PROGRESS REPORT for EPC-19-060

March, 2021

Recipient Project Manager: Sarah Kurtz

Commission Agreement Manager: Jeffrey Sunquist

What we planned to accomplish this period

1. We will complete the deliverable to document the results of the Baseline modeling. This will be a primary focus in March. We also held the first CPR.
2. We will continue to meet with stakeholders and community representatives to gather inputs and request feedback
3. If the editors respond to the submitted draft of "Long-duration Storage" we will move toward publishing it
4. We will continue evaluations of the value of long-duration storage using simplified calculational approaches to facilitate exploration of a large parameter space. In particular, we are using that to identify an estimate of the types of storage needed by a zero-carbon grid and to understand how adding off-shore wind may affect the types of storage needed
5. We will start work on the website that was included in the Knowledge Transfer plan

What we actually accomplished this period

1. Deliverables: We completed the deliverable to document the results of the Baseline modeling. This was a primary focus in March. It was an interesting study because it was completed the week after the SB100 results were posted, enabling comparisons. The content of that report will be appended to this monthly report for reference. Here, we discuss some findings that weren't included in the report.

Using the current version of RESOLVE (which uses 37 independent days to simulate a year), we found that reaching zero emissions is difficult. The SB100 report shows that the SB100 modelers also struggled with this: there is a desire for zero emissions in 2045, but the 37-day version of RESOLVE shows an impractical result. However, we note that the 37-day version of RESOLVE does not allow use of cross-day storage (all energy used through the night must be generated in that same day when the days are modeled independently). Thus, the buildout of solar is determined by the worst of the 37 days.

We graphed the dispatch in 2045 for the 2018 RSP (not attempting to go to zero emissions) for the 37 days in Fig. 1 and for the two most difficult days (days 27 & 28) in Fig. 2. The 37 days include five days from January: days 1, 2, 18, 27, and 28 (see Table 1). Of these, day 28 is requiring the most natural gas, with day 27 and day 2 not too far behind. The 37 days were chosen to represent an entire year, not to define the capacity expansion to reach zero emissions. We are in the midst of modifying the inputs to RESOLVE to be able to run the simulation without days 27 and 28 to see how much that changes the expansion of solar.

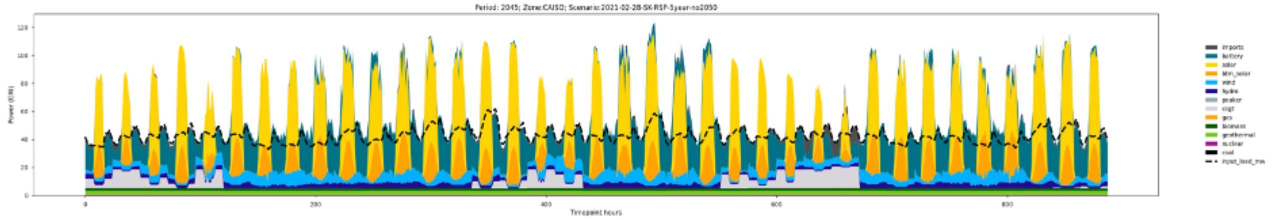

Fig. 1. Dispatch for 37 days in 2045 for 2018 RESOLVE RSP.

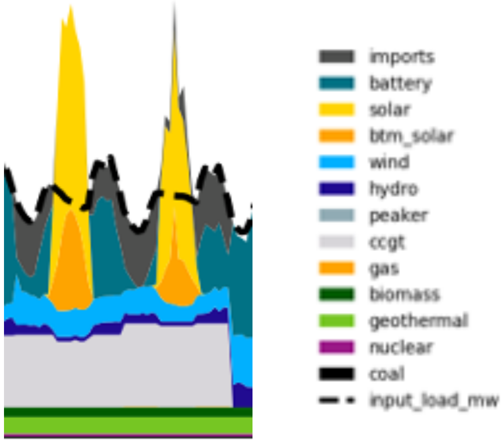

Fig. 2. Dispatch for days 27 and 28, duplicating the same data as in Fig. 1.

Table 1. Days representing January of the 37 days used by RESOLVE

Day number	Day weight	Data from this date
1	14.25	1/1/07
2	5.91	1/2/07
18	0.66	1/28/08
27	0.88	1/6/09
28	7.92	1/21/09
Total	**29.63**	

E3 notes that they plan to send the new version of RESOLVE at the end of April. It will be useful to see whether the version that allows cross-day storage selects the long-duration storage over an impractical overbuild of solar. In the meantime, in the April report, we intend to share the effect of moving the day weights currently assigned to days 27 and 28 to day 2 to identify the change in solar expansion that is selected.

March 25th, we also held the first Critical Project Review. The slides for this are attached for reference. We have not yet heard whether there are action items to address from this.

2. Stakeholder meetings: During the month of March, we met with:

- Teresa Feo and Geoff Hollett of the California Council on Science and Technology
- Jen Dowdell of TURN
- David Williams of Disigno
- Daniel Huck of SGRE COG IS EST TE SI
- Polly Shaw of Plus Energy Storage
- Julia Prochnik of Long Duration Energy Storage Association of California
- Priya Sreedharan of Gridlab
- Ron Sinton of Sinton Instruments
- Tri Luu of Hydrostor

We also met with E3 and CAM to discuss coordination of the two efforts.

3. Talking about Long-duration storage: The editors of "Issues in Science and Technology" responded to our draft, indicating interest in publishing something, but requested that we write a response to a piece that was published at the end of March[1] which concludes that investments in "firm clean power" will be meaningful better than investments in "long-duration storage." We have made a first draft of a response, but are still discussing it before submission. We welcome CEC's thoughts on this, so include the draft here:

Draft for "Issues in Science and Technology"

Clean Firm Power versus Long-Duration Energy Storage

In "Clean Firm Power is the Key to California's Carbon-Free Energy Future" Long, et al argue for investment in clean firm power over long-duration storage, saying "Long duration storage may provide another useful arrow in the quiver, but systems with clean firm power remain meaningfully less expensive." We disagree and encourage California to broaden its research agenda rather than choosing winners at this point.

The goal of a long-duration storage technology is to provide clean firm power. Fundamentally, clean firm power *is* long-duration storage. Is there benefit in distinguishing them when they are essentially the same thing? Rather than arguing that there is a fundamental difference between the two types of technologies, we understand Long, et al, to make the case for investing in improvement of conventional technologies over investing in high-risk, unproven technologies. But history shows that we have a poor track record of predicting cost reductions. Solar electricity was long predicted to be too expensive to be practical, but is now considered to be the lowest cost source of electricity in some locations. Similarly, oil production was predicted to peak as sources of easily recovered oil were exhausted, but technology advancements enabled

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[1] https://issues.org/california-decarbonizing-power-wind-solar-nuclear-gas/

the United States to increase oil production spectacularly. Do we really know enough about tomorrow's clean energy technologies to predict which ones will be lowest cost? It is too early to declare winners. A broad definition of the research agenda can spur innovation and uncover opportunities that may be missed if winners are identified too early. Here, we explore storage needs of today's and tomorrow's energy systems to motivate innovation toward a range of solutions.

Storage needs today and tomorrow

In today's world, huge stores of fossil fuels enable fossil fuel power plants to provide firm power (assuming the fuel can be transported to the plant in a timely way). As shown in Fig. 1, today's fossil fuel storage reservoirs collectively contain enough energy to run the country for months. Some of this is stored to meet seasonal needs, some is stored just as a matter of practicality, and some is stored for national security reasons (*e.g.,* the Strategic Petroleum Reserve was created to protect from disruptions of oil imports).

In the future, will the need for energy storage be greater (because of the variability of solar and wind power) or less (because we may not need to be protected from disruptions of imports)?

As we envision the energy system of the future, it is probable that electrification will change how we use energy in many sectors. Electric vehicles are already replacing internal-combustion-engine vehicles and heat pumps are replacing natural gas furnaces. Some applications may continue to use fuels. For example, aviation may continue to use jet fuel, biogas, or other fuel. Tomorrow's version of Fig. 1 will need to provide energy security for not only the power sector, but also for the transportation sector, industrial sector, and for all applications that are energy hungry. As we explore our options for storage to keep the power sector running, there is value in considering what storage we may be maintaining for other sectors.

Opportunities for innovation around the intersections of the energy system

We assert that our search for clean firm power and long-duration storage will benefit from investigating and innovating around synergies with energy usage in other sectors. For example, if heavy-duty vehicles use hydrogen-powered fuel cells, there will develop a robust infrastructure for distributing hydrogen, making it more available to the power sector. Similarly, the fuel-cell-powered vehicles could also be turned into power houses to convert hydrogen to electricity when the vehicle is parked using the much-discussed "vehicle-to-grid" concept. Could tomorrow's fuel-cell powered trucks become effectively "peaker plants on wheels"? Such a concept may seem far off today, but innovations both on the technical and business side may identify opportunities for the transportation and power sectors to support each other.

The opportunities for innovation become almost ubiquitous when one considers interplay between the power sector and heating applications. When looking for low-cost storage options, it's hard to beat the fleet of hot water and chilled water tanks that exist in buildings across the country. Some large buildings currently chill a tank of water during the night to use for air conditioning during the day. The cost of switching to chilling the water during the day when the sun is shining only requires someone to change the programming of the chiller. Collectively, such tanks in the U.S. represent storage of X TWh. Most of these are designed only for diurnal storage, but some communities are developing seasonal thermal storage by capturing heat during the summer and using it to heat buildings during the winter, reducing electricity or other energy needs during the winter.

Waste-to-power concepts have supplied heat throughout mankind's history. In today's world, dairy farms are selling biogas in addition to milk. Wastewater treatment plants use their digesters to not only generate biogas from the wastewater, but to also process fat, oil, and grease (FOG), providing a useful waste-disposal process while also supplying a storable fuel (biogas). Most studies conclude that waste-to-power processes will be unable to make a big enough dent in our energy needs to be considered an important solution. Nevertheless, as a society, we need to deal with waste, and waste-to-power innovations might provide solutions for our waste and our energy needs at the same time.

The power sector may find some of the best synergies with the chemical industry. If green hydrogen could achieve the cost reductions that solar, wind, and batteries are demonstrating, surplus electricity from solar and wind farms could be used to supply hydrogen for many purposes. Fertilizer and other chemicals may be more easily stored that electrical energy. Perhaps tomorrow's version of Fig. X will include wedges for hydrogen, ammonia, and a range of other chemicals.

Value of a broader definition of clean firm power and long-duration storage

Thus, we encourage investment not only in developing clean firm power and in long-duration storage technologies for the power sector, but also in technologies that enable storing energy for all of the energy-related sectors. The opportunities we've suggested above are unproven, but innovations lead to technology advances that often surprise us. How many people were predicting in the year 2000 that the United States would today be a net exporter of oil? Are we really ready to identify what tomorrow's energy system will look like? Keeping the door open to all solutions has the best chance of reaching low-cost clean energy quickly.

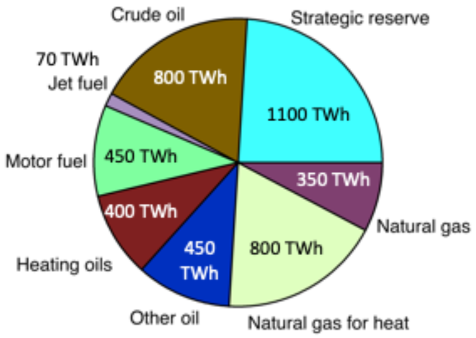

Fig. X. Approximate energy storage used to supply the transportation, heating, power, and chemical sectors. The natural gas stored for heating applications was estimated from the depletion of the stored natural gas during the heating season. The 350 TWh "Natural gas" may be used for power generation, heating, or other uses. The strategic petroleum reserve is the largest single category of storage on this pie chart. Should review this in more detail before publishing it.

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4. Full year simplified calculations: We have continued to apply this simple calculation and gather results to inform our future work with RESOLVE. Here we summarize some of the results obtained in March.

In particular, we find that using off-shore wind and on-shore wind affects the needed storage in different ways. The calculated number of cycles expected for the storage when we insist that the first bin is always used before the second and the second used before the third, etc. allows us to identify both the size of storage for each application and use of that storage (number of times per year). We compare the use of a central storage reservoir in the extreme when we use off-shore wind and on-shore wind in Fig. 3. (Note that the calculation assumes perfect ability to transmit the energy to the load.)

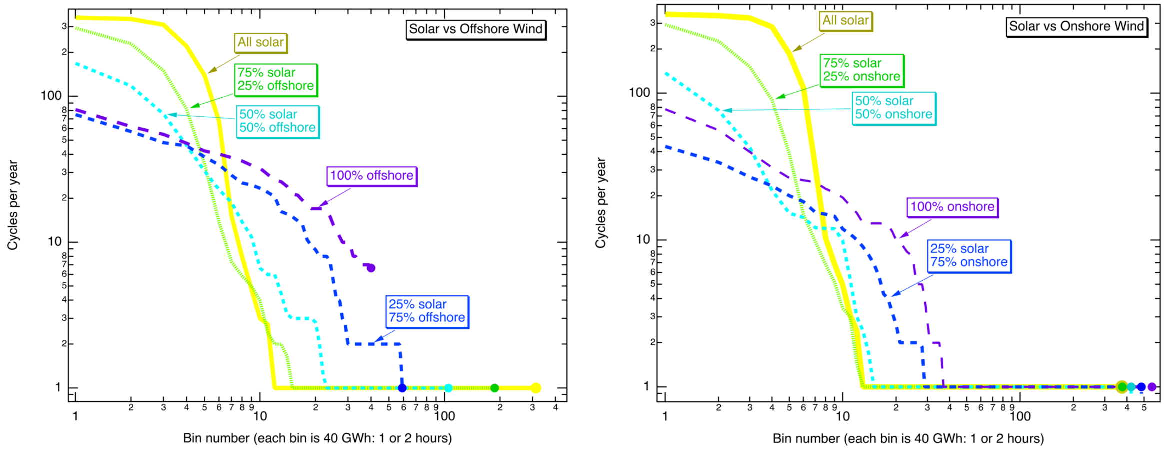

Fig 3. Cycles needed for bins of storage when the first bin is charged or discharged before the second, etc. Effect of offshore wind (left) and onshore wind (right)

When we model the use of extreme amounts of wind, we recognize that we are exploring a space that is impractical, but it helps us to develop an intuition about the effects of the wind. The effects are also dependent on the ratio of the generation to load. These two graphs had generation-to-load ratios of 1.26 for offshore and 1.19 for onshore.

The conclusions of the effect of wind on the different applications of long-duration storage are summarized in Table 2. Note that these calculations used data from 2019 for the generation profiles. A different year would provide slightly different conclusions, but the trends we find to be the same (data not presented here).

Table 2. Size and use of long-duration storage for different generation sources when the generation-to-load ratio is about 1.2.

	Diurnal storage	**Cross-day storage**	**Seasonal storage**
Solar	< 0.4 TWh Used > 350 X/year	0.2 TWh Used tens of X/year	12 TWh Used 1-2 X per year
Offshore wind	< 0.4 TWh Used tens of X/year	1 TWh Used tens of X/year	< 1TWh Used 1-2 X per year
Onshore wind	< 0.4 TWh Used tens of X/year	1 TWh Used tens of X/year	20 TWh Used 1-2 X per year

5. Items in Knowledge Transfer plan

As planned, we have begun establishing a website for the project. The website can be found at

https://sites.ucmerced.edu/ldstorage/overview

Additionally, we have posted a video introducing the project at

https://youtu.be/8fCT-uueI4g

Additionally, we now have a Linked In page at

https://www.linkedin.com/company/long-duration-storage-study-circle/posts/?feedView=all&viewAsMember=true

These are still being refined and will be updated as the project progresses.

How we are doing compared to our plan

The work is progressing commensurate with the expenditures and following the new plan. Some of the dates will still need to be revisited. We propose to do that after we have seen the RESOLVE code and can assess the extent to which we will want to do additional revisions.

Significant problems or changes

We are having a delay with the invoicing. The first invoices that include the University of North Carolina expenses (as matching cost) have now been sent. The delay was partially caused by correspondence that was sent by mail to an address that was different from where people were working, so it took some time to find the correspondence. We have now updated the address to be one that will deliver the item to where people are working during the pandemic. There were also questions about how to report the indirect expenses (some are in the "match" column and others will be reimbursed.) In the future, we expect that things will progress in a more timely way, but we note that we have not yet received our first invoices from UC San Diego and UC Berkeley, so that could cause a further delay.

The baseline definition will be a multi-step process. Given that the modifications to RESOLVE will not be available until the end of April, we have not yet been able to start our final definition of our scenario. We plan to update the baseline when we receive the new RESOLVE version at the end of April. We anticipate being able to report on the new RESOLVE code and develop a plan for our next steps in the May monthly report.

What we expect to accomplish during the next period

- We are working on multiple papers and hope to be able to report on some partial drafts (or at least preliminary results) at the end of April.
- We will continue to meet with stakeholders and community representatives to gather inputs and request feedback
- We will edit the draft of an opinion piece and submit to "Issues in Science and Technology"
- We will quantify the effect of removing days 27 & 28 on the challenge of reaching zero emissions
- We will continue evaluations of the value of long-duration storage using simplified calculational approaches to facilitate exploration of a large parameter space. In particular, we are using that to identify an estimate of the types of storage needed by a zero-carbon grid
- We will continue work on the website that was included in the Knowledge Transfer plan

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
		Final TAC meeting schedule	TBD	Tentative dates 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	
		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	7/2/21	
		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	7/2/21	
		CPR #2	**Summer**	
4.2	Grid scenario selection	Draft grid scenario summary	6/11/21	
		Final	8/13/21	
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	7/2/21	

		Presentation materials	7/2/21	
	Public workshop with CEC and TAC to present proposed scenarios		7/16/21	
		Workshop summary	7/23/21	
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	

SUMMARY OF BASELINE MODEL RESULTS for EPC-19-060

(Deliverable for Subtask 2.3)

March 2021

Recipient Project Manager: Sarah Kurtz

Commission Agreement Manager: Jeffrey Sunquist

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Executive Summary

This Summary of Baseline Model Results provides a preliminary summary of baseline results. This evaluation will be updated when the new version of RESOLVE is received and after the Multi-day model optimization is completed.

Key preliminary conclusions include:

- The SB100 targets can be met, but asking RESOLVE to reach zero emissions for the electricity that is lost in the system (not retail sales) results in an impractical solar build, motivating review of the model inputs
- Comparison between SWITCH and RESOLVE suggests that enabling use of out-of-state resources (in particular, wind resources) enables meeting the targets with a more practical solar build
- RESOLVE selects essentially all of the non-solar resources that were allowed in the 2018 RSP, further motivating a reconsideration of the available resources
- Comparison of our results with the latest SB100 Joint Agency Report confirms the value of adding additional candidate resources
- Increased loads from electric vehicles and electrolyzers increase the need for additional capacity buildout, but counter-intuitively reduce the use of pumped storage
- The description of the Li batteries has substantial effect on the selected storage and demand management resources

1. Introduction

This Summary of Baseline Model Results describes the implementation of the Baseline Description and Modeling Approach Description provided by Tasks 2.1 and 2.2 into the current version of RESOLVE and SWITCH.

The code for RESOLVE is currently being updated by E3 to introduce the ability to model multiple contiguous days. Such capability is necessary to capture the performance of multi-day storage. The new version of RESOLVE is not yet available, so this proposal of a baseline is considered to be preliminary. Nevertheless, the summary presented here will provide a starting point and useful information to be implemented in the new version of RESOLVE when it is ready.

We review both the results from RESOLVE and from SWITCH. In section 2 we review the changes made relative to the RESOLVE RSP baseline. In section 3 we present the results when all changes are made simultaneously and then explore the impact of removing each change one by one in order to see if the effect reflects the change that was associated with that change in Section 2. In Section 4 we compare the results from the new baselines for RESOLVE and SWITCH.

2. Changes made in RESOLVE baseline relative to RESOLVE RSP

The Baseline Description and Modeling Approach deliverables submitted to the CEC in February 2021 described several changes we propose to make relative to the Reference System Portfolio (RSP) from 2018. Table 2.1 provides a summary of these changes made in RESOLVE, the description of the change in the deliverables from February, and the result reported in this document.

Table 2. 1. Summary of changes made in RESOLVE relative to the Reference System Portfolio (RSP)

Change from RSP	Description of change	Modeling result
5-year intervals for periods and no financial calculation beyond the final year	Section 3.1 in Modeling approach	Section 2.1
Greenhouse gas targets set to zero in 2045	Table 7.1 Baseline description	Section 2.2
Add offshore wind as candidate	Section 3.2 Baseline description	Section 2.3
Add additional EV load	Section 2.4	Section 2.4
Add additional electrolyzer load (high hydrogen)	Section 6 Baseline description	Section 2.5
Increase planning reserve margin	Section 7 Baseline description	Section 2.6
Change Li-battery model	Section 4.1 Baseline description	Section 2.7

To create this baseline, the following steps were executed:

- Using the Scenario Tool, select the following options and create a set of input files:
  - 46MMT_20200527_2045_2GWPRM_NOOTCEXT_RSP_PD as starting point
  - Under “Load Assumptions” for “Hydrogen” select “CEC Pathways High Hydrogen”
  - Under “CAISO GHG Target (incl. BTM CHP emissions)” select “0 MMT by 2045 Statewide”
  - Under “Renewables” for “Off-shore wind available?” select “True”
  - Under “Simulation Years” select 2020, 2025, 2030, 2035, 2040, and 2045
  - Under “Financing Years Post Final Year” enter 0
- Modify the resulting files:
  - In the “zone_timepoint_params.tab” file, increase the CAISO loads for years 2025, 2030, 2035, 2040, and 2045 by the factors 1.028, 1.089, 1.156, 1.188 and 1.198, respectively to account for increased EV charging. Increase the annual load values in the “planning_reserve_margin.tab” by a similar value.[1]
  - File “resource_vintage_params.tab” replace “Annual_fixed_cost_by_vintage” for “CAISO_New_Li_Battery” (also for batteries 2-6) with values in Table 4.7 of Baseline Description.
  - File “resource_vintage_storage_params.tab” replace “Energy_storage_cost_ dollars_per_kwh_yr” for “CAISO_New_Li_Battery” (also for batteries 2-6) with values in Table 4.6 of Baseline Description.

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[1] When considering electric vehicle charging and operation of an electrolyzer, we choose not to include these in the calculation of the power needed for the planning reserve margin since these are loads that could be shed in an emergency. However, we retain the electric vehicle charging in the annual load, but not the electrolyzer load. This assumption could be debated.

- Add 99999 GW capacity limits for CAISO_New_Li_Battery5 & 6 by changing the flag in “resources.tab” to 1 for “capacity_limited” and adding the 99999 limits for all periods to file “capacity_limits.tab”.
- In the “planning_reserve_margin.tab” file, increase the “period_planning_reserve_margin” for years 2025-2045 from 0.15 to 0.207. Increase the values for “prm_peak_load_mw” for years 2025-2045 by a ratio of 1.207/1.15.[2]

2.1 Years modeled in RESOLVE

More detailed understanding of the evolution of the grid can be ascertained using 5-year increments in modeling. The periods used in the Reference System Portfolio (RSP) are designed for near-term planning, while we are exploring what will happen in later years. The comparison graphs were shown in the previous deliverable, but are shared again here for easy reference in Fig. 2.1.

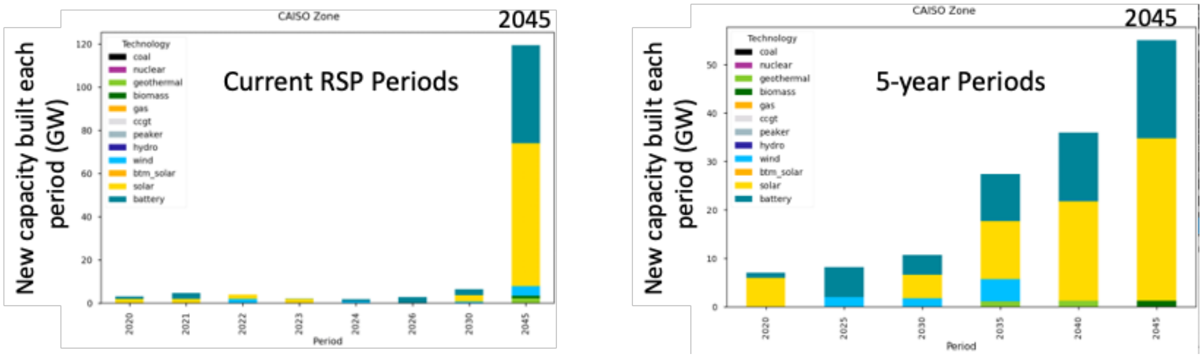

Fig. 2. 1 Comparison of RSP outputs using RSP periods (left) and 5-year periods (right)

We compared the objective function (total cost) for the RSP calculated from the original set of periods and the 5-y periods. The value was found to be consistent within 1%, as shown in Fig. 2.2. The RSP weights the final period more than others by adding 20 years past the final period. This is somewhat balanced by applying the 5% discount rate, but it also adds uncertainty by including costs extrapolated to 2065. We have chosen to count the final 2045 period as 3 years, effectively ending the simulation in the year 2045 with zero years appended. This reduces the calculated cost (objective function) by 34% (as shown in Fig. 2.2). If an additional 5-year period is added to include 2050, the reduction is only 21%. If 2050 is included with an additional 20 years appended beyond 2050, the value is increased by 7%. We also considered setting the discount rate to 0%, which places more emphasis on the later years. The cost of the scenario ending in 2045 is doubled when the discount rate is set to zero relative to 5% as shown in Fig. 2.3.

Most of the calculations reported in the rest of this report build on the scenario in Fig. 2.2 labeled “5-y 2045 end” which includes 2020, 2025, 2030,2035, 2040,and 2045, with no added years simulated beyond 2045. As we move into 2021 it is no longer appropriate to optimize the capacity expansion in 2020. We retained it here as a reference point, but note that the SB 100 report shifts to using 2027, 2030, 2035, 2040 and 2045 as the periods for optimization.[3]

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[2] The decision to increase the planning reserve margin from 15% to 20.7% is not yet finalized and it is not clear whether it should include the EV and electrolyzer loads nor whether it should include behind-the-meter storage, etc. The effect of electrification on the needed planning reserve margin is a topic worth studying separately.

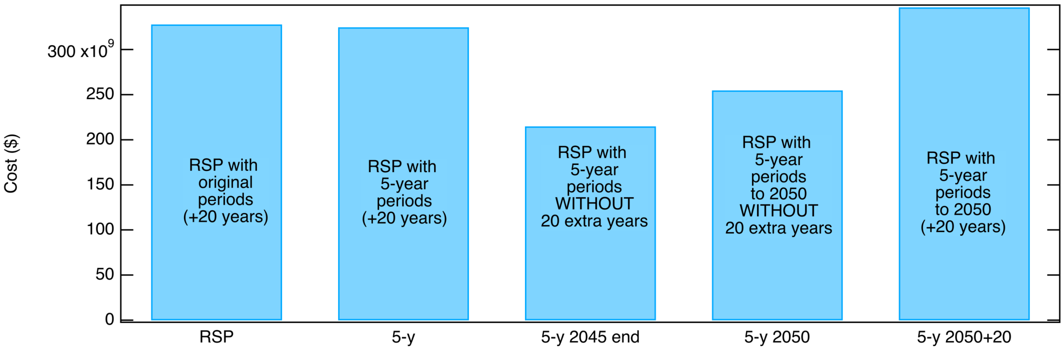

Fig. 2. 2 Objective function (total cost) optimized by RESOLVE for various period definitions.

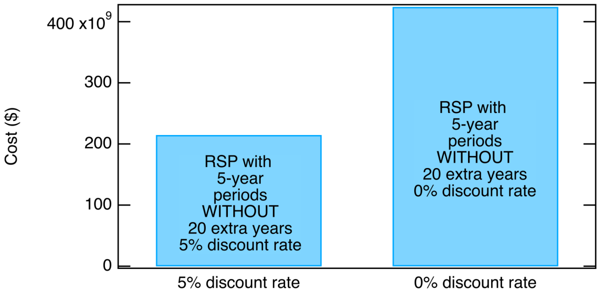

Fig. 2. 3 Objective function (total cost) with and without discount rate for 5-year scenario.

2.2 Greenhouse gas emissions targets set to zero in 2045

California Senate bill 100 sets the goal of zero-carbon emissions by 2045, but it left some ambiguity about what exactly that meant. The recent SB100 study concludes[3] that the modeling should include the retail sales, as explicitly indicated by SB100, but should exclude line losses, as shown in Fig. 2.4. While the “SB100 core” study excludes the line losses, we feel we will bring greater value if we include the line losses as this scenario better represents our aspirations. The SB100 study also includes a scenario with the more stringent goal. By defining what it would take to reach those, we can empower the CEC and CPUC to decide whether to take the corresponding action. So, we have selected to set the baseline to reach zero carbon emissions (including the line losses) in 2045. We will consider other targets in our sensitivity analysis. The stricter targets result in a very large increase in solar and storage built in 2045, as shown in Fig. 2.5. The build out in 2020 to 2040 is slightly greater, but the build in 2045 is almost five times greater. This results in a large amount of curtailment, as shown in Fig. 2.6 by the hatched part of the bar at the top. The electricity used to charge the battery is shown on a negative-going bar. Note the different scales on the graphs.

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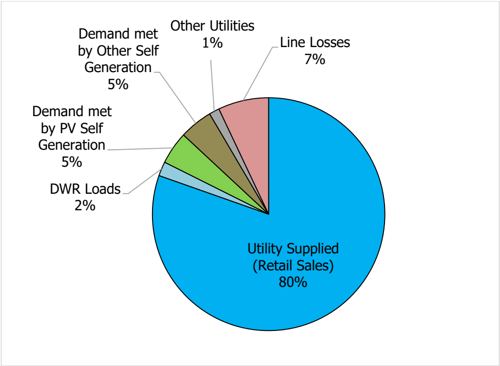
[3] https://efiling.energy.ca.gov/GetDocument.aspx?tn=237167&DocumentContentId=70349



Source: 2019 California Energy Demand and the Quarterly Fuels and Energy Report Demand filings

Fig. 2. 4 Breakout of electricity demand[4] to define the parts included in this study

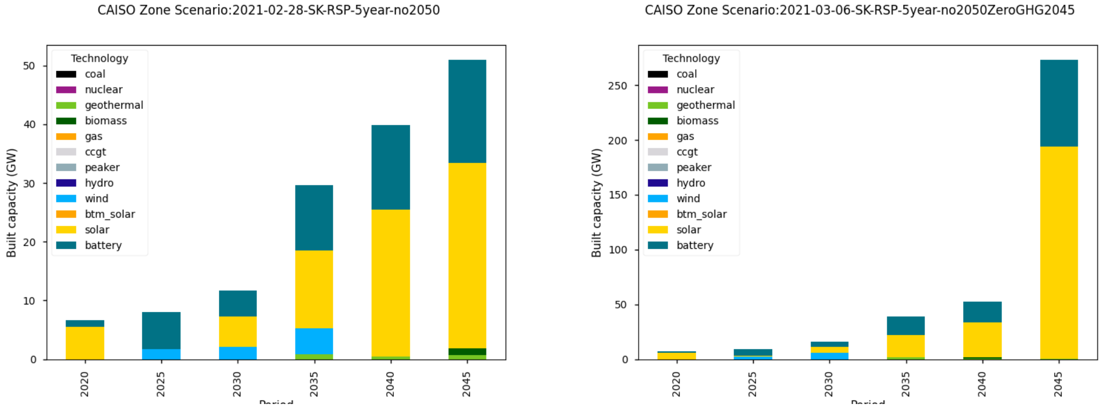


Fig. 2. 5 Comparison of resource builds for RSP (left) and RSP with zero emissions in 2045 (right).

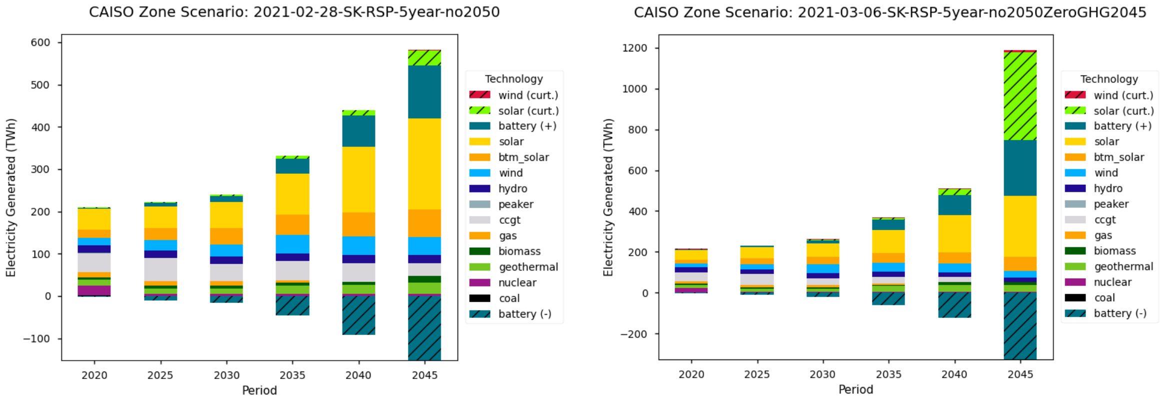


Fig. 2. 6 Comparison of electricity generation for RSP (left) and RSP with zero emissions in 2045 (right).

The fractional resource buildouts for these two scenarios are shown by technology for 2040 and 2045 in Figs. 2.7 and 2.8, respectively. The fractional buildout is relative to the resources that

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[4] https://efiling.energy.ca.gov/GetDocument.aspx?tn=237167&DocumentContentId=70349

RESOLVE was allowed to build. In 2040, the zero-emissions scenario is found to build out all of the allowed biomass and more geothermal than the RSP. Surprisingly, it then selects to build less pumped storage in 2040.

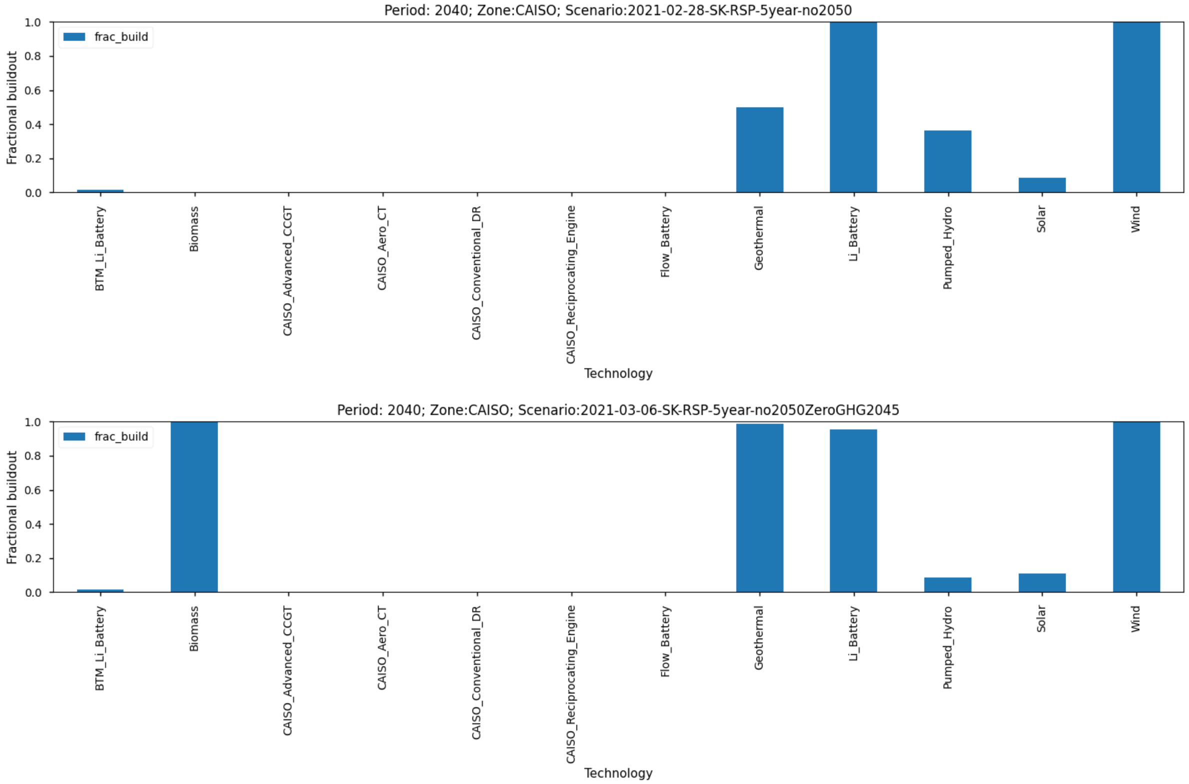


Fig. 2. 7 Fractional buildout for Period 2040 for RSP (top) and RSP with zero emissions in 2045 (bottom)

In the period 2045 (Fig. 2.8) both scenarios build all of the available biomass, and the RSP selects to build most of the geothermal while the zero-emissions scenario builds all available geothermal. Again, the amount of pumped-hydro that is built is substantially less than that built by the RSP. In this case, the reason is much more obvious: the solar build out is huge, requiring less storage.

