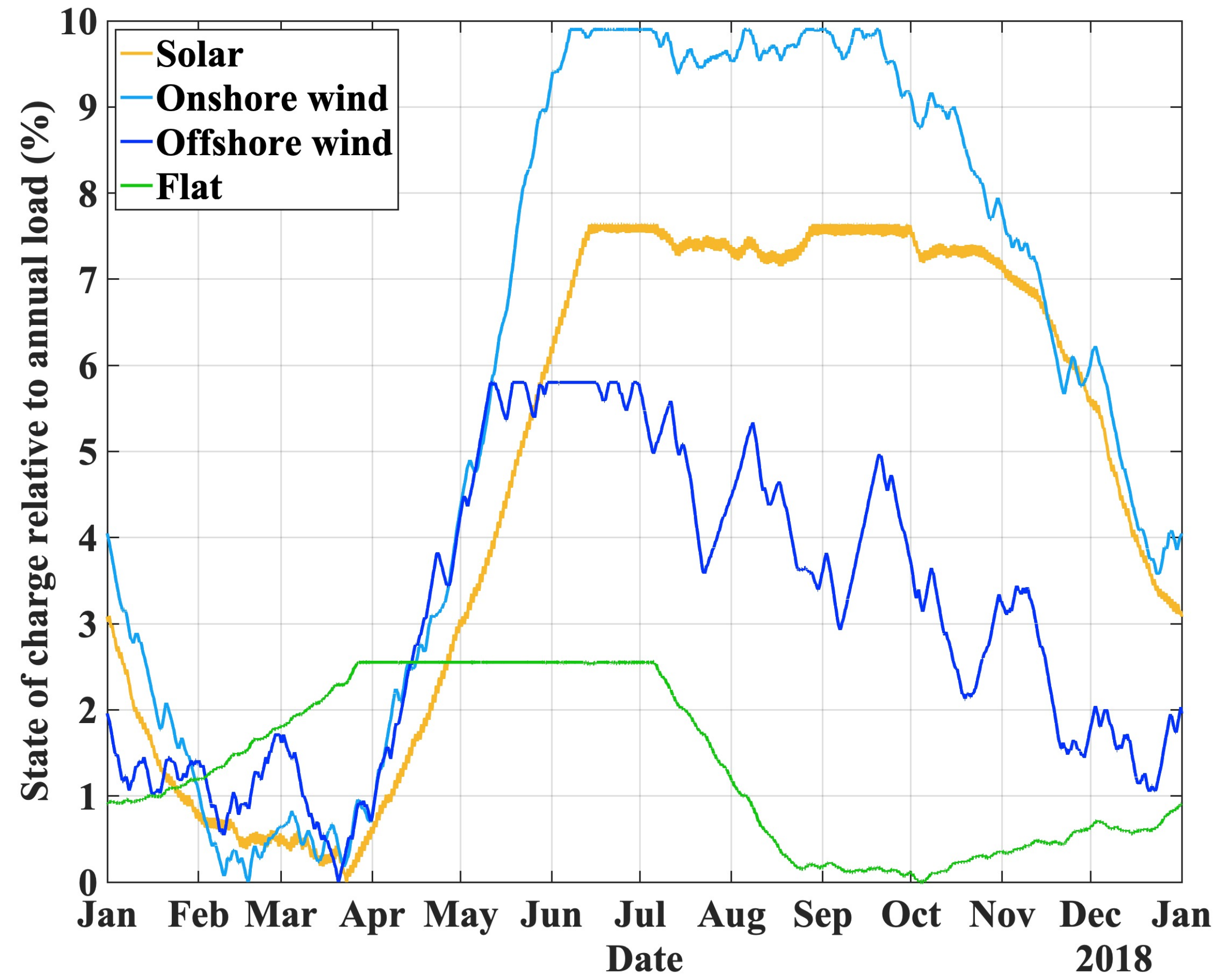

Fig. 3. Calculated storage state of charge using 2018 generation and load data with thermal, nuclear, and imports replaced with electricity generation from a single technology (as indicated) to deliver total generation equal to 105% of the annual load.

