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California's approach to decarbonizing the electricity sector and the role of dispatchable, low-carbon technologies

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ABSTRACT

California's Senate Bill 100 establishes a goal to reach a zero-carbon grid by 2045, which opens the door for currently available low-carbon, dispatchable energy sources to contribute to California's decarbonization. This study utilizes a detailed capacity expansion and dispatch model of California to assess the role that low-carbon, dispatchable resources can have for California's energy future. The results show that including dispatchable, low carbon resources result in a significantly cheaper decarbonized system. In addition, leaving the optionality for more resources provides less uncertainty for future energy systems costs across varying technology cost estimates, weather patterns, and operational constraints. While California's 2045 zero-carbon grid policy establishes a strong premise for optionality, other regulatory updates will be necessary to deploy low-carbon, dispatchable resources efficiently.

Introduction

Deep decarbonization of electricity systems will be critical in meeting the goal set out by the Paris Climate Agreement of 2015 to hold average global temperature increase to 2°C (IPCC, 2014; Larson et al., 2020; Wei et al., 2013; Williams et al., 2021,Williams et al., 2012). Electricity systems undergoing deep decarbonization will experience drastic transformation, and there is a large level of uncertainty about how to cost-effectively achieve a 100% carbon free grid while maintaining the level of reliability and power quality in the US as of today. California has long been a leader in energy policy and has committed itself to meeting the 2°C goal as set out by the Paris Agreement. It is the fifth largest economy in the world, and its decarbonization pathway will provide invaluable lessons for other regions committed to deep decarbonization of the power sector. As part of its efforts, California recently passed Senate Bill 100 (SB100) (State of California, 2018), which sets a 60% Renewable Portfolio Standard (RPS) goal by 2030, and a goal for 100 percent of total retail sales of electricity in California to come from eligible renewable energy resources and zero-carbon resources by 2045. The new legislation is a break from previous California energy policy which was largely driven by RPS goals. Relative to the RPS, the standard for allowable resources to meet the 2045 goal is more encompassing and includes certified renewable energy sources as well as zero-carbon resources.

Energy system models have become indispensable in informing future policies and exploring cost-optimal pathways to reduce emissions from the electricity sector (Pfenninger et al., 2014). Models that combine capacity expansion and economic dispatch in particular have been used for their ability to consider not only the capital costs for developing different technologies, but also their ability to simulate detailed time-scale dynamics (Gacitua et al., 2018). Due to increases in the use of behind-the-meter power generation and increases in supply of electricity from variable renewable generation, matching supply and demand has become more complex (Tarroja et al., 2012). System operations must account for the changing temporal intermittency of variable renewable resources, more dynamic and changing loads, operational constraints of thermal resources, transmission constraints, and the spatial distribution of load and generation.

With the drastically decreasing costs of intermittent renewable generation sources such as wind and solar, and declining costs for grid-scale storage with Li-ion batteries (Feldman et al., 2021), many studies have utilized capacity expansion and economic dispatch models to assess achieving deep decarbonization with high levels of variable renewable resources (Bistline, 2017; Després et al., 2017; Dowling et al.,

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2020; Frew et al., 2016; Heuberger and Mac Dowell, 2018; Mileva et al., 2016; Sepulveda et al., 2021; Zappa et al., 2019; Heuberger et al., 2017a). The studies have found that while short-term intermittency can be mitigated with batteries or transmission expansion, seasonal variability, high-levels of curtailment, and balancing needs are still likely going to be a significant challenge (Després et al., 2017; Frew et al., 2016; Heuberger and Mac Dowell, 2018; Mileva et al., 2016). Complementing variable renewable generation sources with dispatchable, low-carbon resources such as biomass, geothermal, nuclear, and gas power plants with carbon capture and storage (CCS) have been shown to provide a lower cost pathway to deep decarbonization (Baik et al., 2021; Brick and Thernstrom, 2016; Heuberger et al., 2017b, 2017a; Nelson et al., 2012; Sepulveda et al., 2018; Sithole et al., 2016; Yuan et al., 2020).

Despite the value of these resources, California has just begun including dispatchable, low-carbon generation technologies in its resource mix for state-level analyses (California Energy Commission, 2019). Even so, the dispatchable, low-carbon resources considered in state-level analyses are modeled as representative technologies without concrete indication of the types of technologies that would fill such a role. Baik et al. (2021) has highlighted the distinct operations of various dispatchable, low-carbon resources, which emphasize the need to better understand the implications of different clean, dispatchable technologies in California's energy future (Baik et al., 2021).

This analysis aims to inform California's future energy policy by providing a detailed picture of the role of two different types of clean, dispatchable resource: gas with carbon capture and storage and nuclear power. This study utilizes a capacity expansion and economic dispatch model that comprehensively encompasses many different technologies, simulates all hours of the year, and models multiple regions with transmission constraints. The analysis provides a detailed look into the operation of the resources as well as sensitivity of the system to different assumptions for the modeled resources, which have previously not been explored for California. By providing a range of cost and capacity estimates of generating and energy storage resources that would be needed to meet California's SB100 goals, we hope to inform the policies that would be needed to facilitate the transition in a timely manner.

Material and methods

The analysis is conducted using *urbs*, which is an open-source, linear optimization model that co-optimizes capacity expansion and hourly operation of various generation, storage, and transmission units Dorfner, 2017 . The California electricity grid is modeled as ten regions linked via intrastate transmission lines, and four additional regions outside of California are modeled to incorporate imports of electricity and renewable resources from other states. Demand outside of California is not modeled, and the out-of-state regions in the model are abstract representations of the energy mix outside of California, modeled as potential capacity that can be directly imported to California. The model represents the California Independent System Operator (CAISO) balancing area, and the energy mix outside of California is validated against historical CAISO imports, and the California model as a whole is validated with CAISO's historical 2016 generation, weather patterns, and demand needs. Results of the model validation exercise can be found in the Supplementary Information Section 9.

