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What is different about different net-zero carbon electricity systems?

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ABSTRACT

In deeply decarbonized electricity systems with significant shares of variable renewable energy, the additional availability of *at least one* firm electricity generating technology can overcome reliability challenges and substantially reduce electricity costs. Firm resources can operate at any time of the year and for as long as needed to maintain electricity system reliability. Low- and zero-carbon firm technologies include flexible resources with high variable and low capital costs, such as biogas or hydrogen combustion, capital-intensive resources with low or zero variable cost, including nuclear and geothermal, as well as intermediate resources such as natural gas plants with carbon capture and sequestration (CCS). This paper explains the distinct roles of nuclear, CCS, and combustion of zero-carbon fuels in decarbonized electricity systems as examples of each class of firm resources. We analyze and compare results from three long-term electricity system capacity expansion models for California and the U.S. Western Interconnection, demonstrating robustness of our conclusions to different model assumptions and domains. Individually, each firm technology delivers substantial cost reductions relative to portfolios restricted to wind, solar, and energy storage alone. Additionally, because each technology occupies a distinctive functional niche in the electricity system, having all of these technologies available optimizes the utilization rate of each resource and reduces system costs by up to 10% relative to cases with just one class of firm resource. The analysis highlights the benefits of an expansive range of technology options to meet emissions reductions goals for the power sector while maintaining operational reliability and affordability.

1. Background

An increasing number of states in the US and nations around the world have committed to reaching a net zero carbon economy by 2050. A decarbonized electricity sector is a critical component of reaching a net zero carbon economy [1,2]. Nearly 40% of the global electricity generation was met with coal, and 23% with natural gas, resulting in 13 Gt CO2 emitted from the electricity sector in 2018 [3]. In addition to the need to reduce emissions directly from the electricity sector, decarbonizing other end uses of energy, such as transportation and buildings, will also rely on a clean grid and subsequent electrification of vehicles and buildings. Cost-effective decarbonization of the grid is thus critical to ensure electricity is a cost competitive substitute for fossil fuels in transport, heating, and industry and for reaching a net zero carbon economy affordably [1,2,4].

Among the states and nations making progress towards decarbonizing the economy, California has taken early action and has one of the most aggressive GHG regulations and energy policies in the United States. The state has a statutory commitment to reduce GHG emissions by 40% below 1990 levels by 2030, and a longstanding policy goal of 80% reductions by 2050. An executive order established in 2018 also commits the state to reach carbon neutrality across all sectors by 2050 [5]. In 2018, the California legislature passed SB100: a legally binding target for the electricity sector that requires retail sales in 2045 to be met with renewables energy or other zero carbon resources [6]. The electric sector is expected to play a critical role in meeting California's economy

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wide emissions reduction targets, eventually powering most of California's energy use [7]. Therefore, understanding the portfolio of options available to supply a 100% carbon-free electricity is crucial to enable cost-effective, equitable, reliable, and rapid decarbonization in California and beyond.

Several previous studies have highlighted the operational and economic challenges associated with systems that approach decarbonization of the electricity sector with 100 percent penetration of variable renewable energy sources (e.g. wind and solar power). These studies have established the usefulness of clean firm electricity generation resources to minimize the costs associated with achieving emissions reduction goals [8–15]. Firm zero-carbon electricity generation resources are referred to in the literature with varying terminology such as firm, dispatchable, and non-renewable low carbon resources. This analysis focuses on the definition of clean firm resources as established in Sepulveda et al.[9]. Clean firm resources are "technologies that can be counted on to meet demand when needed in all seasons and over long durations (e.g., weeks or longer)" [9]. These include but are not limited to nuclear, fossil with carbon capture and storage, geothermal, biomass, and biogas or other zero carbon gas fueled power plants.

Most of the previous studies on non-intermittent zero-carbon resources focus either on the economic benefits from the availability of any one of these technologies as a part of a broader electricity generation portfolio, or on the characteristics of individual technologies that improve their provision of grid services [10,16,17]. Sepulveda et al. demonstrated the role and value of the general class of clean firm resources. No study has yet compared the operational performance of different clean firm resources within the context of the same grid or provided a clear techno-economic explanation of the distinctive and complementary roles that various clean firm resources can play in a carbon-free power system. Furthermore, electricity system modeling studies that analyze the role of these technologies as a part of a broad portfolio show additional cost savings in cases where multiple firm technology options are available [18], but few have explored the operational mechanisms responsible for this finding. To address this gap, this paper seeks to explain the distinct roles played by different firm low-carbon generation technologies in decarbonized electricity systems, including nuclear power, natural gas plants with carbon capture and sequestration (CCS), and combustion of zero-carbon fuels (ZCF) (e.g. hydrogen, biogas). Through detailed analysis and comparison of operational results from three long-term electricity system capacity expansion planning models on electricity decarbonization in California and the U.S. Western Interconnection, we demonstrate and explain why each technology has the potential to occupy a distinctive functional niche and provide incremental value to a zero-carbon system, highlighting the benefits of an expansive range of technology options to meet emissions reductions goals for the power sector while maintaining operational reliability and affordability.

2. Methods

2.1. Overview of models

The analysis in this paper uses three different capacity expansion and production simulation models to draw robust conclusions about the role and value of different technologies to grid operations. All three models minimize the total fixed and variable costs of a generation portfolio to meet projected peak and energy demands, while meeting a set of engineering and policy-related constraints as well. More detailed descriptions of each model can be found in Energy and Environmental Economics [19], Dorfner [20], and Jenkins and Sepulveda [21], as well as the Supplementary Information (SI). All three models are state-of-the-art models that are able to capture complex and detailed dynamics of capacity expansion and generation, which simpler capacity expansion models may not be able to. Furthermore, all RESOLVE model runs include an additional modeling analysis called RECAP [22], which ensures reliability of the optimized system across multiple weather years. Key differences across the models are summarized in Table 1.