The documentation of more storage buildout for the zero-emissions scenario in Fig. 2.5 and less fractional buildout in Fig. 2.8 at first appears to be contradictory. However, this is an artifact of batteries 5 and 6 being unlimited. The larger buildout of batteries 5 and 6 shows up in Fig. 2.5, but is not documented in Fig. 2.8 since these two candidate resources are flagged for unlimited build. In Section 3, when we explore the final version of the baseline, we add reasonable limits on batteries 5 and 6 to help us track their expansion in more detail using a graph like Fig. 2.8.

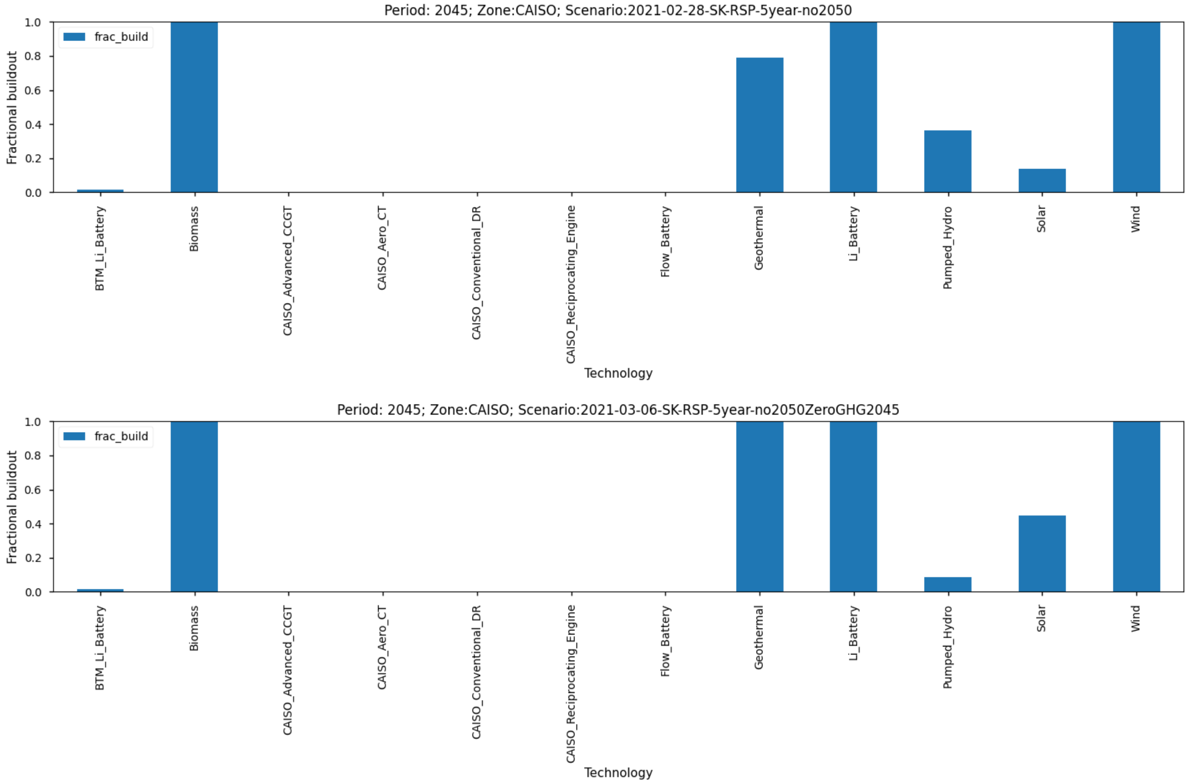


Fig. 2. 8 Fractional build out for Period 2045 for RSP (top) and zero-emissions-in-2045 scenario (bottom)

2.3 Addition of Offshore wind candidates

The addition of offshore wind as a candidate has been suggested by offshore wind companies to be of obvious value. Offshore wind is progressing quickly for Denmark and on the east coast of the United States. For consistency, we adopt in our baseline to use the same offshore wind candidate resources that have been identified in the RESOLVE Scenario Tool. The comparison of the RSP (same data as above, but repeated for ease of comparison) with a scenario with added offshore wind is shown in Fig. 2.9. RESOLVE selects to build the additional wind primarily in 2035 and 2040.

The electricity generation for these two scenarios is shown in Fig. 2.10. The increased production from wind is evident in 2035, 2040, and 2045.

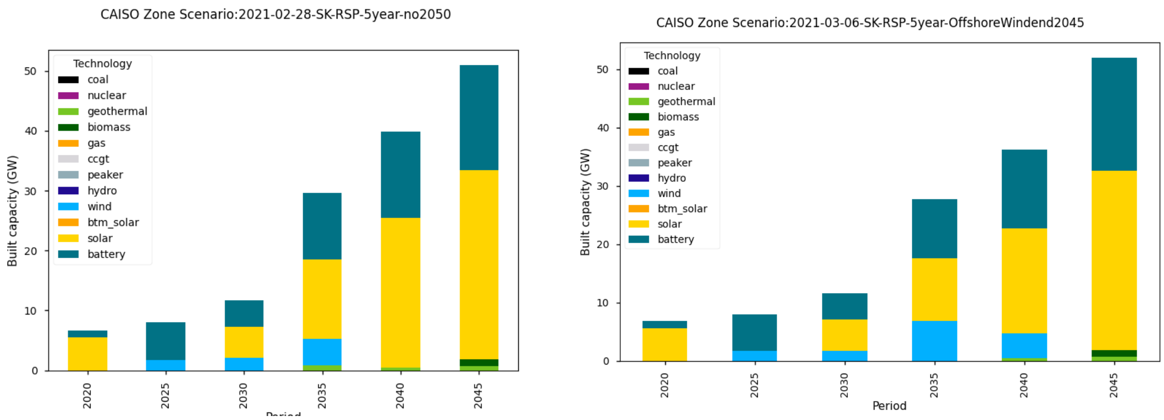


Fig. 2. 9 Comparison of resource builds for RSP (left) and RSP with offshore wind (right).

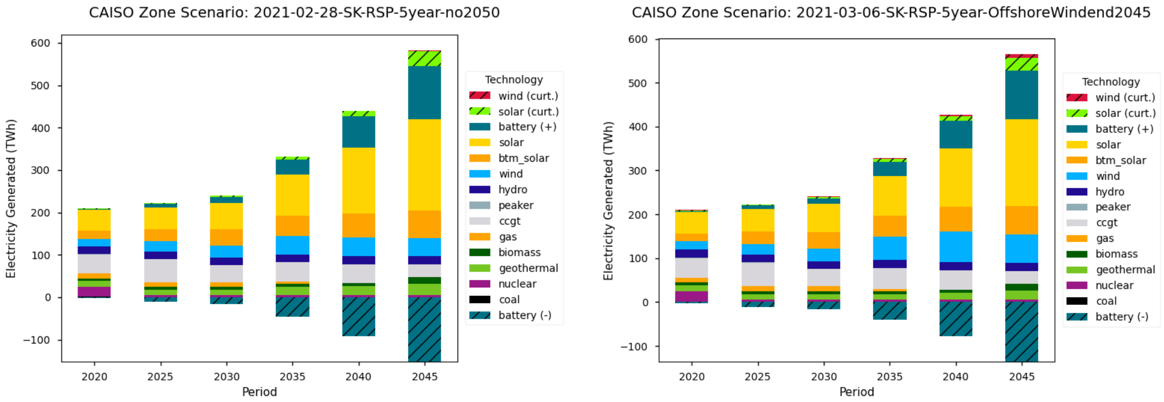


Fig. 2. 10 Comparison of electricity generation for RSP (left) and RSP with offshore wind (right).

The fractional buildout for the RSP and for the RSP with offshore wind added is shown for periods 2040 and 2045 in Figs. 2.11 and 2.12. In 2040, the buildout of geothermal and pumped hydro is selected to be less than half of that in the RSP. The on-shore wind is built out just slightly less. Similar observations are made for 2045, though the buildout of geothermal effectively doubles. The reduced buildout of solar (especially in 2035 and 2040) is more easily seen in Fig. 2.9 than in Figs. 2.11 and 2.12.

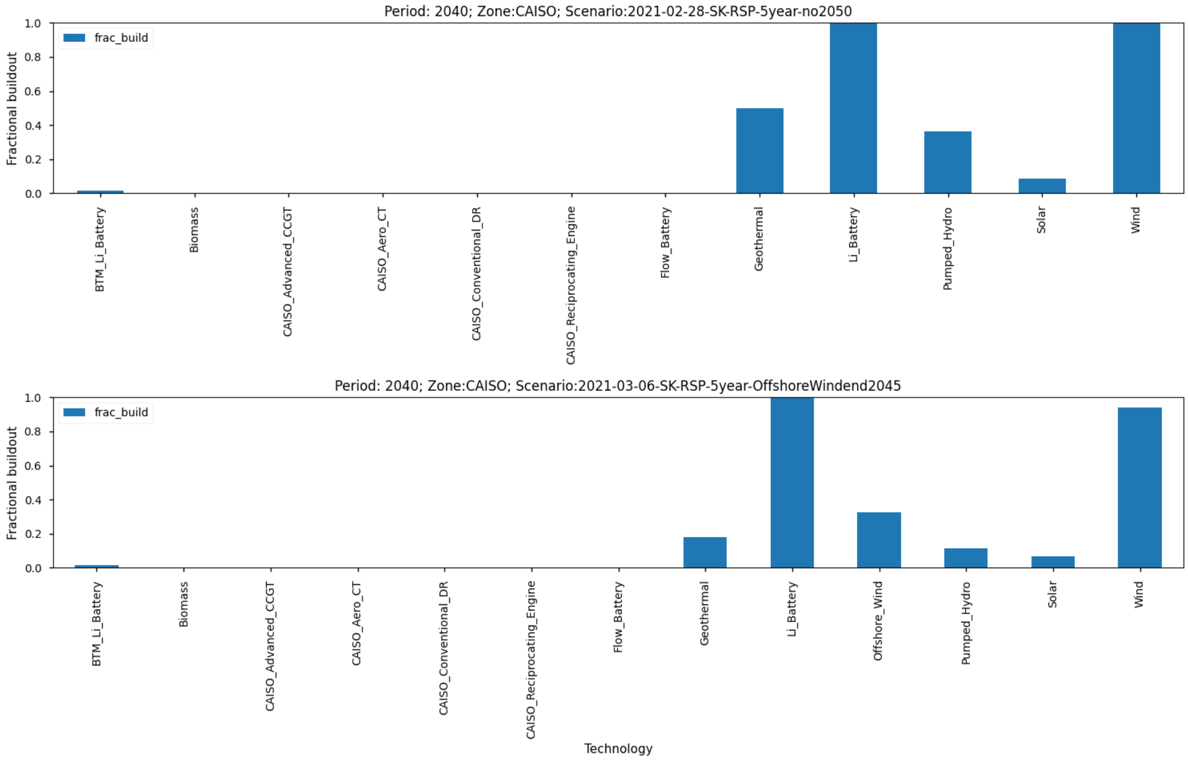


Fig. 2. 11 Fractional buildout for Period 2040 for RSP (top) and RSP with offshore wind (bottom)

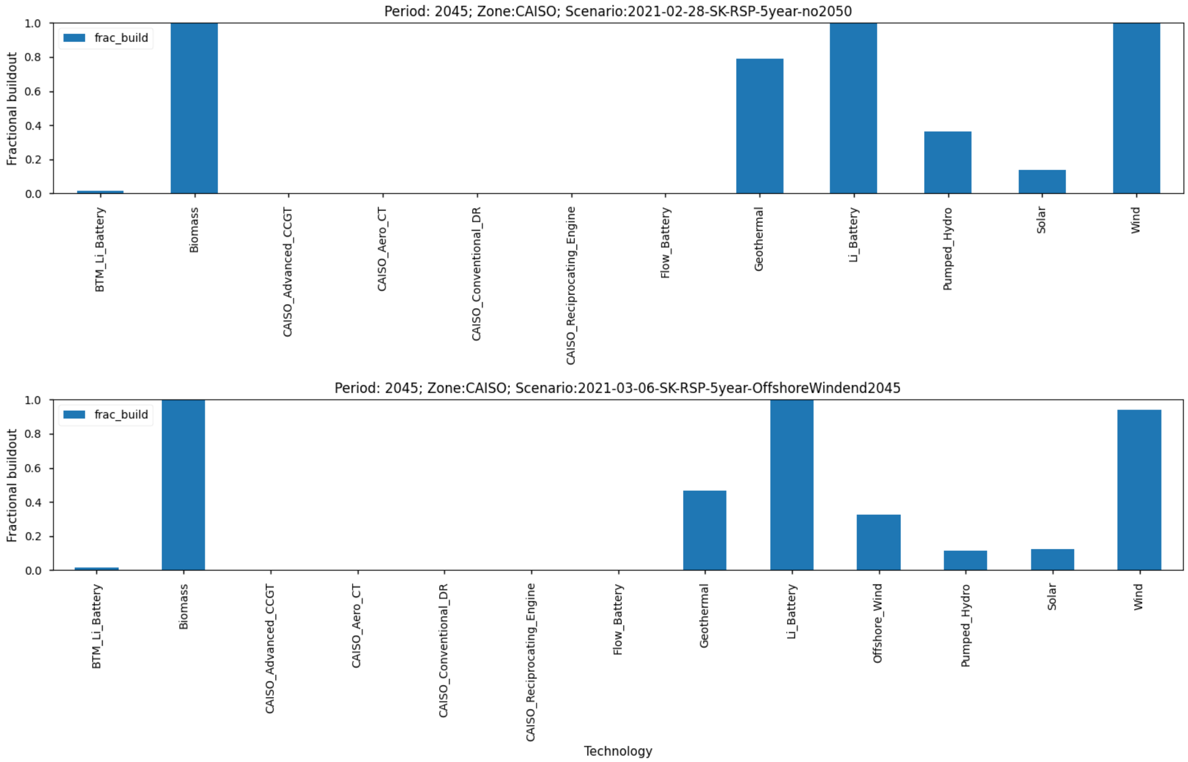


Fig. 2. 12 Fractional buildout for Period 2045 for RSP (top) and RSP with offshore wind (bottom)

2.4 High-electric-vehicle baseline

The governor's announcement in September of 2020 of a 2035 target for reaching 100% electric vehicles for sales of passenger cars motivated us to revisit the assumptions about the load associated with electric vehicles. We expect that the state will be identifying anticipated growth of the load associated with this transition and that we will be investigating a range of scenarios for electric vehicle (EV) charging. For our baseline estimate we have assumed 36 million vehicles on the road, with 1/15 of those vehicles replaced every year. We assumed linear growth in sales of EVs, reaching 100% in 2035. We assumed 4100 kWh annual electricity use per EV. These loads were compared with the EV-related loads documented for the RSP and the total loads were multiplied by a constant factor, simulating a flat charging profile. The calculated data are shown in Table 2.2 and in Fig. 2.13.

Table 2. 2 Annual load data (TWh) estimated for increased EV deployment (CAISO zone)

Year	Annual TWh for EVs	RSP EV load	RSP total CAISO load	Proposed baseline load
2020	NA	1.11	243	243
2025	12.4	5.0	254	261
2030	34.2	11.1	259	282
2035	63.7	17.6	302	349
2040	89.1	24.0	346	411
2045	107	30.5	383	459

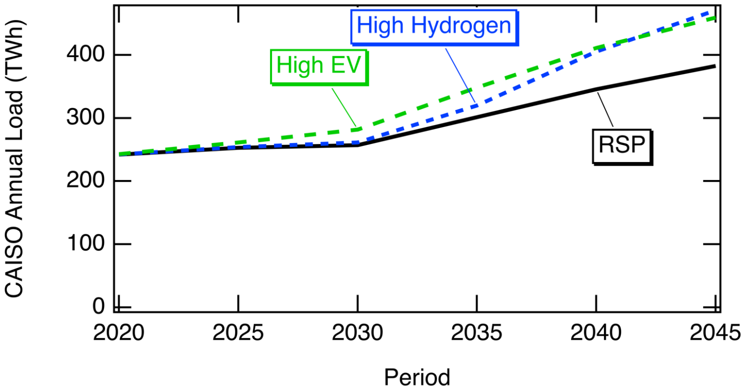


Fig. 2. 13 CAISO annual load for RSP and with added EV and hydrogen loads

The results of the higher EV load implemented in the RSP are shown in Figs. 2.14-2.17, presented similarly to the graphs in the previous section. We see that wind and geothermal are built earlier to meet the increased load. By 2045, the bulk of the added load is met by solar, since the other resources have been exhausted. The increase in load calculated from Table 2.2 (459/383) is 20% which is consistent with about 20% increase in electricity seen in Fig. 2.15. Fundamentally, the capacity limits set for geothermal, biomass, and wind in the RSP limit the ability of the grid to meet expanded loads in future years, resulting in solar being the only option.

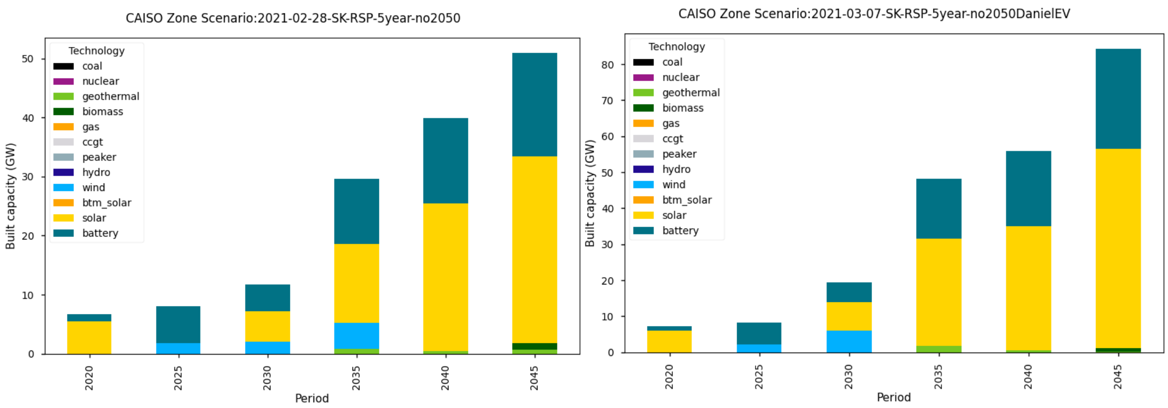


Fig. 2. 14 Comparison of resource builds for RSP (left) and RSP with higher EV load (right).

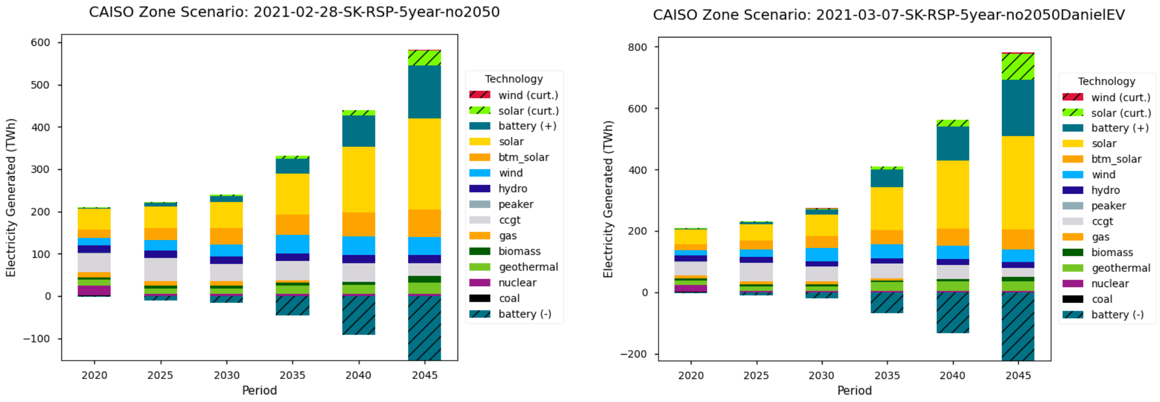


Fig. 2. 15 Comparison of electricity generation for RSP (left) and RSP with higher EV load (right).

The SB100 Report also increases the loads for EVs and electrolyzers. Similar to our conclusion that we would want additional wind to meet these larger loads, the SB100 Report identifies additional wind resources both onshore and offshore. These are an appropriate change for the baseline assumptions.

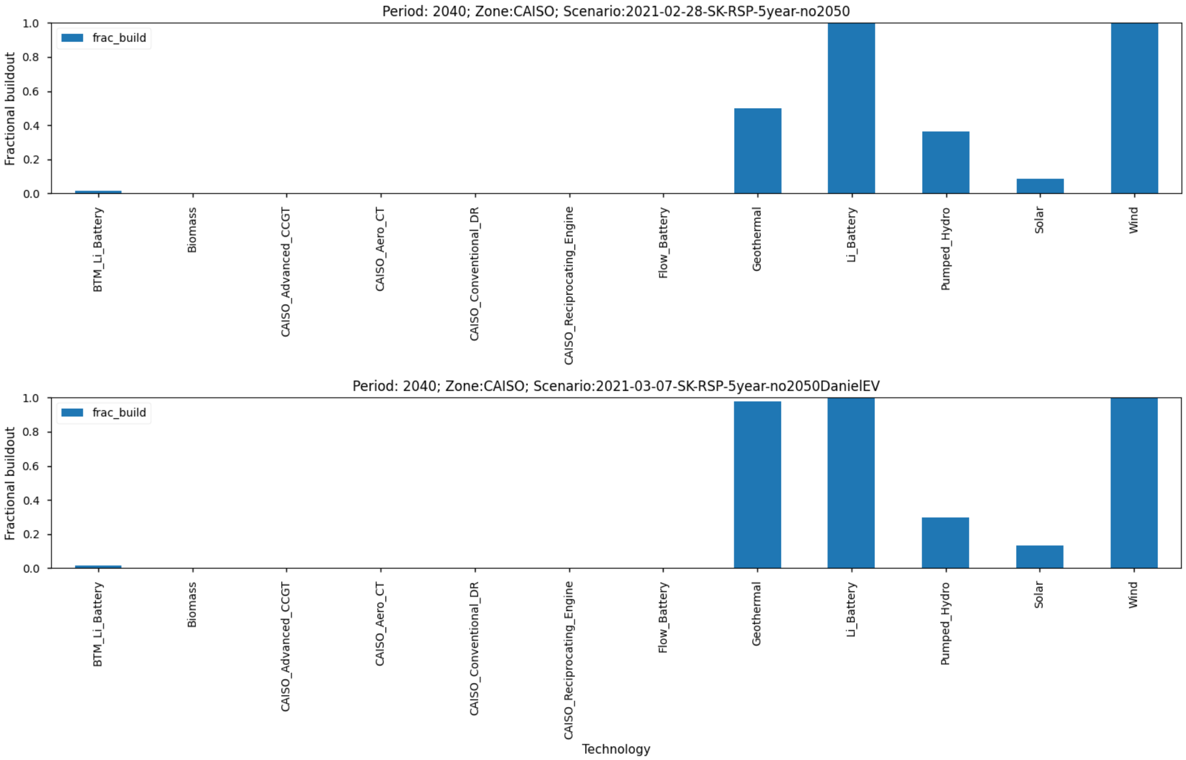


Fig. 2. 16 Fractional buildout for Period 2040 for RSP (top) and RSP with higher EV load (bottom)

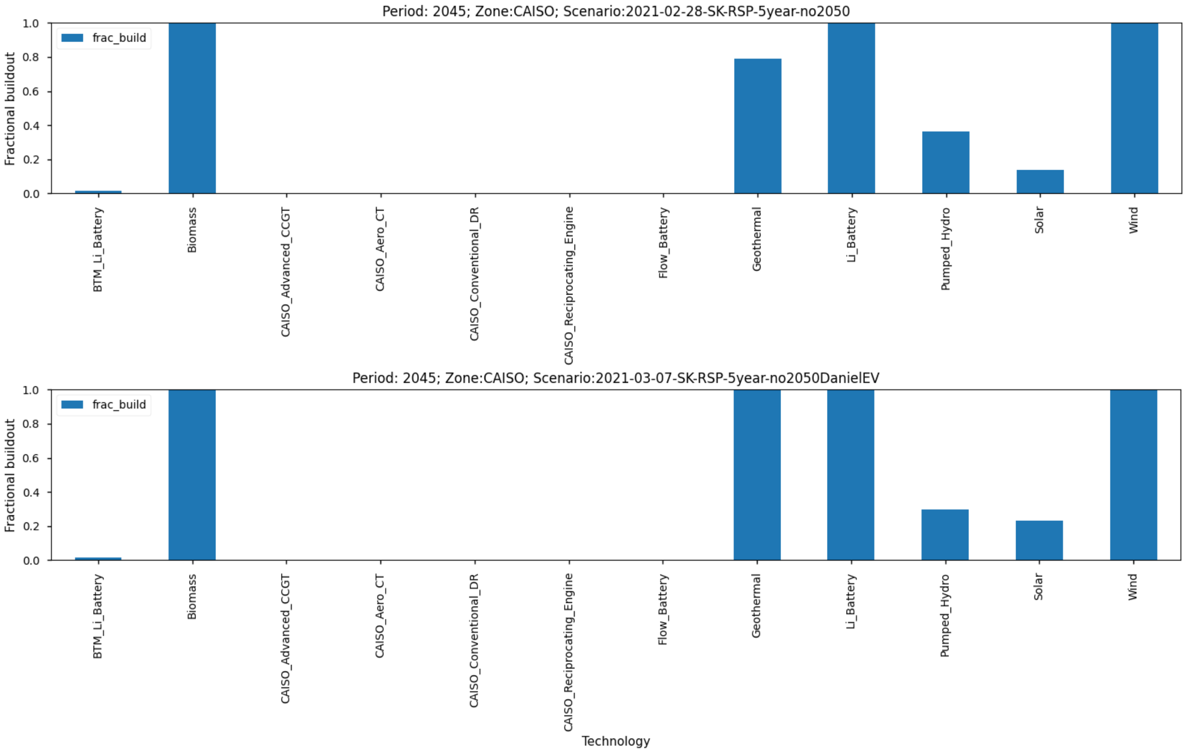


Fig. 2. 17 Fractional buildout for Period 2045 for RSP (top) and RSP with higher EV load (bottom)

2.5 High-hydrogen (high electrolyzer load) baseline

The high-hydrogen scenario provided by the Scenario Tool results in the increased CAISO load documented in Fig. 2.13. Based on the recent announcements of investments in hydrogen in multiple parts of the world, we anticipate that the deployment of electrolyzers to generate hydrogen will advance at a rate closer to the high-hydrogen baseline than to the baseline used in the RSP. The results of the high-hydrogen scenario are summarized in Figs. 2.18-2.21. The results differ from the higher EV load in that the build out occurs slightly later, but the net result is the same – biomass, geothermal, and wind are built to their limits and then solar expands in a large way to meet the additional load.

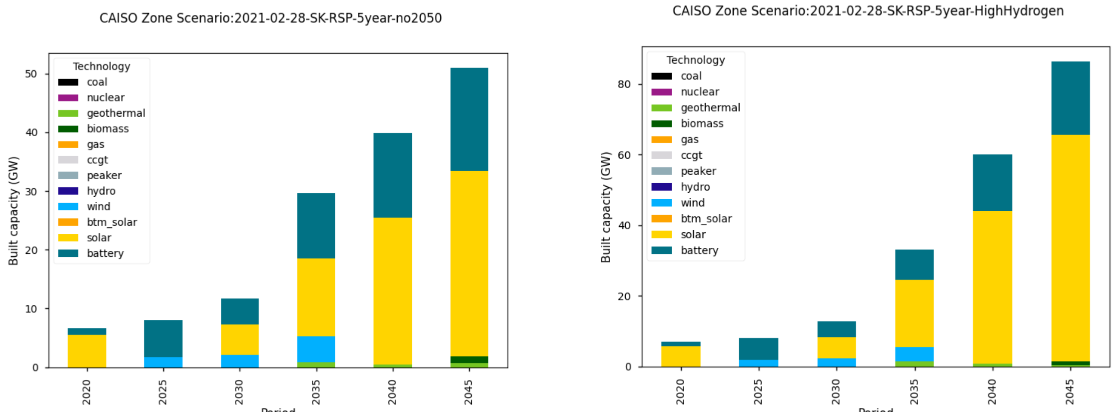


Fig. 2. 18 Comparison of resource builds for RSP (left) and RSP with higher electrolyzer load (right).

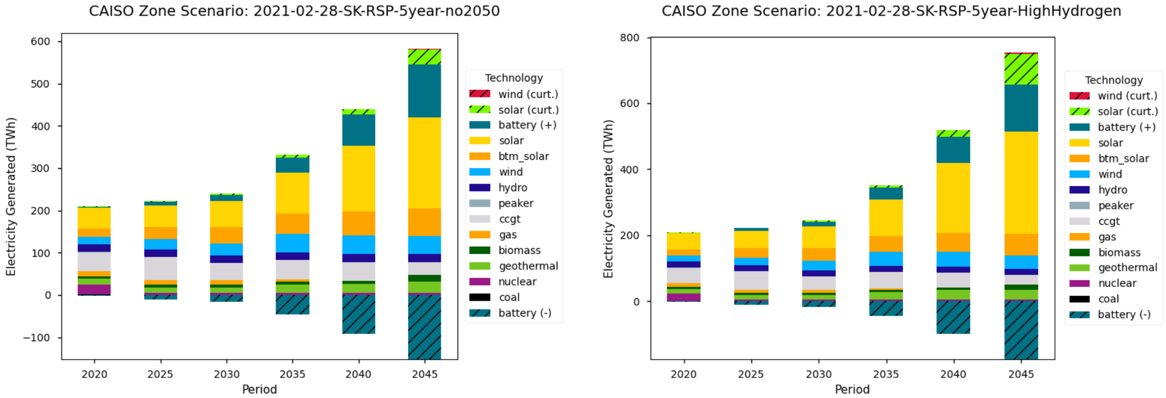


Fig. 2. 19 Comparison of electricity generation for RSP (left) and RSP with higher electrolyzer load (right).

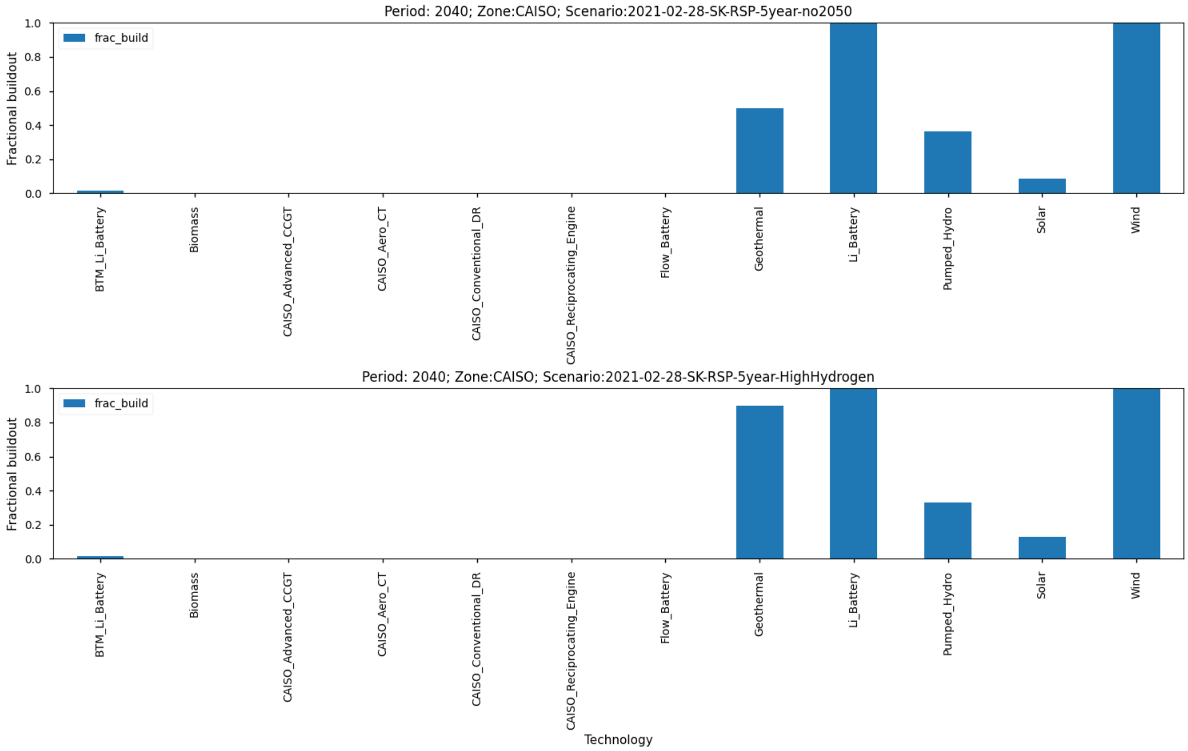


Fig. 2. 20 Fractional build for Period 2040 for RSP (top) and RSP with higher electrolyzer load (bottom)

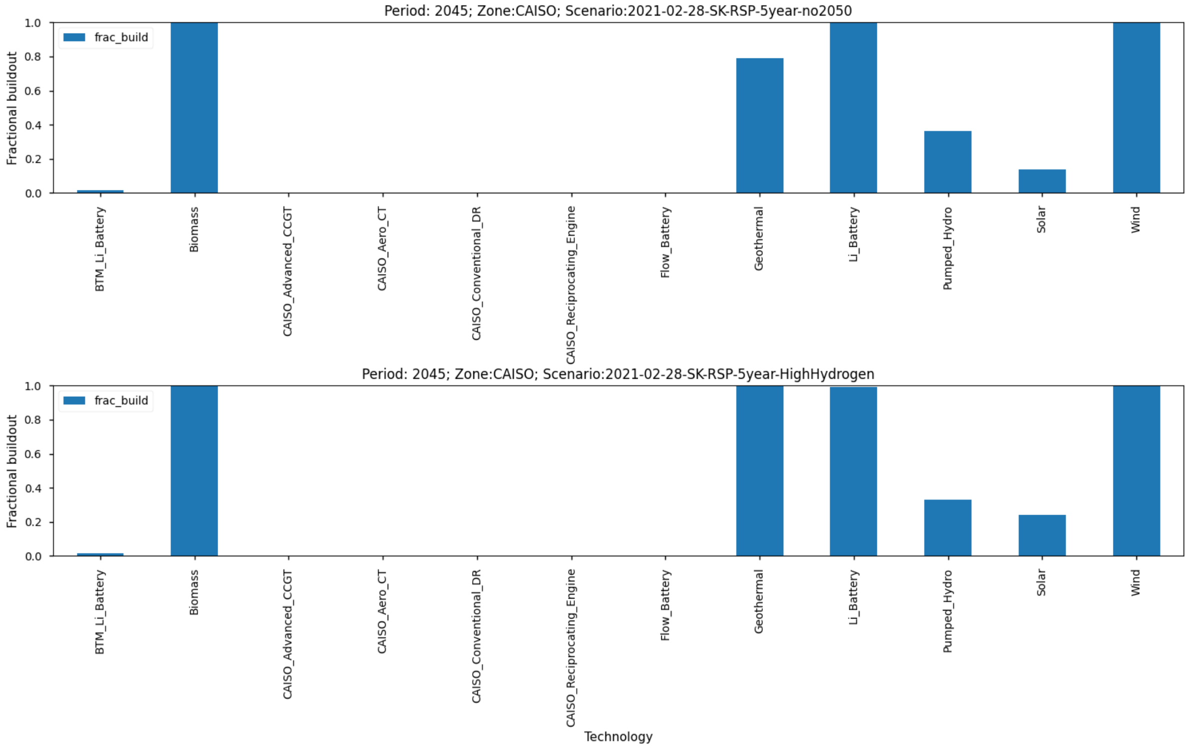


Fig. 2. 21 Fractional build for Period 2045 for RSP (top) and RSP with higher electrolyzer load (bottom)

2.6 Higher planning-reserve-margin baseline

There is current discussion to increase the planning reserve margin in the 2025 timeframe to 20.7% (from the current 15%). Although this decision has not been finalized, we believe that the change is likely to occur and that it will be wise to have a larger margin in the next years while we are transitioning the energy system and while climate change may create surprisingly extreme weather. Of course, if more extreme weather is used for planning, then it may not be as important to plan capacity expansion with such a wide margin.