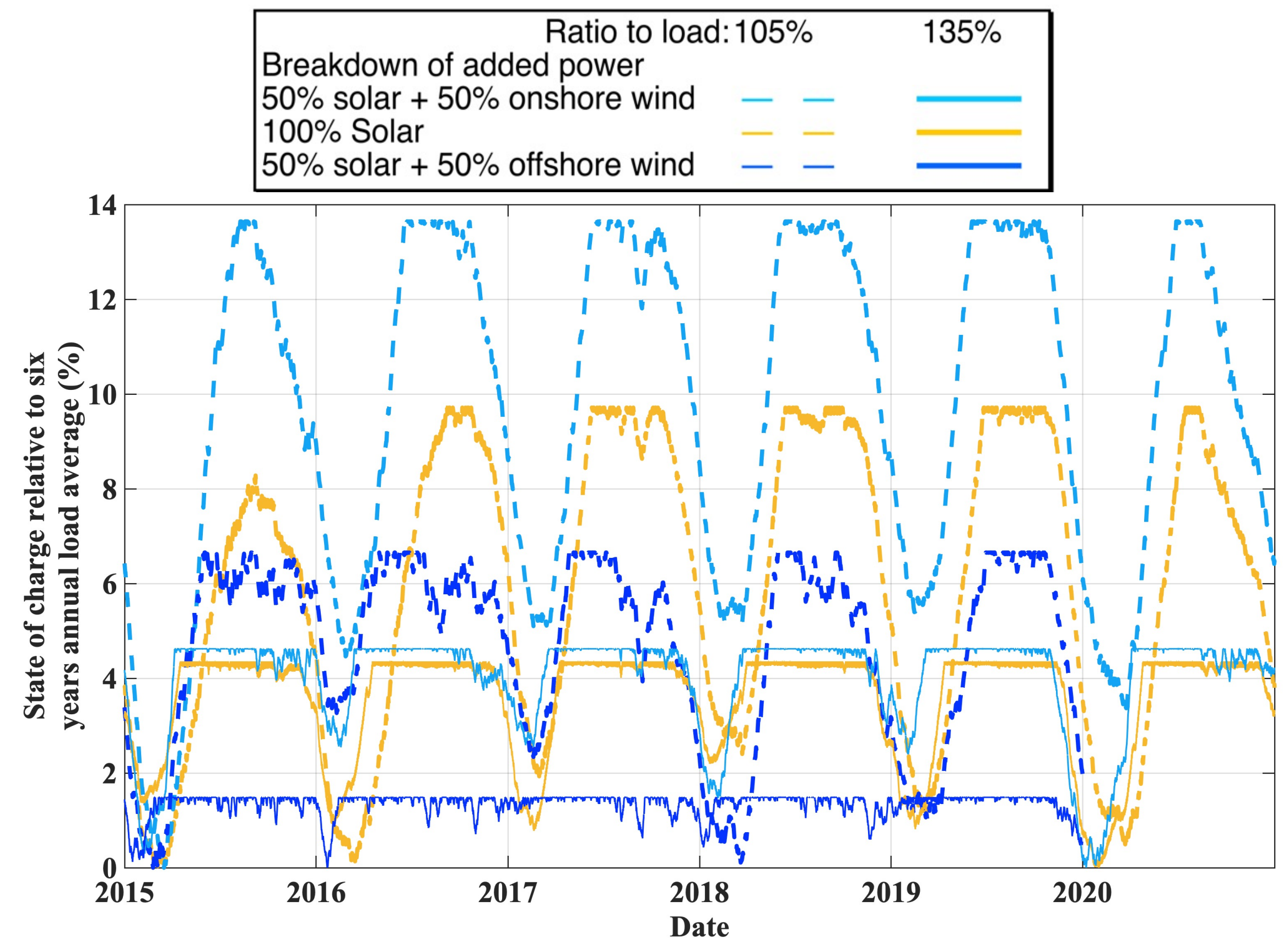

Fig. 4. Calculated state of charge for stored energy using renewables generation and load data for years 2015-2020 adding additional solar and wind generation as indicated in the legend to replace thermal, nuclear and imports. Offshore wind speed data were not available for 2020.

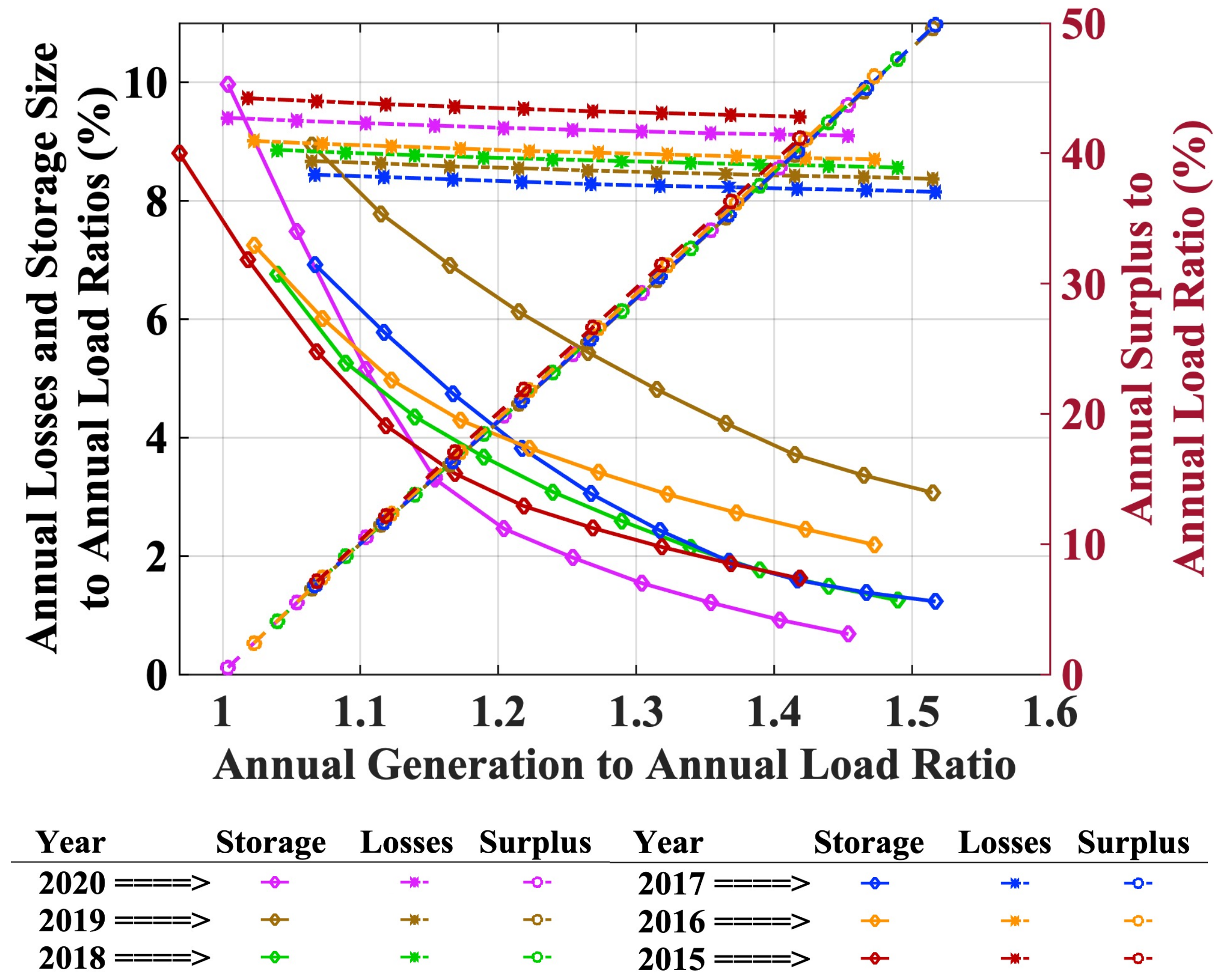

Fig. 5. Storage needed to meet minimal resource adequacy and the losses due to storage round-trip efficiency (left axis) and associated surplus electricity (right axis) as a function of solar build out.