In meeting the same load assumptions, each model enforces reliability differently. RESOLVE includes a 15% Planning Reserve Margin (PRM) constraint to ensure that sufficient resources are maintained to meet an assumed long-run reliability standard as well as an Energy Reserve Margin (ERM) constraint to ensure an equivalent loss of load expectation (LOLE) below 2.4 h/year (per California Independent System Operator's definition of a reliable system). urbs includes a 15% PRM as well, while GenX assumes a high cost of loss of load of approximately $9,000/MWh. Transmission constraints slightly vary by model and further details can be found in the SI.

2.2. Scenario development and input assumptions

2.2.1. Input assumptions

All three models maintained a consistent set of input assumptions across all scenarios.

The load growth assumptions and hourly load shapes are taken from the High Electrification Scenario of the 2018 Deep Decarbonization in a High Renewables Future study commissioned by the California Energy Commission (CEC) [23]. Given the expected cost-effectiveness of electrification of loads in California [23], we assumed significant electrification in the transportation (19 million battery electric vehicles, and approximately 80% electrification other transportation) and buildings sector (91% of buildings are electrified). This results in a near doubling of California's electricity demand by 2045 relative to ~260 TWh in 2018 (Table 2).

The power generation resources in 2018 are derived from the California Public Utilities Commission (CPUC) databases [24]. The generation mix in California in 2018 was approximately 47% gas, 32% renewables (13% PV, 7% Wind, and 6% Geothermal) and 11% hydro [25]. Capital cost assumptions for generating resources within the modeling horizon (2018–2045) are taken from National Renewable Energy Laboratory's (NREL) 2018 Annual Technology Baseline (ATB) [26], while the capital cost assumptions for storage are taken from Lazard's Levelized Cost of Storage Analysis v4.0 [27]. Changing capital costs throughout the modeled horizons are taken into account in the models, and the full range of cost assumptions over time can be found in the SI. Table 3 summarizes the base capital costs assumptions for 2045. In addition to capital costs, financing assumptions for investments are important considerations in assessing costs of various technologies. Detailed assumptions on financing for all resources considered in the analysis are included in the SI as well. We also model a range of alternative cost assumptions in sensitivity cases, discussed in Section 3.2.2 and presented in the SI.

All three models optimize future grids upon the existing California grid in 2018. All resources in 2018, including hydro, geothermal, and clean import capacities, are assumed to be available through 2045 unless explicit retirements have been announced (as in the case of Diablo Canyon). However, the models can also choose to retire certain resources such as gas power plants, which may not operate in 2045 depending on the scenario considered. While California is rich with PV resources, some other renewable and clean resources are limited in expansion. In particular, no additional hydro capacity is assumed to be available, and only small amounts of onshore wind and geothermal capacity are assumed to be available for expansion within California [32]. Battery storage and all clean firm resources are assumed to have unlimited availability for expansion. Table S4 in the SI shows further detail on capacity expansion assumptions. SI files for each model also have more detail on the operational assumptions for all technologies.

2.2.2. Scenario overview

As established in SB100, all three models enforce a 60% Renewable Portfolio Standard in 2030 and a zero-carbon emissions constraint in 2045. urbs models a single 2030 60% RPS scenario portfolio in which no

Table 1
Three models used and key difference summarized.

	RESOLVE	urbs	GenX
Model Type	Linear Programming Model with linearized unit commitment constraints	Linear Programming Model	Linear Programming Model with linearized unit commitment constraints
Temporal Resolution	37 representative days with hourly resolution time steps (888 h)	1 year with hourly resolution time steps (8760 h)	16 representative weeks with hourly resolution time steps (2688 h)
Spatial Resolution	3 zones: CA, SW, NW	10 CA zones; 2 out of state zones (SW, NW)	2 CA zones; 7 out of state WECC* zones
Zones Optimized	California	California	WECC*-wide
Regional Definition	Neighboring states assumed to adopt deep decarbonization measured which is reflected in their assumed resource build	Neighboring states assumed to adopt deep decarbonization measured which is reflected in their assumed resource build	All states within WECC* adopt the same energy and carbon policies
Imports/ Exports to/ from CA	2000 MW of firm imports assumed Unspecified imports are treated as gas resources with a CA carbon adder applied at 0.43 tCO2/MWh	Firm imports modeled and unspecified imports treated as gas resources with a CA carbon adder applied at 0.43 tCO2/MWh	Capacity outside of California co-optimized with inter-regional transmission network flow constraints and endogenous transmission capacity expansion without an additional carbon adder

*WECC (Western Electricity Coordinating Council)

Table 2
California electrical load assumptions.

California Load Assumptions	2018	2030	2045
Annual Load [TWh/yr] (includes load met by Behind the Meter PV)	~260	317	475

Table 3
Summary of capital and operating costs as well as key operating assumptions for resources allowed to expand in California in 2045. Ramping flexibility indicates the percentage of capacity that can be ramped in a single hourly timestep, and the range of ramping flexibilities shown in the table indicates the modeled flexibility across the three models. Further information can be found in the SI. Long-duration storage and a variety of alternative cost assumptions were also modeled in sensitivity cases, and further details on cost assumptions and results can be found in the SI.