As of 2018, CAISO's energy mix consisted of 30% gas 10% hydro, 22% net imports, and 26% renewables, nearly half of which consisted of solar and 30% of which consisted of wind (California Independent System Operator, 2017). Note that this analysis utilizes the same definition of certified renewables as California. Resources considered renewable include PV, wind, biomass, geothermal, and small hydro ($<$ 30 MW). The model builds upon the existing generation resource capacities as of 2017. Each region has a mix of generation and storage capacities, as well as a unique load profile, and renewable resource potentials. Transmission between each region is modeled and limited by historically existing transmission capacity, with the option to expand the transmission system if needed. The entire year is modeled in hourly time steps, capturing all the variability and extremes that exist in weather and load conditions in a given year.

In 2018, CAISO's load was approximately 226 TWh with a peak load of 46 GW (California Independent System Operator, 2019). The demand profile in the future is projected to change largely due to the increase in electric vehicles (EV) (California Energy Commission, 2018a) that will increase the net load demand, as well as the increase in distributed energy sources (Kavalec et al., 2018) that will decrease the net load demand. The net energy demand is posed to increase by 11% from 2018 to 2030 reaching 255 TWh and the peak load to increase to 52 GW in 2030 (California Energy Commission, 2018b; Kavalec et al., 2018; McCarthy et al., 2006). Further growth in vehicle electrification and distributed generation is projected to 2045 with the load reaching 311 TWh (36% growth relative to 2018) and the peak reaching 65 GW. Further information on the model and assumptions can be found in the Supplemental Information and the GitHub page with the urbs open source code.

The analysis will first assess meeting California's 2030 60% RPS goals, then assess the 2045 energy system which utilizes California's 2030 60% RPS grid as a starting point. Relative to 2030, a wider range of technologies including gas power plants with carbon capture and storage (CCS), biomass power plants with carbon capture and storage (BECCS), and nuclear energy are considered in the long-term for meeting the 2045 zero-carbon power system goal. The No Dispatchable Scenario allows existing dispatchable technology to exist, but no new expansion of CCS or nuclear technologies. Table 1 summarizes the various scenarios that are considered in this analysis.

Capital cost and financing assumptions for technologies are taken from NREL's 2018 Annual Technology Basis and can be found in Table 2 NREL (National Renewable Energy Laboratory) 2018. NREL's ATB is a comprehensive dataset of U.S. based technology costs that is widely used by federal agencies, grid operators, and academics alike (Vimmerstedt et al., 2020). Three different levels of cost estimates are provided for each technology, and the medium assumption is taken in this analysis. Low and high technology costs are considered in the sensitivity analysis as well. Note for utility-scale PV in particular, NREL ATB assumes a learning curve, with capital costs in 2045 reaching 65% of the capital cost relative to 2018.

Battery power and energy cost components are applied separately

Table 1
Summary of scenarios. Emissions reduction level policies for the electricity sector for 2045 are relative to the Reference scenario in 2045. Policies noted with SB100 are policies compliant with SB100.

2030		2045	
Scenario Name	Policy	Scenario Name	Policy
Reference 60% RPS	*·No Policy* *·SB100 - 60% Renewable Portfolio Standard*	Reference No Dispatchable	*·No Policy* *·50% Emissions Reduction* *·75% Emissions Reduction* *·SB100 - 100% Emissions Reduction*
		Dispatchable (CCS)	*·50% Emissions Reduction* *·75% Emissions Reduction* *·SB100 - 100% Emissions Reduction*
		Dispatchable (Nuclear)	*·50% Emissions Reduction* *·75% Emissions Reduction* *·SB100 - 100% Emissions Reduction*

Table 2
Average 2030–2045 costs of key generating technologies taken from NREL's Annual Technology Basis (2018) (NREL (National Renewable Energy Laboratory), 2018).

		Low Cost Scenario	Reference Scenario	High Cost Scenario
Gas power plant w/ post-combustion CCS (90% Capture)	Capital Costs (retrofit)	–	$1840/kW ($1030/kW)	$2320/kW ($1510/ kW)
	Ramping Constraint (/hr)	–	0.60	0.60
Nuclear power plant	Capital Costs	–	$5200/kW	$7800/kW
	Ramping Constraint (/hr)	–	0.02	0.02
Geothermal	Capital Costs	–	$5370/kW	
Solar	Capital Costs	$520/kW	$760/kW	–
Onshore Wind	Capital Costs	$710/kW	$1380/kW	–
Offshore Wind	Capital Costs		$3200/kW	
Li-ion Battery	Capital Costs	$110/kW $90/kWh	$150/kW $170/kWh	–
Gas Prices	Fuel Cost	$3.3/ 1000cf	$5.9/1000cf	$9.7/ 1000cf

such that battery duration (energy-to-power ratio) is optimized to best fit the system needs. All CCS power plants in the analysis are assumed to be retrofits of existing NGCC power plants in California with 90% capture. In 2045 scenarios reaching net-zero emissions, the residual emissions from CCS power plants are offset by negative emissions from retrofitting existing biomass power plants in California with carbon capture as well. Planned retirement of Diablo Canyon nuclear plant and all coal-fired power plants in California were considered included in the assumptions. More detailed assumptions of the technologies modeled can be found in the Supplementary Information.

Results

2030. Scenarios

The reference scenario for 2030 builds upon the existing energy system as of 2017, and is a scenario that represents the lowest cost pathway to meeting future load growth without any emission constraint present other than an implied carbon tax of $52/ton from California's cap-and-trade market in 2030 (Borenstein et al., 2017). The 2030 reference scenario result shows that only additional capacities of utility-scale PV and Li-ion batteries are needed beyond 2018 to meet future load growth cost-effectively, and the system reaches a 40% renewable generation share.

Relative to the 2030 reference scenario, the 2030 60% RPS scenario requires more PV and Li-ion battery capacity to ensure meeting the RPS requirement, but no additional gas generation. Due to the limited potential of in-state wind (Wu et al., 2019), and limited access to out-of-state resources which are capped by California's RPS policy definition (California Public Utilities Commission, 2019a), the majority of renewable generation built in California to meet the 60% RPS consists of in-state utility-scale PV, and Li-ion batteries. To meet the 60% RPS, California will have to build approximately 29 GW of solar in addition to the 11 GW that exist in 2018 (California Independent System Operator, 2020), as well as reach a total of 10 GW of utility-scale Li-ion battery capacity with an average duration of seven hours. Similarly, the 60% RPS scenario requires nearly six times as much energy storage capacity and three times as much power capacity from storage. Despite the additional capacity needed to meet the 60% RPS goal relative to the 2030 Reference scenario, the overall cost of achieving a 60% RPS is less than ¢1/kWh more expensive than the Reference scenario, indicating that meeting California's 60% RPS goal can be done cost-effectively with continued development of PV and Li-ion battery resources in-state.