Conclusions

We find that the resource adequacy will be most challenged for a renewable-electricity-driven grid around sunrise during January, February, or March, depending on the amount of solar generation that is built. The seasonal storage needed to balance supply and demand may be cut in half by building 30% more electricity generating capacity.

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Understanding the impact of consecutive days for energy storage modeling

Storage balancing time horizon for capacity expansion models

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Background

Energy storage coupled with clean renewable electricity is one way to transition a zero-carbon electrical grid. Utility scale storage deployment is on the rise and is considered in most of the tools used in for long-term planning processes. Yet modern tools consider only storage assets with up to 4-hrs of duration and undermine the potential for longer duration energy storage. (LDES)

Objectives

- Understand how additional consecutive days in the storage balancing horizon impact the selected storage capacity in MW and MWh.
- Identify opportunities and use cases for LDES technologies in a WECC-wide zero-carbon grid.

Methods

We created a set of scenarios using the open-source capacity expansion models SWITCH[1] for the Western Interconnect (WECC) region.

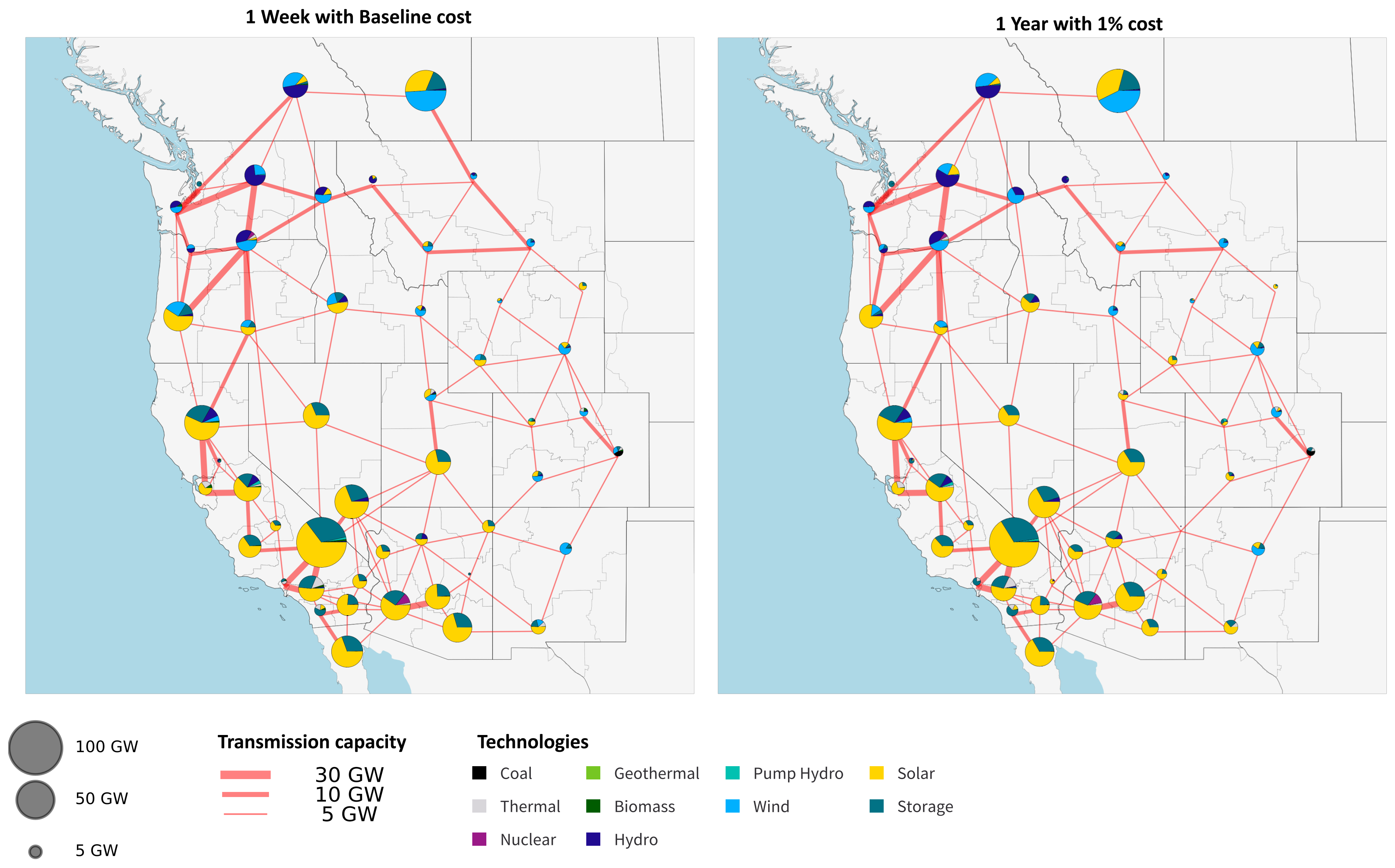
Model formulation

- Cost assumptions: NREL ATB 2020.
- Using the latest SWITCH-WECC model[2].
- Modeled a zero-carbon WECC-wide (50 load zones) by 2045.
- Only 2050 (10-year period) was modeled.
- 4-hour resolution for an entire year with a total of 2190 points modeled
- 7854 power plants (existing and candidate) modeled across WECC.