Resource Type	Capital Costs in 2045 (2018 $/kW)	Operating Assumptions	Capital Cost References
Utility-Scale Solar PV (in-state avg.)	**$958***	No fuel cost; Single axis tracking; ~33% CF	NREL ATB 2018 [26]
Onshore Wind (in-state avg.)	**$1,548**	No fuel cost; ~ 36% CF	NREL ATB 2018 [26]
Offshore Wind (Floating)	**$3,999**	No fuel cost; ~ 52% CF	NREL ATB 2018 [26]
Geothermal	**$4,656**	No fuel cost	NREL ATB 2018 [26]
CCGT with CCS at 100% Capture** (CCS)	**$1,816**	Natural gas cost ~ $7/ MMBTU 50–100% ramp up/ down flexibility [28]	NREL ATB 2018 [26] with ~ 3 $/MWh for T&S.
Advanced new nuclear (SMRs)	**$5,416**	Low fuel cost Uranium ~$0.7/MMBTU 25% ramp up/down flexibility [29,30]	NREL ATB 2018 [26]
Zero Carbon Fuel *** (Biogas or Hydrogen)	**$0 (has associated fixed costs)**	Fuel cost of $33/ MMBTU (see SI for sensitivity analyses of fuel costs at $15/ MMBTU) 54-64% ramp up/down flexibility	
New CCGT	**$1,099**	Natural gas cost ~ $7/ MMBTU	NREL ATB 2018 [26]
Li-Ion Battery Capacity ($/kW) / Energy ($/kWh)	**$85/$124**	Round trip efficiency of 92%; Battery duration optimized within model	Lazard LCOS v.4.0 [27]

*PV costs are in $/kW-AC and include a DC-AC ratio of 135% based on NREL ATB 2018 [26]. The capital costs for PV in 2045 are $710/kW-DC.
** Non-Allam Cycle 100% capture cost assumption from Feron et al. [31]
***Assumes retrofitting existing gas turbines for ZCF combustion

clean firm resources are available, and the various 2045 scenario portfolios are built upon this 2030 baseline. On the other hand, for each scenario considered, GenX optimizes a portfolio for 2030 and a subsequent portfolio for 2045, and allows for consistent technology sets to be available in 2030. RESOLVE has intertemporal modeling capabilities, and co-optimizes investment and dispatch over a multi-year horizon that includes 2030 and 2045 [24].

For this study, we developed a range of scenarios to explore the key operational differences between net-zero systems that have different low or zero carbon on-demand resources available. As a starting point, we developed a Renewable energy and Batteries (ReB) only scenario, which does not have any clean firm resource such as CCS, nuclear, or zero-carbon fuel (ZCF) available. This scenario represents a future in which low-carbon technologies are limited to those that are mature and scalable today (e.g. wind, solar PV, batteries) and highlights the operational challenges associated with systems that do not have any firm resources. ReB provides a benchmark to which the other scenarios are compared.

We then construct alternative portfolio scenarios to understand the changes to grid operations when firm technologies are made available, one at a time. To examine the changes to the total portfolio, investment and operational costs, as well as operations, we construct 3 single firm technology scenarios where CCS, nuclear and ZCF are made available and compare these to the ReB reference case. The main goal of the single-technology cases is to isolate the value provided by the individual technologies. To test the substitutability of the technologies, we then construct scenarios with two or all three firm technology options made available simultaneously and evaluate if multiple technologies provide additional value when compared to the single technology scenarios. Table 4 summarizes the modeling scenarios run across all three models.

3. Results

Across all three models, base technology cost scenarios that include at least one form of clean firm resource result in generation and transmission system costs of approximately 7.1–10.2 cents/kWh. For context, California's IOU rate (generation and transmission) in 2019 was 9.1 cents/kWh [33] (Fig. 1). The only scenario that significantly exceeds those costs is the ReB scenario, in which no clean firm resources are made available. This result is consistent with previous studies that have highlighted the role of clean firm resources [8,9,16,34], and can be attributed to the need for reliable energy and power during sustained

Table 4
Nomenclature of modeled scenarios .

Scenario Name	Expansion Technologies Considered.
ReB	PV, Onshore Wind, Offshore Wind, Battery Storage
ReBC	PV, Onshore Wind, Offshore Wind, Battery Storage, CCS
ReBN	PV, Onshore Wind, Offshore Wind, Battery Storage, Nuclear
ReBF	PV, Onshore Wind, Offshore Wind, Battery Storage, ZCF
ReBCF	PV, Onshore Wind, Offshore Wind, Battery Storage, CCS, ZCF
ReBCN	PV, Onshore Wind, Offshore Wind, Battery Storage, CCS, Nuclear
ReBNF	PV, Onshore Wind, Offshore Wind, Battery Storage, Nuclear, ZCF
ReBCNF	PV, Onshore Wind, Offshore Wind, Battery Storage, CCS, Nuclear, ZCF

periods of low solar and wind generation. All clean firm resources explored in this analysis have higher capital and/or variable costs than intermittent renewable resources. Despite their higher costs, the clean firm resources are largely utilized during times when the output from intermittent resources drop. During these times, the marginal value of energy supply increases significantly. Clean firm resources are able to dependably dispatch during these periods, capturing greater value per megawatt-hour produced than variable renewable resources. The higher average value of firm resources justifies their higher cost (relative to wind or solar) and explains why these technologies can contribute to a lower overall system cost.

Without clean firm resources in the ReB scenario, significant capacities of PV and energy storage must be overbuilt to ensure energy adequacy and reliability in periods of low renewable energy output. Due to the limited capacity expansion potential of other renewables resources such as wind, geothermal, and hydro, most of the renewable expansion in-state is dominated by PV and storage resources. Despite the low capital costs of PV and energy storage, the sheer volume of capacity required and the subsequent decrease in marginal value and utilization rates for PV and storage resources result in higher system costs for the ReB scenario. Furthermore, all RESOLVE model runs include a RECAP analysis [22], which ensures reliability of the optimized system across multiple weather years. RECAP analysis for ReB results in significant additions of capacity for reliability purposes, explaining the larger capacity required in the ReB scenario for RESOLVE relative to urbs and GenX. The RECAP analysis highlights that interannual variability of wind and solar resources may contribute to even higher costs of ReB scenarios.