2045. Scenarios

The 2030 60% RPS policy mandate serves as the starting point for the 2045 scenarios. For the power system in 2045, a wider range of technologies including gas power plants with carbon capture and storage (CCS), biomass power plants with carbon capture and storage (BECCS), and nuclear energy are considered. Technologies currently under development such as longer duration Li-ion battery storage and deep-water floating offshore wind are also considered to be available in 2045. Between 2030 and 2045, PV and battery costs are assumed to have further decreased, while capital costs for dispatchable, low carbon technologies such as CCS, geothermal, and nuclear remain costly on a per kW basis relative to solar and battery resources NREL (National Renewable Energy Laboratory) 2018. The operational and capital cost assumptions for the different 2045 scenarios are summarized in Table 2.

The ramping constraint in Table 2 indicates the fraction of the total capacity that can ramp up or down on an hourly basis, and represents the flexibility of the resource within the grid. Existing dynamic experimental data from pilot-scale solvent-based CCS plants indicates that flexible operation of CCS plants is possible by optimizing plant operation (Gaspar et al., 2016; International CCS Knowledge, 2018; Rúa et al., 2020; Tait et al., 2016). Nuclear is assumed to be less flexible based on historic operation of nuclear in the Northwestern US which operates at base-load but ramps generation on a seasonal basis (EPRI, 2018). This analysis chooses representative ramp rates to showcase two different types of dispatchable technologies, but also considers sensitivity cases with varying flexibility of dispatchable resources.

The 2045 Reference Scenario builds upon a 2030 60% RPS scenario. With sufficient existing gas capacity and newly built PV capacity in 2030, no significant new resources are needed to meet the load effectively in 2045 relative to the 2030 60% RPS scenario. Only an additional 7 GW (13 GWh) of Li-ion battery capacity is needed and as a result, approximately 48 million tons of CO_2 is emitted in the reference scenario. In addition to the reference scenario, three main scenarios for 2045 are considered: 1) No Dispatchable power, 2) Flexible dispatchable power using carbon capture and storage (which includes CCS and BECCS), and 3) Inflexible dispatchable power (Nuclear).

The No Dispatchable Scenario shows the highest capacity build across all three scenarios, where a total of 92 GW of solar and 16 GW of deep offshore wind power plants would be needed by 2045. In a sensitivity scenario without the development of offshore wind, a total of 159 GW of solar capacity would be needed by 2045. The No Dispatchable Scenario also requires 45 GW of an average 11-hour duration of battery capacity beyond 2030 to support a system with zero emissions and renewable resources. 11-hour duration batteries are currently not commercialized in the market place and would require additional maturing for deployment at the costs modeled here. Scaling battery, solar, and offshore deep-water wind generation capacity to reach levels needed under a No Dispatchable Scenario by 2045 would require significant development in the coming years. Furthermore, even with the large amount of batteries built to absorb over-generated energy from intermittent resources, approximately 50 TWh, or 22% of the total solar resources generated is curtailed in 2045. On the other hand, for the Dispatchable (CCS) scenario, building 13 GW of CCS and 0.4 GW of BECCS results in only 47 GW of utility-scale PV and 28 GW of 8-hour duration Li-ion battery storage. Similarly, the Dispatchable (Nuclear) scenario results in 20 GW of new nuclear capacity, and 39 GW of utility-scale PV and 26 GW of 7-hour duration Li-ion battery storage.

Fig. 1.

The average daily generation profiles for the three scenarios are illustrated in Fig. 2(A). For comparison, we also show two other cases for each scenario corresponding to 50% and 75% emissions reductions. For the 50% emissions reduction scenario, there is nearly no CCS or nuclear capacity built, indicating that reducing emissions and meeting load with utility-scale PV and battery is cost-optimal. However, at 75% emissions reduction, small capacities of less than 10 GW of CCS and nuclear