Scenario construction

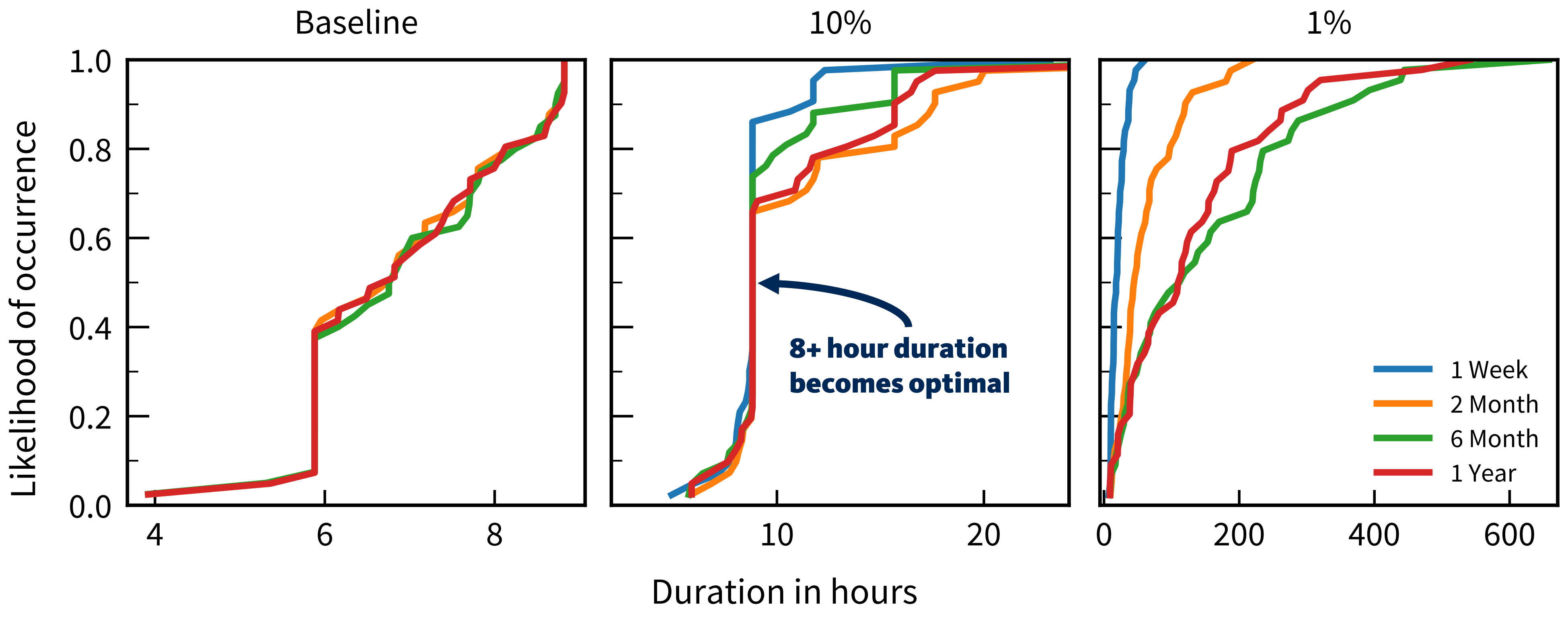
- We created a 4 storage balancing time horizons scenarios.
- We created two cost scenarios for LDES using a percentage (10% and 1%) of the energy cost from a 2020 Li-ion battery **$130/kWh.**