3.1. *Cost-effectiveness of individual clean firm resources*

In the ReBC, ReBN, and ReBF scenarios with only one type of clean firm resource available, each least cost portfolio deploys the available

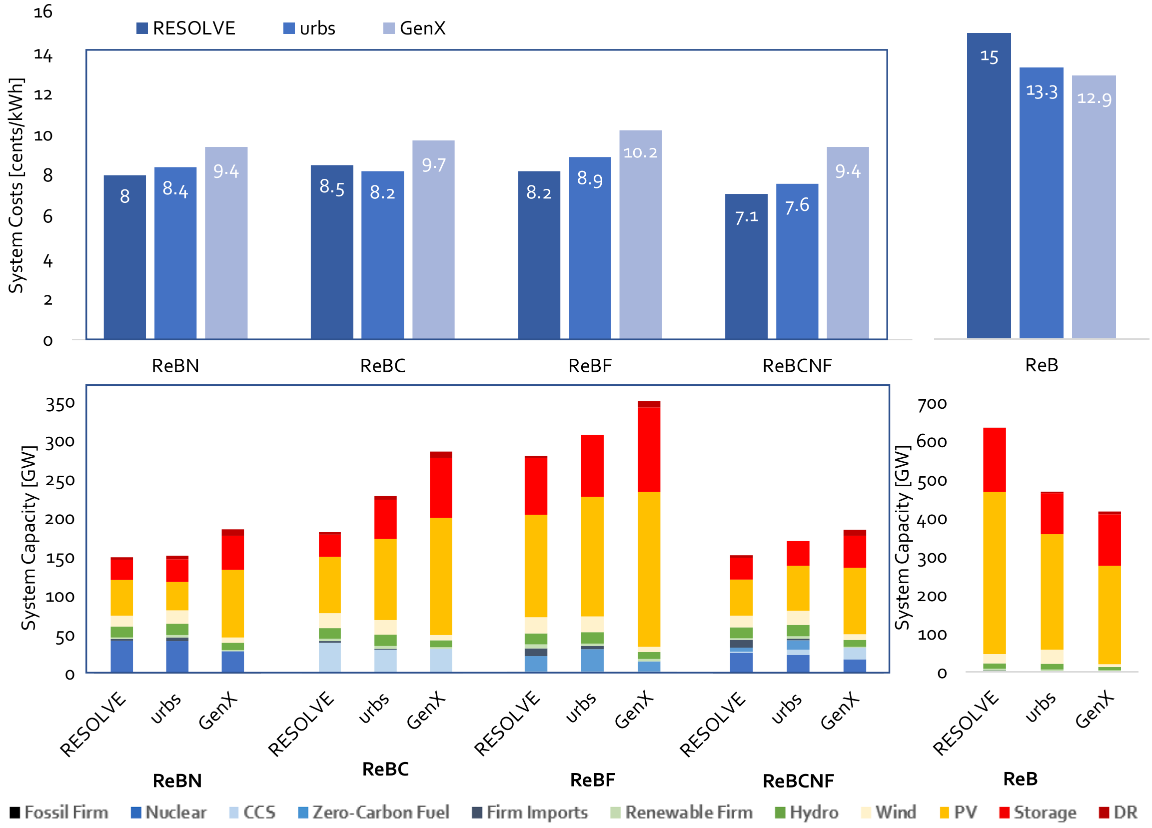

Fig. 1. Annualized generation and transmission system cost for California and associated system capacity in California for zero-carbon grid scenarios in 2045 across the three models. Scenarios with clean firm resources have significantly lower system costs and system capacity builds relative to the scenario without any clean firm resources. The ReBCNF scenario which includes all three clean firm resources shows the lowest system cost, highlighting that multiple clean firm resources complement each other to provide further cost savings. *Note: Costs are rounded to the nearest tenths. Reported clean firm power capacity for all three models includes California's share of Palo Verde nuclear power plant in Arizona (1.08 GW). RESOLVE includes 2-10 GW of firm import contracts depending on the case. RESOLVE and urbs also include new out of state firm resources dedicated to California utilities in the reported totals above. In contrast GenX results include only clean firm power physically located within the state of California, with the exception of the California share of Palo Verde. GenX dispatches additional out of state clean firm resources as part of a Western Interconnection-wide least-cost optimization, and some of this capacity may contribute to California needs. ZCF capacity in GenX ReBCNF scenarios is built outside of California, and is thus not represented in this figure. All RESOLVE model runs include a RECAP analysis* [22]*, which ensures reliability of the optimized system across multiple weather years. RECAP analysis for ReB results in significant additions of capacity for reliability purposes, explaining the larger capacity required in the ReB scenario for RESOLVE relative to urbs and GenX.*

clean firm resource, with installed firm capacity ranging from 25–40 GW across scenarios and models. Despite significant differences in the techno-economic characteristics of each clean firm resource, all three of these scenarios result in similar system costs. This shows that any individual clean firm resource can provide similar cost-saving value in decarbonizing the grid. However, while providing similar impacts on system costs, each clean firm resource has distinct characteristics that result in varying overall system capacity and composition.

Nuclear power, with high capital costs but low variable costs, results in ReBN scenarios that have relatively high nuclear capacity (28–42 GW) and low shares of PV relative to the other scenarios (36–87 GW of PV). Variable renewable resources deliver most of their value via energy substitute (or ‘fuel saving value’). When available, these zero-marginal cost resources displace energy generation from other sources with non-zero fuel costs. As such, the marginal value of wind and solar is affected by the selection of clean firm resources; higher shares of low- or zero-marginal cost resources like nuclear or geothermal reduce the fuel-saving value of variable renewables, resulting in less wind or solar capacity in the cost-optimized portfolio than for scenarios featuring larger shares of fuel-consuming firm resources. CCS technology with mid capital and variable costs results in ReBC scenarios with relatively moderate shares of both CCS (29-38 GW) and PV (73–151 GW of PV). Finally, a grid with ZCF resources, with low capital costs but high variable costs, results in the highest share of PV (133–200 GW of PV) and lowest share of ZCF capacity at 13–29 GW across the three individual scenarios.