This section describes the impact of increasing the planning reserve margin to 20.7% for the periods starting in 2025. An increase from 15% to 20.7% would increase the needed capacity by 120.7/115 = 5%. This is quite noticeable in 2025 when more batteries are built, then the build out in 2030 and 2035 changes slightly. This added investment in capacity increases the cost. However, it doesn't change the operating costs. The objective function is found to increase by about 3%.

The graphs are shown, as above, in Figs. 2.22-2.25. The difference is easy to see in 2025-2035 in Fig. 2.22, but very difficult to see in Fig. 2.23, since the generation of electricity is mostly unaffected. Most notably in Figs. 2.24 and 2.25 is the addition of demand response.

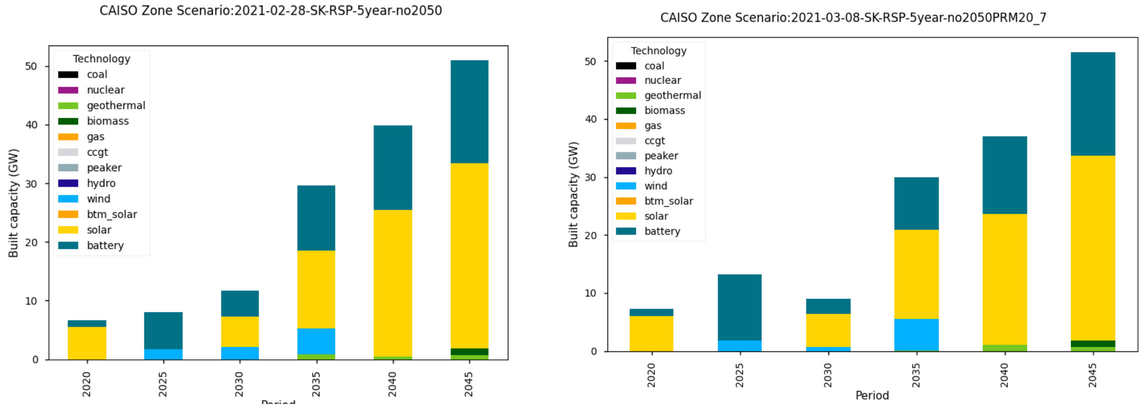


Fig. 2. 22 Comparison of resource builds for RSP (left) and RSP with 20.7% planning reserve (right).

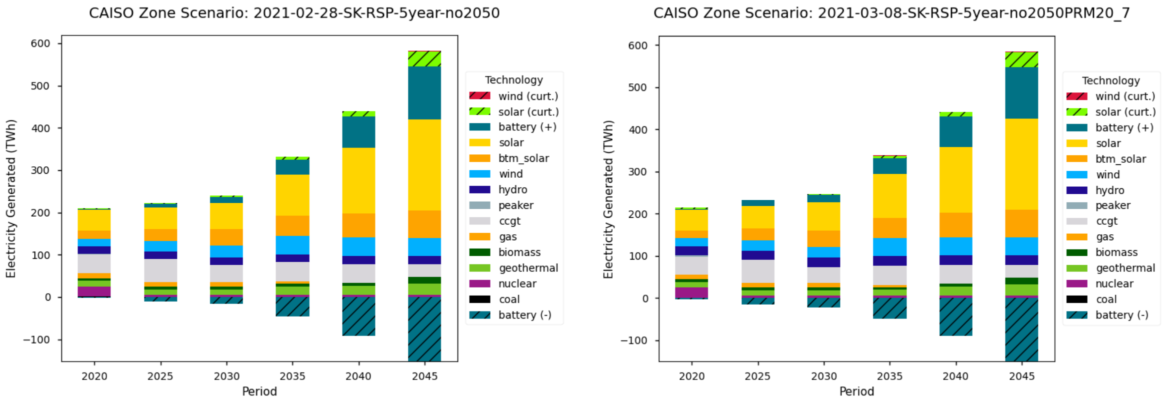
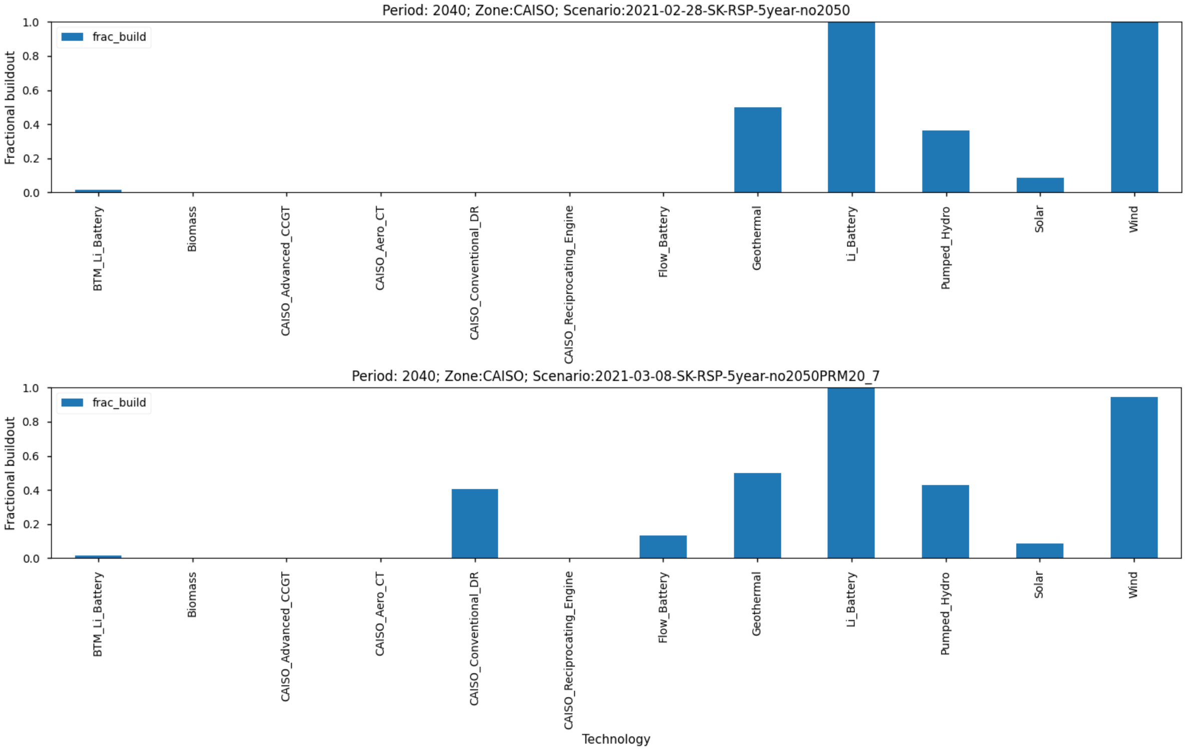
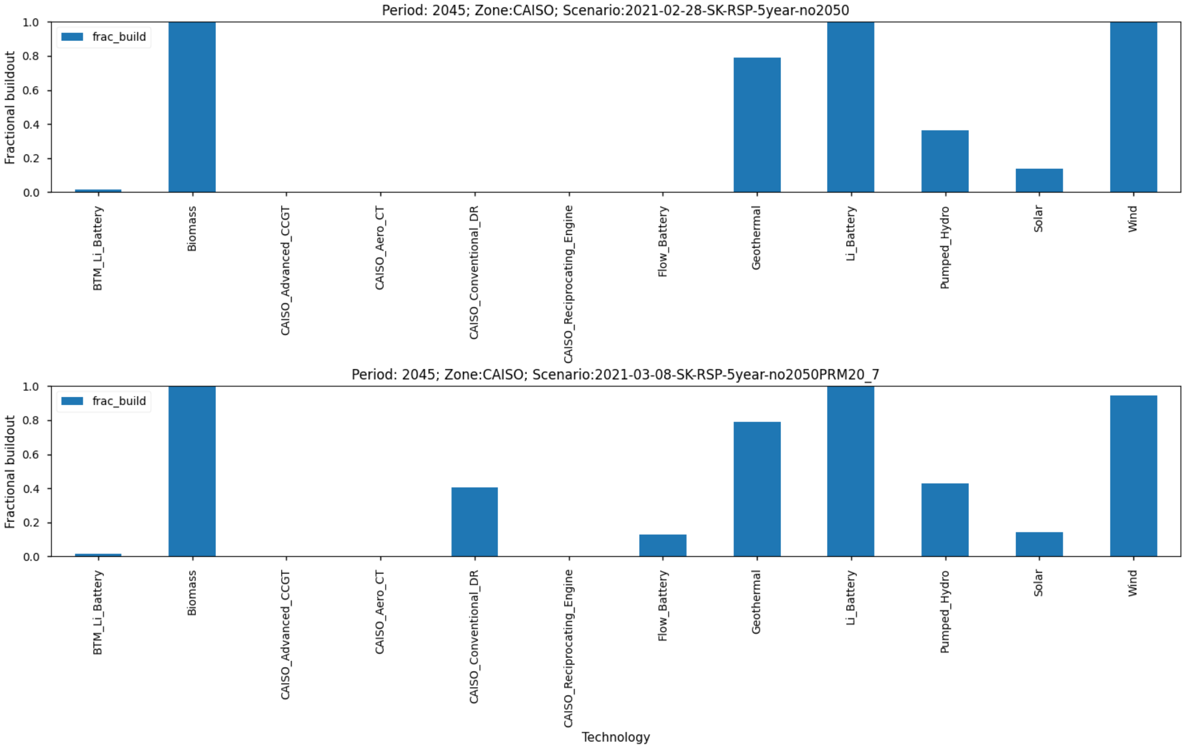


Fig. 2. 23 Comparison of electricity generation for RSP (left) and RSP with 20.7% planning reserve (right).


Period: 2040; Zone:CAISO; Scenario:2021-02-28-SK-RSP-5year-no2050

Period: 2040; Zone:CAISO; Scenario:2021-03-08-SK-RSP-5year-no2050PRM20_7

Fig. 2. 24 Fractional build for Period 2040 for RSP (top) and RSP with 20.7% planning reserve (bottom)


Period: 2045; Zone:CAISO; Scenario:2021-02-28-SK-RSP-5year-no2050

Period: 2045; Zone:CAISO; Scenario:2021-03-08-SK-RSP-5year-no2050PRM20_7

Fig. 2. 25 Fractional build for Period 2045 for RSP (top) and RSP with 20.7% planning reserve (bottom)

2.7 Four-hour lithium-ion battery baseline

New batteries being installed in California are mostly being installed as four-hour batteries to be able to benefit from increased capacity credit, as discussed in Section 4.1 of the Baseline Description. The RSP allows investment in lithium-ion batteries with any duration greater than 1 hour. The cost of installing the batteries in the RSP is split between the \$/kW and the \$/kWh, so is cheaper to build one 8-hour battery (1 X the cost per kW + 8 X the cost per kWh) compared with two 4-hour batteries (2 X (1 X the cost per kW + 4 X the cost per kWh)). As a result, the RSP selects to invest in batteries with long durations. Some of the cost of a battery is associated with the power rating (for example, the cost of the power electronics), but much of the cost is associated with the energy rating. We are unconvinced that one 8-hour battery costs so much less than two 4-hour batteries, so we modified the baseline to place 100% of the upfront cost with the \$/kWh input, as described in Section 4.1 of the Baseline Description. The results of that change on the RSP outputs are shown in Figs. 2.26-2.29. The effect is surprisingly large, with significantly fewer batteries built in 2030 and 2035. Figs. 2.28-29 show that Li-ion batteries are replaced by pumped hydro storage, flow batteries and demand response.

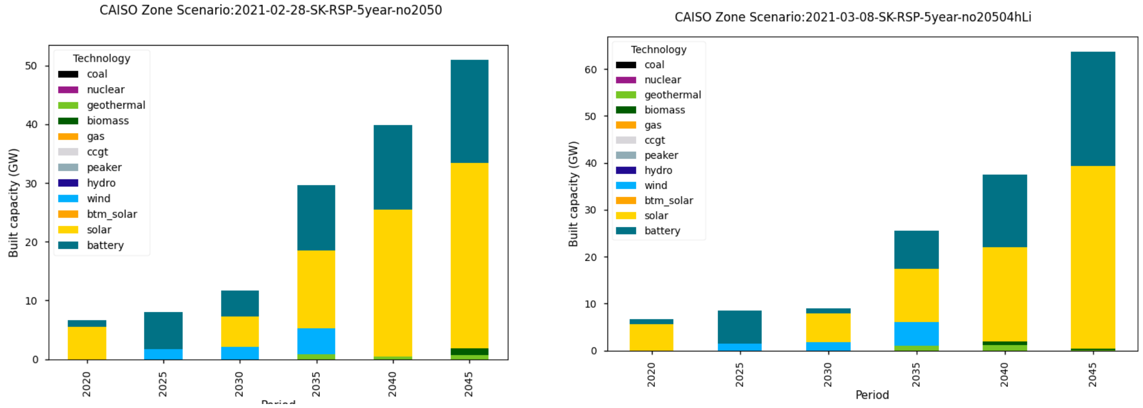


Fig. 2. 26 Comparison of resource builds for RSP (left) and RSP with 4-h lithium batteries (right).

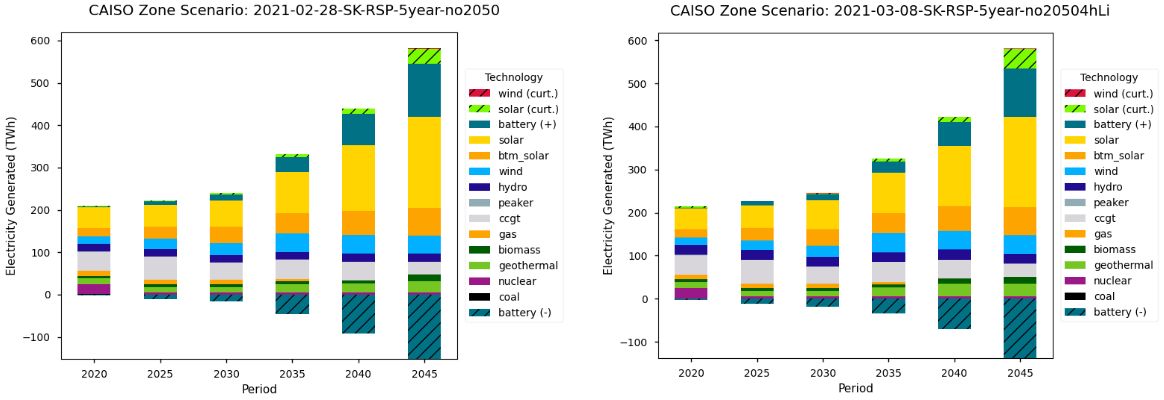


Fig. 2. 27 Comparison of electricity generation for RSP (left) and RSP with 4-h lithium batteries (right).

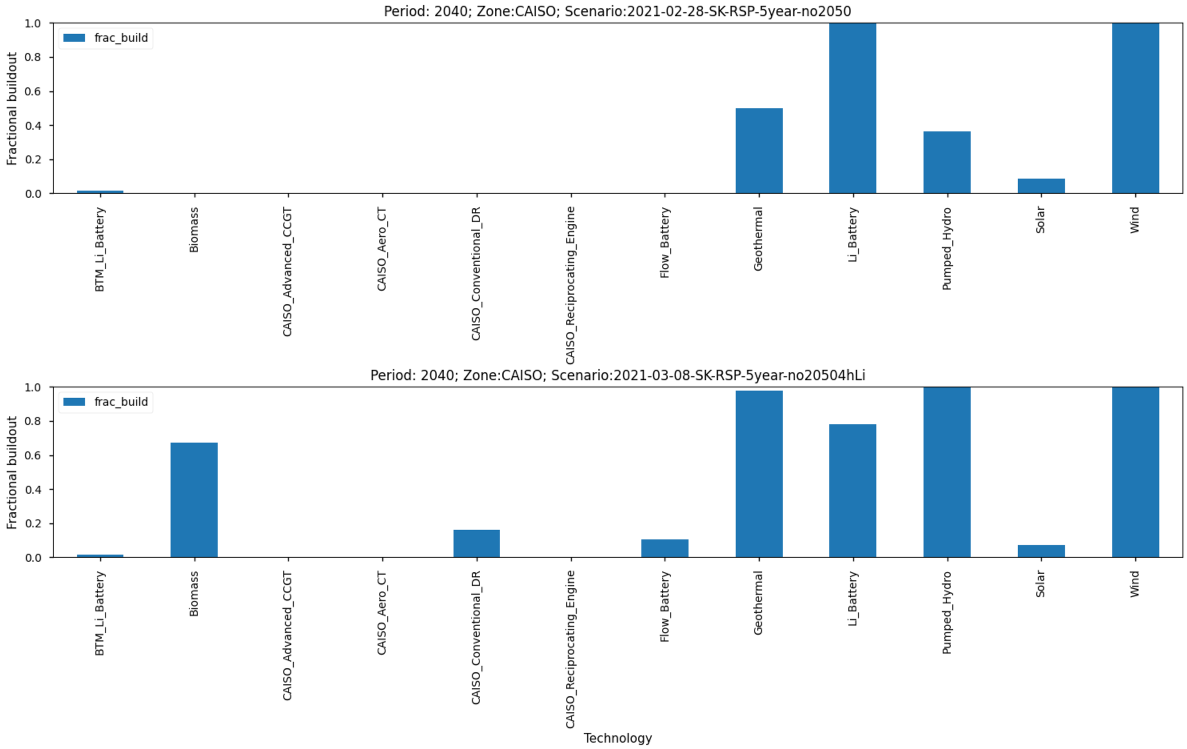


Fig. 2. 28 Fractional build for Period 2040 for RSP (top) and RSP with 4-h lithium batteries (bottom)

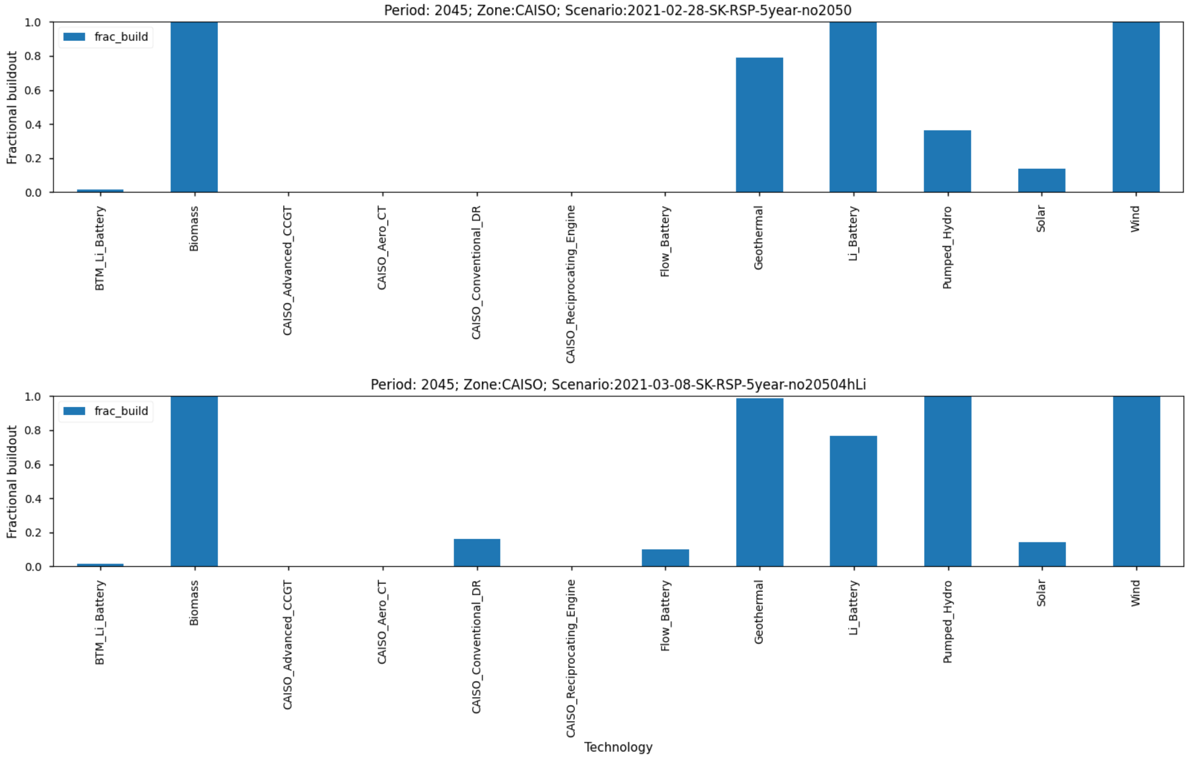


Fig. 2. 29 Fractional build for Period 2045 for RSP (top) and RSP with 4-h lithium batteries (bottom)

2.8 Effect of changes on cost of baseline

As each change was made to the 2018 RSP, the total cost, as optimized by the RESOLVE objective function sometimes increased and sometimes decreased as shown in Table 2.3 and Fig. 2.30.

Table 2. 3 Cost-sensitivity analysis for RESOLVE baseline scenario

Zero emissions in 2045	Add off-shore wind	Higher EV charging load	Higher electrolyzer load	20.7% planning reserve margin	4-h Li battery definition	Objective function (total cost) ($billions)	Relative total cost
Based on 2018 RSP with 5-year periods through 2045							
						215	100%
✓						260	121%
	✓					213	99%
		✓				254	118%
			✓			235	109%
				✓		223	103%
					✓	225	105%
New baseline							
✓	✓	✓	✓	✓	✓	391	100%
	✓	✓	✓	✓	✓	301	77%
✓		✓	✓	✓	✓	394	101%
✓	✓		✓	✓	✓	327	84%
✓	✓	✓		✓	✓	351	90%
✓	✓	✓	✓		✓	385	99%
✓	✓	✓	✓	✓		375	96%

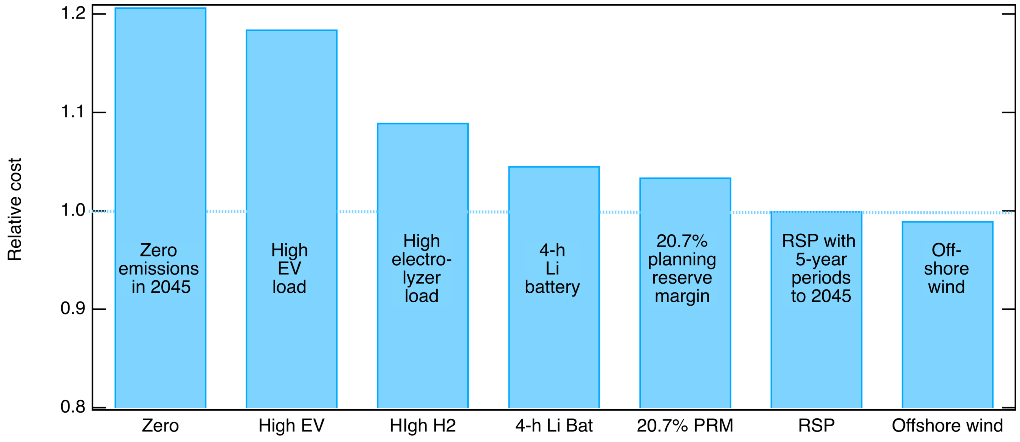


Fig. 2. 30 Relative costs of the 2018 RSP with each of the modifications made individually

In Section 3 we document the results of making all of the changes in a single scenario then consider the effect of removing each of the changes individually, reflecting the check marks in Table 2.3. As expected, the relative effects of each change are similar to what has been documented in Section 2, although removing each assumption in most cases decreases the cost. To aid in an easy visual comparison to Fig. 2.30, we have plotted the relative decrease (instead of increase) in cost in Fig. 2.31. The general trend is the same.

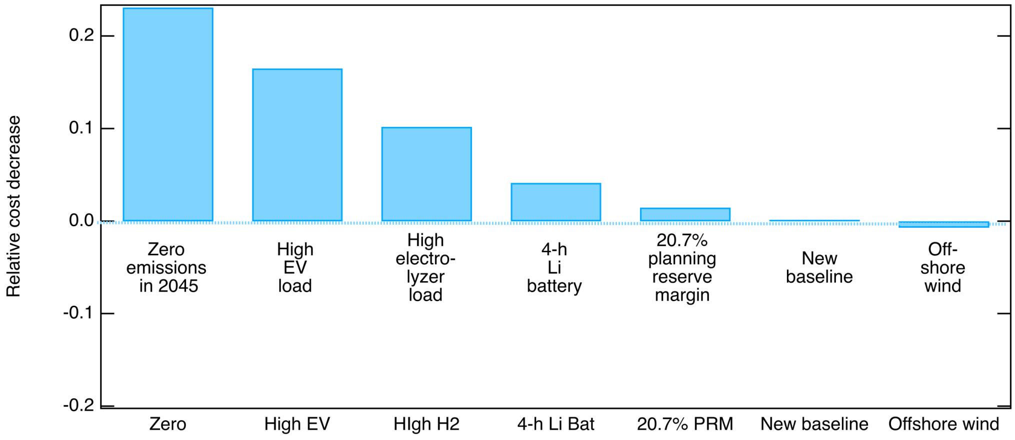


Fig. 2. 31 Relative costs of the new baseline with each of the modifications taken out individually

Of these costs, setting the target to deliver zero-carbon electricity for all of the electricity – including the line losses – has the biggest effect. The increased cost associated with a high EV load would be offset by the reduced need to use gasoline to power conventional cars. Similarly, the high electrolyzer load would result in generating hydrogen which would provide value to the system.

3. New RESOLVE baseline's sensitivity to changes

The new baseline (based on the changes summarized in Section 2) is substantially different from the RESOLVE RSP defined in 2018. This part of the report complements Section 2 to show the effect of removing each of these changes from the new baseline, enabling a fuller understanding of each change that complements how having that change affected the 2018 RSP.
We emphasize that these are preliminary results. The implementation of the baseline in a RESOLVE run that includes a full year of continuous simulation may give a different answer than this implementation that uses 37 independent days, preventing any use of cross-day energy storage.

3.1 Comparison of 2018 RSP with new RESOLVE baseline

The 2018 RSP results are compared with the new RESOLVE baseline results in Figs. 3.1 to 3.4. Note that the scales for the vertical axes of Figs. 3.1 and 3.2 differ. In particular, the build capacity axis for the new baseline is roughly seven times larger than the build axis for the 2018 RSP (Fig. 3.1). The bigger buildout partially reflects the higher electricity demand, as shown in Fig. 3.2. However, the total load only increases about 60%, requiring less than a factor of two increase in electricity generation, much less than the factor of seven higher buildout shown in Fig. 3.1. The suggested build of close to 300 GW in the 2045 period could translate to about 60 GW per year. It is not clear that this will be practical. Similarly, the build of close to 100 GW of storage in that same period may not be practical and is not likely to be needed in a scenario that enables more wind to be built.

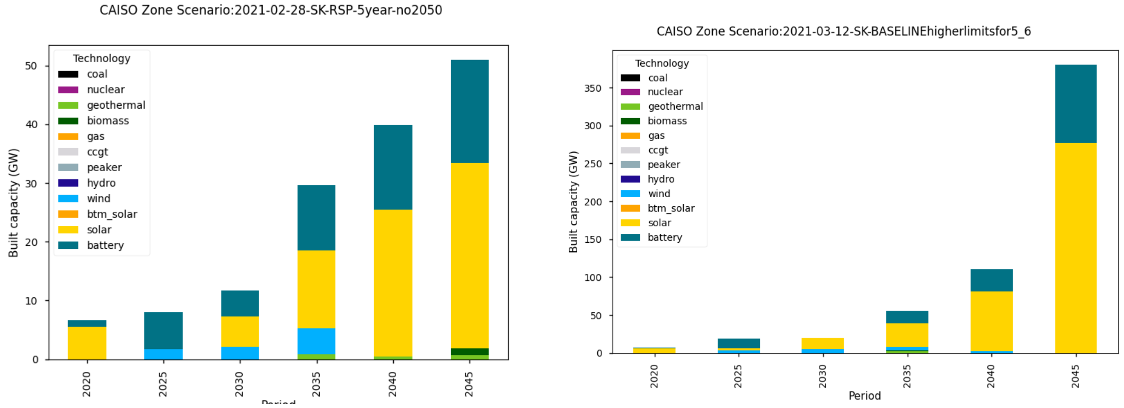


Fig. 3. 1 Comparison of resource builds for 2018 RSP (left) and new baseline (right).

The curtailment in the new baseline is much larger than in the 2018 RSP. As shown in Section 2, this comes largely from the requirement to strictly reduce emissions to zero (including the line losses) in 2045. We emphasize that we do not believe that this calculation correctly reflects the situation. Key conclusions to consider:

- The massive build of solar in 2045 is largely because that was the only option provided to the model. If more wind, geothermal, or other renewable generation source were offered, it is likely that they would be selected. This motivates revisiting the assumptions about the build limits for each of the zero-carbon generation technologies as has been done in the SB100 report.

- The current version of RESOLVE looks at 37 days independently, so does not provide the option of using cross-day storage. The availability of low-cost seasonal storage might reduce the amount of solar needed to meet load during a cloudy winter day.

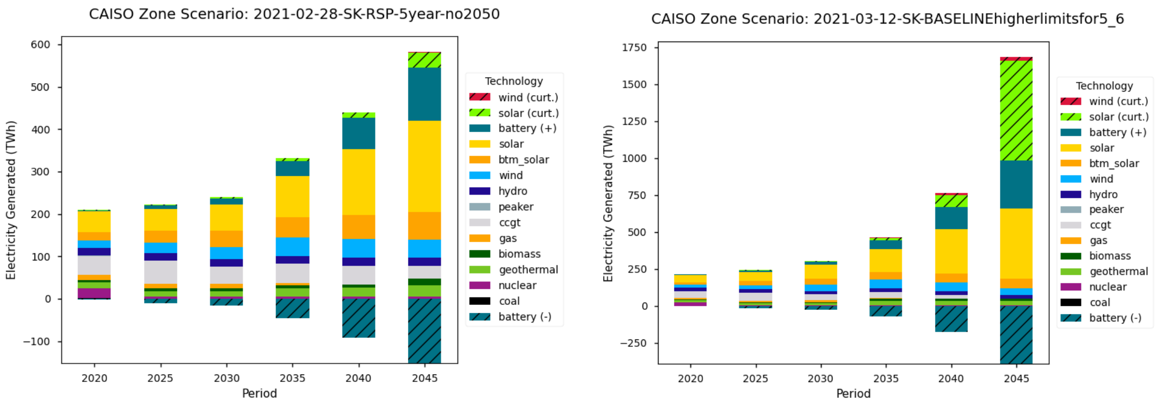


Fig. 3. 2 Comparison of electricity generation for 2018 RSP (left) and new baseline (right).

- We retained the 2018 RSP's assumption that there would be no imports to CAISO. This assumption is convenient because it avoids the reliance of neighboring regions to reach zero-carbon electricity in a similar time frame. We anticipate that imports of wind and other electricity from nearby states could help to meet California's targets. The results from SWITCH reported below support this anticipation.
- The model currently does not offer any natural gas plus carbon capture and sequestration or any mechanism to offset carbon dioxide emissions. It is modeled that a small amount of carbon sequestration will be very beneficial in meeting the zero-emissions target, but the uncertainty of how to model the carbon sequestration has moved that part of the model out of the baseline and into a sensitivity analysis (to be reported on later).

Thus, we anticipate that the high solar build and the associated large amount of curtailment will be reduced when we implement the baseline in the new RESOLVE code and provide more flexibility in how to meet the 2045 zero-emissions target. This is consistent with the latest SB100 report.

The details of the buildout are shown in Figs. 3.3 and 3.4. Biomass, geothermal and onshore wind are built to the limits given by the inputs. Pumped hydro is also built to its limit. It appears that the build of Li batteries is reduced, but this is an artifact of the lack of constraint on Li batteries 5 & 6 in the 2018 RSP. We have added a capacity limit of 9999 GW for Li batteries 5 & 6 in the new baseline to better track the buildout of these in Figs. 3.3 and 3.4. These limits are set high enough not to interfere with the optimization, but low enough that we can see the amount that is built. Some flow batteries and demand management are also now selected.

Substantial offshore wind is built, but it is not built to the limit (Table 3.1). Offshore wind built near the existing Diablo Canyon nuclear power plant (Diablo Canyon and Morro Bay) benefits from using the transmission lines now used by the nuclear plant. Currently, there are no plans for transmission lines that would accommodate the offshore wind sites in northern California beyond the use of the electricity locally. The addition of a robust transmission line for offshore wind in northern California would substantially reduce the pressure on the build of solar and storage.