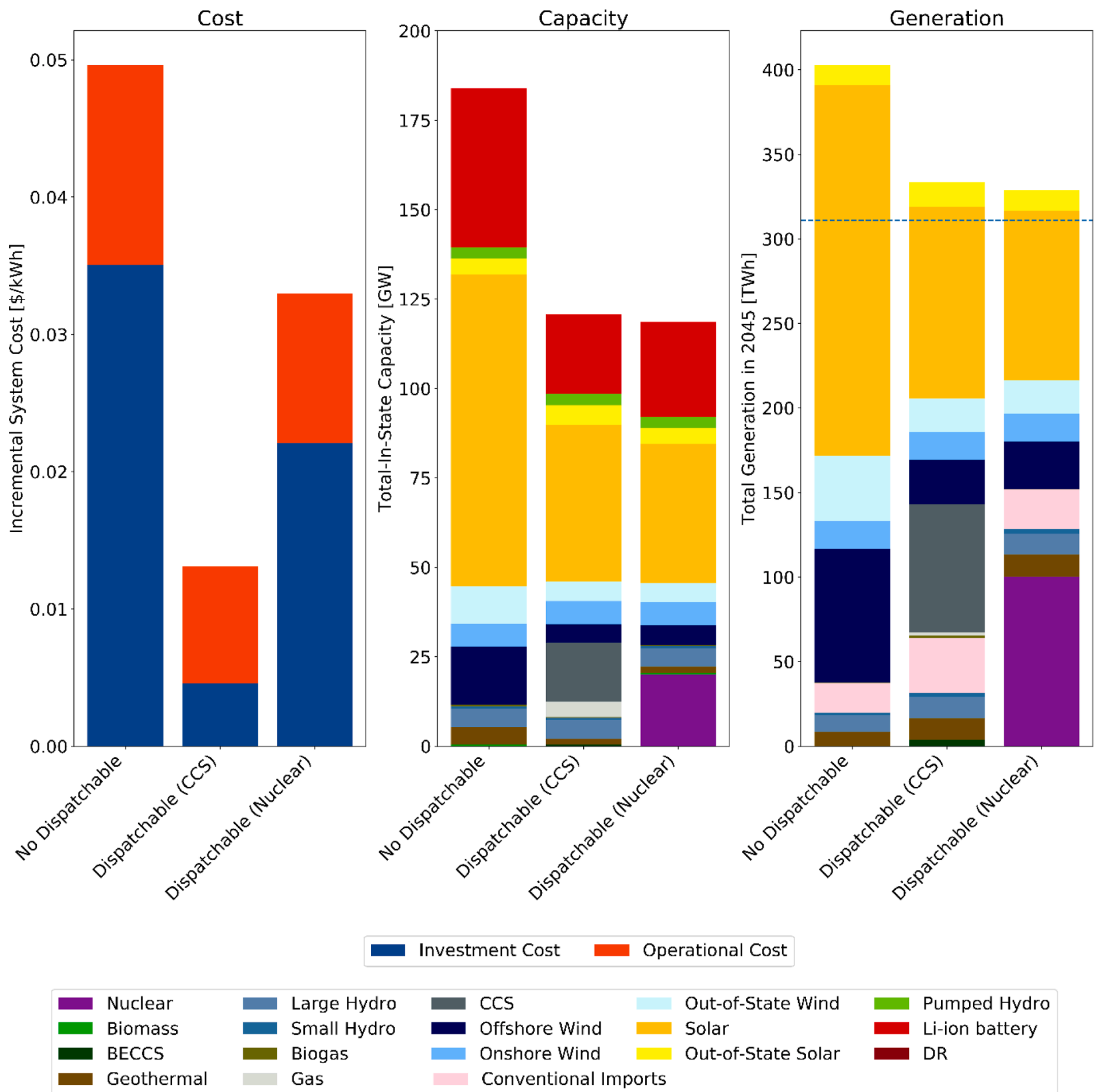

Fig. 1. Summary of the incremental system cost, capacity build, and generation of the 2045 100% Emissions Reduction for No Dispatchable, Dispatchable (CCS), and Dispatchable (Nuclear) Scenarios. The incremental system cost is relative to the 2045 Reference Scenario.

become cost-effective despite their higher capital cost, and are built instead of PV and Li-ion batteries. This is even more apparent at the 100% emissions reduction levels scenario that is compliant with California's SB100 goals, in which there is a large overbuild of PV and storage resources in the No Dispatchable Scenario, but moderate capacities of CCS and nuclear built in the Dispatchable scenarios instead.

To meet increasing levels of emissions reduction without any dispatchable resources, significant portions of conventional generation sources, often operating at night time in California, will have to be generated with intermittent resources. Given the limit of wind resources in California, there has to be enough solar generation and battery storage to serve nighttime demand reliably throughout the year. The PV generation should also cover the demand during early mornings and evenings when the sun is rising or setting. Finally, the total capacity of combined solar and battery resources need to meet the peak load despite seasonal mismatches. However, due to the diurnal nature of PV, as PV capacity in the system increases, PV's contribution in meeting the load decreases. As a result, even with significant PV capacity of 92 GW, only 40% of the load can be met directly with PV (Fig. 2(B)). For all these reasons, there must be a significant overbuild of solar generation, evident by the as amount of curtailment during the day (Fig. 2(A)).

The Dispatchable scenarios show that relatively small capacities of dispatchable technologies can replace a significant amount of solar and battery capacity and reach the same emissions levels because the capacities are not seasonally constrained. Consequently, including a dispatchable, low-carbon technology within the generation mix drastically decreases the total system capacity built and reduces over-generation.

Nuclear and CCS are both dispatchable technologies but have very different operating characteristics and cost components. Overall, nuclear has a large capital cost and low variable cost, while CCS has a relatively low capital cost and high variable costs. This difference is evident in comparing the generation profiles for CCS and nuclear in the two dispatchable scenarios (Fig. 3). On a daily and weekly basis, CCS ramps diurnally and adjusts its generation output with solar, while nuclear operates as a base-load and helps decrease the overall load need to be met by PV and storage. On an annual basis, nuclear operates largely during the winter time and remains idle or at low capacity factors during the spring and summer seasons. In both cases, the annual capacity factor