In California, PV and storage are one of the most cost-effective options for providing electricity, but increasing shares of PV and storage capacity result in decreasing marginal values of these resources to the grid [35,36]. For a clean firm resource with higher variable costs, such as ZCF, the marginal cost of building more PV and storage in the grid may be more cost-effective than operating the clean firm resource with very high marginal cost of generation. This explains the reason least cost portfolios with clean firm resources with increasing variable costs have increasing shares of PV and storage in the mix, and also reflects the difference in systems costs across the different clean firm resources modeled. For all models, the ReBF scenario is slightly costlier than the ReBN and ReBC scenarios. This indicates that availability of clean firm resources with moderate to low variable costs may be more cost-effective in supplementing renewable resources regardless of their higher fixed capacity costs.

Given the varying cost profiles of the clean firm resources, the hourly operation of the grid with each clean firm resource also varies with the different levels of PV and storage capacity in the grid mix. Fig. 2 shows a daily generation profile for California in September for each model across the three individual scenarios. Fig. 2 shows nuclear operating as a flexible base resource that operates largely at maximum rated capacity but reduces output during the day to accommodate PV generation. CCS shows more diurnal variation with a larger reduction in generation during the daytime relative to nuclear. On the other hand, in the ReBF scenario that has much larger capacities of PV and storage, the system load is largely met with PV and storage, with ZCF only stepping in to fill smaller gaps in the supply/demand balance. In all three cases, the operations of clean firm resources are shaped by the large share of intermittent renewable resources that exist in the grid. The operation of each clean firm resource is also consistent across all three models, which

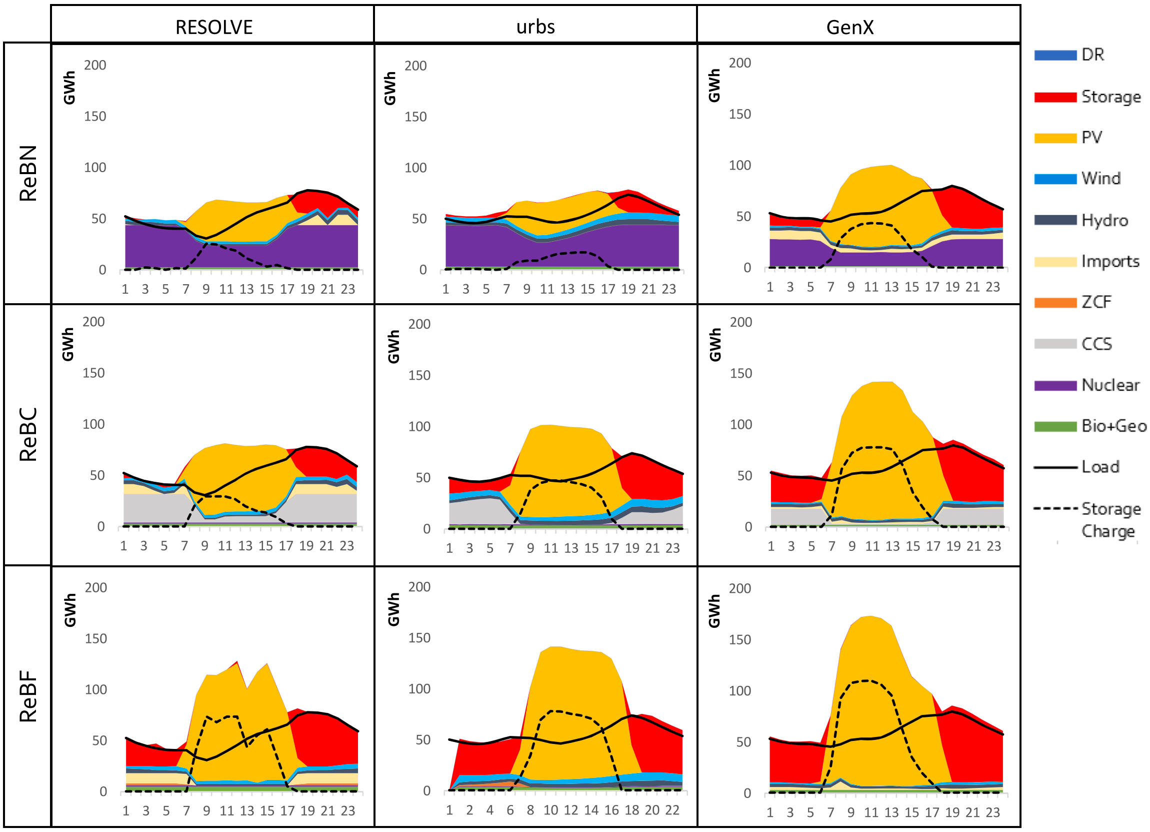

Fig. 2. Daily generation pattern of California of the three models on an example September day in 2045 for ReBN, ReBC, and ReBF scenarios. Each clean firm resource shows distinct daily operations that are consistent across all three models. Nuclear operates nearly as baseload and reduces output during the day, while CCS shows a more drastic ramp down during the day to accommodate higher shares of PV. ZCF operates minimally, only to supplement a system largely dominated by PV and storage. *Note: Representative September day used for RESOLVE, average generation profile for all days in September used for urbs, and average generation profile of representative September weeks used for GenX. GenX imports indicate net imports of California, and may be representative of ZCF resources operating outside of California that are imported. For GenX and urbs, load and generation of representative nodes in California are summed to show California generation patterns.*

further emphasizes that clean firm resources operate as a function of their operating economics and not as a function of any specific model structure or assumptions.