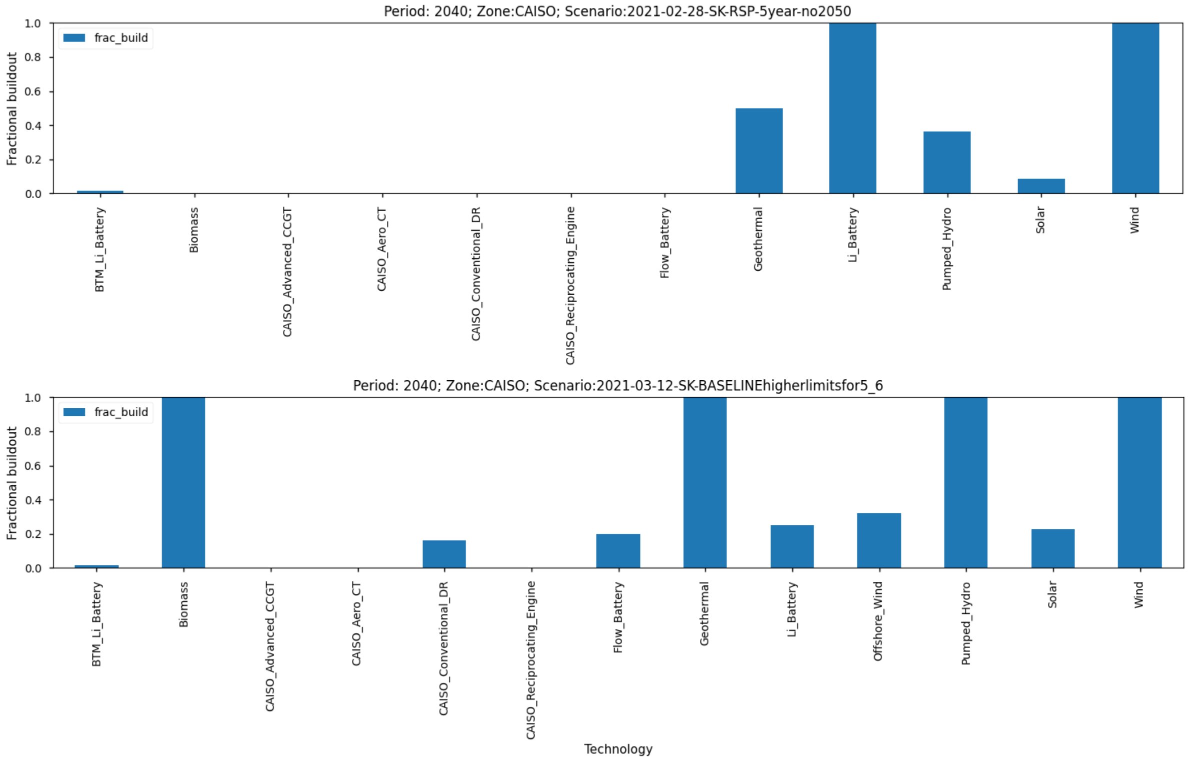


Fig. 3. 3 Fractional build for Period 2040 for 2018 RSP (top) and new baseline (bottom)

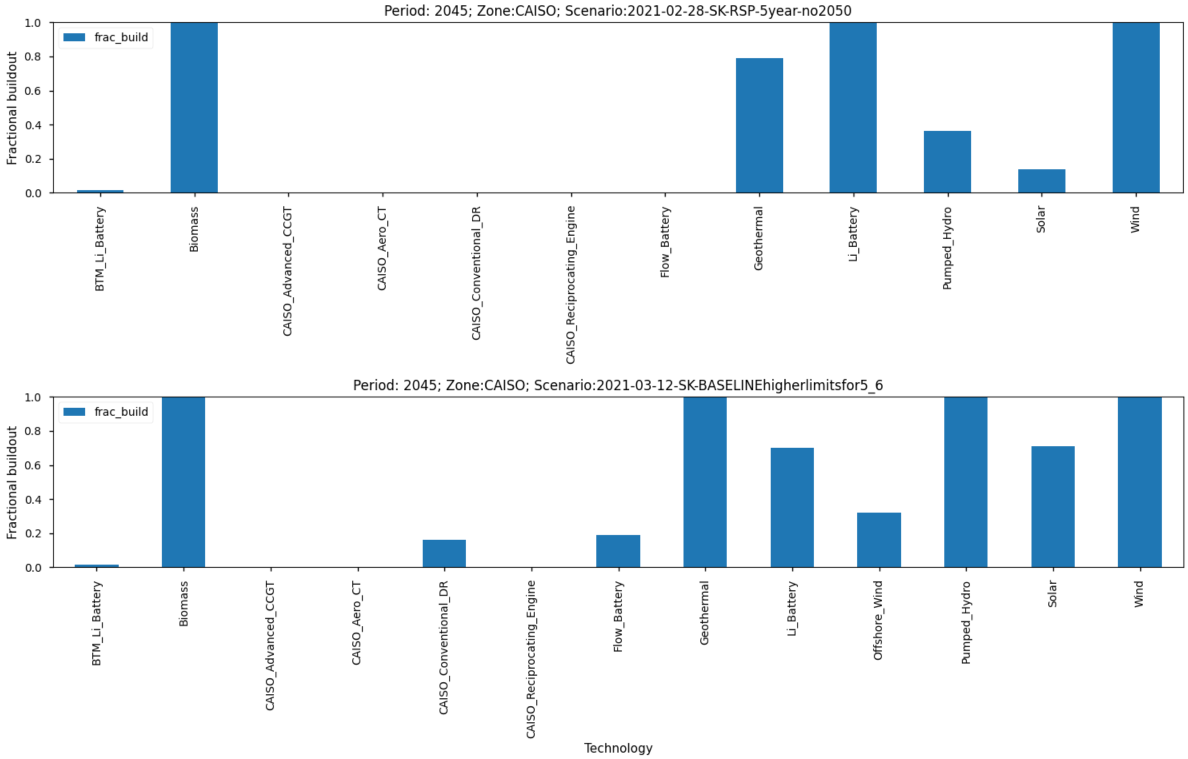


Fig. 3. 4 Fractional build for Period 2045 for 2018 RSP (top) and new baseline (bottom)

Table 3. 1 Offshore wind inputs and results for new baseline scenario

Resource	Build limit (MW)	Selected build	Transmission limited
Diablo_Canyon_Offshore_Wind	2324	2324	
Humboldt_Bay_Offshore_Wind	1607	66	X
Morro_Bay_Offshore_Wind	2419	2419	
Diablo_Canyon_Offshore_Wind_Ext_Tx	2000	2000	
Cape_Mendocino_Offshore_Wind	6216	0	X
Del_Norte_Offshore_Wind	6604	0	X

3.2 New baseline with zero-GHG targets vs original GHG targets

The new baseline is very demanding in year 2045. Section 2 showed that requesting to reach zero emissions in 2045 placed stress on the system resulting in a large buildout of solar and storage. Figs. 3.5-3.8 compare the new baseline with a similar scenario but using the 2018 RSP GHG targets. As expected, the solar and storage builds in 2045 are decreased. The decrease is by more than a factor of three. However, the total cost of implementing the scenario is decreased only by 23%. As anticipated, the generation in 2045 differs in several ways. Some thermal generation is restored (Fig. 3.6, right) and the use of storage decreases by almost a factor of two. The fractional generation from wind is greater and from solar is smaller.

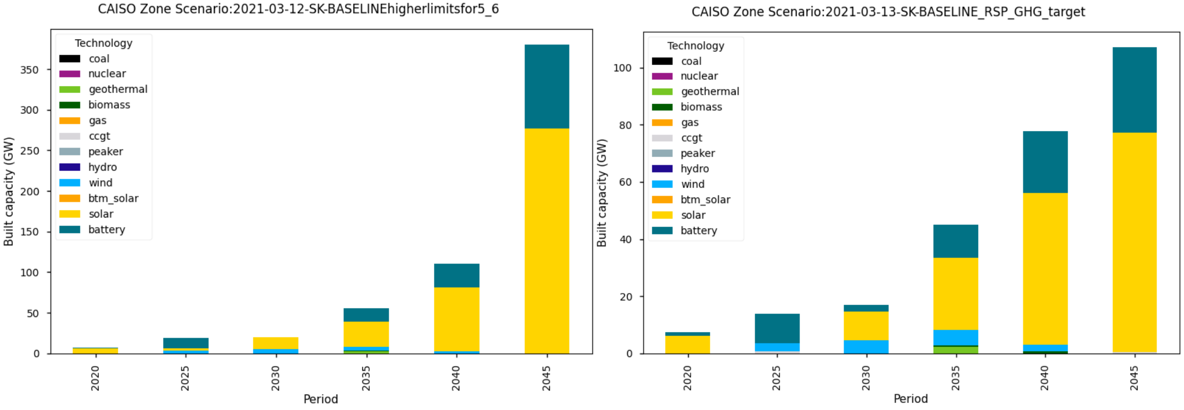


Fig. 3. 5 Resource builds for new baseline (left) and new baseline with 2018 RSP GHG targets (right).

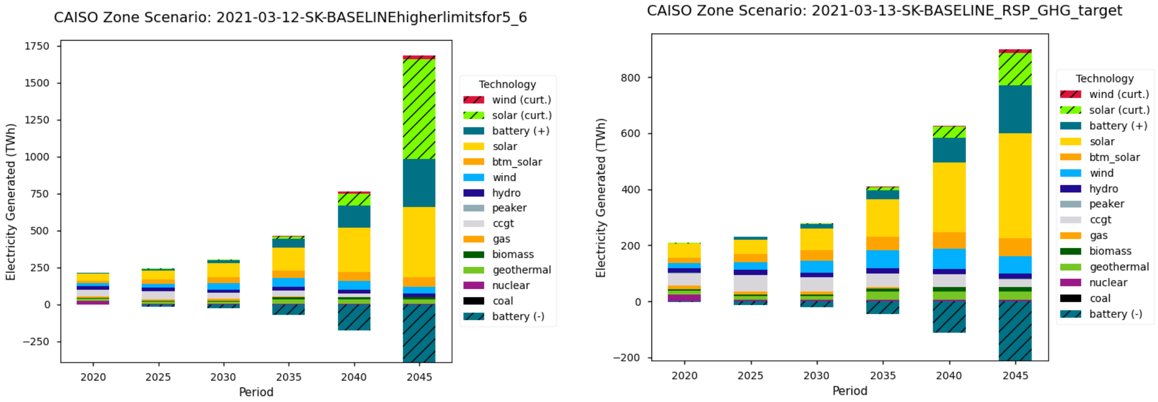
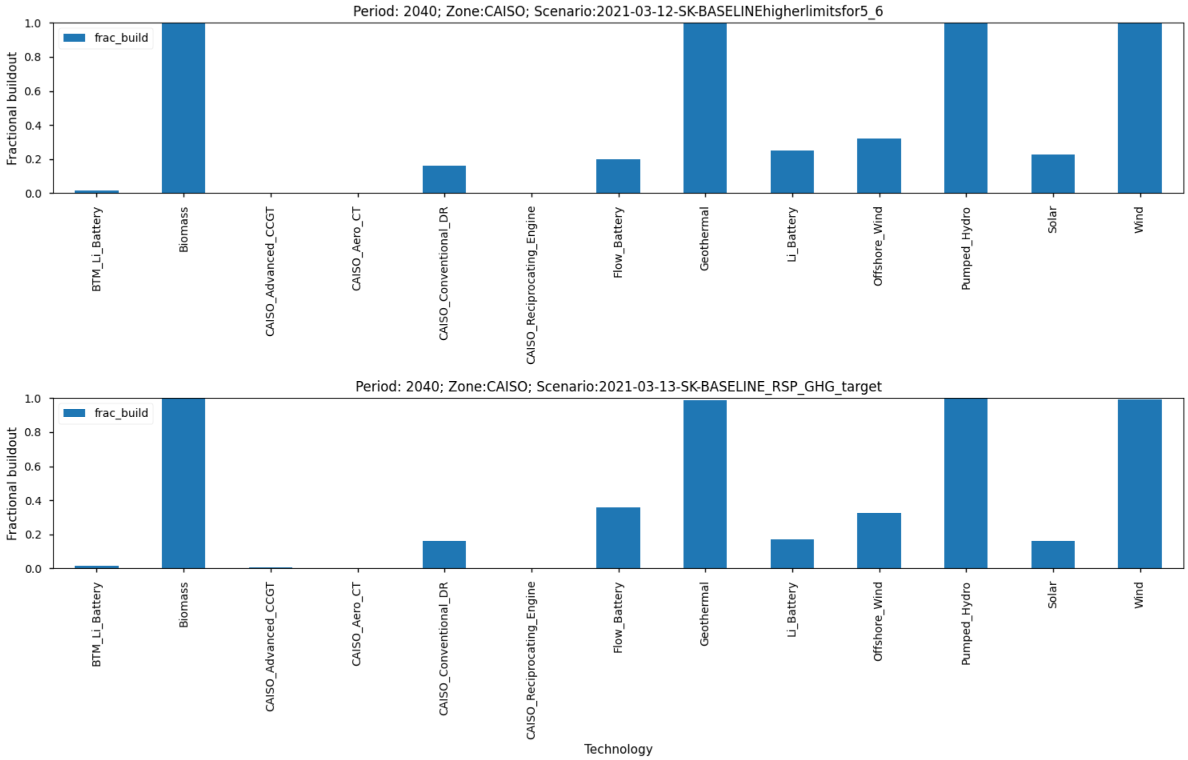


Fig. 3. 6 Electricity generation for new baseline (left) and new baseline with 2018 RSP GHG targets (right).

Figs. 3.7 and 3.8 show the detail of how the build of solar and of the Li batteries is reduced when the GHG target is relaxed. The use of flow batteries increases significantly, probably because of the reduced solar build, increasing the need for storage (though the use of Li batteries is reduced). The pumped hydro is built to the stated limit in both cases, underscoring the importance that the model places on storage, in general, in 2045.



Period: 2040; Zone:CAISO; Scenario:2021-03-12-SK-BASELINEhigherlimitsfor5_6

Period: 2040; Zone:CAISO; Scenario:2021-03-13-SK-BASELINE_RSP_GHG_target

Fig. 3. 7 Fractional build in 2040 for new baseline with zero (top) and original (bottom) GHG targets

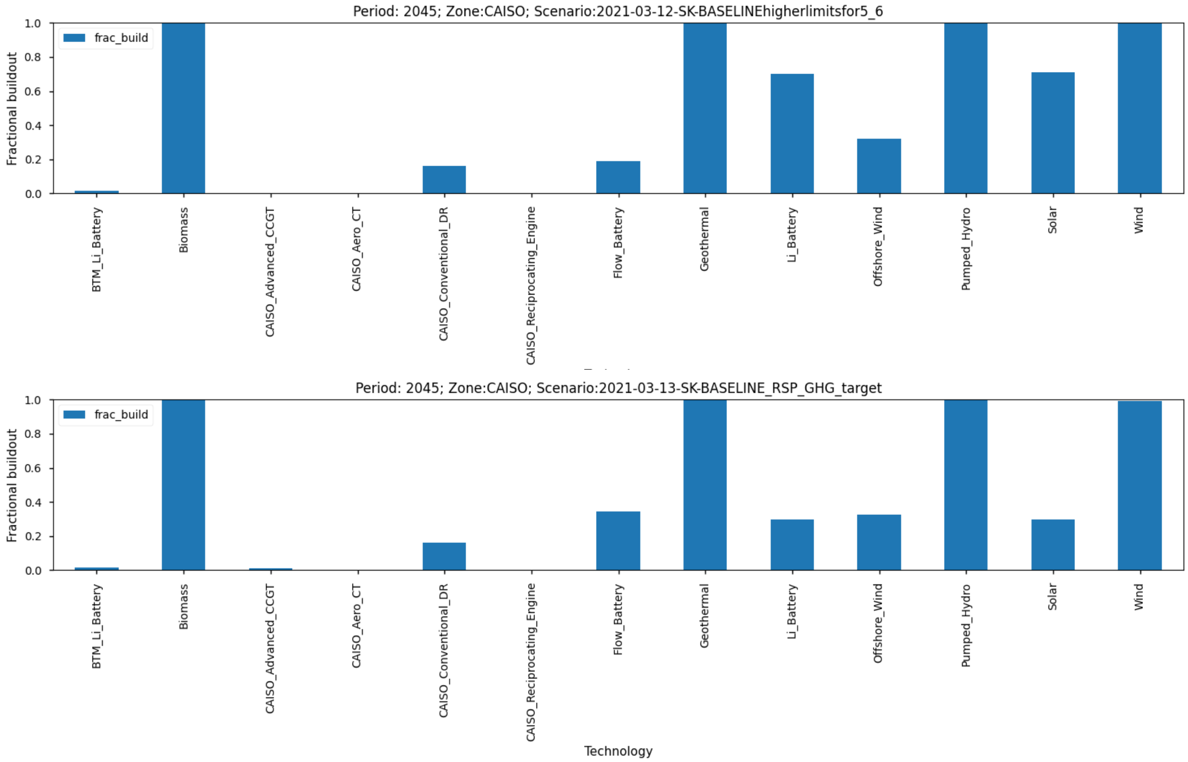


Fig. 3. 8 Fractional build in 2045 for new baseline with zero (top) and original (bottom) GHG targets

3.3 New baseline with and without offshore wind

The inclusion of offshore wind has very little effect on the build of solar and storage as shown in Fig. 3.9. Less wind is built, but, otherwise, it is difficult to see the difference between the left and right in Fig. 3.9. Greater electricity generation by wind is more obvious in Fig. 3.10, starting especially in 2035. The total cost of implementation increases less than 1% when the offshore wind is removed. Figs. 3.11 and 3.12 show the buildout in more detail with similar conclusions.

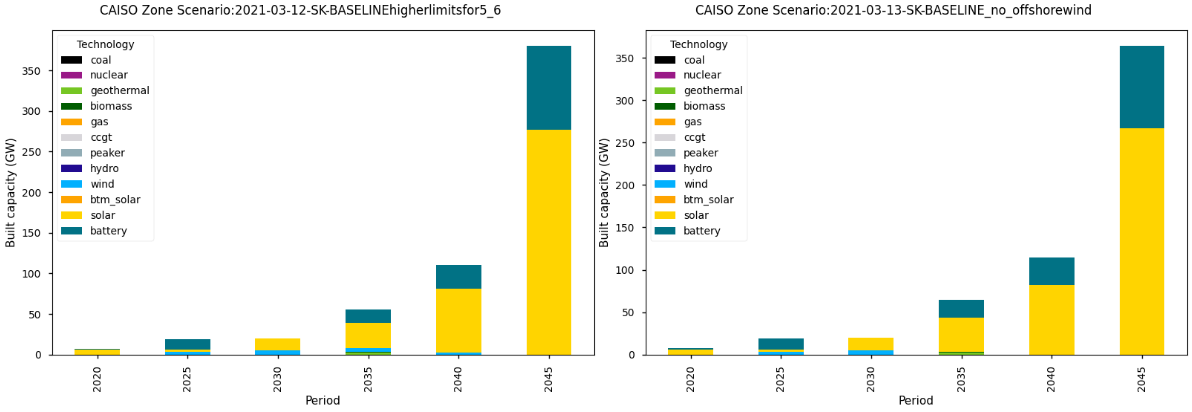


Fig. 3. 9 Resource buildout for new baseline with (left) and without (right) offshore wind.

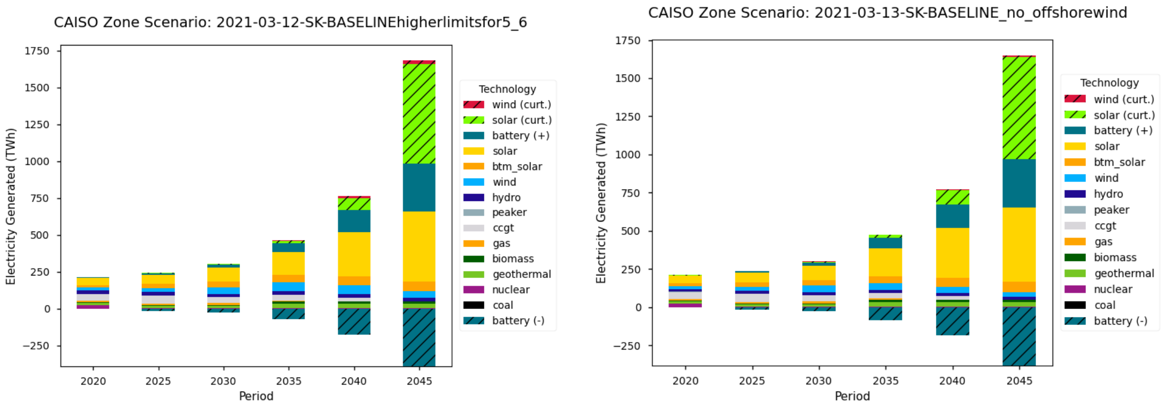


Fig. 3. 10 Electricity generation for new baseline with (left) and without (right) offshore wind.

While we note the relatively small effect of the addition of offshore wind, the offshore wind added in this baseline scenario is restricted to the southern part of California, since the resource is allowed to be built in the north, but the transmission is not provided as shown in Table 3.1. Offshore wind speeds are greater in northern than in southern California. The potential offshore wind resource if transmission were available would be substantially greater. The resource limits estimated in the Scenario Tool would enable about 3 times more offshore wind if transmission were available (see Table 3.1), which would reduce the need for solar build in 2045 by perhaps 10%.

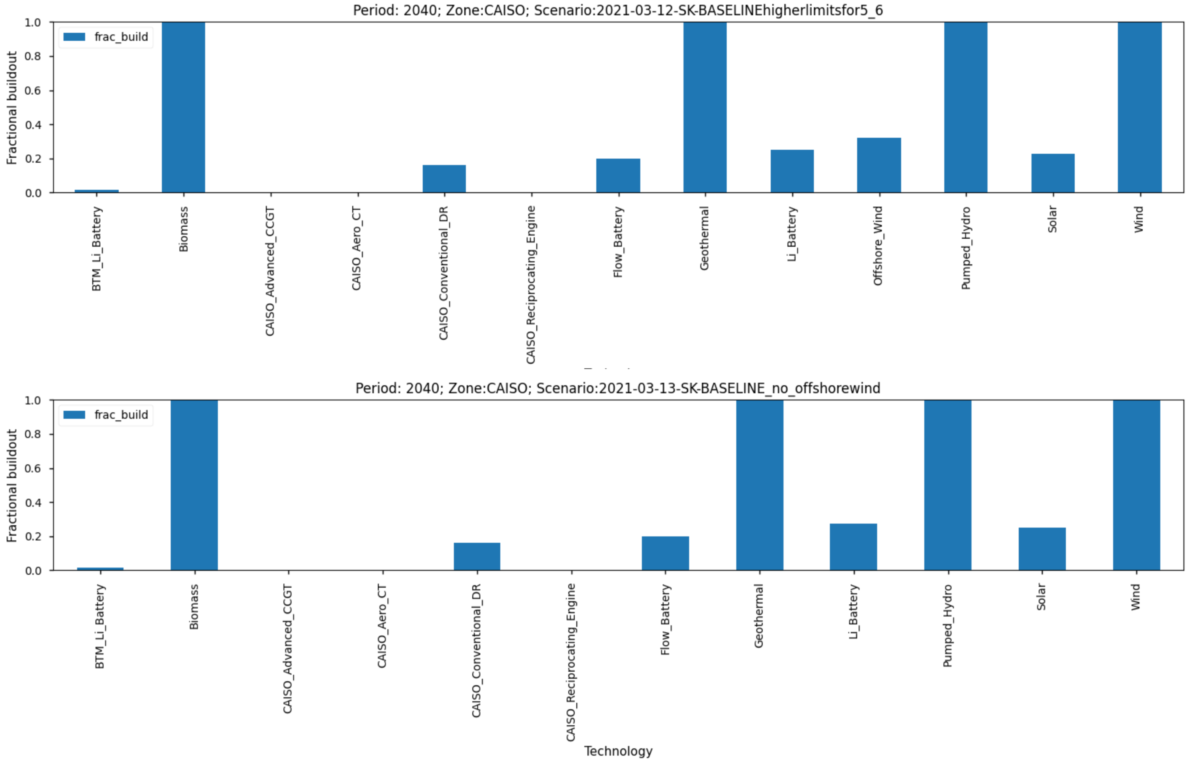


Fig. 3. 11 Fractional build in Period 2040 for new baseline with (top) and without (bottom) offshore wind

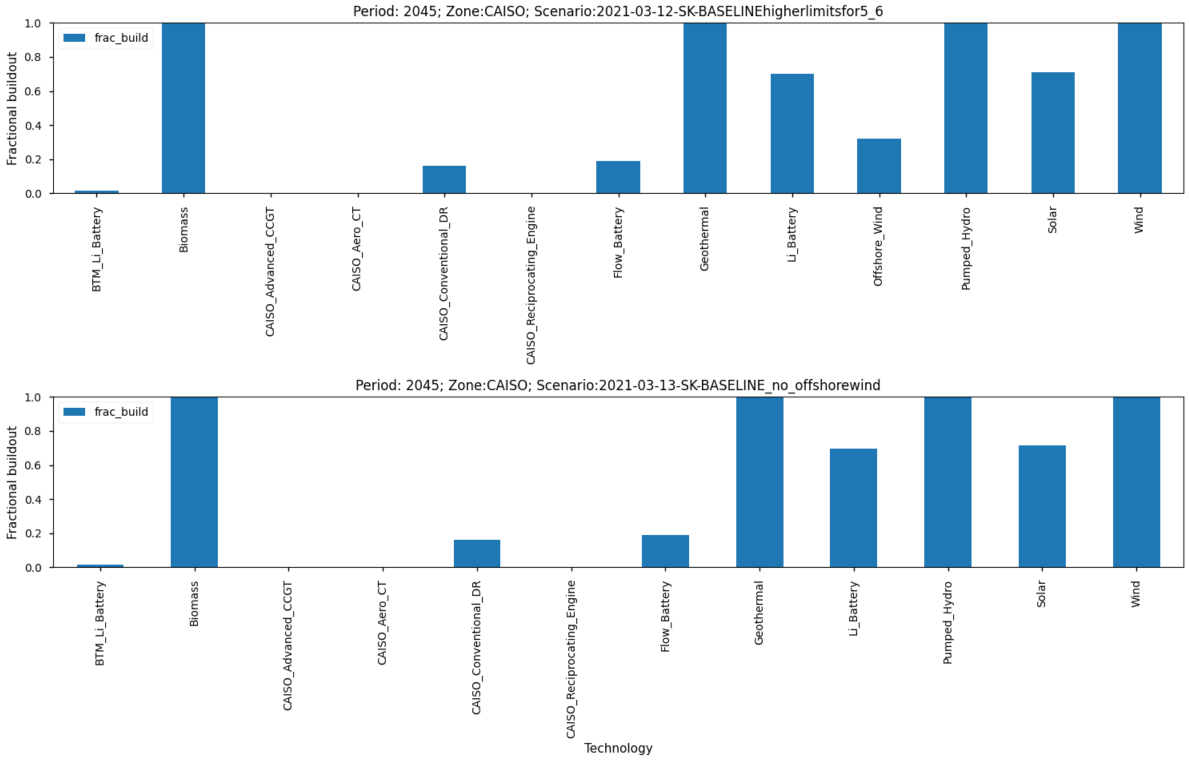


Fig. 3. 12 Fractional build for Period 2045 for new baseline with (top) and without (bottom) offshore wind

The latest SB100 studies indicate a plan to increase the available candidate wind resources in state, offshore and out of state. A comparison between the 2018 RSP and the proposals documented in the SB100 studies[5] is provided in Table 3.2. Some of the changes reflect the inclusion of additional balancing zones in the optimization process. Others reflect the expectation that new transmission lines will be built. The ability to expand wind beyond what is documented in the 2018 RSP is quite substantial. The question is not so much whether there should be additional candidate wind resource, but what is the accurate way to model it. The costs and timelines of building new transmission lines have high uncertainties.

We will proceed by following the publicly vetted inputs from the SB100 studies in our baseline, then consider modifications as explicit sensitivity analyses with emphasis on the impact of the change on the use of storage. Other modeling shows that offshore wind reduces the need for seasonal storage, while any wind reduces the need for short-duration and diurnal storage, but may increase the need for cross-day storage.

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[5] https://efiling.energy.ca.gov/getdocument.aspx?tn=234532

Table 3. 2 Comparison of 2018 RSP and SB100 build limits on candidate wind resources

Wind resource	2018 RSP New Build Capacity Limit (MW)	SB100 New Build Capacity Limit (MW)
Carrizo_Wind	287	288
Central_Valley_North_Los_Banos_Wind	173	398
Greater_Imperial_Wind	-	785
Greater_Kramer_Wind	-	445
Humboldt_Wind	34	34
Kern_Greater_Carrizo_Wind	60	69
Kramer_Inyokern_Ex_Wind	-	81
New_Mexico_Wind	1,500	6,000
Northern_California_Ex_Wind	866	866
NW_Ext_Tx_Wind	1,500	1,500
SCADSNV_Wind	-	100
Solano_subzone_Wind	18	50
Solano_Wind	542	576
Southern_California_Desert_Ex_Wind	-	48
SW_Ext_Tx_Wind	500	500
Tehachapi_Wind	275	802
Southern_Nevada_Wind	442	442
Wyoming_Wind	1,500	6,000
Baja_California_Wind	600	600
Onshore Total	8,297	19,584
Cape Mendocino	-	6,216 (Full) 1,649 (Limited)
Diablo Canyon	-	4,324
Morro Bay	-	2,419
Humboldt Bay	-	1,607
Offshore Total	-	14,566 (Full) 10,000 (Limited)
Total Wind	8,297	34,150 (Full) 29,584 (Limited)

3.4 New baseline with higher and lower EV load

A change in the load assumed for electric vehicle (EV) charging affects the build out of solar and storage somewhat, with about 10% decrease in the 2045 buildout and electricity generation, as shown in Figs. 3.13 and 3.14. The total cost changes by more, being reduced by about 16% when the EV load is reduced to that in the 2018 RSP. The conclusions from the fractional buildout graphs in Figs. 3.15 and 3.16 are the same.

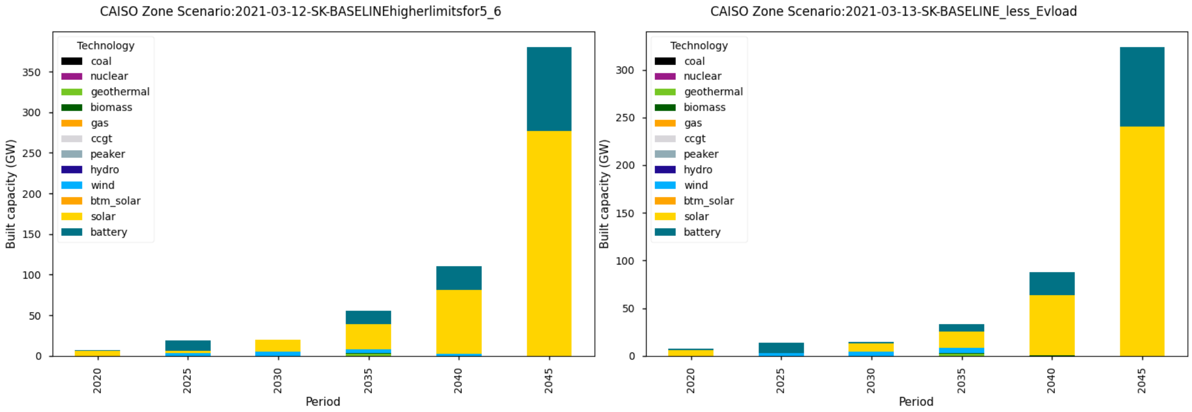

Fig. 3. 13 Resource buildout for new baseline with high (left) and low (right) EV load.

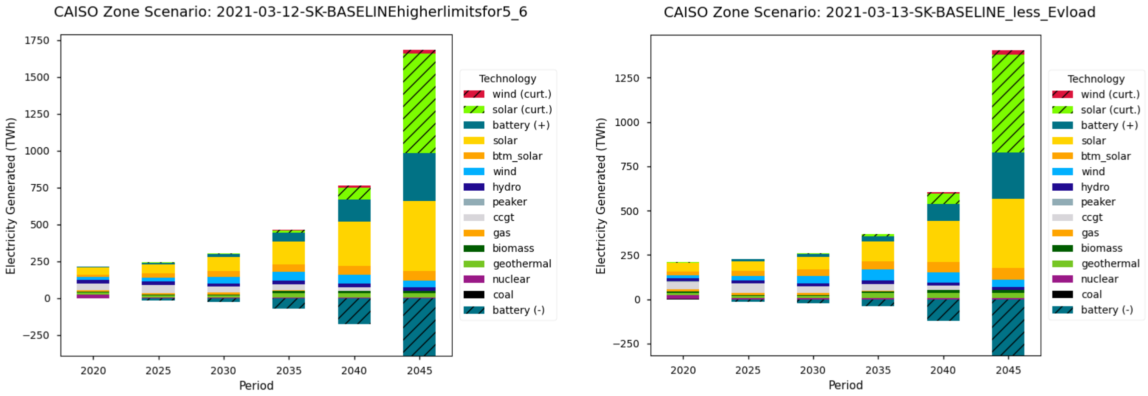

Fig. 3. 14 Electricity generation for new baseline with high (left) and low (right) EV load.

The added EV load was applied as a constant multiplier to the CAISO load. The benefit of adjusting the charging time to a time when electricity is more available is not included in this baseline and will be explored in the sensitivity analysis.

The detail shown in Figs. 3.14 and 3.15 identifies that not only is less solar built when the load is decreased, but less offshore wind and fewer Li batteries. More demand management is added.

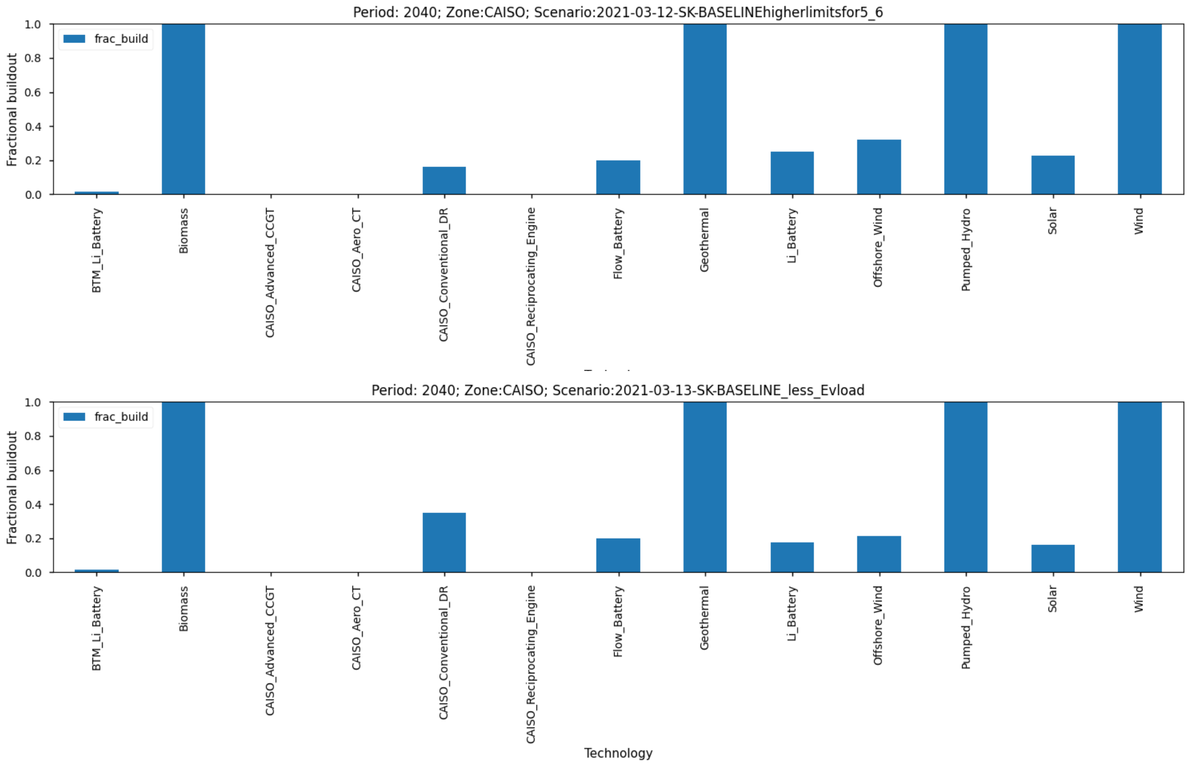

Fig. 3. 15 Fractional build in Period 2040 for new baseline with high (top) and low (bottom) EV load

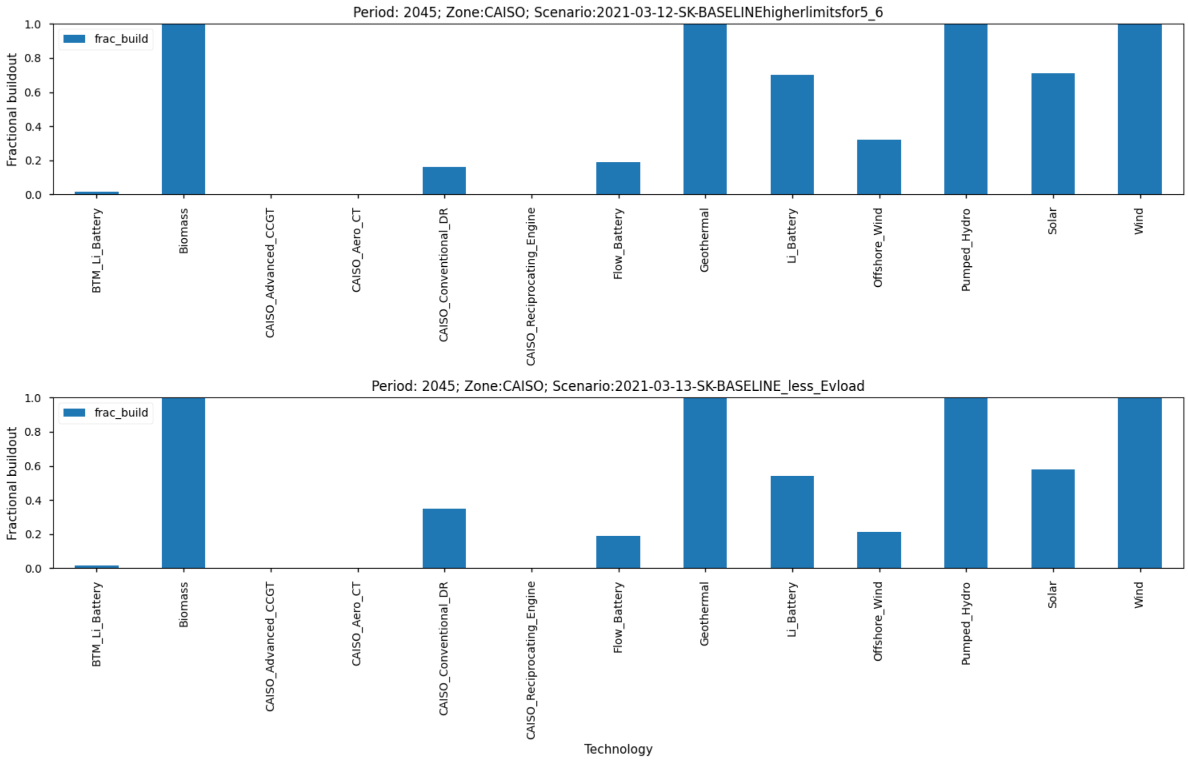

Fig. 3. 16 Fractional build for Period 2045 for new baseline with high (top) and low (bottom) EV load

3.5 New baseline with higher and lower electrolyzer (H_2) load

A change in the load assumed for electrolyzers affects the buildout of solar and storage somewhat, with about 15% decrease in the 2045 buildout and electricity generation, as shown in Figs. 3.17 and 3.18. The total cost changes by less, being reduced by about 10% when the electrolyzer load is reduced to that in the 2018 RSP.