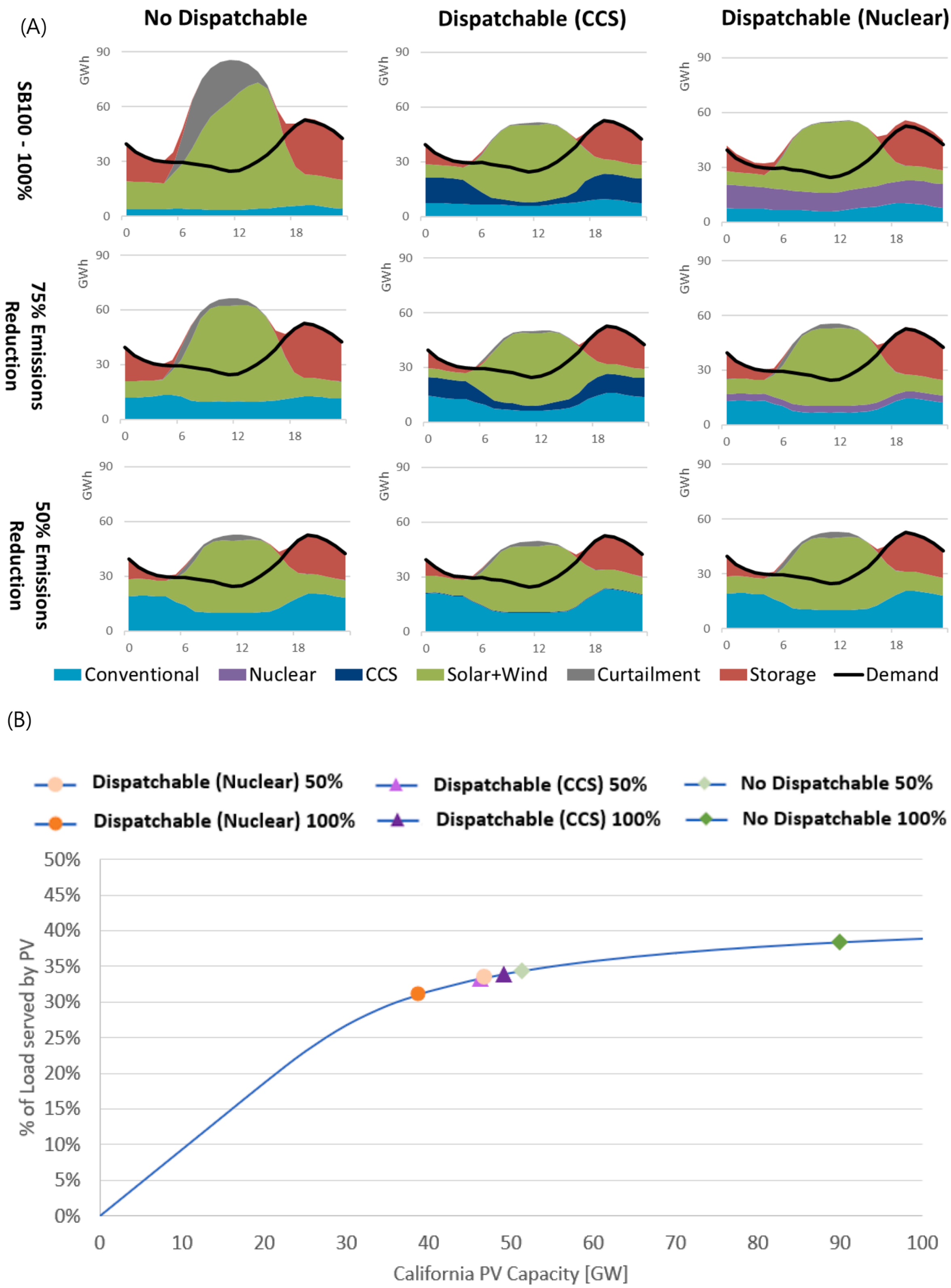

Fig. 2. (A) Average daily generation profiles of varying CO_2 emissions reduction scenarios in 2045 for the No Dispatchable, Dispatchable (CCS), and Dispatchable (Nuclear) Scenarios. Conventional resources include large and small hydro, geothermal, biomass, biogas, and gas power plant generation. (B) Curve showing the decreasing marginal contribution to load in the system from increasing PV capacity for the 100% and 50% emissions reduction scenarios. Even with the significant build of PV in the No Dispatchable 100% emissions reduction scenario, only approximately 40% of the load can be met directly with PV, indicating that the rest of the PV generation has to be stored or curtailed. This implies that PV is underutilized in the No Dispatchable scenario relative to the Dispatchable scenarios, and explains the high level of curtailment in Fig. 2(A). The No Dispatchable scenario also shows the most drastic increase in PV capacity between the 50% and 100% emissions reduction scenarios, illustrating the overbuild of PV resources in achieving 100% emissions reduction. Curve was calculated by scaling PV generation in California and graphing the corresponding incline in percentage of load directly met with increasing PV generation.

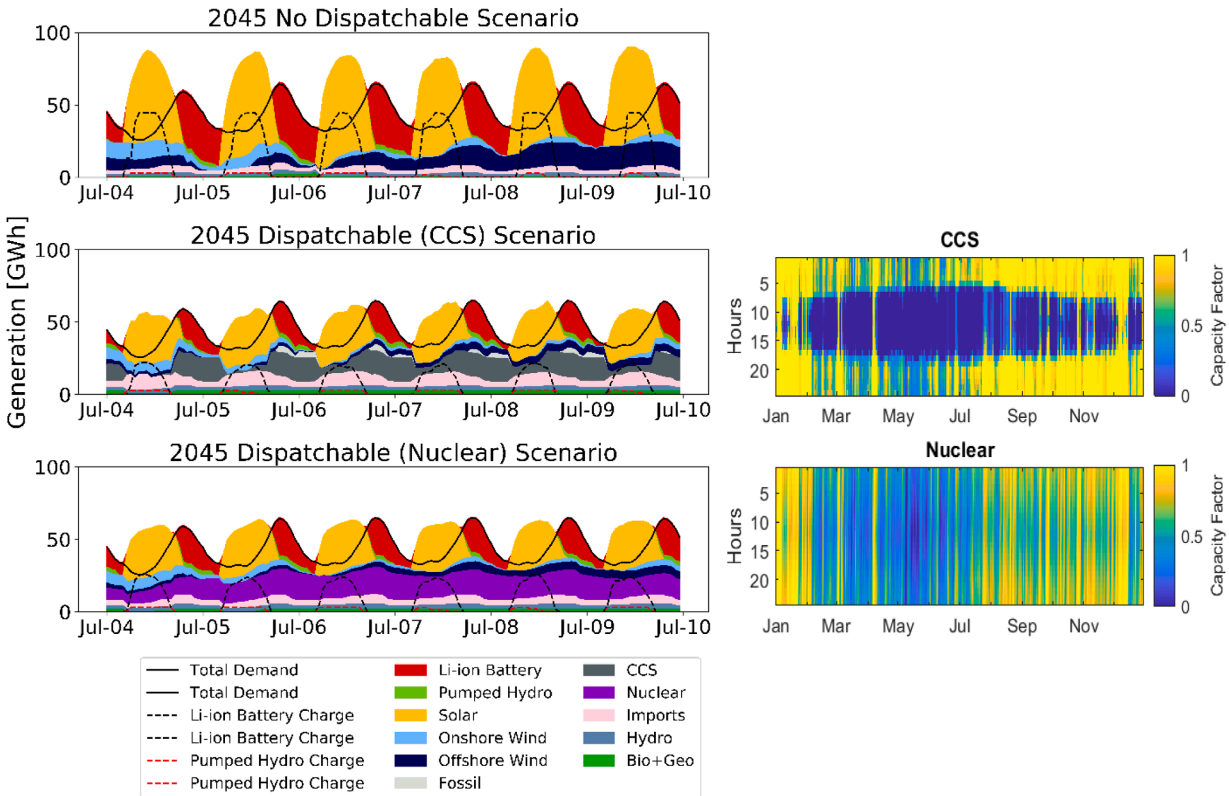

Fig. 3. Weekly generation patterns for a summer week in 2045 for No Dispatchable, Dispatchable (CCS), and Dispatchable (Nuclear) Scenarios for 100% emissions reduction, and associated seasonal and daily variation in generation of CCS and nuclear.

for the resources are around 50–60%.