Fundamentally, the value of clean firm resources relate to their resource availability and ability to adapt production output in order to meet variable demand [9]. The grid is optimized for the right balance of cheap intermittent resource buildout with the capacity buildout and utilization of clean firm resources to ensure reliability and low overall system cost. Depending on the type and cost of clean firm resources, this balance may vary. However, this analysis shows that regardless of the type, having a clean firm resource that is available to support variable renewable generation results in cost-effective power sector decarbonization.

3.2. *Clean firm resources complement each other*

While having at least one clean firm resource can help achieve cost-effective decarbonization of the grid, Fig. 1 also shows that the scenario with all three clean firm resources provides more cost savings relative to the scenarios with each individual clean firm resource alone. In the ReBCNF scenario, all three clean firm technologies are deployed as part of the least cost portfolio across all three models[1]. If the clean firm technologies were perfect substitutes, the optimal portfolio would consist of the economically dominant technology alone. Instead, all three technologies are selected as a part of the optimal portfolio, suggesting the complementary contributions of these technologies to the electric grid.

Fig. 3 uses 'screening curves' to explain the role of each clean firm resource in meeting the net load of the grid and in delivering a cost-effective system [37]. The linear equation utilized to generate the total cost curve is shown below, where fixed costs include annualized capital costs and fixed O&M costs (providing the intercept), and the variable costs include fuel costs and variable O&M costs (providing the slope).

$$Total\ Cost\ \left[\frac{\$}{MW{\cdot}yr}\right] = Fixed\ Costs\ [\$/MW{\cdot}yr] + (8760\ hours * \%\ hours\ operating\ in\ a\ year) *\ Variable\ Costs[\$/MWh]$$

The total cost curve for each technology based on the percentage of hours operating in a year is overlaid with the net load duration curve that needs to be served by clean firm resources for the ReBCNF scenario.

The figure shows that different clean firm resources are each the most cost-effective when operating for different amounts of time over a year. For example, given these specific cost assumptions, Fig. 3 illustrates that to meet the net load at a level that requires operation at above 70% of the hours in a year, nuclear is the most cost-effective clean firm resource to fill that role, while ZCF is the most cost-effective to meet net load that occurs less than 15% of the year. CCS is the most competitive for meeting the net load between 15% and 70% hours of the year. This point is further illustrated by the annual operating hours of each clean firm resource in the modeled ReBCNF scenario (denoted by the dots), which are each within the range in Fig. 3 wherein the resource is the most cost-effective firm option. As such, each clean firm resource has varying fixed costs and variable costs that allow each resource to occupy a specific operating niche in meeting the grid's needs. This explains how three clean firm resources can together provide the most cost-savings in a decarbonized grid.

Screening curves as shown in Fig. 3 have conventionally been used to demonstrate the trade-off between different thermal and dispatchable resources, and were often used as a predictive tool to determine optimal shares of these resources to meet load. Screening curves have particularly been useful in classifying so-called 'baseload,' 'mid-load' or 'load-following', and 'peaker' resources in conventional grids. However, as the share of intermittent resources and energy storage in the grid increases, screening curves can no longer be used as accurate predictive tools given time variable generation of intermittent resources as well as utilization of energy storage resources that fundamentally shift the net load that dispatchable resources have to meet. While the screening curve may not be utilized for predictive purposes, this analysis shows that the screening curve can be a useful *ex post* (with a net load curve based on cost-optimized results) as a descriptive tool in understanding the tradeoffs and operation of various clean firm resources, even in a grid that has significant shares of intermittent variable resources. In addition, the old terminology for dispatchable resources defines each resource class in relation to the share of the load duration curve it supplies. In systems with high shares of variable renewables and storage, this old taxonomy no longer applies. Instead, firm resources should be classified based on their own operating patterns, which are affected by not just demand patterns, but also renewables and storage dispatch. A more appropriate taxonomy for firm resources is proposed in Section 3.2.1 below.

Similar to the individual technology scenarios, the ReBCNF scenarios with all three clean firm resources are accompanied by high shares of renewable resources (45–57% of PV and wind generation shares across the three models). PV, wind, and storage are cost-effective low carbon generation technologies that play central roles in net zero carbon grids across all cases. Because of this, the operations of the clean firm resources within the ReBCNF scenarios (as well as the individual scenarios) are shaped by intermittent renewable and storage generation. In serving the net load shaped by intermittent and storage resources, the clean firm resources build upon each other to effectively meet the net load throughout the day.

3.2.1. ***Operation of clean firm resources operating together***

The operating patterns of the clean firm resources are defined largely by their respective techno-economics, as demonstrated by Fig. 3. Because of this, the operation of each clean firm resource is consistent across both the individual technology scenarios and the ReBCNF scenario where multiple clean firm resources co-exist (Fig. 4). Based on the similarity of operating patterns, the annual capacity factor for each resource is relatively consistent across the various scenarios as well as the three models. Nuclear operates with at capacity factor above a 60%, while CCS operates between 30%–40% annual capacity factor cycling on and off with diurnal patterns. ZCF is also flexible at cycling but operates at less than 15% annual capacity factor given high variable costs (Table 5).