Energy mix for an optimal zero-carbon WECC electrical grid

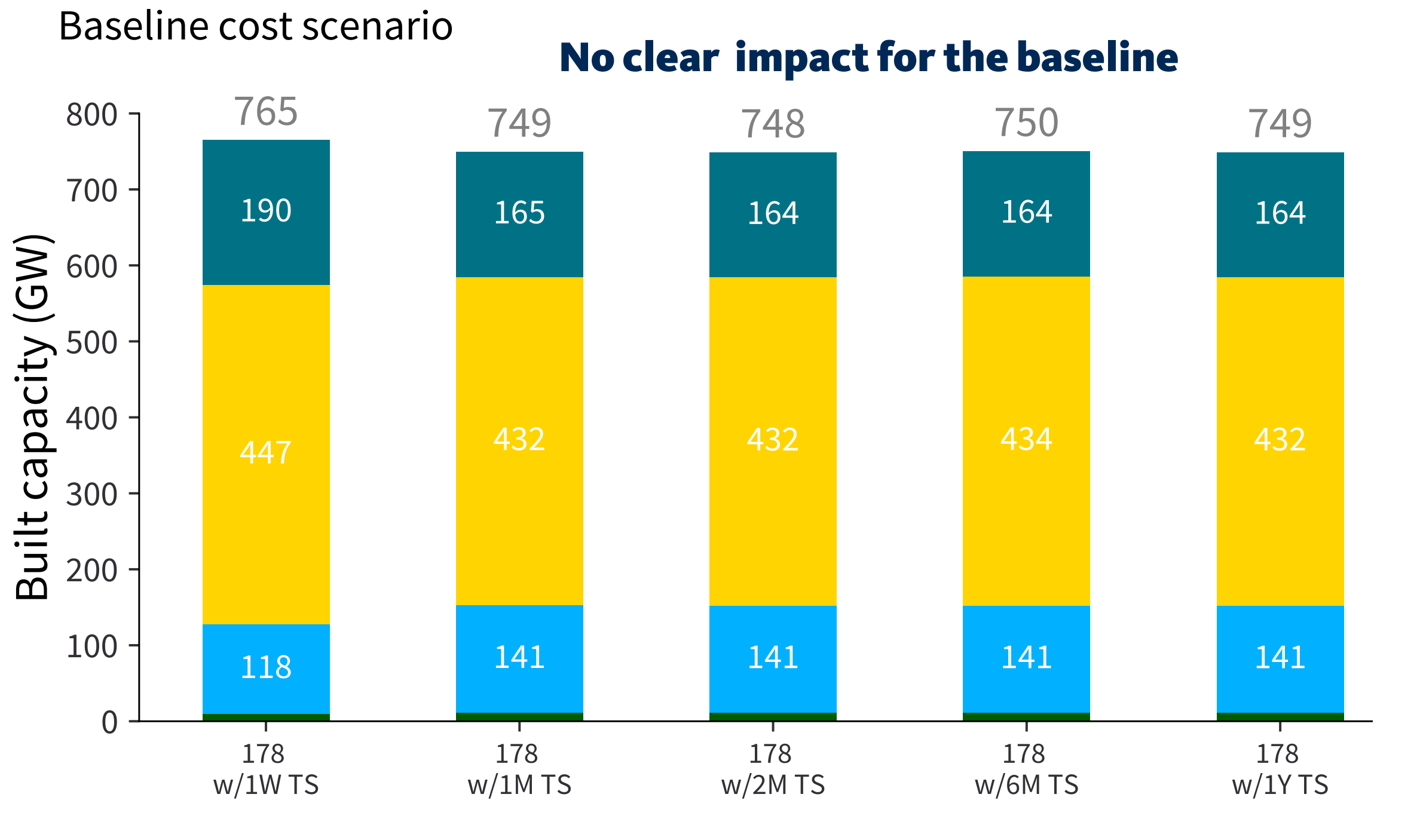


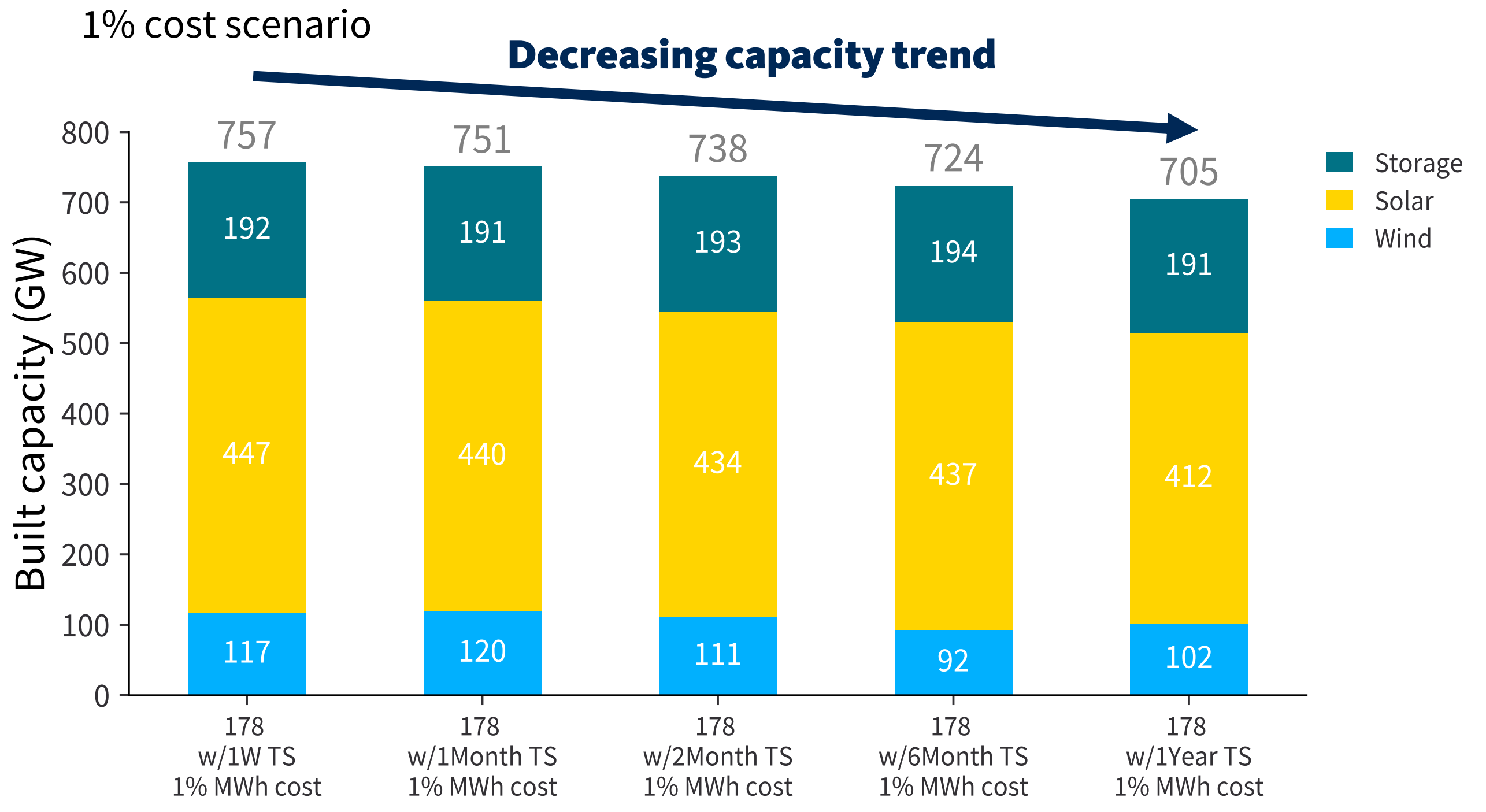
- Year-round balancing horizon reduces transmission expansion in northern regions of the WECC.
- Less wind gets for selected in the year-round horizon as most of the capacity shifts into energy storage.
- Solar and storage dominate capacity additions in both scenarios

Optimal power to energy ratio by storage balancing horizon



- No substantial difference observed for the baseline cost scenario.
- The balancing horizon changes the optimal duration if we reach 10% and 1% of the storage cost by 2050.