The total system cost consists of the annualized investment cost of new capacity built and the annual operational costs, which include the fixed and variable O&M in dispatching resources. Despite the low capital cost of solar and battery resources, the sheer amount of capacity needed to provide the required power demand over the course of the entire year in the No Dispatchable scenario drives a higher system cost. Including low-carbon dispatchable resources that have higher capital costs reduces

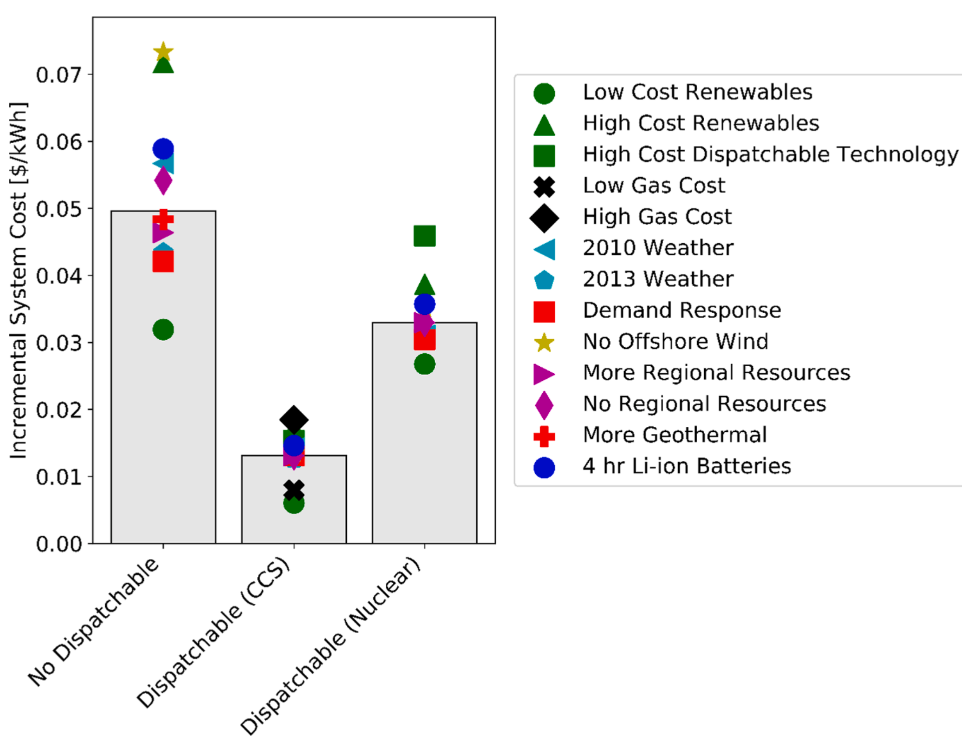

Fig. 4. Sensitivities for 2045 No Dispatchable, Dispatchable (CCS), Dispatchable (Nuclear) for 100% emissions reductions.

the overall system cost of achieving a zero-carbon grid significantly compared to the No Dispatchable approach. While PV and Li-ion battery reach grid parity and are cost-effective generation technologies, reaching 100% carbon free grid with only those resources results in a system that is \$0.05/kWh more expensive relative to the reference scenarios, which is nearly twice as costly as the scenarios with dispatchable technologies. The difference in costs between the dispatchable scenario translates to \$5–11 billion annually. Given that California's current state-wide revenue requirement for investor-owned electric utilities is approximately \$30 billion/year (California Public Utilities Commission, 2019b), \$5–10 billion/year in savings may have tangible impacts on electricity rates in the future. This emphasizes the value that dispatchable, low-carbon resources such as CCS or nuclear can have in achieving a deeply decarbonized grid.

Sensitivity to model assumptions

A sensitivity analysis is conducted to test the robustness of these conclusions subject to uncertainty in model inputs (e.g. costs) or constraints (e.g. battery duration). Uncertainties surrounding future energy systems involve electricity loads and weather pattern, costs of technologies, battery duration, and resource availability. The demand response scenario includes 6 GW of load shedding at \$200/kW to build capacity and \$600/MWh to operate. The result of the sensitivity analysis on incremental system costs are shown in Fig. 4. Overall, across all the sensitivities, the No Dispatchable Scenario demonstrated a wider span of variability than the Dispatchable Scenarios. The uncertainty for the No Dispatchable case spanned \$13 billion/year (\$0.042/kWh), while the uncertainty of costs only spanned \$5–6 billion/year (\$0.016–\$0.019/kWh) for Dispatchable scenarios. The span of uncertainty indicates that building a future energy system without dispatchable energy sources may require significantly more or less capacity than is expected depending on future load and weather patterns. The uncertainty of capacity needed creates risks that result in either stranded assets or conversely, even higher costs. Furthermore, the costs of generating technologies have a much larger impact on the results of scenarios without dispatchable resources, due to the significant capacity build that drives the overall systems costs. With future technology costs remaining uncertain, limiting decarbonization efforts to resources that require significant capacity build exposes ratepayers to risks of unrealized cost abatement expectations. The small variability in results of systems including dispatchable resources reflect a more robust system in light of uncertainty. Furthermore, the low-cost renewable scenarios have the biggest benefit when deployed in the cases that also include dispatchable resources, in particular, the case with CCS. This implies that decreasing costs of renewable resources can be developed in parallel with dispatchable resources to achieve the most cost-effective decarbonized grid. Opening the system to a larger set of low carbon technologies results in a more flexible system that can better withstand future uncertainties.