Across all models and scenarios, the total firm capacity needed to support a large share of renewable resources on the modeled California system in 2045 is consistently in the 25–40 GW range. When only one type of clean firm resource is available in the system, the single resource has to meet a large share of the capacity needs. On the other hand, with multiple clean firm resources, different technologies are able to contribute towards meeting this capacity need, resulting in less of each capacity built relative to the single technology scenarios (Table 5). As a

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[1] For GenX, ZCF capacity in the ReBCNF scenario is built outside of California, but included in the lowest cost generation mix

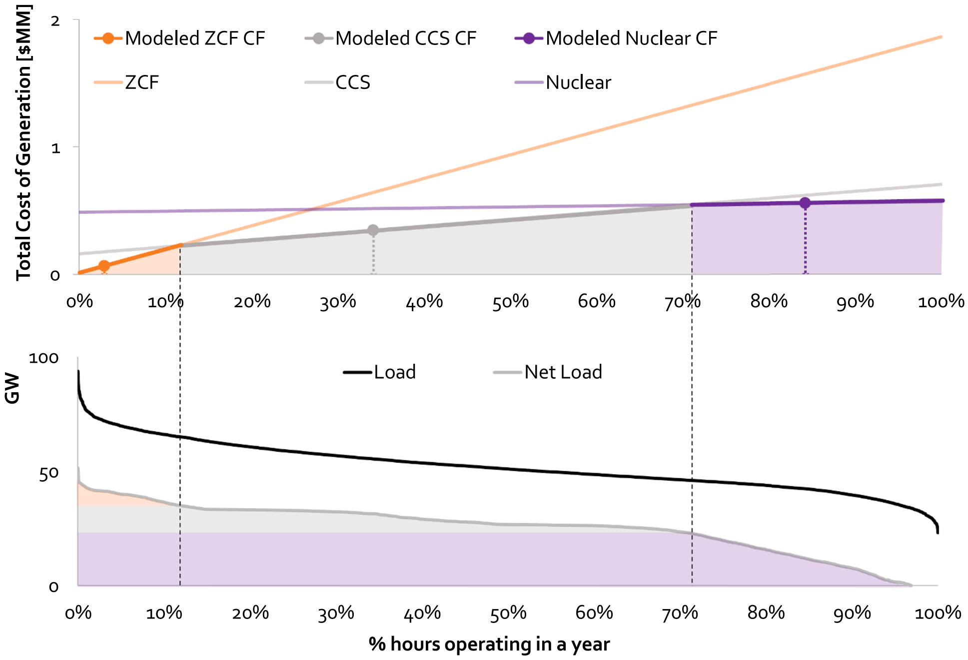

Fig. 3. Total cost curve of the three clean firm resources considered in this analysis and the net load served by the clean firm resources in the 2045 ReBCNF scenario of urbs for California. Depending on the percentage of hours the resource operates in a given year, each clean firm resource has the lowest cost of generation. Because of this, each clean firm resource is able to occupy a functional niche in the grid and provide incremental value to a zero-carbon system. *Note: The net load curve is the load net of intermittent renewable generation, hydro generation, and storage charging and discharging.*

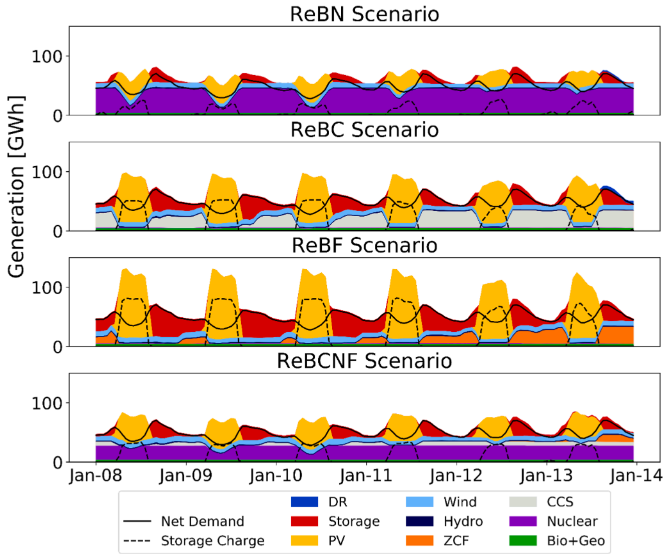

Fig. 4. Representative winter week in 2045 for California for ReBN, ReBC, ReBF, and ReBCNF scenarios from urbs. The figure illustrates that the operating pattern of each clean firm resource is consistent across the individual scenarios (ReBN, ReBC, ReBF) and the ReBCNF scenario. *Note: the results are a sum of the generation and load for all modeled regions in California, and represent a week in the entire modeled timeframe in urbs.*

result, the capacity factors of the clean firm resources are better aligned with their cost-effective operating niches in the scenario where they all co-exist (ReBCNF) relative to the scenarios where they exist independently.

In the REBCNF scenarios, the capacity of each clean firm resource built is right-sized to fill its operational niche in helping the system meet load[2]. Because each resource operates squarely in its niche, in the ReBCNF scenario, less capacity of each clean firm resource is built and each resource operates closer to the ideal capacity factors as identified in Fig. 3 (Table 5). This is also visible in the annual operating patterns of the clean firm resources, where there are more times when each technology is operating at part load in the individual firm resource scenarios relative to the ReBCNF scenario (Fig. 5). For example, comparing the individual resource scenarios to the ReBCNF panels in Fig. 5, we can see that nuclear power operates at a lower utilization rate than is ideal, CCS operates at part load more often, and ZCF operates at higher capacity factor, as each resource is stretched to play a broader role than it is techno-economically ideal. In the ReBCNF scenario, each clean firm resource can operate within its ideal operating niche, providing more cost-effective decarbonization of the grid.

Notably, Table 5 shows that CCS has the least variation in capacity factor between the individual scenarios and ReBCNF scenario. This indicates that clean firm resources with both moderate fixed and variable costs can be more flexible resources in adjusting to different operating niches the most. CCS is able to serve the capacity and energy needs of the grid cost-effectively given moderate costs for both, relative to nuclear or ZCF which would cost more to meet higher capacity needs or energy needs of a grid, respectively, given higher fixed or variable cost structures. Given the variability of different grid types and clean firm resources, developing resources with intermediate cost structures may provide more flexibility in the system to adjust to varying levels of intermittent resources as well as the presence of other clean firm resources. Another reason CCS shows the least variation in capacity factors between the two scenarios might also be due to the fact that with the given cost assumptions, CCS has the widest operating niche relative to the other modeled clean firm resources (Fig. 3).