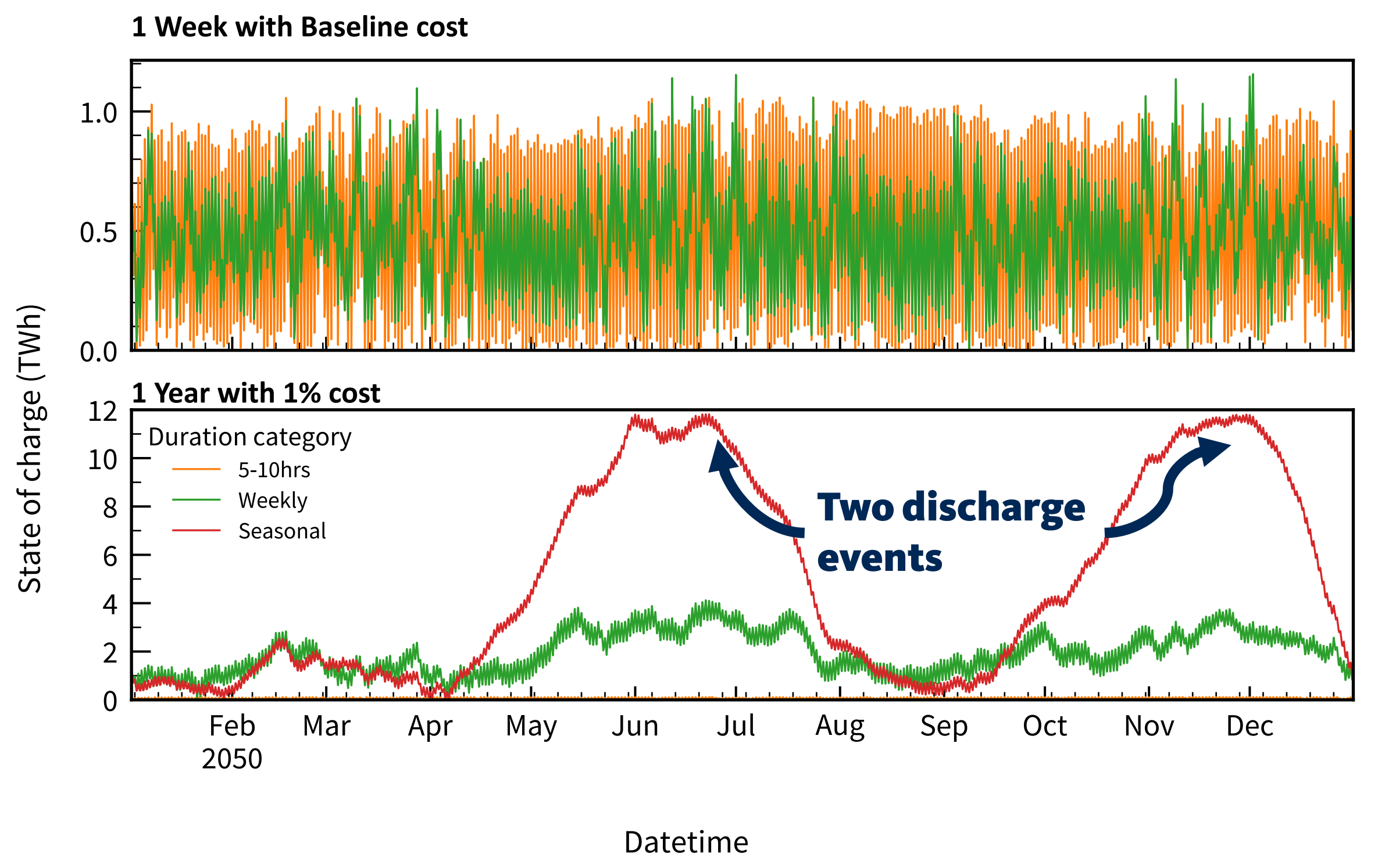




State of charge formulation

The SWITCH model keep tracks of the energy in storage using a state of charge equation and constraining the beginning and end state of charge for a storage balancing horizon.

Storage balancing horizon shifts short duration energy storage to weekly/seasonal assets



Conclusions

- The length of the storage balancing horizon impacts the optimal duration when the price reaches 10% of the baseline cost.
- Storage utilization changes depending on the length of the balancing horizon. Storage shifted to optimize for summer and winter peaks for the WECC.

Acknowledgments

This document was prepared as a result of work sponsored by the California Energy Commission (“CEC”). This report has not been approved or disapproved by the Energy Commission nor has the Energy Commission passed upon the accuracy of the information in this report.

References

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Geographical Variability of Summer- and Winter-dominant Onshore Wind

Download the poster
doi: link goes here

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Background

The large-scale deployment of renewable electricity resources for the power sector is a major driver of decarbonization and mitigation of climate change. Throughout the state of California, one of the biggest challenges in reaching a zero-carbon grid is identifying sources of electricity that match the seasonal profile of the load. Summer-dominant solar electricity generation can often be balanced by winter-dominant wind electricity generation. Together with long-duration storage, balanced solar and wind generation are well positioned to provide reliable renewable electricity. However, in some locations the wind may not complement solar energy so well.

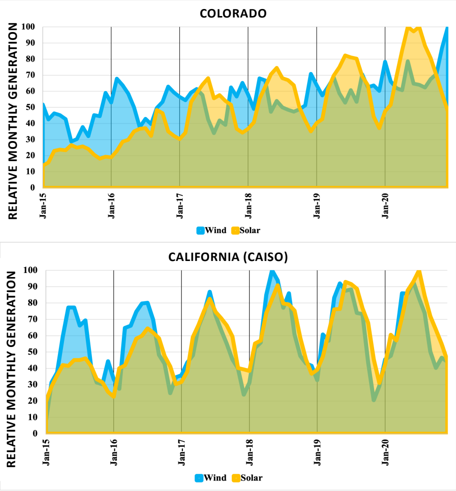

Fig 1: Seasonality of solar and wind generation for Colorado (top) and California (bottom)

Objectives

- To analyze the seasonality of the generation from existing and potential California wind plants
- To find the resource complementary to solar in California

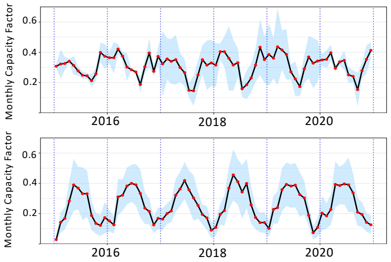

Fig 2: Monthly capacity factor (vertical dashed lines indicate January) for (a) winter-dominant (top) and (b) summer-dominant wind plants (bottom) in California from 2015 to 2020. The solid lines and blue shaded regions represent the mean and one standard deviation of all the analyzed plants, respectively, as calculated for each month