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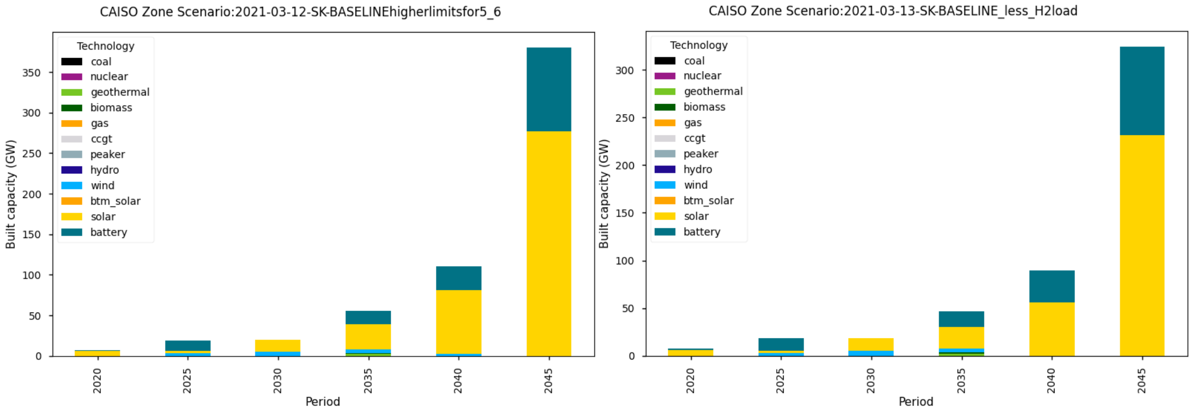


Fig. 3. 17 Resource buildout for new baseline with high (left) and low (right) H_2 load.

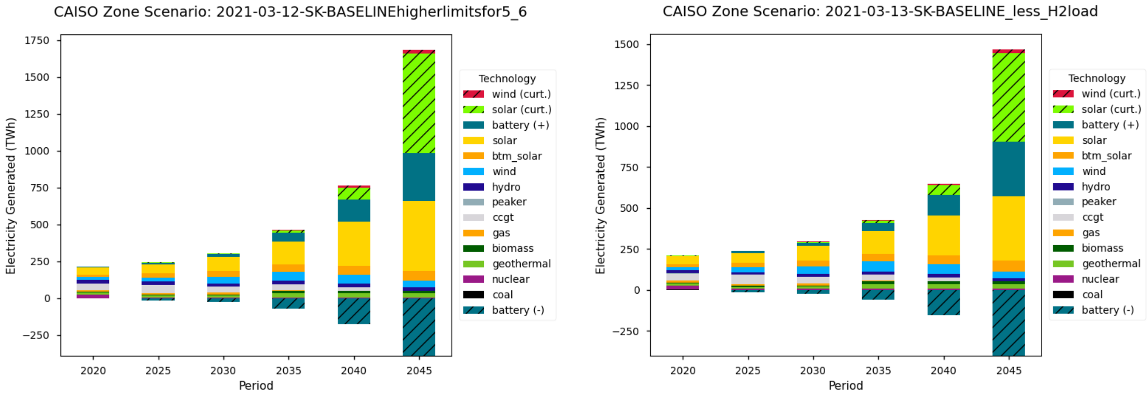
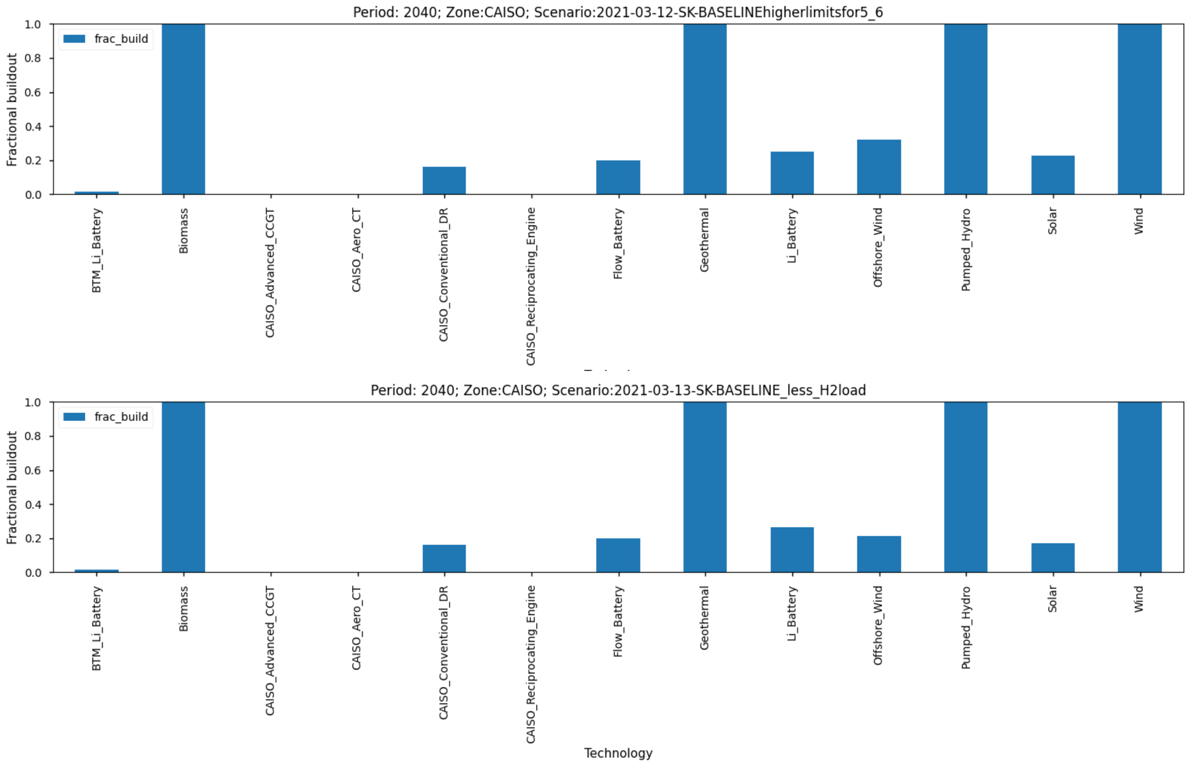


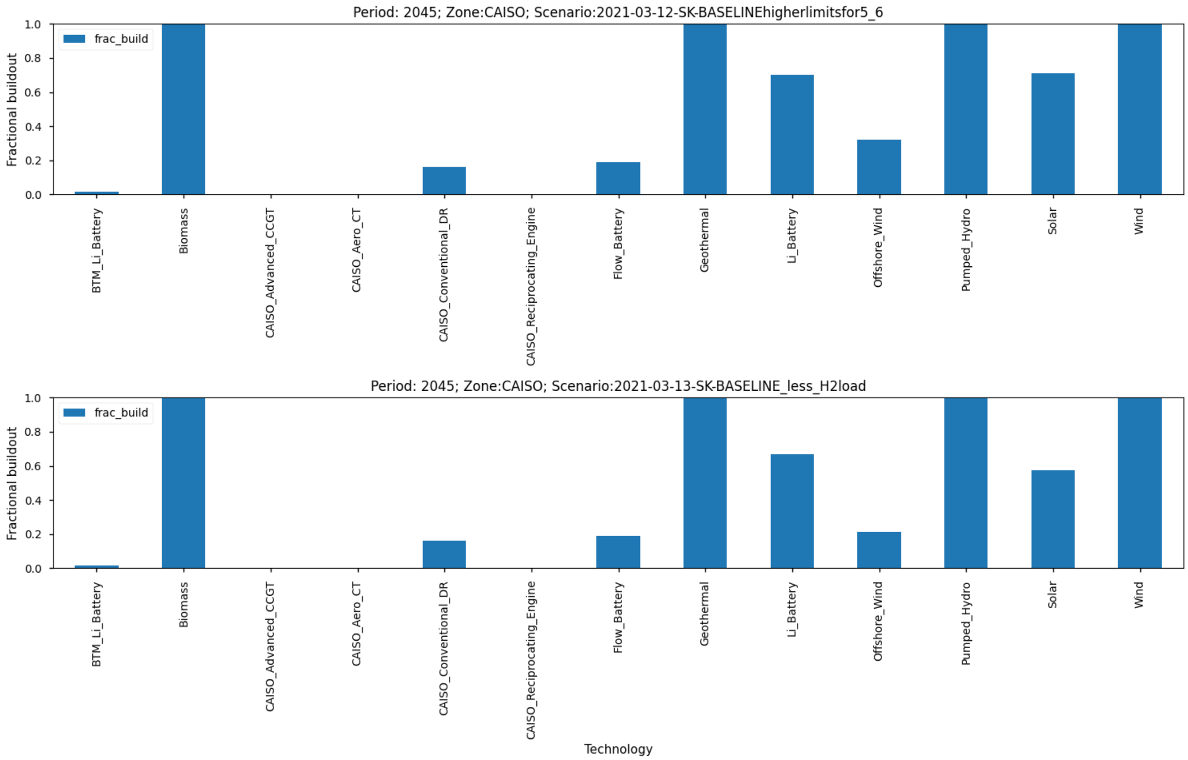
Fig. 3. 18 Electricity generation for new baseline with high (left) and low (right) H_2 load.

The fractional buildouts for the new baseline with and without the higher electrolyzer load are shown in Figs. 3.19 and 3.20. The changes are fairly similar to what was reported for the change in EV load, above, but the reduced electrolyzer load scenario requires more Li batteries than when the EV load is reduced.


Period: 2040; Zone:CAISO; Scenario:2021-03-12-SK-BASELINEhigherlimitsfor5_6

Period: 2040; Zone:CAISO; Scenario:2021-03-13-SK-BASELINE_less_H2load

Fig. 3. 19 Fractional build in Period 2040 for new baseline with high (top) and low (bottom) H_2 load


Period: 2045; Zone:CAISO; Scenario:2021-03-12-SK-BASELINEhigherlimitsfor5_6

Period: 2045; Zone:CAISO; Scenario:2021-03-13-SK-BASELINE_less_H2load

Fig. 3. 20 Fractional build for Period 2045 for new baseline with high (top) and low (bottom) H_2 load

3.6 New baseline with 20.7% and 15% planning reserve margin

When implementing the 20.7% planning reserve margin (PRM) along with the higher load scenarios, a question arises about whether we need to have resource adequacy associated with the additional electrolyzer and EV charging loads. There is a high probability that the electrolyzers will be designed to operate when electricity prices are low, so are likely to be turned off whenever there is a resource adequacy problem. Similarly, we would be wise to design EV charging to be shifted to a time of low demand, assuming that the low demand time comes within hours, rather than days. These assumptions may differ from others' assumptions. A change in the planning reserve margin has a smaller effect than the above changes. The small changes are shown in Figs. 3.21 – 3.24. Primarily, more storage is built starting in 2025.

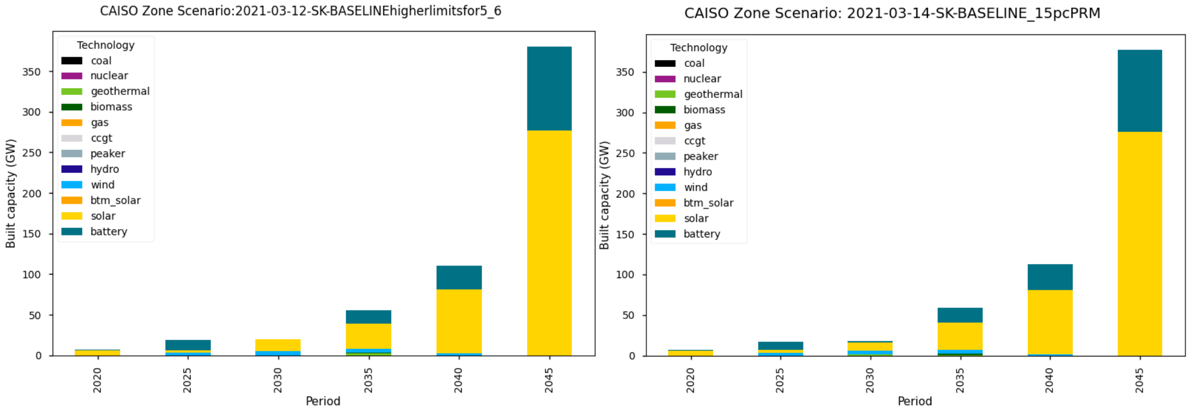


Fig. 3. 21 Resource buildout for new baseline with 20.7% (left) and 15% (right) planning reserve margin.

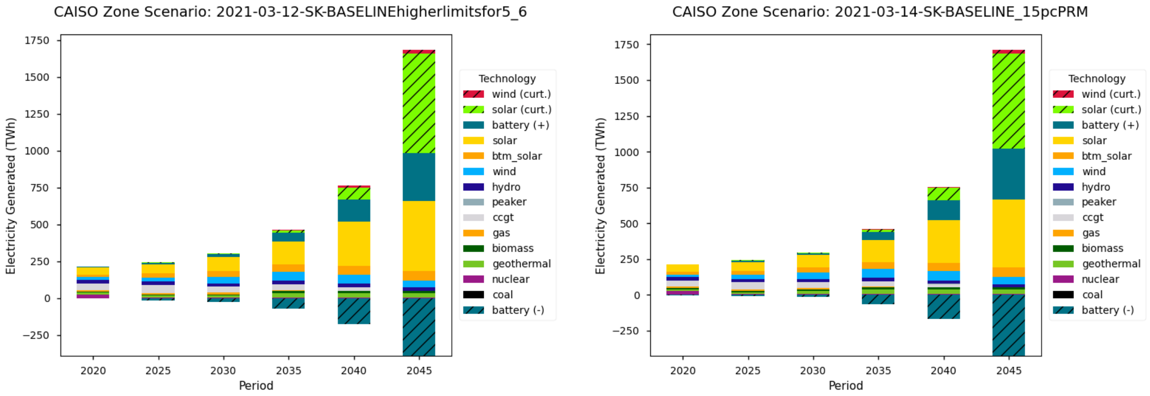
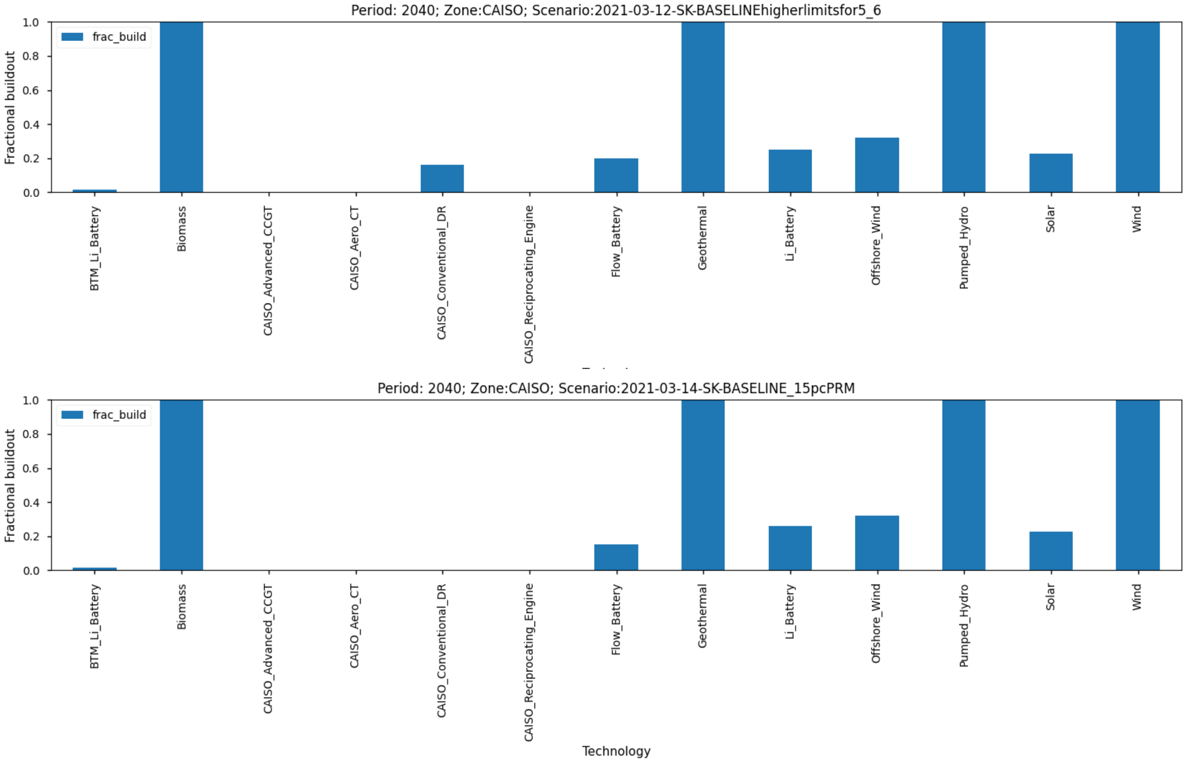


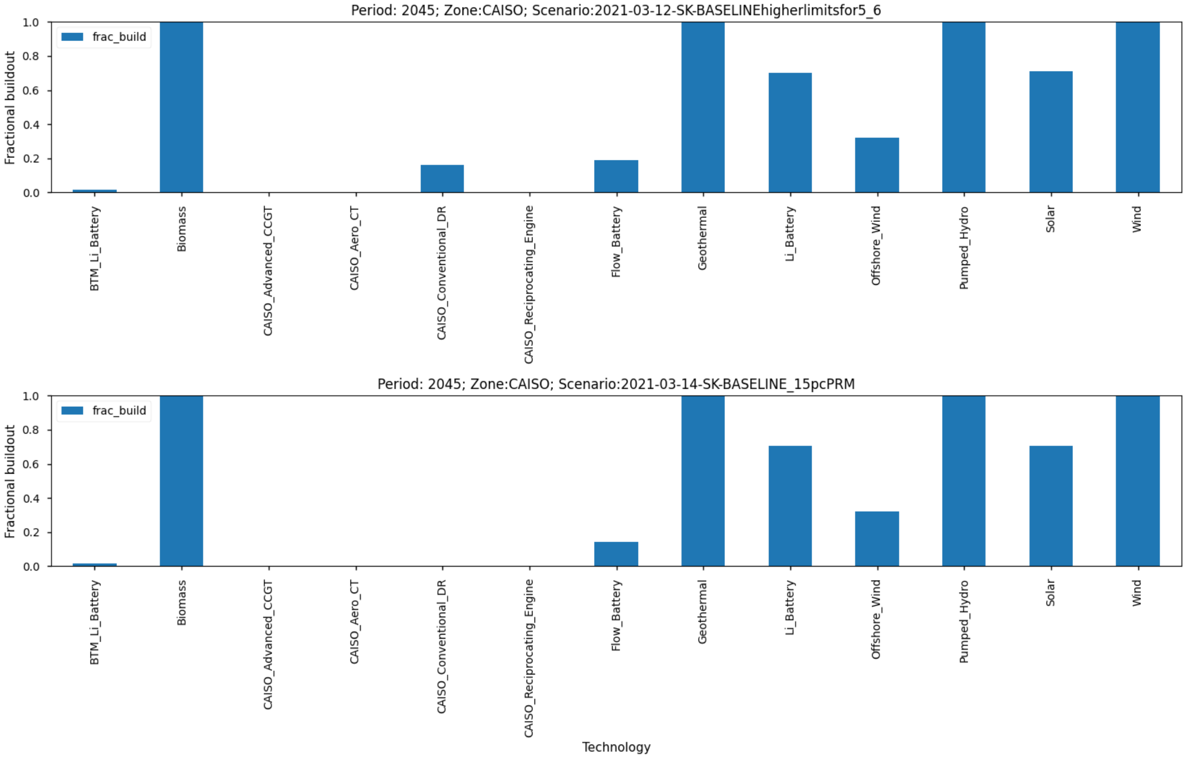
Fig. 3. 22 Electricity generation for new baseline with 20.7% (left) and 15% (right) PRM.

The primary effect of reducing the planning reserve margin (PRM) to 15% is shown in Figs. 3.23 and 3.24 to be the removal of the demand management that is selected in the baseline. Also, slightly fewer flow batteries and Li batteries are built for the 15% PRM case.


Period: 2040; Zone:CAISO; Scenario:2021-03-12-SK-BASELINEhigherlimitsfor5_6

Period: 2040; Zone:CAISO; Scenario:2021-03-14-SK-BASELINE_15pcPRM

Fig. 3. 23 Fractional build in Period 2040 for new baseline with 20.7% (top) and 15% (bottom) PRM


Period: 2045; Zone:CAISO; Scenario:2021-03-12-SK-BASELINEhigherlimitsfor5_6

Period: 2045; Zone:CAISO; Scenario:2021-03-14-SK-BASELINE_15pcPRM

Fig. 3. 24 Fractional build for Period 2045 for new baseline with 20.7% (top) and 15% (bottom) PRM

3.7 New baseline with and without the 4-hour Li battery model

A change in the Li battery model affects the buildout very little, as shown in Figs. 3.25 and 3.26. The total cost is reduced by about 4% when the 2018 RSP Li battery model is used.

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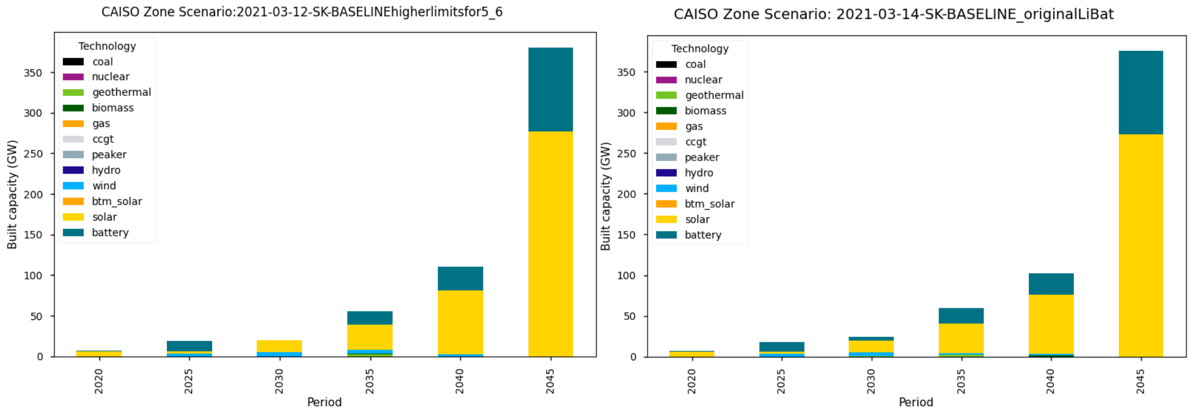
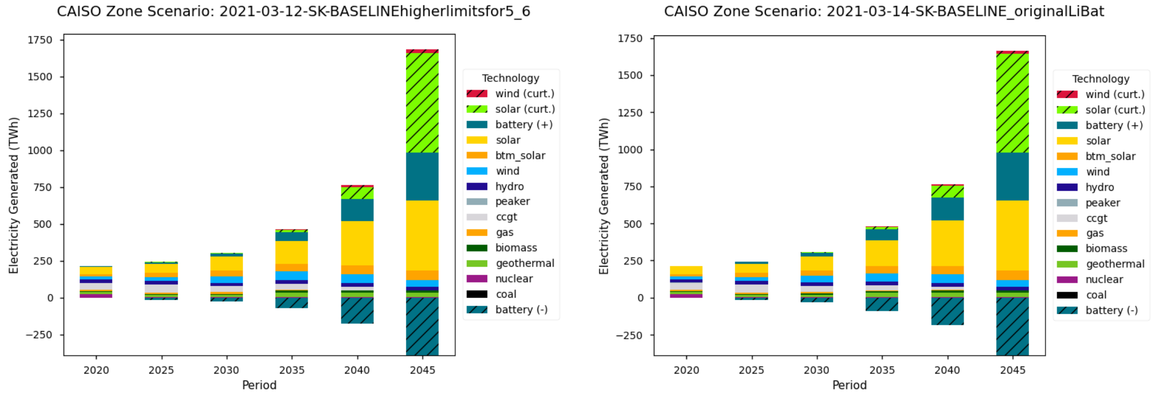

CAISO Zone Scenario:2021-03-12-SK-BASELINEhigherlimitsfor5_6

CAISO Zone Scenario: 2021-03-14-SK-BASELINE_originalLiBat

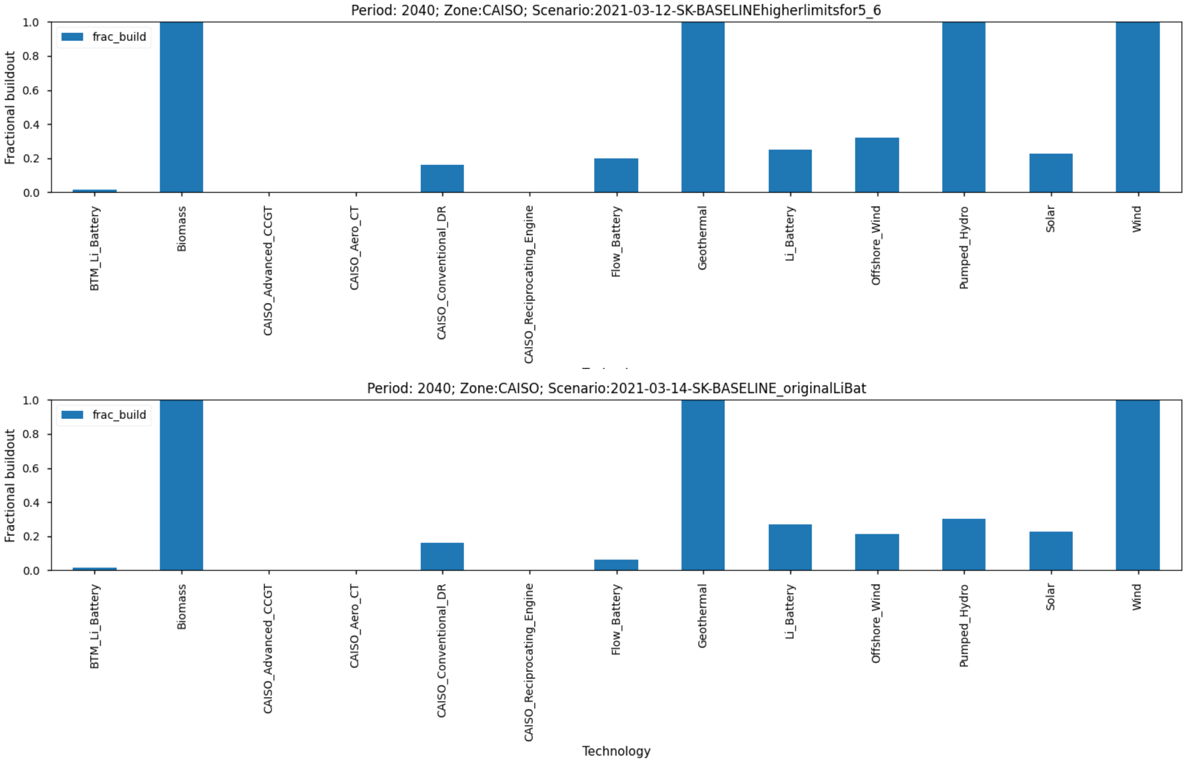
Fig. 3. 25 Resource buildout for new baseline with 4-h (left) and original (right) Li-battery models.


CAISO Zone Scenario: 2021-03-12-SK-BASELINEhigherlimitsfor5_6

CAISO Zone Scenario: 2021-03-14-SK-BASELINE_originalLiBat

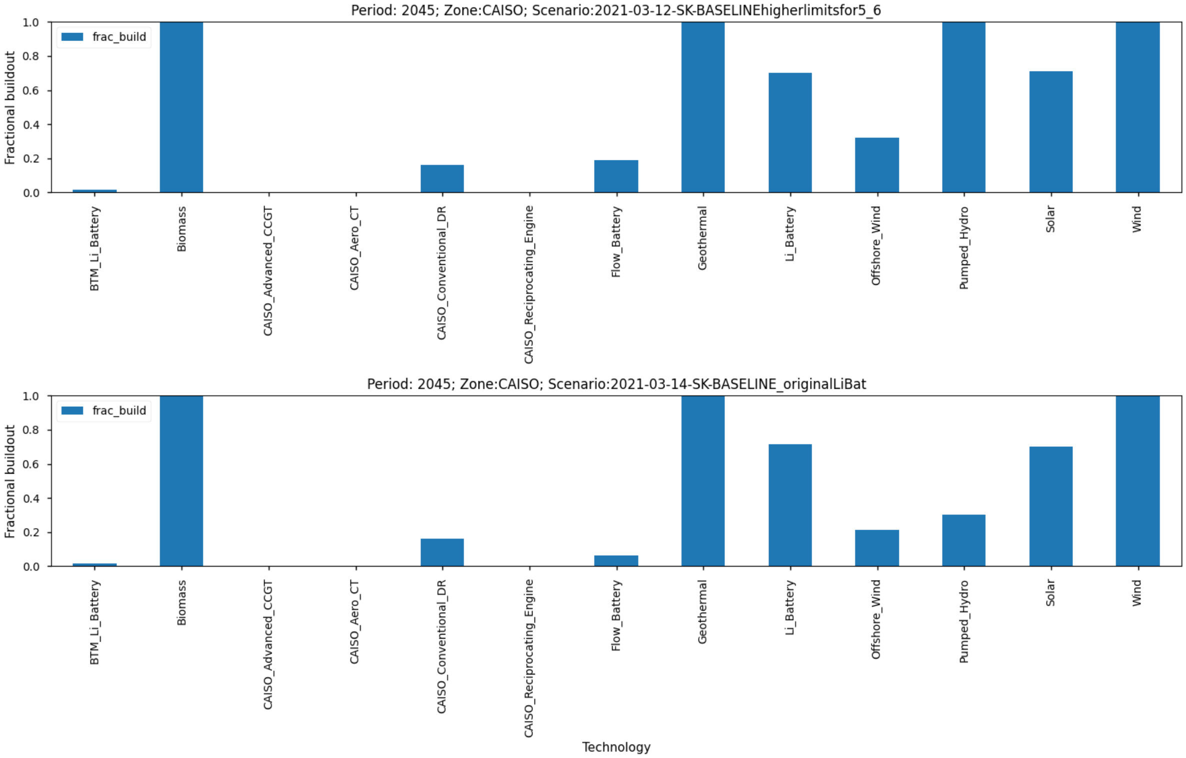
Fig. 3. 26 Electricity generation for new baseline with 4-h (left) and original (right) Li-battery models.

The fractional buildouts for the new and original Li battery models in the new baseline are shown in Figs. 3.27 and 3.28. The detail shows that, although the total storage build out is almost the same, the selection of the type of storage is sensitive to the details of the Li battery model, with the original model favoring the build of more Li batteries and the 4-h Li battery model favoring the build of pumped hydro storage and flow batteries.


Period: 2040; Zone:CAISO; Scenario:2021-03-12-SK-BASELINEhigherlimitsfor5_6

Period: 2040; Zone:CAISO; Scenario:2021-03-14-SK-BASELINE_originalLiBat

Fig. 3. 27 Fractional build in 2040 for new baseline with 4-h (top) and original (bottom) Li-battery models


Period: 2045; Zone:CAISO; Scenario:2021-03-12-SK-BASELINEhigherlimitsfor5_6

Period: 2045; Zone:CAISO; Scenario:2021-03-14-SK-BASELINE_originalLiBat

Fig. 3. 28 Fractional build in 2045 for new baseline with 4-h (top) and original (bottom) Li-battery models

4. SWITCH baseline development

Substantial work was completed in updating the SWITCH-WECC model. Here, we include an update on that work in two sections (software and baseline development) before presenting the modeling results.

4.1 SWITCH software development

Updated to Python 3.7+ from Python 2.7

The SWITCH-WECC model code was updated using the most recent version of Python. This update required modification to all the modules that were previously written in Python 2.7 to a more recent stable and maintained version 3.7. This allows the use of new features such as formatted strings (f-strings), faster model constructions, and additional speedup gains through the core packages utilized by the SWITCH model.

Long-duration storage module

Although the current version of SWITCH 2.0 was designed with the capability to use flexible timepoints (which will be useful for studying long-duration storage) it was not originally designed to study long-duration storage. We have begun adding the appropriate analytical formulation to capture the operations of different long-duration storage technologies, for example, separate charging and discharging efficiencies and different balancing decisions by a range of consecutive days. Additionally, we are improving the efficiency of how we define the Sets and Variables constructed inside of the module for the analysis of long-duration storage. We anticipate that this code will have additional room for improvement and expansion as we introduce new storage constraints to be modeled.

Time sampling strategies for Long-duration Energy Storage

Although SWITCH 2.0 was designed with the capability to use flexible timepoint and timeseries selection, the methodology for selecting these has not been developed in the context of studying long-duration storage. For this, we will study the impact of different sampling strategies on the overall resulting capacity-expansion. We want to capture different (probable) business models of long-duration energy storage resources (daily balancing, multi-day balancing, seasonal balancing) and how does the model adjust the buildout as we move forward a zero-carbon grid.

This work has begun and is expected to produce a peer-reviewed journal publication due to the lack of literature on this topic. It will be completed as part of Task 4.1 “Multi-day Model Optimization.”

Module to model California policies imports constraints from other states

We are using the SWITCH 2.0 with scenario data for the entire WECC. The interpretation of these results in the context of California's energy use requires being able to track imports and exports between California and the rest of WECC load zones.

We created a new module that will incorporate California's policies aligned with the latest IRP and SB-100 results. For example, we created a constraint that will force the model to produce at least 80% of the retail sales withing California footprint. This constraint will force the model to reduce the imports to California which is important considering that other load zones inside of the WECC region have different energy policy goals that might not align with California's aggressive targets.

Module to model assumptions on residential PV growth in California

The SWITCH model includes a candidate technology that represent the residential PV installations. However, the cost of residential PV is always higher than centralized PV for each of the periods, so the model will not select residential PV as the most economical option. Therefore, we decided to use the same assumption from the latest IRP modeling results and remove residential PV from the pool of candidate resources. Instead of optimizing it, we included it using an expected growth rate for California and used the same values as reported from the IEPR and IRP.

Module to track and restrict air pollutants

The SWITCH model has a built-in module that calculates the CO_2 emission for each of the power plants provided and constrains operations to a given carbon cap. To capture additional benefits of a zero-carbon grid, we have added the capability to track and restrict additional air pollutants (NOx, SOX, CH_4.) by calculating the annual emissions per power plant and assuming a carbon. This module and restriction is currently tracking CO_2 emission, but we will explore the impact of the different pollutants as part of the sensitivity analysis

4.2 SWITCH baseline development

The SWITCH baseline development was reported in the deliverables completed last month, but an update is given here for completeness:

Updated model inputs and assumptions

We updated the set of existing and planned generators using the latest EIA-923 and EIA-860 forms, technology costs (based on NREL-ATB), and the regional costs for new expansion of transmission lines. Also, we updated the hydropower generation to be the historical average of 2004 - 2018 data which is the most recent and complete set of years at the time.

We included a planned reserve margin of 15% across the entire WECC. This value was assigned to each of the utilities as a total number across all the load-zones they provide service. We did not exclude any generators from contributing capacity to meet the PRM. However, we are aware that there is a current ruling of the IRP mid-term reliability analysis proposing to increase the

PRM to 20.7%. This value may be incorporated into the baseline as part of the sensitivity analysis.

WECC database at UC San Diego and UC Merced

The current version SWITCH-WECC is designed to pull the required scenario inputs from a central database. This database has been hosted at UC Berkeley but was not available at either UC San Diego or UC Merced. We were unsuccessful in obtaining easy access to the UC Berkeley database from outside of UC Berkeley because of firewall issues. Therefore, we have now set up the needed hardware and have transferred the data so that it can now be accessed easily on all 3 campuses using UC San Diego as the latest version of the database for scenario constructions.

Configuration selection

Consistent with the description above for RESOLVE, we selected to reach zero carbon emissions in 2045, including zero carbon emissions for line losses as shown in Fig. 2.4 above. We had some discussion about what to assume for the rest of WECC. There is substantial evidence that California's neighbors will be reducing carbon emissions, but the timeline is unclear. Reaching zero emissions is much easier when regional transmission is available. However, it is difficult to track electrons between the different regions to determine whether California's goals were met if California is importing electricity from adjacent regions that have not yet met zero-emissions targets. For the baseline, we have agreed to set a zero-emissions target for all WECC enabling us to identify what would be needed to reach that target, while exploring other options during the sensitivity analysis. We find that allowing imports of wind from Wyoming, for example, can be very helpful as California strives to meet aggressive goals.