The benefits of having a variety of generation resources is also reflected in leaving the option open for more resources outside of California, and in particular, wind from the Northwest US and PV from the Southwest US. Allowing more resources to be built out-of-state to serve California's electricity requirements results in less overbuild of solar and battery resources in-state due to access to generation patterns that are diurnally and seasonally complementary to California's (Naughton, 2015) (Supplementary Info). While a wider geographic region can help reduce challenges with intermittencies, doing so does not negate the need for a dispatchable low-carbon resource.

Impact of flexibility of dispatchable, low-carbon resources

Sensitivities on the flexibility of both dispatchable technologies are also considered to account for potential development or limitations that might occur in operational behavior of dispatchable resources in the grid. The inflexible cases for both technologies reflect a 2%/hour ramp limit, while the flexible cases reflect a 60%/hour ramp limit. The operating behavior of flexible and inflexible dispatchable resources are relatively consistent regardless of the dispatchable technology. Flexible resources operate diurnally at approximately 52% annual capacity factor, while the inflexible resources operate on a seasonal basis at an annual capacity factor of 57% (Fig. 5(A)). Furthermore, the flexibility of the dispatchable resources do not significantly impact the results of the analysis. The overall capacity, and generation shares of dispatchable resources are relatively consistent and the costs between scenarios that are flexible and inflexible vary by less than \$0.01/kWh (Fig. 5(B)). However, the cost and capacity differential between the inflexible and flexible case is larger for CCS, largely attributable to the fact that CCS has lower capital costs and higher variable costs relative to nuclear. More CCS capacity is able to be built at a lower cost relative to nuclear, and with flexibility, operates its high variable cost power plants more sparingly. On the other hand, due to high capital costs, the cost-effective capacity of nuclear is consistent regardless of its flexibility, and has less impact on the overall system costs. While the feasible extent of flexibility of dispatchable resources are still uncertain, this analysis shows that the flexibility of the resources does not significantly impact the value of the dispatchable resources to the grid. The results also highlight that the value of flexibility may be more pronounced for dispatchable resources lower capital and higher variable costs.

Discussion

Decarbonization efforts in California have so far been extremely successful through building solar and wind resources under the Renewable Portfolio Standards. In 2016, the electricity sector achieved a 38% reduction of emissions relative to 1990 emission levels (California Energy Commission, 2017), and future efforts to decarbonize the grid may have an even larger impact as California moves to electrify its transportation and building sectors. However, this analysis shows that maintaining the RPS pathway to reach 100% carbon-free grid may be costly and more uncertain than pathways that include other zero-emission technologies. In 2045, the grid without any dispatchable resources consistent with a 100% RPS scenario, resulted in a system that was \$11 billion / year or ¢4/kWh more expensive than a system with a dispatchable resources. Given the fact that California's 2018 average electricity cost across all sectors was ¢16.40/kWh (EIA, 2019), a ¢ 4/kWh increase, which is nearly a 25% increase from 2018 prices, may have significant implications in a state with already high electricity prices. Furthermore, recent analyses have highlighted the challenges of operating a grid with high shares of intermittent renewable resources due to an increase in frequency volatility (Homan et al., 2021). On the other hand, having a variety of generation resources greatly decreases the uncertainty and risks in meeting the decarbonization goals.

In Dispatchable Scenarios, solar and battery resources still play a dominant role in the electricity system. The 2045 Dispatchable (CCS) scenario reaches a 85% RPS (excluding large hydro), beyond the 60% RPS as mandated in 2030. Due to the expected price decreases in both solar and battery storage technologies, they are cost-effective zero-carbon technologies that play critical roles in achieving deep decarbonization. This analysis demonstrates that dispatchable resources work complementary to solar, battery, and wind resources, largely filling the gaps during times when intermittent renewable generation is low relative to load. The role of dispatchable resources could be further amplified in regions without as diverse and ample renewable resources as in California.

For scenarios without dispatchable resources, significantly more capacities of solar and battery resources are needed, which present challenges in rapid expansion rates and possible land use issues. Across the sensitivities, scenarios without dispatchable resources needed 69–159 GW of solar capacity by 2045 to meet SB100, implying that on average, 2.3–5.9 GW of solar PV would need to be added annually from