Data and methodology

The data we used includes CEC 1304 Power Plant Owner Reporting Database primarily for existing wind power plant capacity and monthly generation, EIA 860 and EIA 923 as a secondary source for some plant capacity and generation, California Protected Areas Database (CPAD) 2020b for exclusion of various protected areas, and NREL Wind toolkit for simulating wind generation. The grid size was taken as 0.02 decimal degree (DD) X 0.02 decimal degree points (approximately 2.22 km X 1.88 km), resulting in 107,670 locations analyzed in total.

$$W/S\ ratio = \frac{Generation\ in\ Dec + Jan + Feb}{Generation\ in\ Jun + Jul + Aug}$$

We simulated the 2012 monthly capacity factors for a number of winter-dominant and summer-dominant plants using 100-m wind speed data from the NREL Wind Toolkit. The simulated capacity factor and W/S ratio were calculated from those wind speeds using a wind power curve for a GE 2.5-120 turbine. We estimate winter-dominant high- quality wind resources in California with and without the exclusion of various protected areas based on the California Protected Areas Database (CPAD) 2020b.

Results

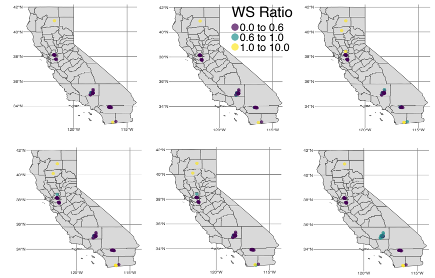

Fig 3: Measured capacity factor for the existing wind plants in California from 2015 to 2020

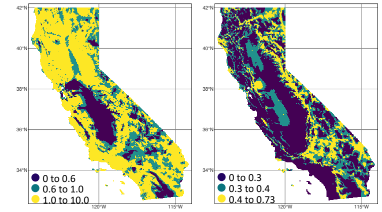

Fig 4: Current wind maps in California showing W/S ratio (left) and annual CF (right)

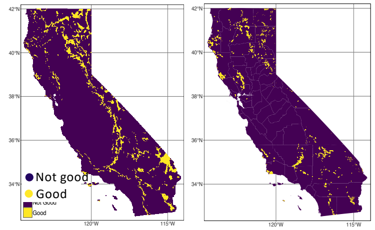

Fig 5: High-CF, winter-dominant, available wind power potential (CF > 0.4, W/S ratio > 1) without (left) and with (right) excluding regions with slope > 20 degree, and protected areas.

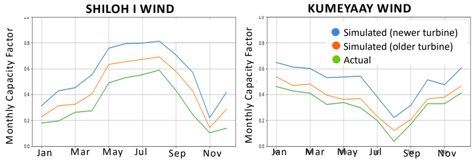

Fig 6: Comparison of monthly CF for simulated and actual generation for a summer (left) and winter (right) dominant plant

Conclusions

- The ratio of winter-to-summer generation can vary from more than 2 to less than 0.4, with the observed seasonality for each location being relatively constant from year to year
- Almost 60% of the state has wind resource that is stronger in winter than in summer, despite today's observation of strongly summer-peaking wind electricity generation
- Disregarding the economic feasibility, we estimate about 22 GW of winter-dominant plants could be sited on available land. These represent 23% of the total potential.

Types	Potential (GW)	Annual generation (TWh/year)	Mean W/S ratio	Area (km^2)
Total Potential	107	428	1.44	35,664
Potential in available areas	25	100	1.42	8,396
Potential in available areas excluding steep slop areas	22	74	1.40	6,437

Table 1: Wind power potential in winter-dominant, high-quality wind resource areas

Acknowledgments

This work was supported by the California Energy Commission [EPC-19-060]. This report has not been approved or disapproved by the Energy Commission nor has the Energy Commission passed upon the accuracy of the information in this report. The authors thank D. Kammen for useful comments on the manuscript. We are also indebted to NREL for making wind data available through the NREL Wind Toolkit.

Evaluating Emerging Long-duration Energy Storage Technologies

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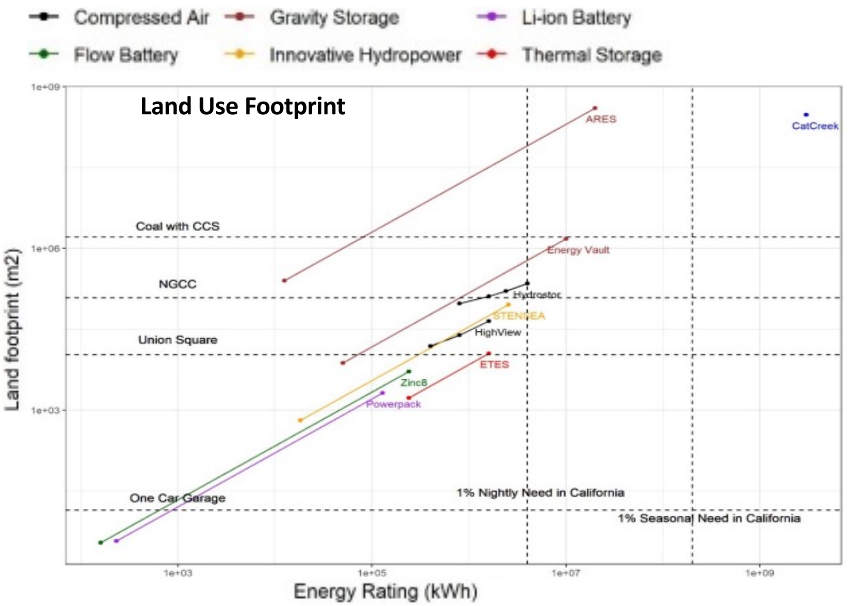
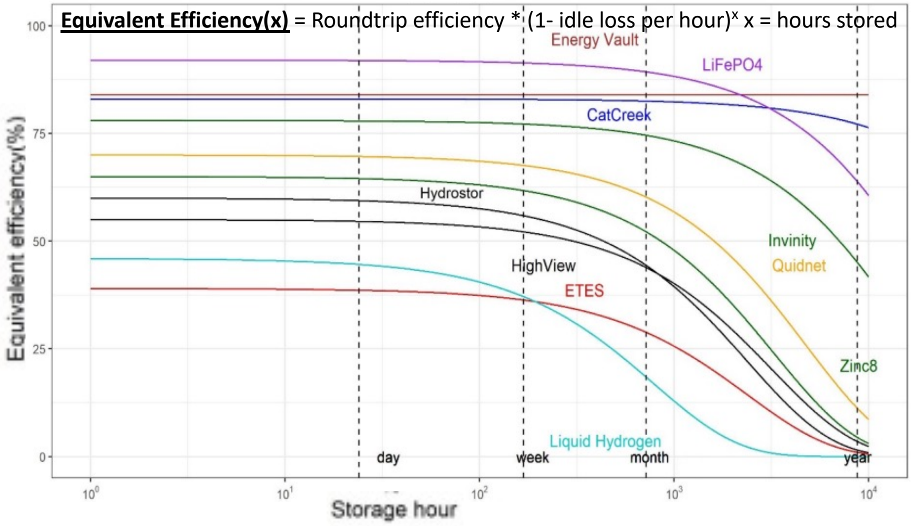
Objective