Timepoint and period selection

As described above, we have begun the study of the optimal tradeoff between run time and accuracy of calculation when considering the number of timepoints to use in the simulation. For this set of results, we used the previous timepoint and period selection from the previous WECC version which is 6 timepoints per day for two days per month (peak and median day) and 10-year periods. The final selection of timepoints and periods will depend on the results of the Task 4.1 "Multi-day Model Optimization" as we aim to capture most of the business models for long-duration energy storage.

Baseline implementation

The resulting baseline results are explored in comparison with the RESOLVE baseline results in the next section.

5. Comparison of SWITCH and RESOLVE baselines

In this section we show some of the results of the baseline model for SWITCH and its comparison with the RESOLVE baseline. As mentioned in the previous section, we updated most of the inputs for the SWITCH-WEECC model incorporating the most updated version of current and planned generators from the EIA dataset, 15% PRM and the latest technology costs from the NREL-ATB. As noted in the Baseline Description these updates align the two models in terms of capturing a recent snapshot, but are not aligned according to the definition of location since RESOLVE includes some generators outside of California in the CAISO zone if there is a contract with CAISO. This comparison will allow us to understand the benefits of having extra geographical and temporal resolution to quantify the value of long-duration energy storage.

Key differences in the baseline model definition of the two models include:

- SWITCH includes California as a subset of WECC, while RESOLVE focuses on California
- SWITCH defines zones according to state lines, while RESOLVE defines balancing zones
- The EV and electrolyzer loads were increased for RESOLVE, but not as much for SWITCH
- The PRM for RESOLVE was increased to 20.7%, while SWITCH is still using 15%

5.1 Operational capacity for the entire WECC

The Baseline Description compared the assumptions of SWITCH and RESOLVE about the legacy power plants highlighting the differences in the zone definitions. In reviewing the results of the simulation, we again find notable difference between the baselines. This relates to the additional geographical spread that SWITCH-WECC has. As mentioned before, the SWITCH model considers in total 52 load-zones for the entire WECC while RESOLVE considers only seven (7). With the additional spatial resolution, we can observe transmission flows between important load zones that might provide electricity back to California (e.g., Wyoming wind).

The operational capacity for the entire WECC baseline results is shown in Fig. 5.1. As expected, solar, wind and energy storage dominate most of the cumulative capacity in the WECC region. Also, we observe that energy storage is installed in most of the load-zones with high solar penetration. The operational storage for this scenario is used mostly to balance solar generation and for planned reserve margins. There is also some remaining additional natural gas in some load-zones, but it is only used for PRM purposes.

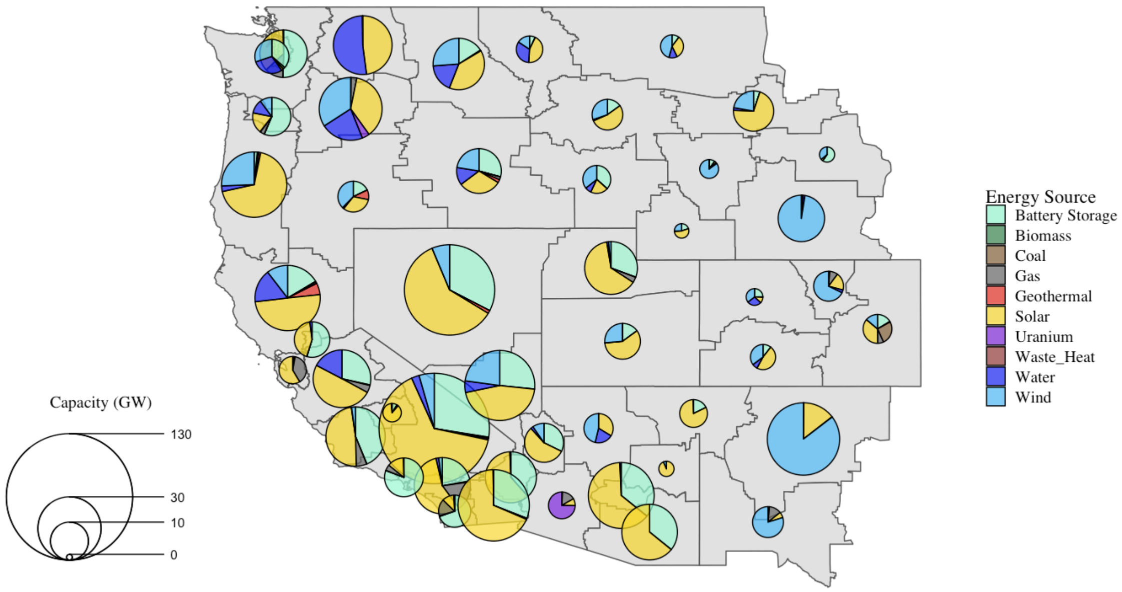


Fig. 5. 1 WECC operational capacity by energy source for each load-zone in 2050. Baseline scenario WECC-wide zero carbon cap and a 15% PRM.

5.2 Operational capacity RESOLVE vs SWITCH

The baseline proposal for SWITCH includes a zero-carbon cap WECC wide by 2050. For this aggressive carbon goal, the model chooses to install zero-carbon technologies across the entire WECC and end's up with less operational capacity in California's load-zones (see Figure 5.2). On the other hand, the latest version of RESOLVE aims to show a future of a self-sufficient California with most of its retail sales being produced within California footprint. Additionally, RESOLVE does not consider capacity expansion outside of the CAISO footprint which will result in substantial new capacity within California to meet the carbon goal.

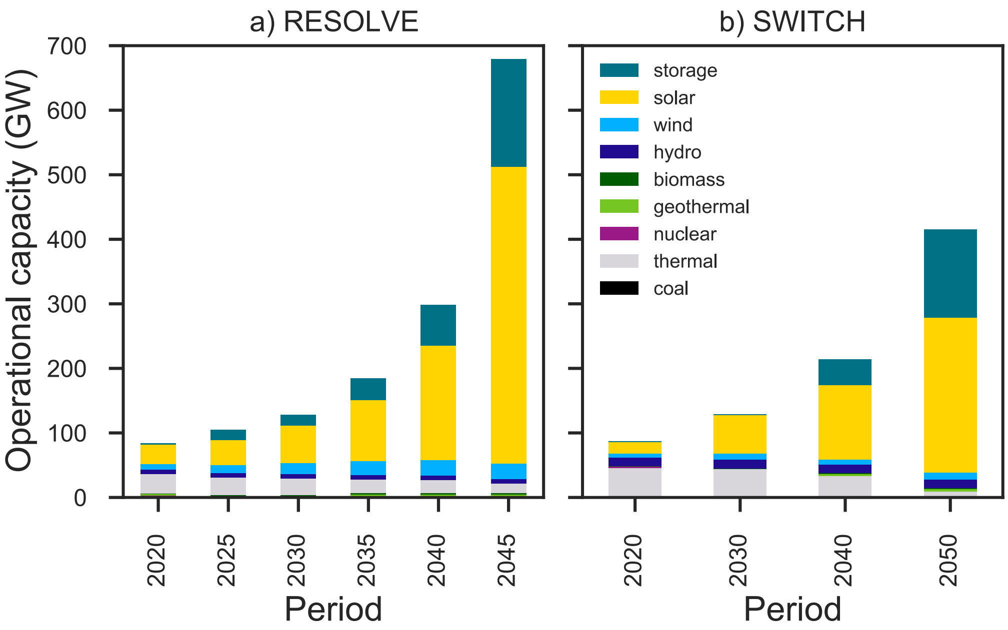


Fig. 5. 2 Operational capacity calculated by RESOLVE and SWITCH for all of California.

5.3 Transmission flows

The baseline proposal for SWITCH allows us to see in more detail the transmission flows between the entire WECC (see Figure 5.3). All the transmission lines modeled by SWITCH are legacy transmission but with the capability of additions if optimal. We expect that as the entire WECC moves to zero-carbon, some load-zones with more available renewable resources will perform as net-exporters. We can observe this on Figure 5.3 in the load-zones with more than 40 TWh of transmission flow.

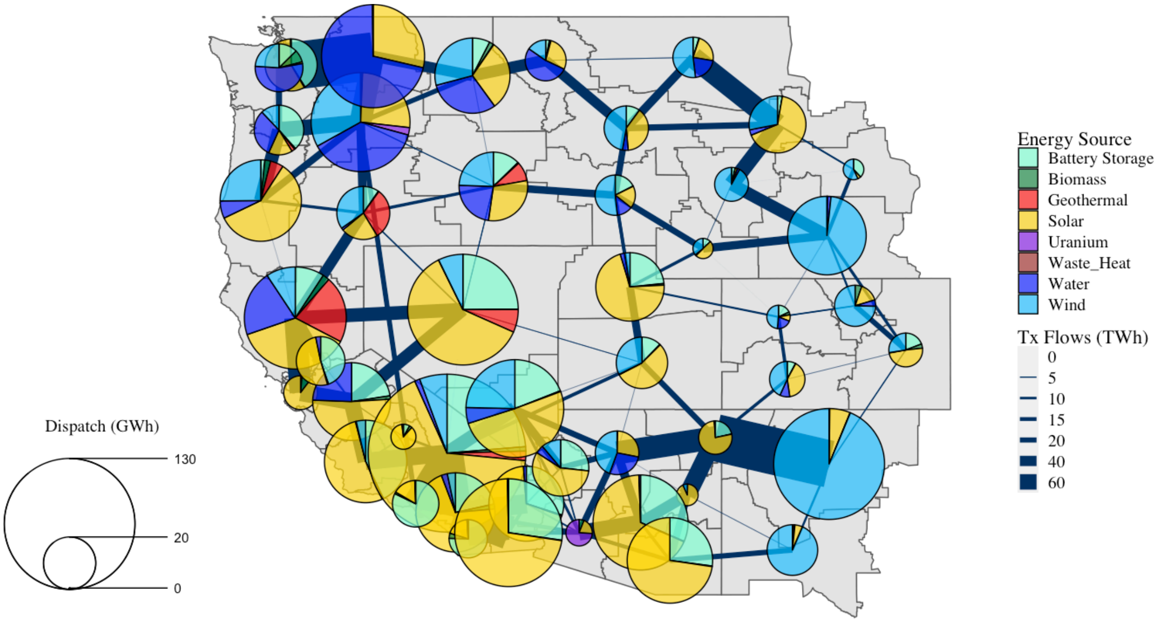


Fig. 5. 3 WECC-wide annual dispatch and transmission flows for 2050. Baseline scenario WECC-wide zero carbon cap and a 15% PRM.

5.4 Imports constraint results

An assumption that we wanted to study in detail is the imports constraint for California. This reflects a scenario where other regions in the WECC will not reduce carbon emissions as quickly as California. In simpler words, we model a zero-carbon California that will not consume any out-of-state electricity to avoid having California use electricity generated with carbon emissions. This assumption affects the overall operation capacity due to the lack of imports. Most of the electricity must be generated inside of California footprint and we end up with more cumulative additions as shown in Figure 5.4. From the results, we can see that as we limit the availability of imports, the total operational capacity increases for SWITCH. However, there is an evident difference between the equivalent scenario for SWITCH (zero-carbon California and import constraints) and the proposed RESOLVE baseline scenario. We suspect that this difference is due to the larger EV and electrolyzer loads used by the RESOLVE baseline. Also, with the additional spatial resolution and capacity-expansion in other zones, there is not a need for additional required capacity.

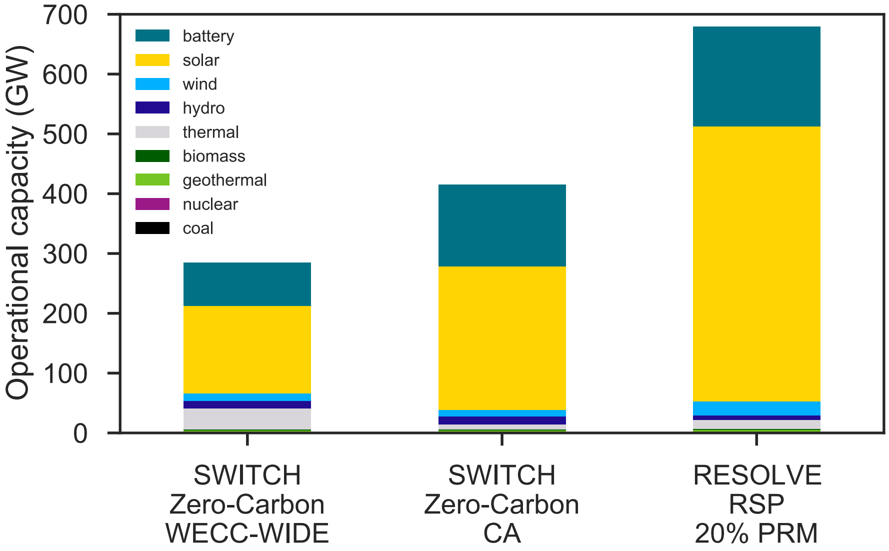


Fig. 5. 4 Operational capacity for the latest modeled period under different scenarios assumptions.

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Modeling of Long Duration Storage for Decarbonization of California Energy System

EPC-19-060 - UC Merced

CPR #1 March 25, 2021

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Agenda

1. **Introductions (5 min)**
   a. **Presenters and Attendees**
   b. **Team Members and Project Partners**
2. **Project Overview & Status (30 min)**
   a. **Project Timeline and Goals**
   b. **Results from the Introductory Public Workshop and Baseline Development (Task 2)**
3. **Project Approach (25 min)**
   a. **Approach to Storage and Energy Technology Summaries**
   b. **Plans for the Scenario Selection Public Workshop**
   c. **Challenges and Opportunities**
4. **Questions (30+ min)**
5. **CPR Determination April 8, 2021**

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Introduction to team

University of California Merced

Sarah Kurtz

UC Berkeley

Dan Kammen

UT Austin

Sergio Castellanos

University of California San Diego

Patricia Hidalgo-Gonzalez

University of North Carolina Chapel Hill

Noah Kittner

Students will be introduced as their work is introduced later…

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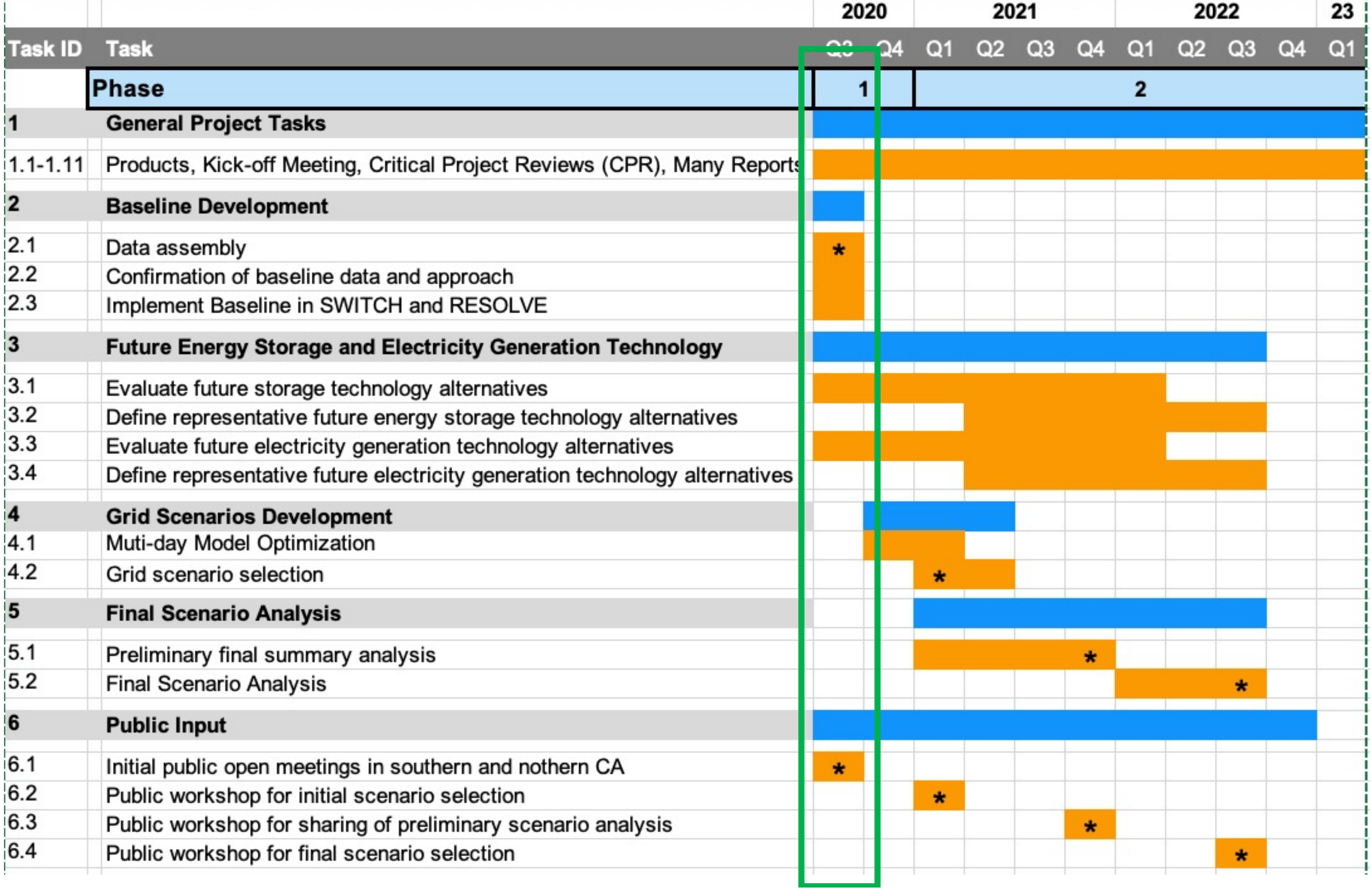
Technical Advisory Committee members

- Erin Childs (CESA) – CESA is doing similar modeling for California
- Paul Denholm (NREL) – NREL has been studying storage
- Jennifer Dowdell (TURN) – TURN studies equitable policies
- Shucheng Liu (CAISO) – CAISO representative
- Keith Parks (Xcel Energy) – Utility representative (Xcel is leader)
- Julia Prochnik (LDES Association of California) – Storage industry
- Ron Sinton (Sinton Instruments) – Has been participating in CO
- Priya Sreedharan (GridLab) – GridLab is studying transition
- David Williams – Brings business perspective

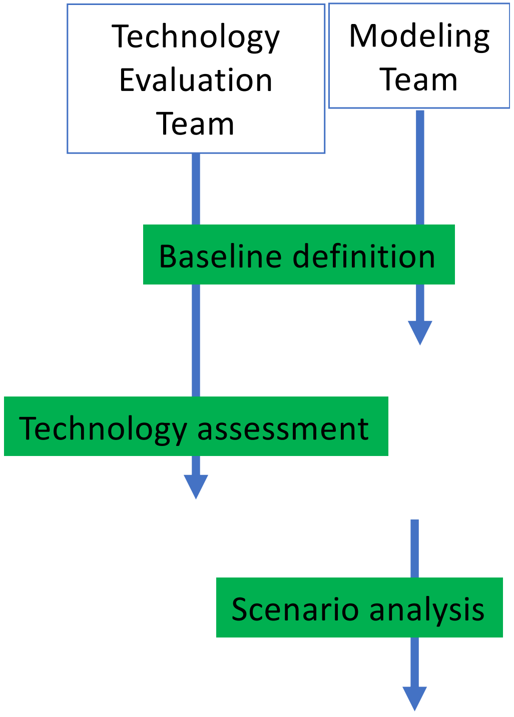
Storage specialists we have engaged with so far

- Antora Energy
- Cat Creek
- EDF
- Energy Vault
- ETES
- GE Renewables
- H2B2
- Harvard University
- Heliogen
- Highview Power
- Hydrostor
- NREL
- Quidnet
- Renewell Energy
- Solar Turbines
- Zinc8 Energy Solutions

PROJECT SCHEDULE



		2020		2021				2022				23
Task ID	**Task**	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1
	Phase	1		2								
1	**General Project Tasks**	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
1.1-1.11	Products, Kick-off Meeting, Critical Project Reviews (CPR), Many Reports	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
2	**Baseline Development**	🟦										
2.1	Data assembly	🟧 *										
2.2	Confirmation of baseline data and approach	🟧										
2.3	Implement Baseline in SWITCH and RESOLVE	🟧										
3	**Future Energy Storage and Electricity Generation Technology**	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦		
3.1	Evaluate future storage technology alternatives	🟧	🟧	🟧	🟧	🟧	🟧	🟧				
3.2	Define representative future energy storage technology alternatives				🟧	🟧	🟧	🟧	🟧	🟧		
3.3	Evaluate future electricity generation technology alternatives	🟧	🟧	🟧	🟧	🟧	🟧	🟧				
3.4	Define representative future electricity generation technology alternatives				🟧	🟧	🟧	🟧	🟧	🟧		
4	**Grid Scenarios Development**		🟦	🟦	🟦							
4.1	Muti-day Model Optimization		🟧	🟧								
4.2	Grid scenario selection			🟧 *	🟧							
5	**Final Scenario Analysis**			🟦	🟦	🟦	🟦	🟦	🟦	🟦		
5.1	Preliminary final summary analysis			🟧	🟧	🟧	🟧 *					
5.2	Final Scenario Analysis							🟧	🟧	🟧 *		
6	**Public Input**	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	
6.1	Initial public open meetings in southern and nothern CA	🟧 *										
6.2	Public workshop for initial scenario selection			🟧 *								
6.3	Public workshop for sharing of preliminary scenario analysis						🟧 *					
6.4	Public workshop for final scenario selection									🟧 *		



Technology Evaluation Team

Modeling Team

Baseline definition

Technology assessment

Scenario analysis

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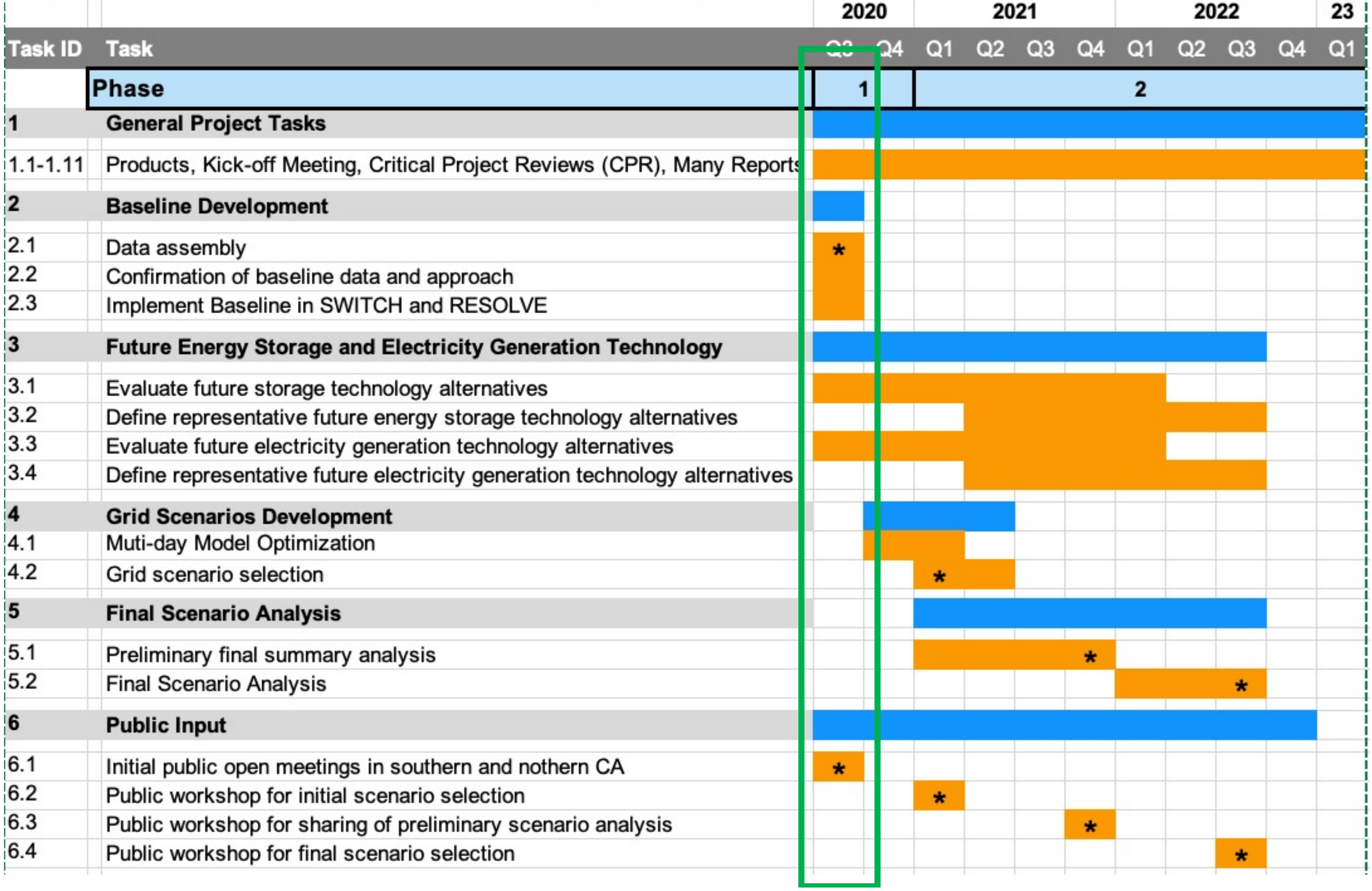
PROJECT SCHEDULE



Task ID	Task	2020 Q3	2020 Q4	2021 Q1	2021 Q2	2021 Q3	2021 Q4	2022 Q1	2022 Q2	2022 Q3	2022 Q4	23 Q1
	Phase	1		2								
1	**General Project Tasks**	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
1.1-1.11	Products, Kick-off Meeting, Critical Project Reviews (CPR), Many Reports	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
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2.3	Implement Baseline in SWITCH and RESOLVE	🟧										
3	**Future Energy Storage and Electricity Generation Technology**	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦		
3.1	Evaluate future storage technology alternatives	🟧	🟧	🟧	🟧	🟧	🟧	🟧				
3.2	Define representative future energy storage technology alternatives				🟧	🟧	🟧	🟧	🟧	🟧		
3.3	Evaluate future electricity generation technology alternatives	🟧	🟧	🟧	🟧	🟧	🟧	🟧				
3.4	Define representative future electricity generation technology alternatives				🟧	🟧	🟧	🟧	🟧	🟧		
4	**Grid Scenarios Development**		🟦	🟦	🟦							
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5.2	Final Scenario Analysis							🟧	🟧	🟧 *		
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6.2	Public workshop for initial scenario selection			🟧 *								
6.3	Public workshop for sharing of preliminary scenario analysis						🟧 *					
6.4	Public workshop for final scenario selection									🟧 *		

Completed work to be presented today:

Status on future work

(2nd part of talk)

Task 2:

Baseline Development

Deliverables submitted

Task 3:

Technology Evaluation

Project initiation

Task 4:

Scenario Development

Initial results

Task 6:

Public

workshop

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PROJECT OBJECTIVES

- **Study Value of Long-Duration Storage**
  - What role(s) will long-duration storage play? (e.g. nighttime vs cloudy days vs seasonal)
  - What cost target must a technology reach to be helpful?

- **Technical questions**
  - Is there an entry market?
  - What will a technology be competing against?
  - What will enable a technology to compete successfully?
    - Cost, efficiency, etc.

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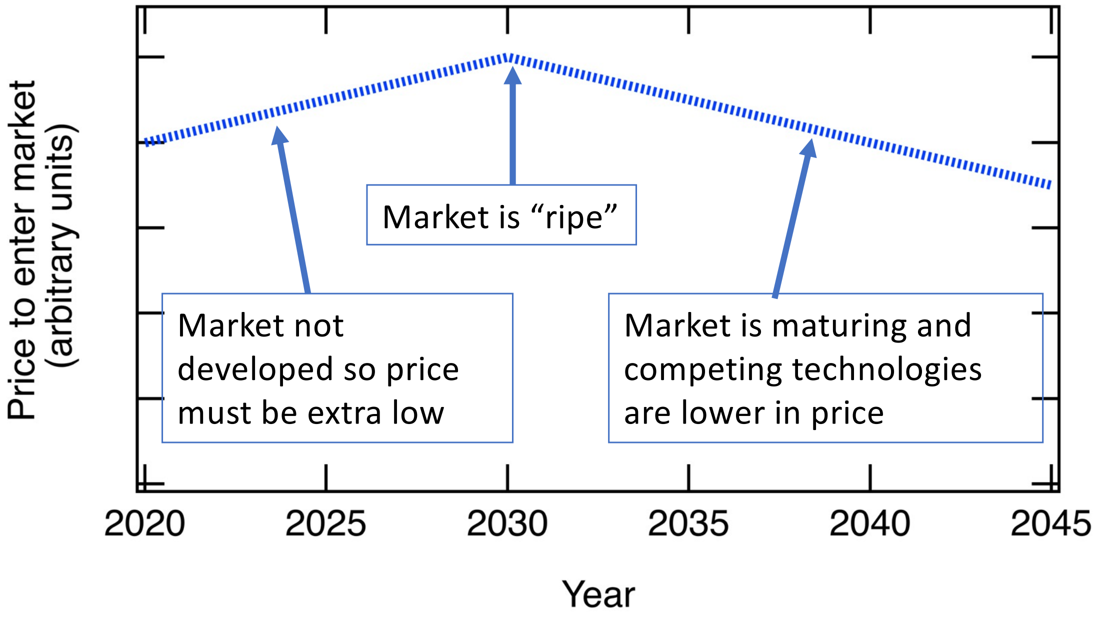
Project goal – Entry market definition

Here is an example of the sort of outcome that will be useful

Create price target graph for
- Each storage application
- Hours of duration
- Efficiency

Compare graph to expected price of each technology



This sort of analysis can help companies align their product design with market entry timing

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Task 6: Results from Public Workshop

- Public workshop was held November 17, 2020
- Opportunities/Challenges:
  - During the workshop, the primary questions were around “What do we mean by ‘Long-duration storage’”?
  - The workshop motivated productive conversations
- Follow up:
  - Have written a draft “Talking about Long-duration Storage” (next slides)
  - *Issues in Science and Technology* is interested in publishing a non-technical version in April – revision in progress
  - May publish technical parts in second publication
  - Conversation has been valuable

“Talking about Long-duration Storage”
From a modeling perspective – time element

- Modeling approach depends on application

- One-day models
  - Short-duration storage to meet peak demand
  - Diurnal storage (through the night)

- Multi-day models
  - Cross-day storage (get through a storm)

- Full-year models
  - Seasonal storage

Some technologies may address multiple applications

To understand big picture, must model all applications simultaneously!

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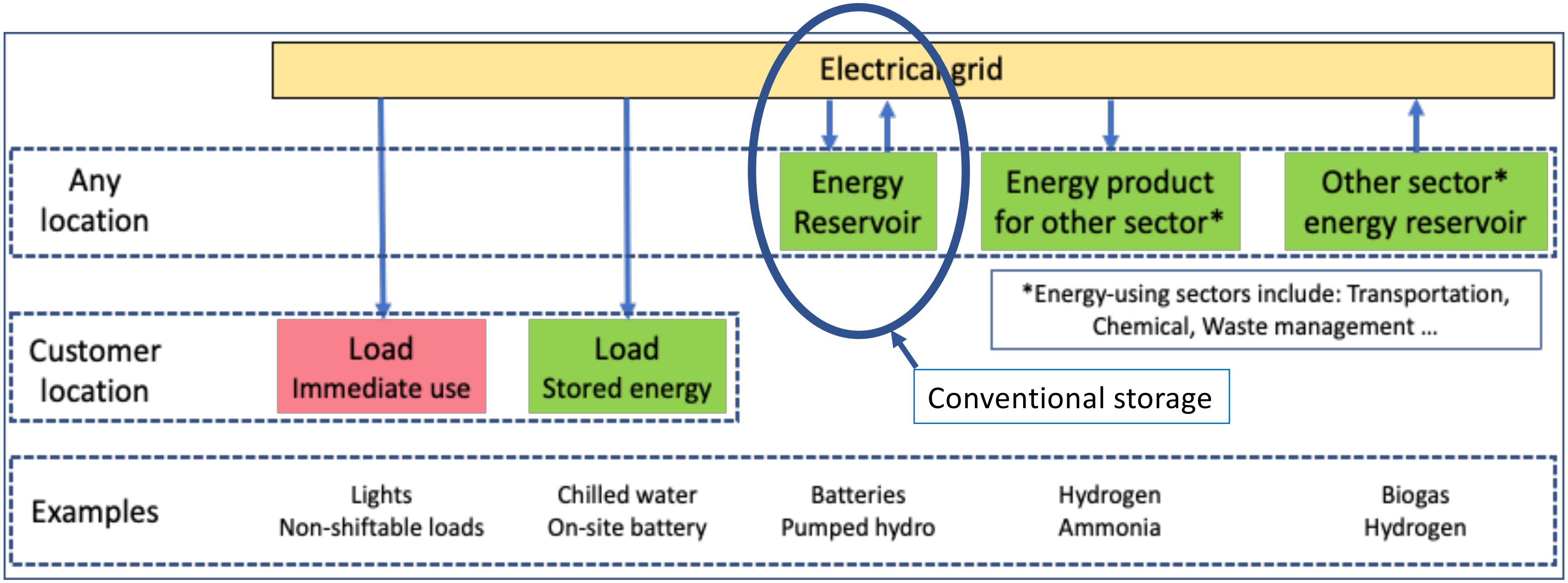
“Talking about Long-duration Storage”
From a modeling perspective – energy flow

Modeling energy flows - need to consider all types



Electrical grid

Any location

Energy Reservoir

Energy product for other sector*

Other sector* energy reservoir

*Energy-using sectors include: Transportation, Chemical, Waste management …

Customer location

Load Immediate use

Load Stored energy

Conventional storage

Examples

Lights
Non-shiftable loads

Chilled water
On-site battery

Batteries
Pumped hydro

Hydrogen
Ammonia

Biogas
Hydrogen

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“Talking about Long-duration Storage” Include all types in modeling

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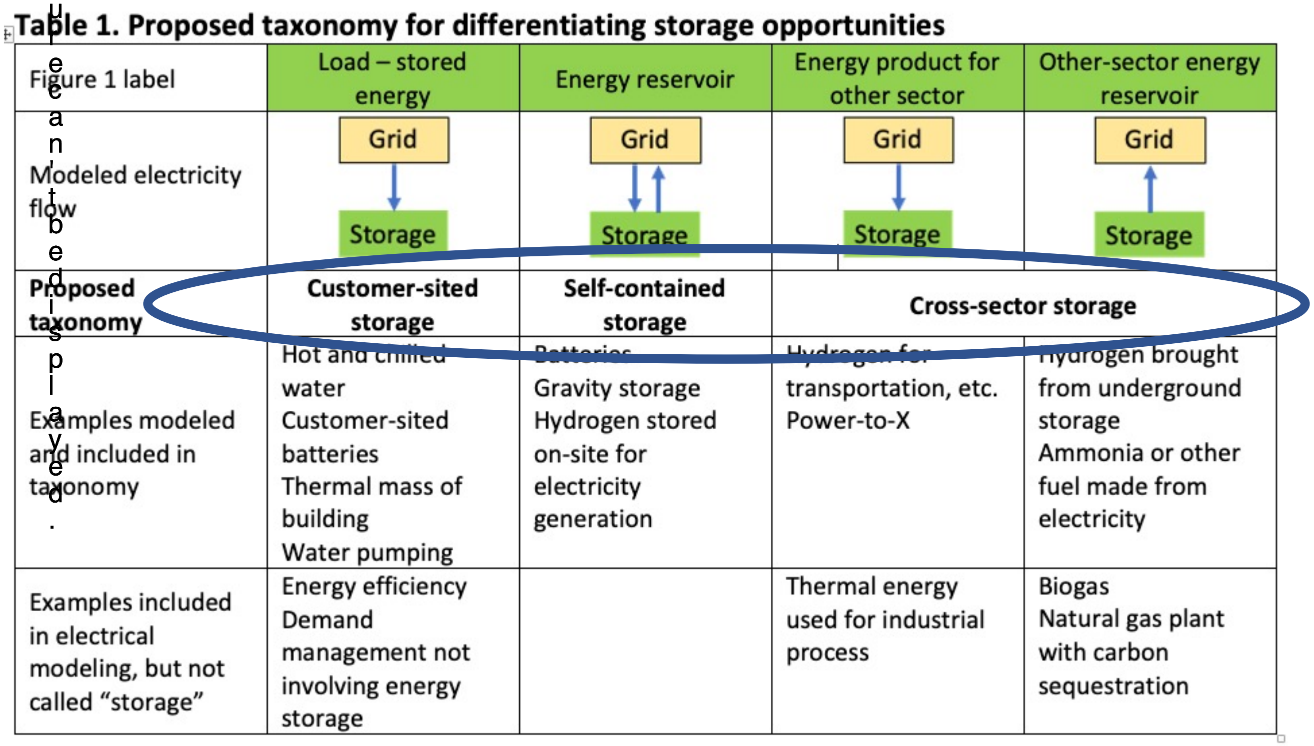
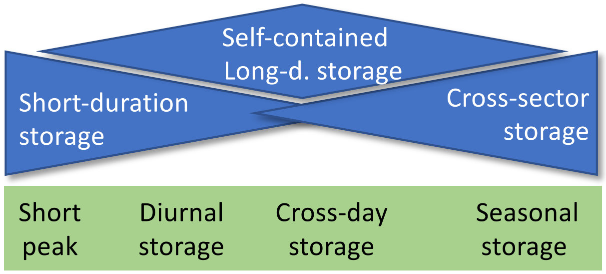