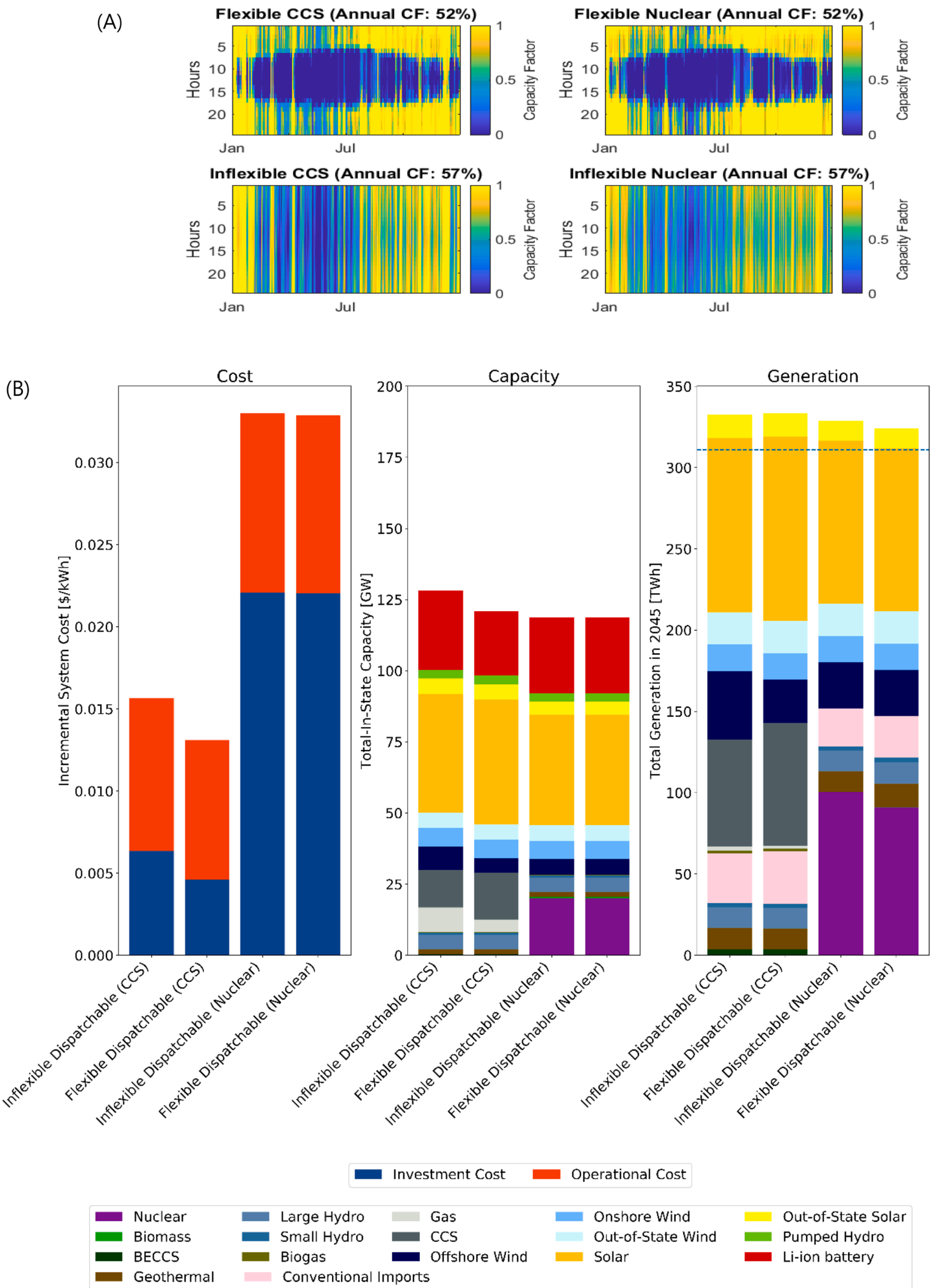

Fig. 5. (A) Seasonal and daily variation in generation of both flexible and inflexible CCS and nuclear (B) Summary of the incremental system cost, capacity build, and generation of the 2045 Dispatchable (CCS), and Dispatchable (Nuclear) Scenarios for both flexible and inflexible cases. The incremental system cost is relative to the 2045 Reference Scenario.

2020 to 2045. The maximum historical annual capacity growth of solar PV in California was 2.7 GW between 2015 and 2016 (California Energy Commission, 2020). The scale of development of solar that would be needed may not be infeasible, but will require maintaining maximum historical rates of solar PV build each year. For scenarios without any dispatchable resources, the need for Li-ion battery capacity is also significant and ranges from 37 to 70 GW with an average duration of 10–14 h. Without longer duration battery resources, there would need to be 109 GW of 4-hour duration Li-ion battery capacity in the No Dispatchable scenario. As a reference, the current scale of li-ion battery manufacturing capacity in the U.S. is approximately 59 GWh (Federal Consortium for Advanced Batteries, 2021). Scaling Li-ion battery capacity from California's current procured level of 1.5 GW (California Energy Commission, 2018c) to reach 37–70 GW needed in the No Dispatchable scenarios will require unprecedented rates of Li-ion battery growth at an average of 3–6 GW per year. In scenarios without any low-carbon dispatchable resources, over 0.7–1.2 million acres of land would need to be utilized to accommodate the 69–159 GW solar capacity needed (Ong et al., 2013). While the cumulative solar area needed is within the capacity of California's land area compatible for solar development, siting the utility-scale power plants without exacerbating environmental tradeoffs will be a challenge (Hernandez et al., 2016).

Scenarios with dispatchable resources also indicate the need for new capacity growth for dispatchable technologies as well. Capacities of the dispatchable technologies needed to reach the zero-carbon grid goal are each on the scale of 3–26 GW for CCS, 20 GW for nuclear, and 10 GW for geothermal. The dispatchable technologies considered in this analysis, including CCS, nuclear, and geothermal, are resources that have not been previously developed in California or have been steadily retiring due to political barriers, public opposition and opinions, and profitability of the power plants. For nuclear in particular, the barrier for deployment is steep, given that California currently has a moratorium for new reactors until a solution to radioactive waste disposal is in place. Facilitating the development of these technology will require California to reconsider related regulations and help pave the pathway to deploying these technologies. There are also a number of breakthrough technologies that can help California meets its decarbonization goals, including long-term seasonal energy storage, hydrogen fuel, or direct air capture and storage of CO_2. However, studies have shown that delayed deployment of existing low-carbon technologies in anticipation of breakthrough technologies may result in oversized and underutilized power systems or systems that are not able to decarbonize intime when the breakthrough technology does not materialize (Heuberger et al., 2018). While breakthrough technologies can be important and further enhance the optionality that California has in meeting future decarbonization goals, California should focus on currently deployable dispatchable resources that will result in cost-effective decarbonization of its power sector. Furthermore, while this analysis focuses on California, the value and role of dispatchable, clean resources shown in this analysis can be applied to broader regions that have similar climates and resource availability as California. Regions such as Spain, Chile, and Portugal also have Mediterranean climate, combined with large solar availability. As global nations strive to decarbonize its power sector, the value of clean, dispatchable resources can be broadly.

Conclusion

This analysis has shown that including low carbon, dispatchable, resources in energy systems provide a significantly more cost-effective pathway for California in meeting its grid decarbonization goals. While solar, wind, and battery resources still play a significant role in decarbonization, including more options greatly reduce variability in face of various uncertainties. The zero-carbon grid goals as established by SB100 establishes a great premise in opening optionality in California's energy future, but more regulatory effort will be needed to ensure efficient deployment of new resources. While this analysis focuses on California, the broader conclusions are applicable to other energy systems and especially more so to regions without cheap and abundant renewable resources available. California represents less than 1% of the world's total emissions, but being able to cost-effectively decarbonize California's electricity grid will demonstrate the feasibility of such pathways and push technologies down the learning curve for deployment elsewhere.

CAS

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ijggc.2021.103527.

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