Give a status report on current energy storage technologies

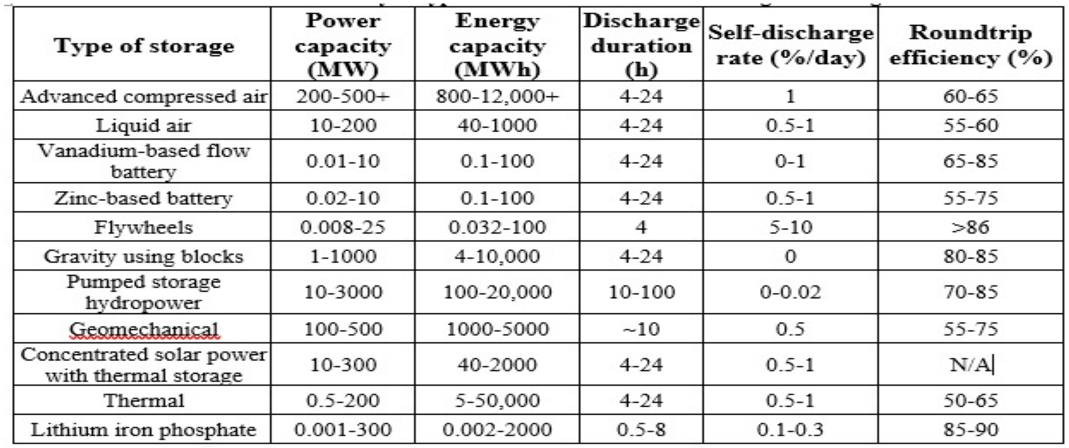




Equivalent Efficiency(x) = Roundtrip efficiency * (1- idle loss per hour)^x x = hours stored

Background

Reaching California's decarbonization goals requires a great expansion of long duration (>10 hours) energy storage. There are many different technology options, and we need a way to compare between them and judge suitability for different use cases.



Type of storage	Power capacity (MW)	Energy capacity (MWh)	Discharge duration (h)	Self-discharge rate (%/day)	Roundtrip efficiency (%)
Advanced compressed air	200-500+	800-12,000+	4-24	1	60-65
Liquid air	10-200	40-1000	4-24	0.5-1	55-60
Vanadium-based flow battery	0.01-10	0.1-100	4-24	0-1	65-85
Zinc-based battery	0.02-10	0.1-100	4-24	0.5-1	55-75
Flywheels	0.008-25	0.032-100	4	5-10	>86
Gravity using blocks	1-1000	4-10,000	4-24	0	80-85
Pumped storage hydropower	10-3000	100-20,000	10-100	0-0.02	70-85
Geomechanical	100-500	1000-5000	~10	0.5	55-75
Concentrated solar power with thermal storage	10-300	40-2000	4-24	0.5-1	N/A
Thermal	0.5-200	5-50,000	4-24	0.5-1	50-65
Lithium iron phosphate	0.001-300	0.002-2000	0.5-8	0.1-0.3	85-90

Conclusions/Strength Comparisons

Technology	Strengths	Opportunities (technical and market)
Lithium batteries	High efficiency; ease of use	Continued growth – is currently expanding rapidly
Pumped hydropower	High-efficiency; least cost over 100-year lifetime; well established	Can provide long-term benefit to the community including water and jobs once completed. Closed-loop implementation may open many new sites
Gravity	High efficiency and the land footprint can be minimal and/or flexible	Negligible idle loss even over months of time
Flow batteries	Potential to be lower cost than Li batteries for higher energy-to-power ratios	May enter market by providing resilience via microgrids during power outages.
Compressed air	Adiabatic version has higher efficiency and more flexibility in siting	Has potential for large scale, low-cost deployment once it demonstrates performance
Liquid air	Leverages existing supply chain to be scalable; May achieve high efficiency; ready to scale	Is ready to scale deployment for > 4-h systems
Thermal – CSP	Recent cost reductions combined with synergy of CSP + storage	Could combine generation with storage as costs come down
Thermal – without solar	Combined with decarbonization of industrial heating. May use very inexpensive storage media like sand or rocks to increase energy capacity at low cost	Could play primary role of decarbonizing industrial heating, then that success could be leveraged to give inexpensive storage; may be incorporated in existing fossil fuel power plants
Geomechanical	Some versions average oil & gas infrstructure; could scale rapidly to GWs; relatively high efficiency	Leverages oil & gas expertise & workforce. Once de-risked could scale very rapidly
Hydrogen	Can be used as a fuel to replace hydrocarbons	Could provide backbone of decarbonized energy system to drive transportation, heating, and chemical synthesis

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