Table 1. Proposed taxonomy for differentiating storage opportunities

Figure 1 label	Load – stored energy	Energy reservoir	Energy product for other sector	Other-sector energy reservoir
Modeled electricity flow	Grid → Storage	Grid ⇅ Storage	Grid → Storage	Grid ← Storage
Proposed taxonomy	**Customer-sited storage**	**Self-contained storage**	**Cross-sector storage**	
Examples modeled and included in taxonomy	Hot and chilled water Customer-sited batteries Thermal mass of building Water pumping	Batteries Gravity storage Hydrogen stored on-site for electricity generation	Hydrogen for transportation, etc. Power-to-X	Hydrogen brought from underground storage Ammonia or other fuel made from electricity
Examples included in electrical modeling, but not called “storage”	Energy efficiency Demand management not involving energy storage		Thermal energy used for industrial process	Biogas Natural gas plant with carbon sequestration



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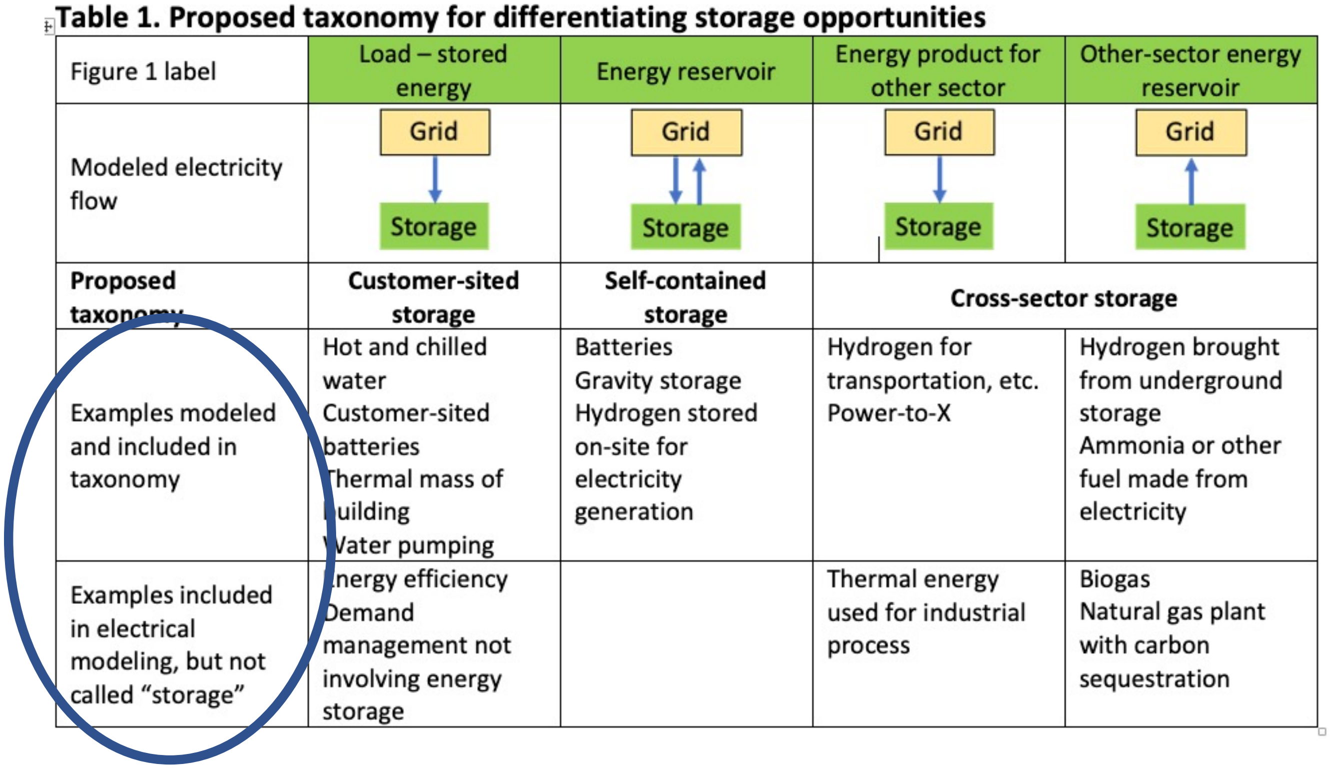
"Talking about Long-duration Storage"
Include all types in modeling



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For our purposes: it's more important to agree on what must be modeled, not what is called "storage"
However, if CEC creates a solicitation to fund "long-duration storage", the companies will want a broad definition

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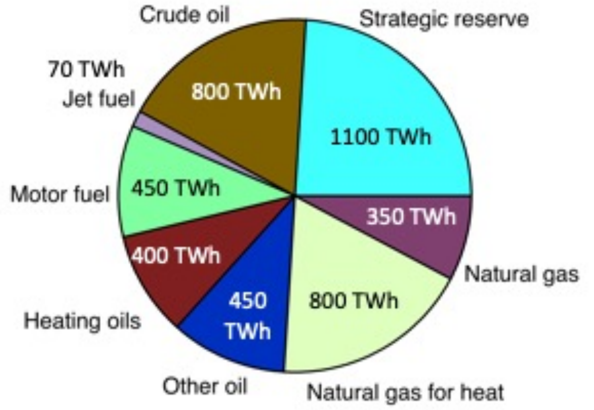
“Talking about Long-duration Storage”
Why think broadly?

Current energy storage for all sectors is huge

Will tomorrow’s energy system need more or less energy storage?

Current energy storage in USA



Natural gas may be stored for:

- Power generation
- Heating
- Chemicals

“cross-sector” storage: reduces costs for all sectors

Conclude:

- *When studying long-duration storage, need to also consider options for large-scale (cross-sector) storage*
- *How will self-contained storage projects compete with these?*
- ***Including cross-sector storage will stimulate innovation***

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“Talking about Long-duration Storage”
Status

- Writing version for non-technical audience for April in *Issues in Science and Technology*
- Will look for periodical that is appropriate for more technical version
- Will include slides in next Public Workshop

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Task 2: Baseline definition – status

Task 2 Deliverables completed

- Baseline Description (Feb. 4 – draft; 25 – final)
- Modeling Approach Description (Feb. 4 – draft; 25 – final)
- Summary of Baseline Model Results (March 23)

All have been completed on time using 2018 version of RESOLVE

E3 is updating RESOLVE to include cross-day capability needed for long-duration storage and other changes. *The above will be reimplemented in the new version of RESOLVE after we have it from E3 (end of April)*.

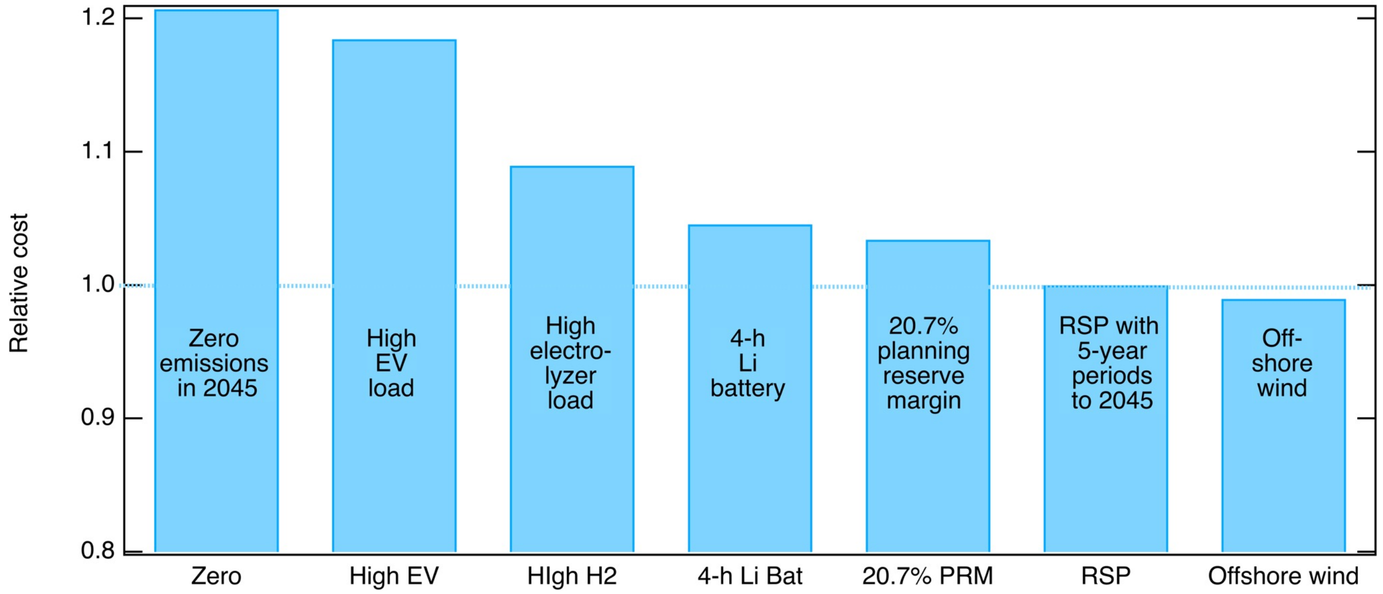
Criteria used to define new baseline for RESOLVE

Start from 2018 RSP – will update this when E3 releases new version

Refrain from “tweaking” – change only in response to changing world:

- Governor’s goal for electric vehicle sales (increase EV charging load)
- Increased investment in hydrogen (increase electrolyzer load)
- Advancement of off-shore wind (add off-shore wind options)
- Li batteries built as 4-hour resource (redefine Li_battery)
- Proposed increase of planning reserve margin from 15% to 20.7%
- Increased enthusiasm to reach zero emissions (zero in 2045)

Implications of changes to baseline
Sensitivity to each change individually



These results raise questions – addressed in the following slides

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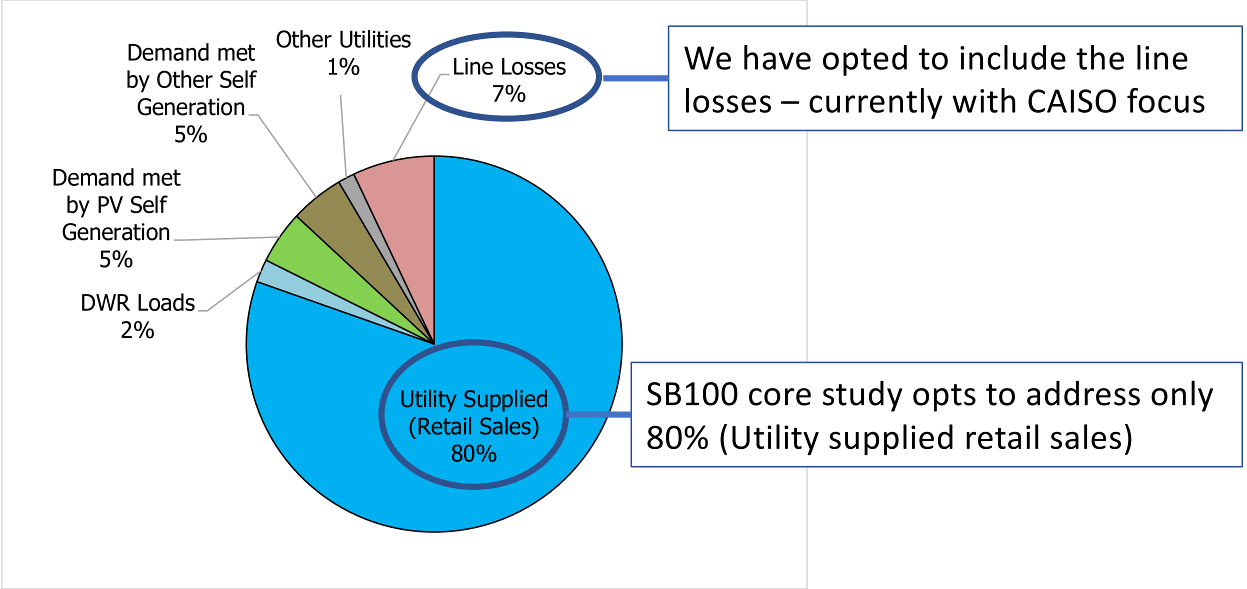
Implications of changes to baseline – zero GHG in 2045

Figure 19: 2018 California Electricity Loads



We have opted to include the line losses – currently with CAISO focus

SB100 core study opts to address only 80% (Utility supplied retail sales)

Source: 2019 California Energy Demand and the Quarterly Fuels and Energy Report Demand filings

https://efiling.energy.ca.gov/GetDocument.aspx?tn=237167&DocumentContentId=70349

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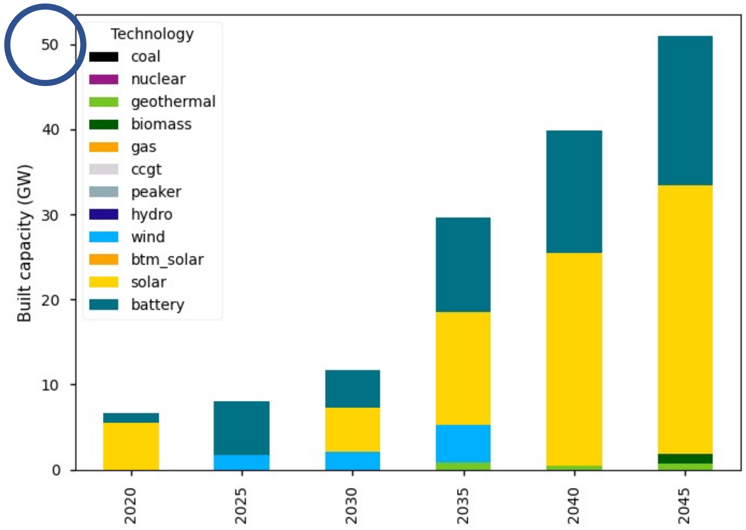
Implications of changes to baseline – zero GHG in 2045
New builds each year

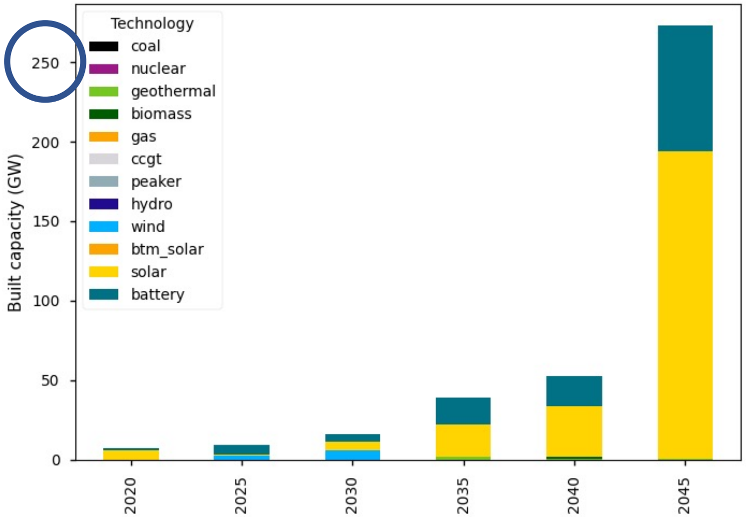
California data – no imports in 2045

5-year RSP (2018 version)



5-year RSP with zero-emissions target in 2045

Scale is 5 X bigger



Builds 200 GW solar in 2045! Could change for multiple reasons…

However, recall that RESOLVE uses 37 independent days: There is no opportunity for cross-day storage.

Question: will solar build be decreased when cross-day storage is included?

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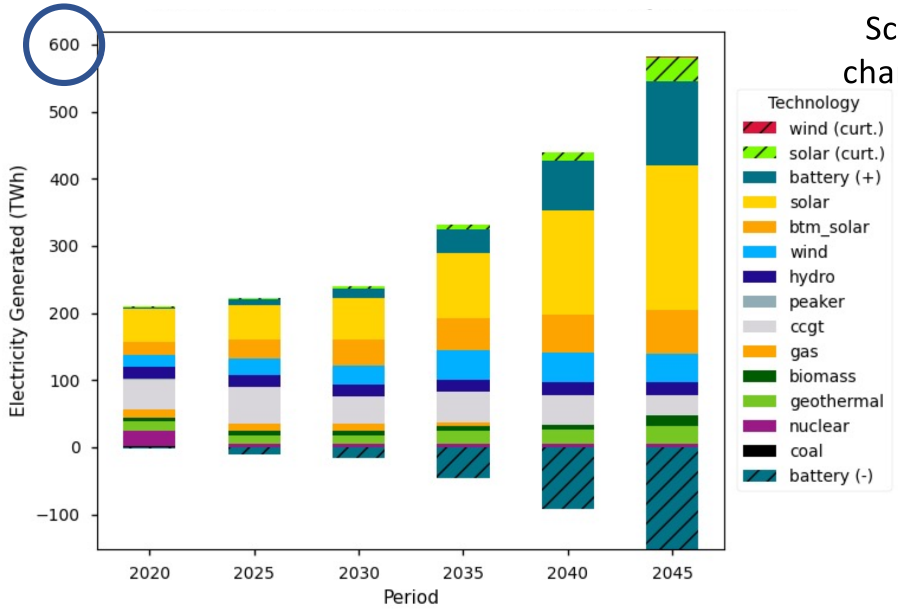
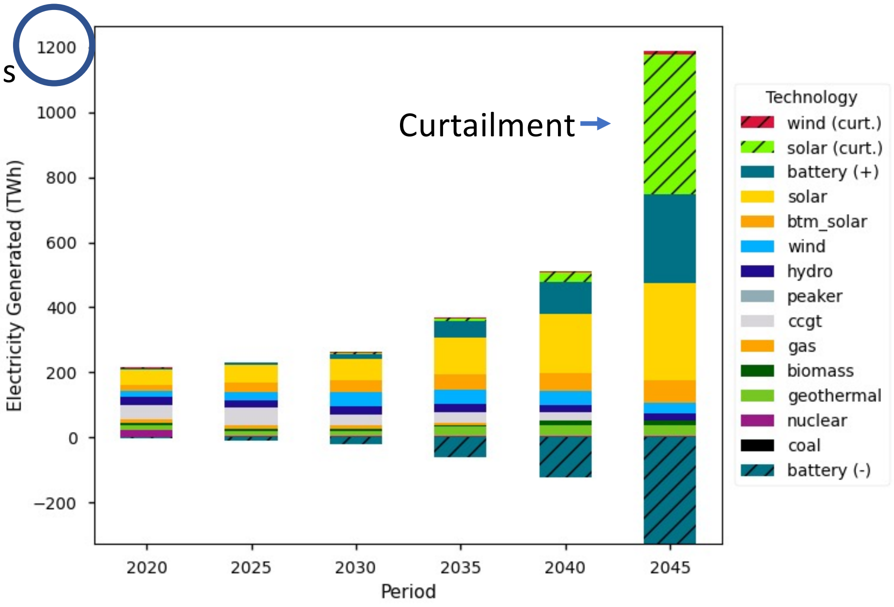
Implications of changes to baseline – zero in 2045

5-year RSP (2018 version)



Scale changes

5-year RSP with zero-emissions target in 2045

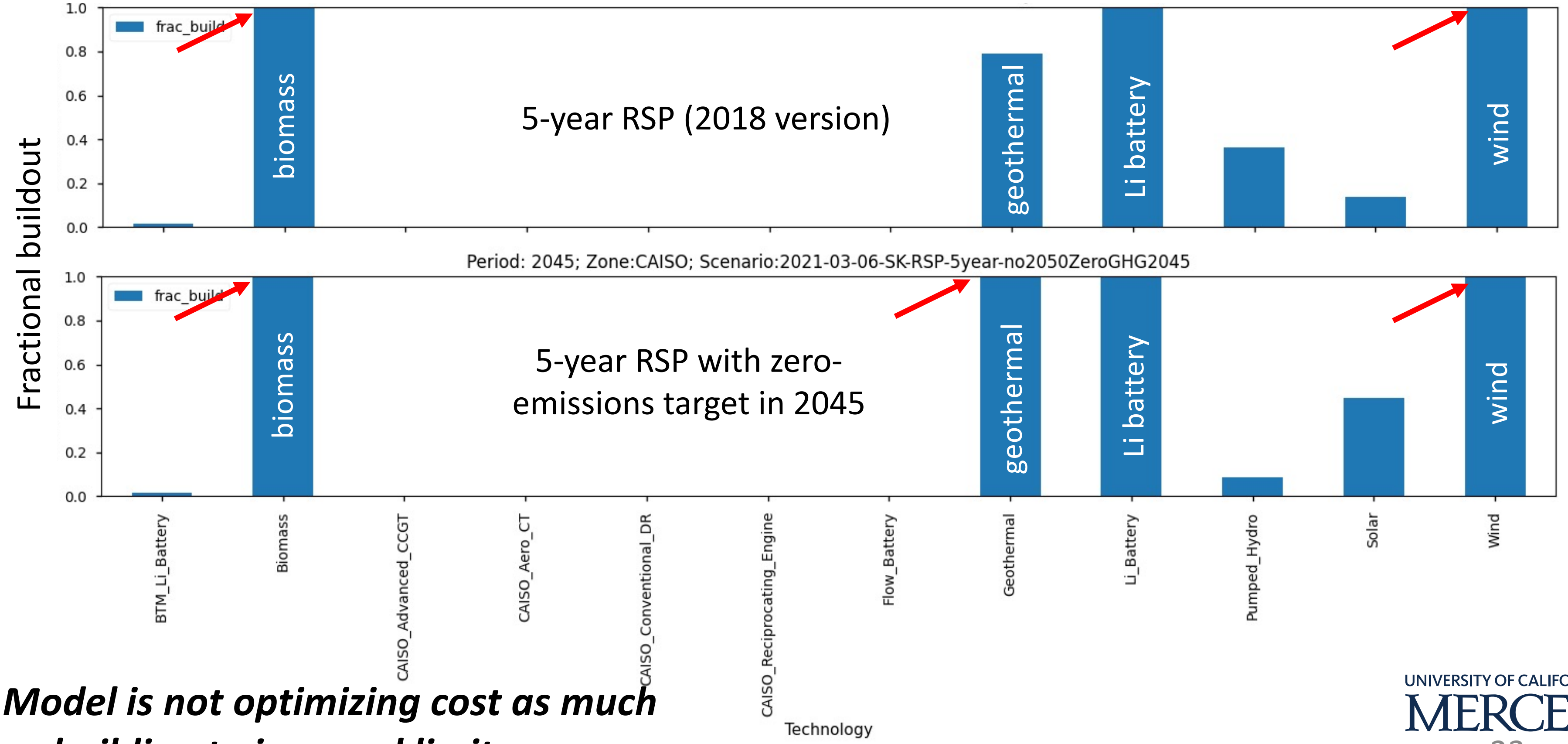


Thermal generation is replaced by more solar and more storage

Use of storage doubles and curtailment approaches total load!

Next slides show more details…

Implications of changes to baseline – zero in 2045
Buildout relative to allowed buildout



5-year RSP (2018 version)

5-year RSP with zero-emissions target in 2045

Model is not optimizing cost as much as building to imposed limits

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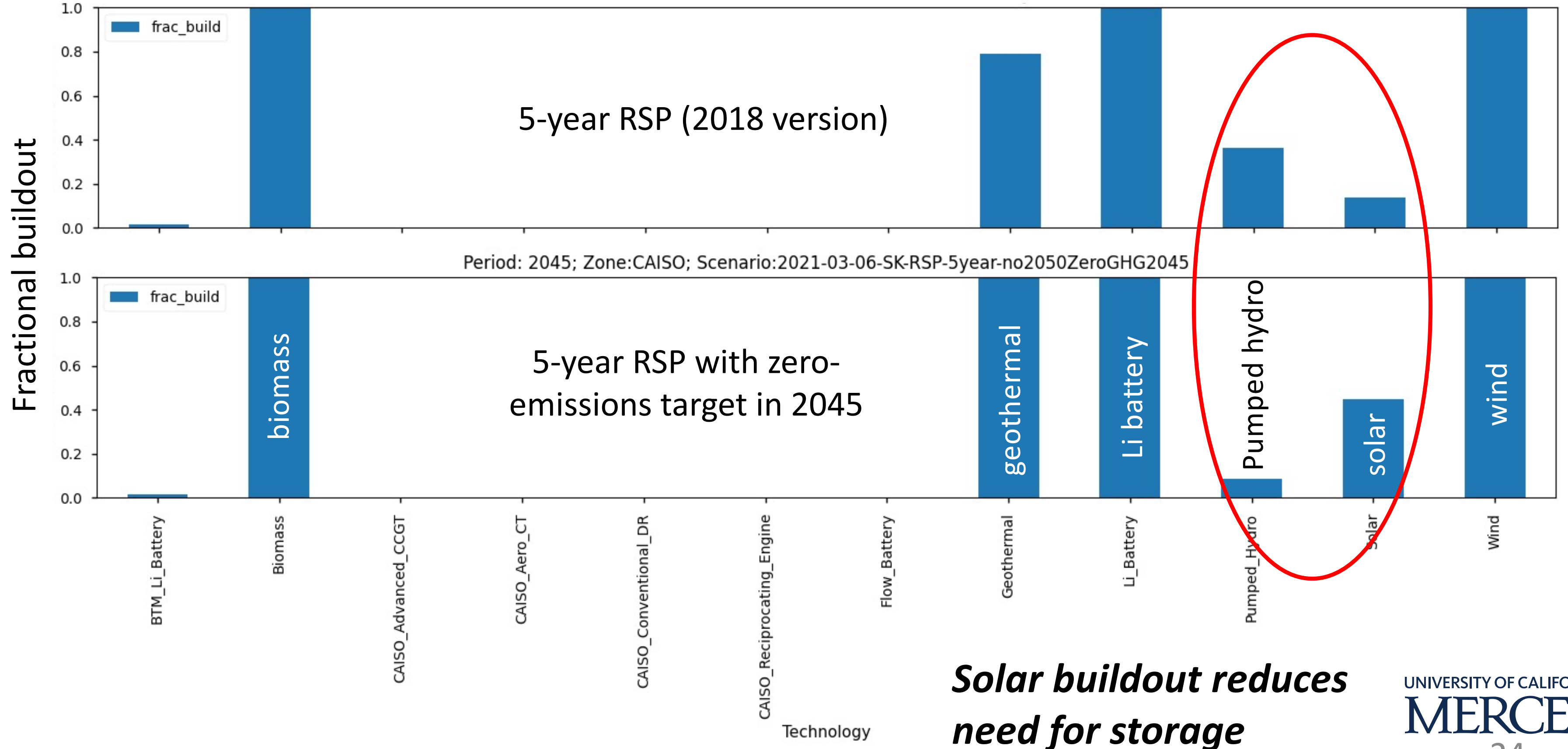
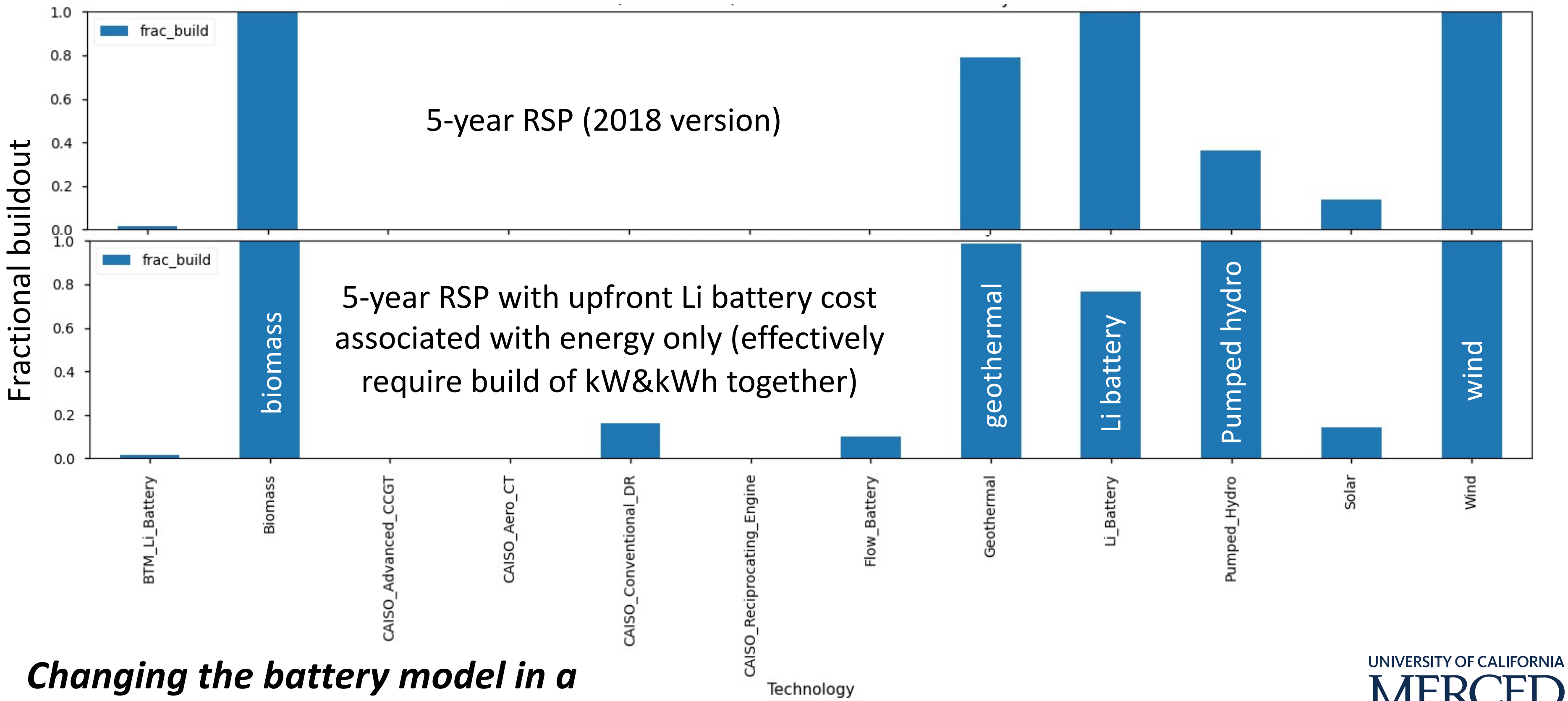
Implications of changes to baseline – zero in 2045
Buildout relative to allowed buildout



Solar buildout reduces need for storage

Implications of changes to baseline – revised Li battery model



5-year RSP (2018 version)

5-year RSP with upfront Li battery cost associated with energy only (effectively require build of kW&kWh together)

Changing the battery model in a subtle way can make a BIG difference!

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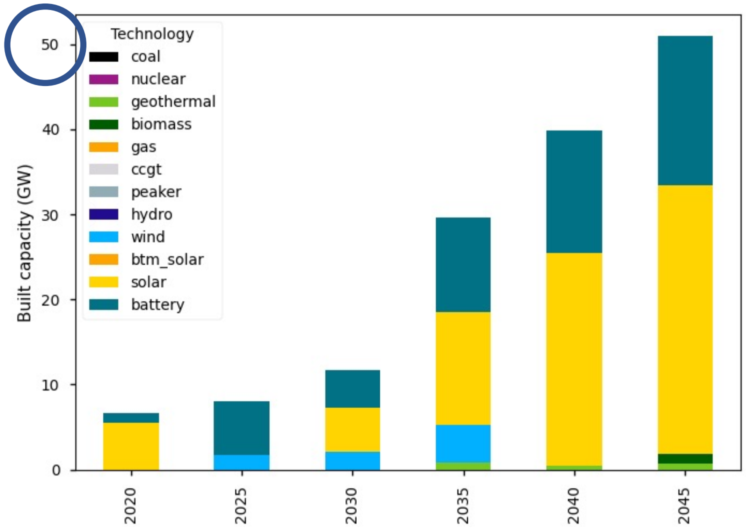
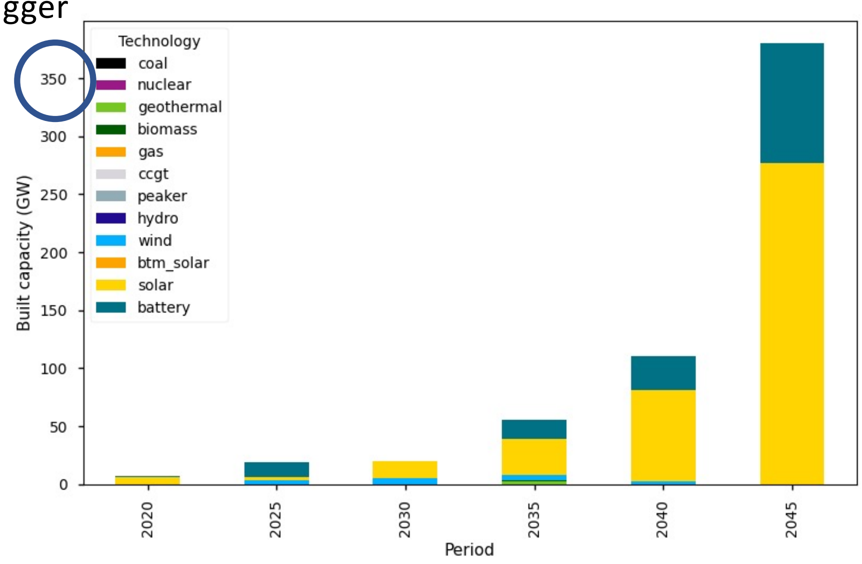
Implications of changes to baseline – all changes

5-year RSP (2018 version)



Scale
is 7 X
bigger

5-year RSP with all changes



Builds 300 GW solar in 2045!

However, recall that RESOLVE uses 37 independent days: There is no opportunity for cross-day storage.

Question: will overbuild be decreased when cross-day storage is included?
Wind will help

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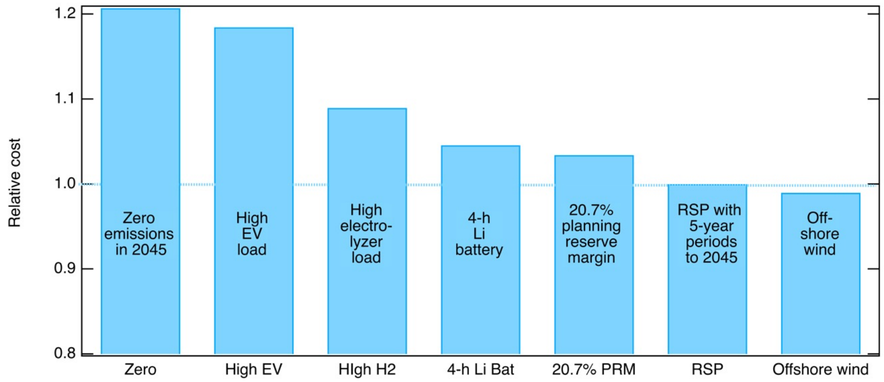
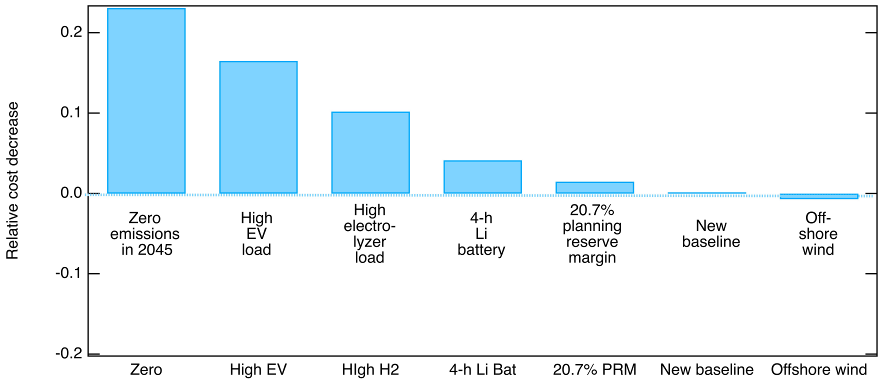
Implications of changes to baseline
Sensitivity to each change individually



Start with RSP and add individual changes



Start with proposed baseline and remove individual changes

Take away messages:

- Need cross-day storage model to reach zero emissions gracefully: Reevaluate with revised RESOLVE
- Results from RESOLVE are limited by allowed new builds: Compare with inputs used in SWITCH
- Storage will depend a LOT on the overbuild of other generation: Can study energy balance in simple model
- Details of storage selected depends on the details of how the storage is modeled: Will be special focus

Details in Modeling results deliverable

Question – how reasonable are the buildout limits?

- In the next slides we compare the build out limits used in SWITCH and in RESOLVE
- For RESOLVE: compare five zones
- For SWITCH: compare locations listed by EIA within California

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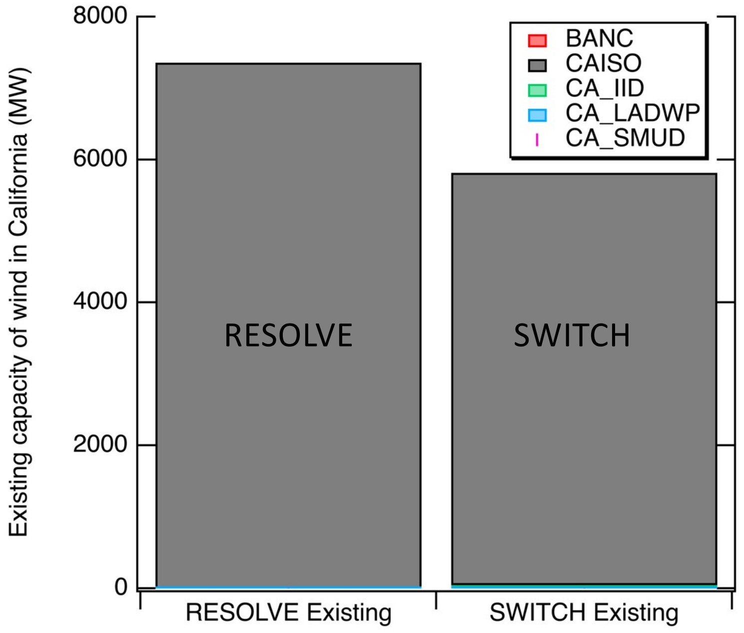
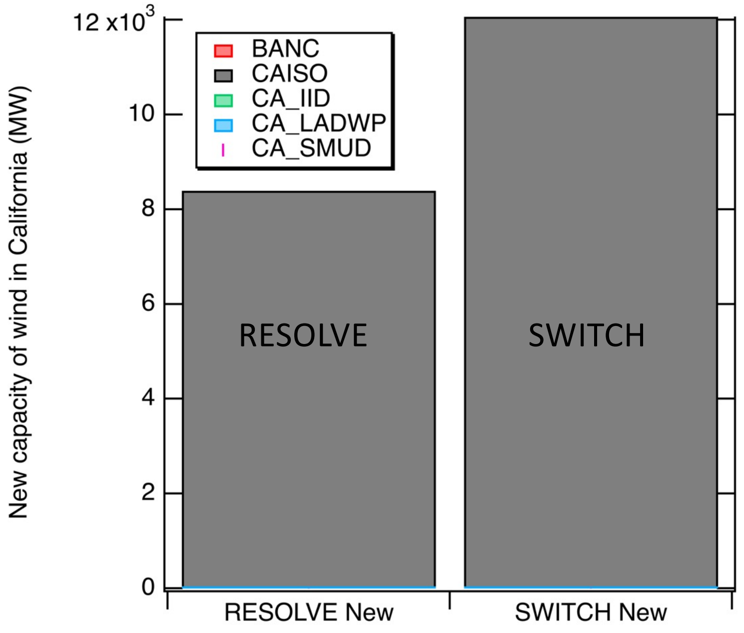
Wind capacity

SB 100 Report adds closer to 30 GW total of available wind.





SWITCH provides for relatively more growth of wind, but starts with less
Note: Wyoming wind is worth discussing in addition to offshore wind

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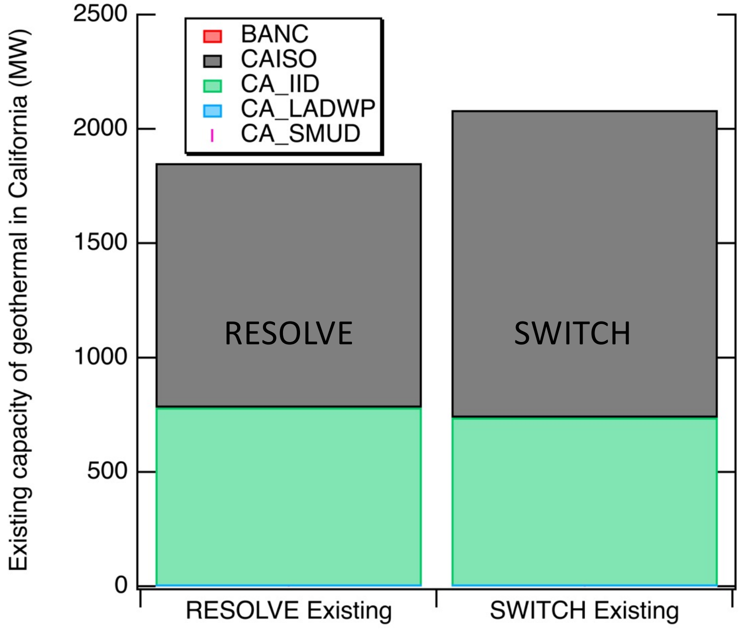
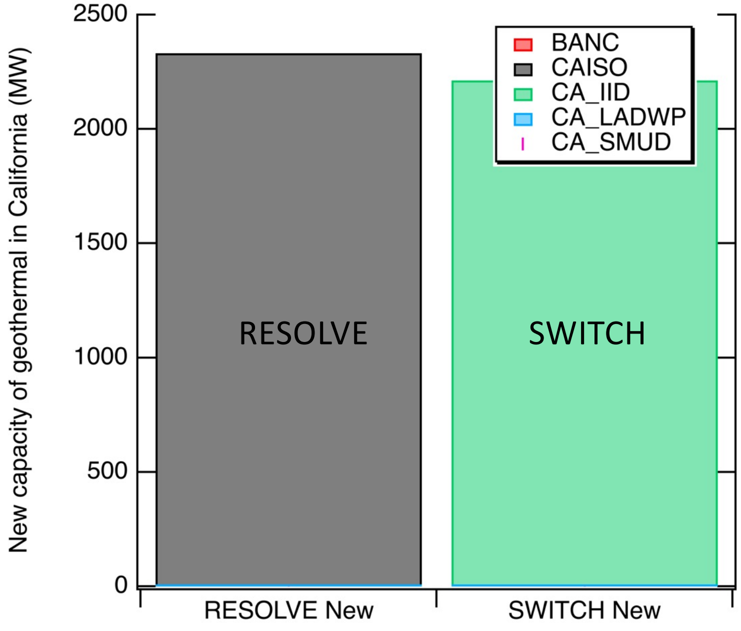
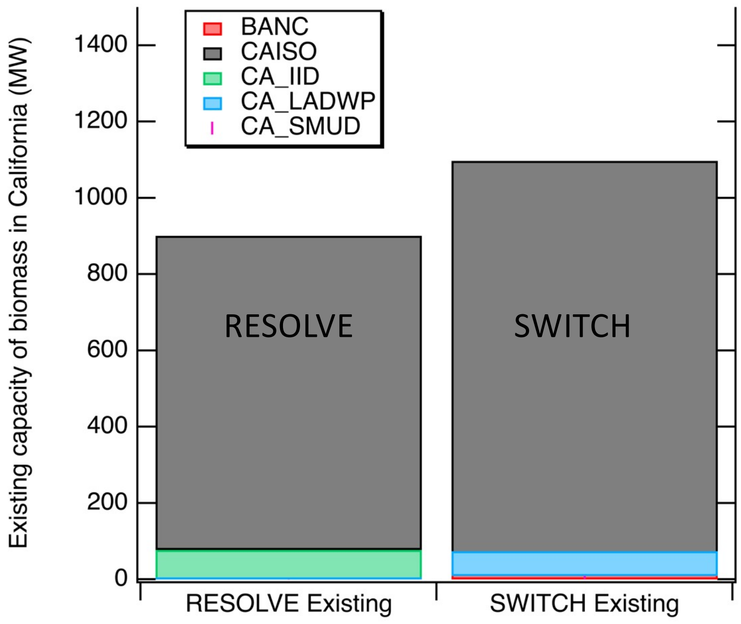
Geothermal capacity

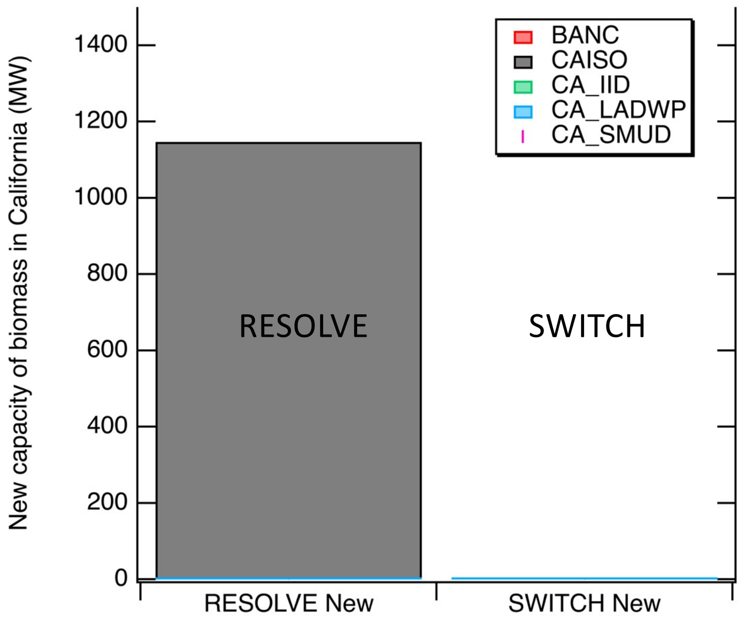




RESOLVE and SWITCH have fairly similar assumptions for Geothermal (except for the location of the possible additions.)

Biomass/gas capacity





SWITCH provides no new biomass/gas options

Preparation of SWITCH Baseline

The work that has been completed to prepare SWITCH can be classified in two categories:

- Software development
- Baseline development

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Preparation of SWITCH Baseline

Software development

- Updated to Python 3.7+ from Python 2.7
- Developed (still in progress) long-duration storage module: analytical formulation for required features (e.g. separate charging and discharging efficiencies) and efficient code implementation
- Started developing capability to use different time sampling strategies
- Implemented module to model California imports constraints from other states
- Implemented module to model assumptions on residential PV growth in California
- Implemented module to track and restrict air pollutants (optional)

Preparation of SWITCH Baseline

Baseline development

- Updated all inputs (*e.g*. EIA list of generators, NREL ATB costs, regional costs for new expansion of transmission lines)
- Set up database access at UC San Diego and UC Merced
- Selected configuration – (*e.g*. zero emissions in 2045, WECC config.)
- Began study of best strategy for selecting time points to optimize trade off between run time and accuracy of calculation
- Implement baseline run (shown on next slide)

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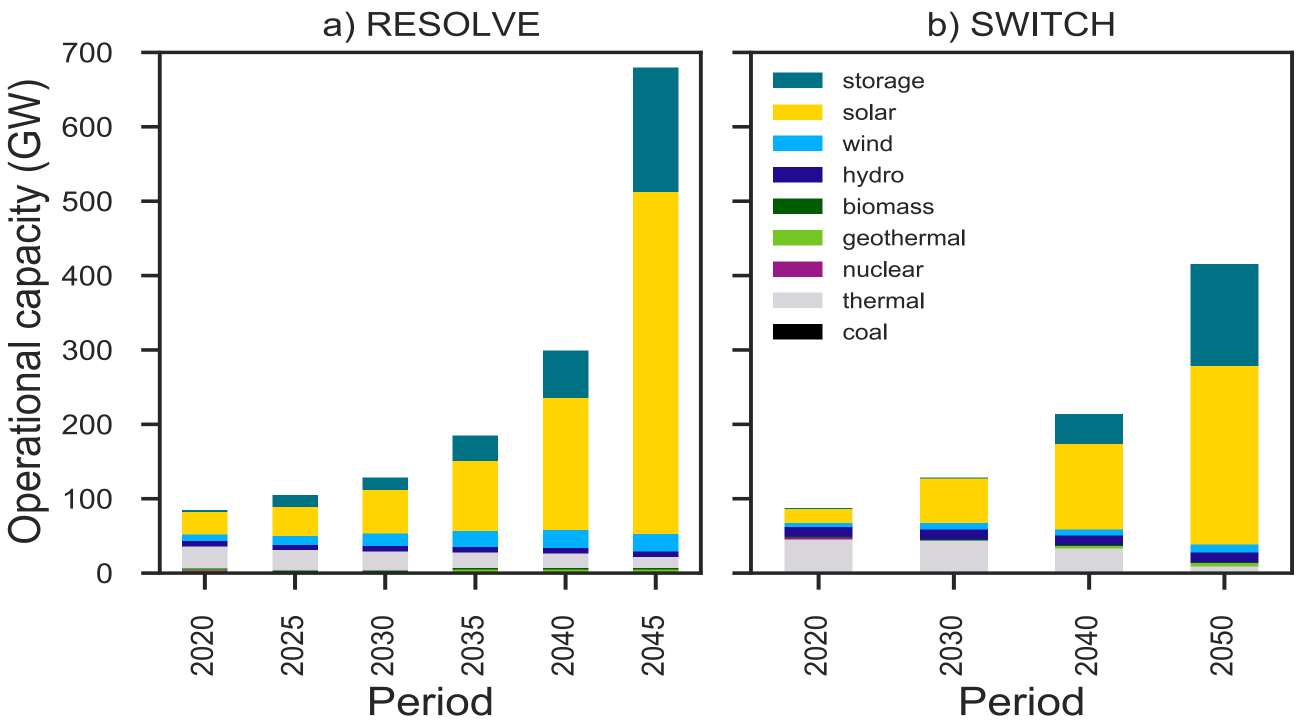
Comparison of SWITCH and RESOLVE baselines



Reflects restriction to CAISO (no imports) and increased load for hydrogen and EVs

Agenda

1. Introductions (5 min)
    a. Presenters and Attendees
    b. Team Members and Project Partners
2. Project Overview & Status (30 min)
    a. Project Timeline and Goals
    b. Results from the Introductory Public Workshop and Baseline Development (Task 2)
3. Project Approach (25 min)
    a. Approach to Storage and Energy Technology Summaries
    b. Plans for the Scenario Selection Public Workshop
    c. Challenges and Opportunities
4. Questions (30+ min)
5. CPR Determination April 8, 2021

Where are we? What's next?

- Identified baselines, but still need to implement baseline in new version of RESOLVE (after received from E3)
- In the meantime, there is a lot we can learn:
- Note that results often reflect the resources given to the model:
  - We can study the energy balance without the full cost model
  - This can enable us to understand the effects of overbuild on needed storage
  - Can use this to differentiate storage applications as a function of the overbuild and generation source

Simple model definition

- Use historical generation-profile data (from CAISO)
- Scale relative generation (remove thermal, add solar and wind, etc.)
- Calculate the generation minus the load and charge or discharge a large storage reservoir accordingly
- Assumptions:
  - No issues with transmission
  - No attempt to consider cost
  - Select relative generation for each technology as a set of input values and consider hundreds of scenarios
  - No calculation of reserve – just calculate energy balance, quantifying:
    - Size of storage needed
    - Cycle times/year for the storage if storage is divided into bins that provide 40 GWh each
    - Surplus electricity (can be used for something else or curtailed)

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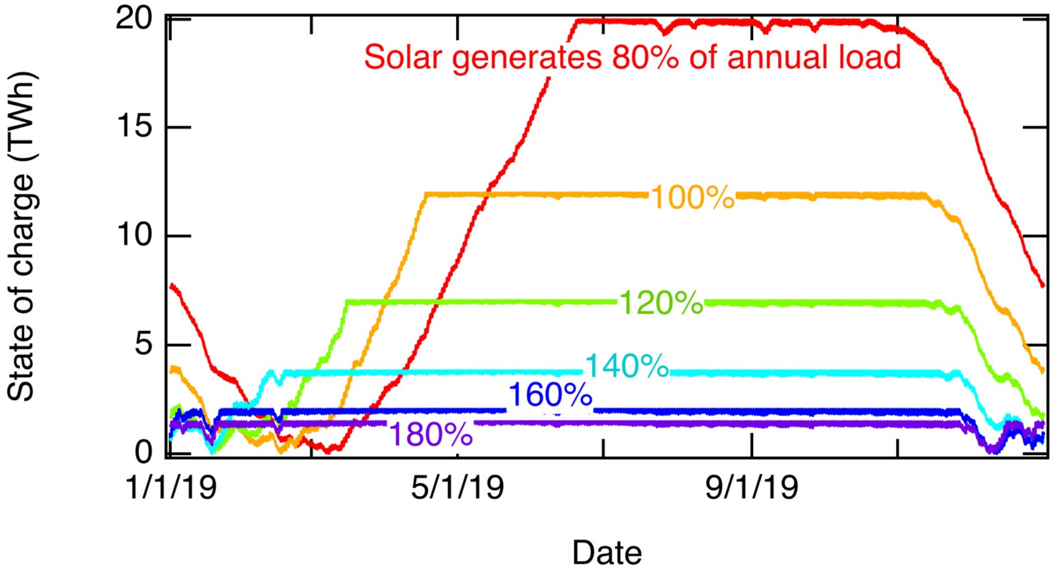
Buildout of solar reduces needed storage



Mahmoud Abido
Abstract submitted to PVSC
Manuscript is being developed

Simple model is applied

- Start with CAISO generation data, but remove thermal and imports
- Build solar to compensate for the removed generation
- Size of seasonal storage decreases 10-fold as solar is increased 2-fold
- Time of year for minimum stored energy shifts as solar is added

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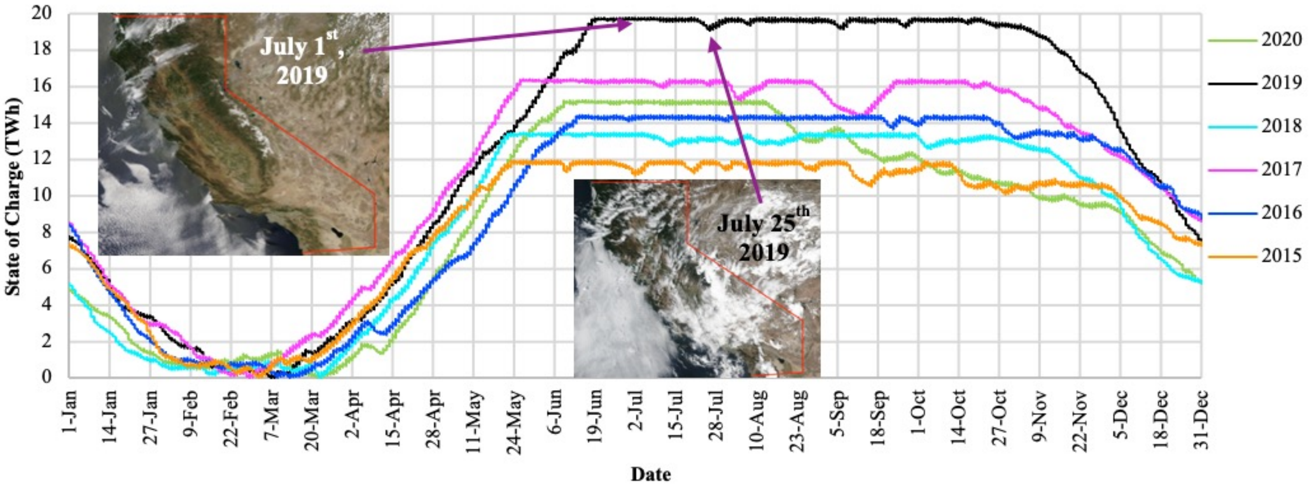
Overbuild of solar reduces needed storage



Mahmoud Abido
Abstract submitted to PVSC
Manuscript is being developed

- Time of year for minimum stored energy shifts

Question: When do we need to be concerned about resource adequacy?

Answer: It depends on the design of our energy system, but may be quite predictable (or may be unpredictable)

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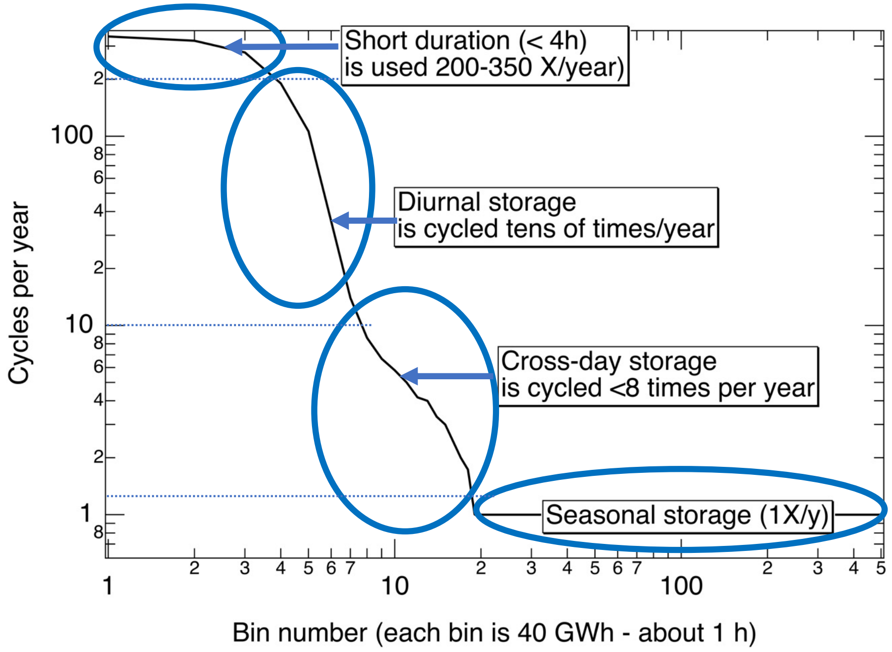
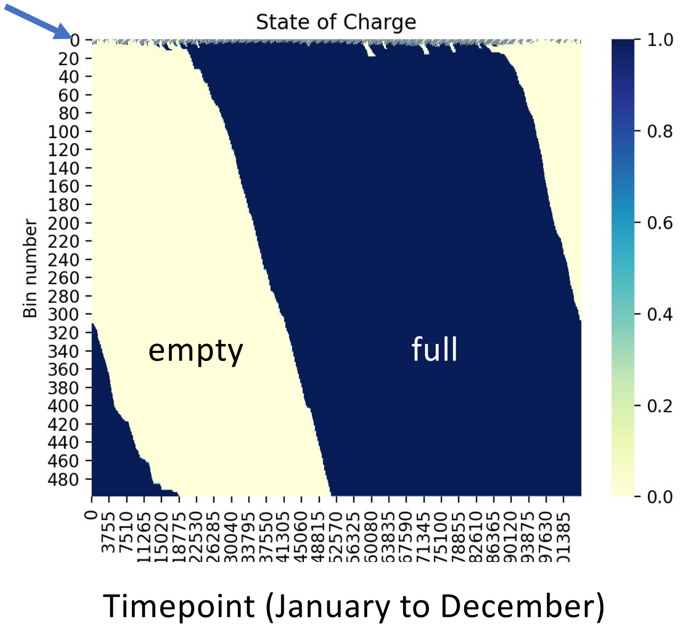
Differentiate use of the types of storage



Always fill or empty bin 1 first



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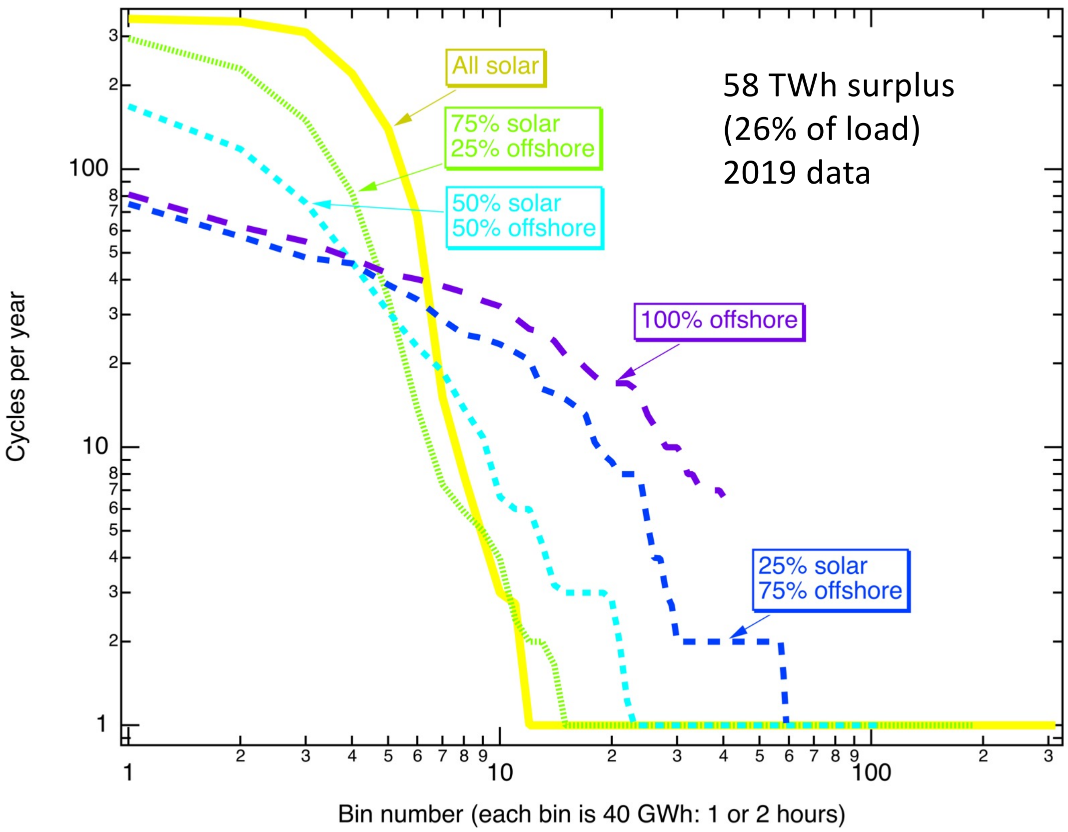
How does offshore wind compare with solar?



58 TWh surplus
(26% of load)
2019 data

"All solar" uses:

- 0.1 TWh short-duration (1-4 h) storage cycles every day
- 0.2 TWh diurnal (4-10 h) storage cycles 10-100X/year
- 12 TWh seasonal storage

"All offshore wind" uses:

- 0.1 TWh short-duration storage may only cycle 80X/year
- 1-2 TWh (4-100 h) storage cycles 10-50X/year
- No seasonal storage

Shows how role of storage can change with choice of generators

Zabir Mahmud

- Manuscript is being developed

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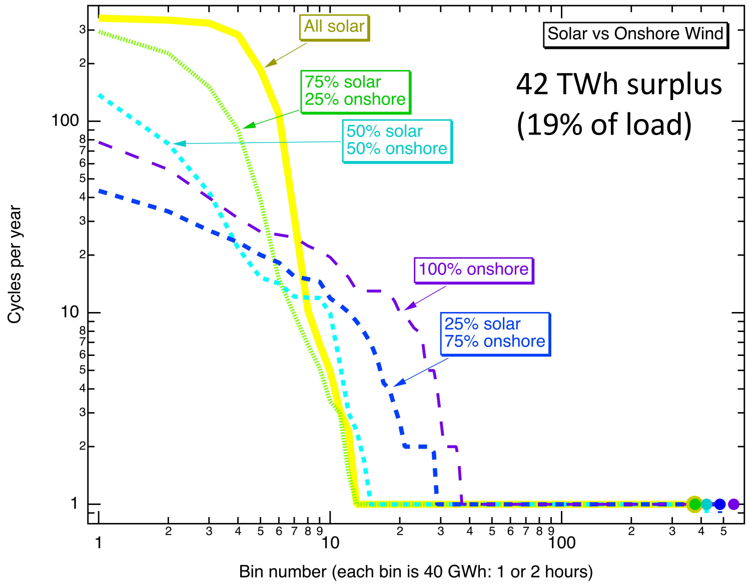
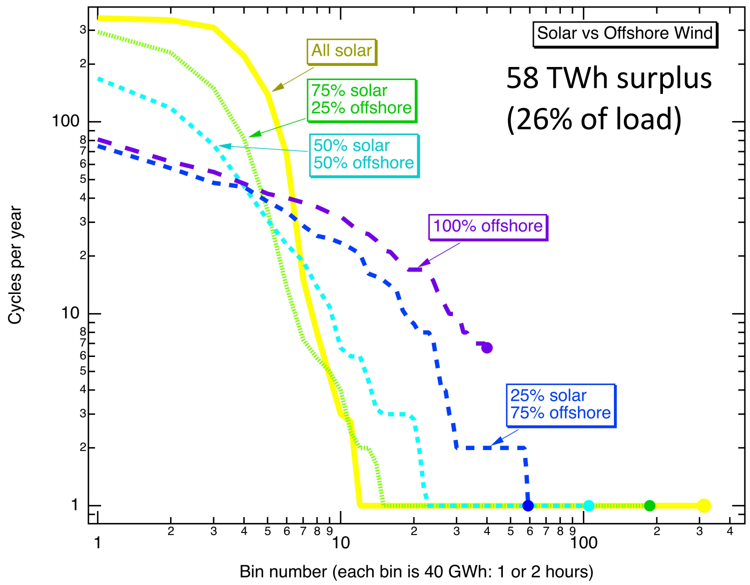
Onshore and offshore wind differ for seasonal storage





Zabir Mahmud

- Manuscript is being developed

2019 data

Offshore wind decreases need for seasonal storage using 2019 data

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Surplus electricity can be used for generating hydrogen

- **Estimate potential supply of hydrogen from the surplus of renewable electricity with various generation mix scenarios in 2045**
- **Assess the size of grid services and long-duration energy storage that renewable hydrogen can provide using SWITCH-WECC model**

Kenji Shiraishi
Exploring how
electrolyzers may use
surplus electricity
under guidance by
Dan Kammen

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Time sampling for SWITCH

- **SWITCH has flexibility to define the time sampling, but the best strategy has not been explored for implementation with long-duration storage**
- **Example sampling strategies to study**
  - **4 representative days per month X 24 hours**
  - **14 consecutive days per month X 24 hours**
  - **31 consecutive days per month X 24 hours**
  - **365 days X 24 hours**
- **Will study run time vs accuracy of results related to understanding storage to select best strategies**

Pedro Sanchez
Studying the time-sampling strategy under guidance by Patricia Hidalgo-Gonzalez

What candidate technologies may address long-duration storage needs?

Long duration energy storage technologies: candidates and use cases

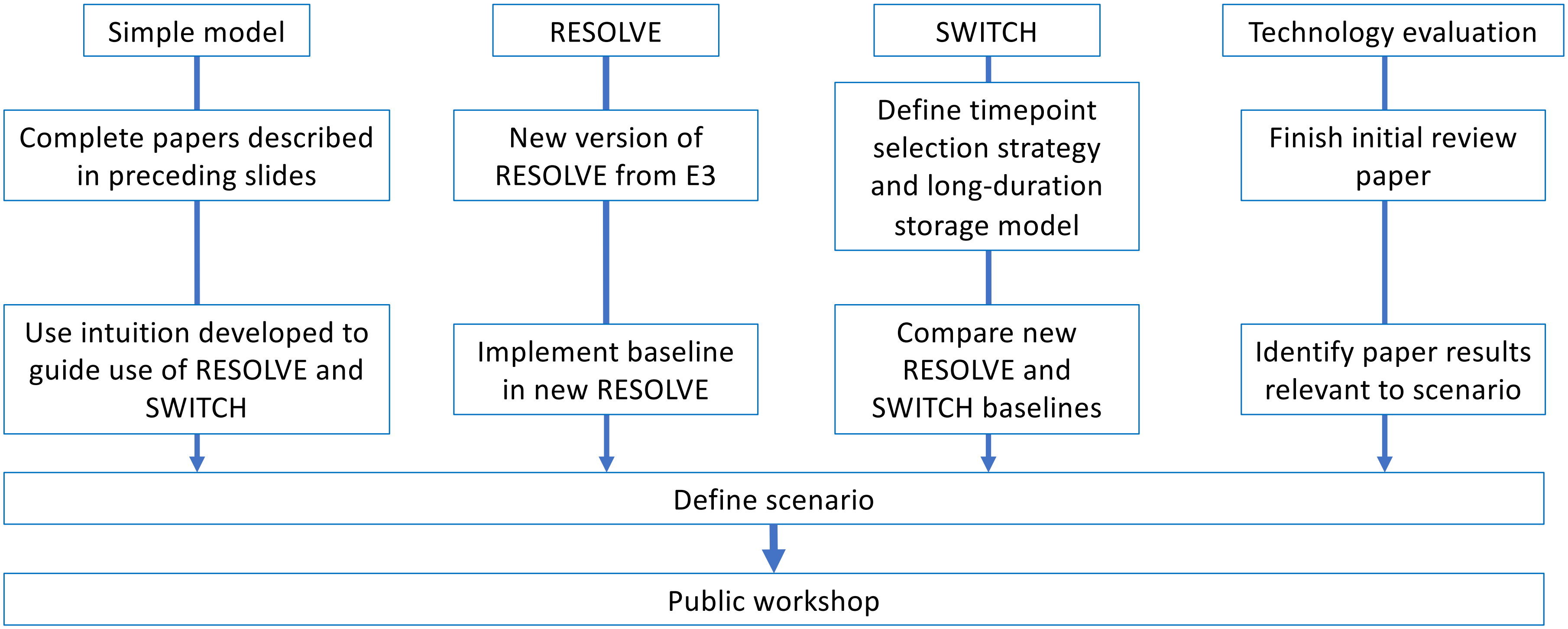
- Pumped storage hydropower
- Other gravity-based solutions
- Compressed air energy storage
- Liquid air storage
- Thermal energy storage
- Flow batteries
- Power to gas

Rui Shan

Jeremiah Reagan

Manuscript is being developed under guidance by Noah Kittner

Plans



Simple model

Complete papers described in preceding slides

Use intuition developed to guide use of RESOLVE and SWITCH

RESOLVE

New version of RESOLVE from E3

Implement baseline in new RESOLVE

SWITCH

Define timepoint selection strategy and long-duration storage model

Compare new RESOLVE and SWITCH baselines

Technology evaluation

Finish initial review paper

Identify paper results relevant to scenario

Define scenario

Public workshop

Challenges and Opportunities
Questions to consider

- The challenge that the revised version of RESOLVE is not yet ready is an opportunity for orthogonal, but useful explorations
- The challenge of defining practical limits for each technology is an opportunity to explore which would be most useful

Questions:

- Target “California”? Include imports?
- Target zero emissions in 2045? For California? For WECC?
- Best way to add carbon sequestration (*e.g*. add hardware cost or carbon price)

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For more information:
https://www.energy.ca.gov/event/workshop/2020-12/staff-workshop-initial-public-workshop-comments-long-duration-energy-storage

We welcome collaboration:
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Dan Kammen – UC Berkeley (kammen@berkeley.edu)
Noah Kittner – U North Carolina (kittner@unc.edu)
Patricia Hidalgo-Gonzales – UC San Diego (phidalgogonzalez@eng.ucsd.edu)
Sergio Castellanos-Rodriguez – UT Austin (sergioc@utexas.edu)

Thank you for your attention!

Special thanks to the California Energy Commission for supporting this project