This result is also consistent across scenarios with only two of the three clean firm resources. Table 6 summarizes the results of scenarios with single, two, and three clean firm resources for each model. Scenarios with two clean firm resources have consistently lower system costs than in the scenarios with single clean firm resources, while still being more costly than the scenario with all three resources. If developing all three clean firm resources for the grid are challenging, developing at least two clean firm resources can still be more cost-effective than developing one. Moreover, this strategy also hedges the uncertainty associated with a single technology's expected cost, technological advancement trajectory, and potential bottlenecks that might constraint

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[2] Note that the capacity of each clean firm resource needed to fill its operational niche in the ReBCNF scenario can be approximated in the cross-section of the net load curve in Fig. 3.

Table 5
Range of annual capacity factor in 2045 and range of capacity build by 2045 in California of each clean firm resource in the ReBC, ReBN, ReBF and ReBCNF scenarios across the three models. The parentheses indicate the average annual capacity factor and capacity build. *Note: GenX capacity factors are for WECC-wide clean firm capacities. Average capacity is taken as the average of capacity in 2045 in California across the three models.*

Clean Firm Resource	Scenario	Capacity Factor (%)	Capacity (GW)	Scenario	Capacity Factor (%)	Capacity (GW)
Nuclear	ReBN	64–79% (73%)	28–42 GW (37 GW)	ReBCNF	84–87% (86%)	18–26 GW (23 GW)
CCS	ReBC	33–38% (36%)	29–38 GW (32 GW)		34–38% (37%)	2–15 GW (8 GW)
ZCF	ReBF	2–13% (9%)	13–29 GW (21 GW)		1–6% (3%)	0–12 GW (6 GW)

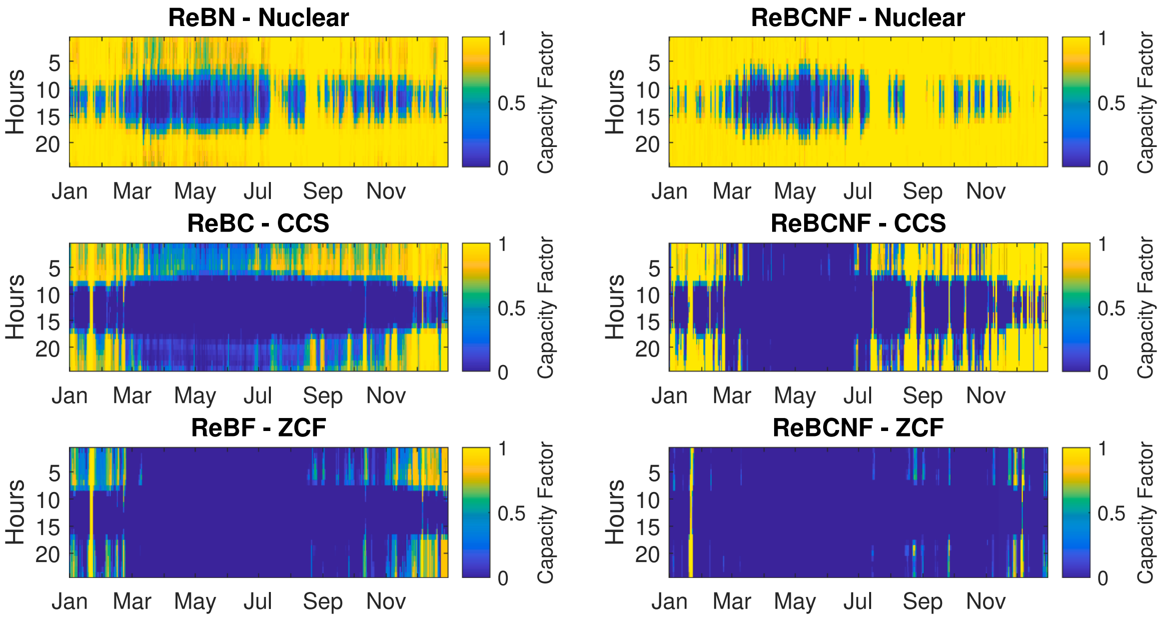

Fig. 5. Annual operating patterns of Nuclear, CCS, and ZCF in 2045 for the ReBC, ReBN, ReBF, and ReBCNF scenarios from urbs. Nuclear operates most of the hours and seasons, CCS operates intermittently but largely diurnally across mostly the fall and winter season, while ZCF barely operates throughout the year other than some winter nights and weeks.

deployment of each clean firm resource.

More broadly, among clean firm resources, these three resources can be classified using the taxonomy provided in [9] as spanning the range of *firm cyclers* and *flexible base resources. Firm cyclers* are resources such as ZCF that have low fixed cost but high variable cost that are offline the majority of the year, but have frequent startups. *Flexible base resources* are resources such as nuclear and geothermal that have high fixed costs but low variable costs. They are online the majority of time but also operate flexibly due to higher shares of intermittent renewables and storage resources on the grid. *Intermediate* resources with mid capital and variable costs like natural gas with CCS operate somewhere between firm cyclers and flexible bases. While analogous to the identification of 'baseload', 'load-following', and 'peaking' resources in conventional energy systems, the integration of higher shares of renewables have changed grid system dynamics and necessitate new classification of resources to reflect new operating dynamics, which depend not just on patterns of load, but rather on the combined interaction of load (including flexible demands), energy storage, and intermittent renewable resources [9].

Table 6
Percentage increase in system cost in 2045 compared to the ReBCNF scenarios in each of the three models. The single clean firm technology scenarios show higher increases in system cost relative to the scenarios with two or more clean firm resources.

Models	Two Clean Firm		Single Clean Firm	
RESOLVE	REBCN	9%	REBN	12%
	REBCF	not modeled	REBC	20%
	REBNF	not modeled	REBF	not modeled
urbs	REBCN	3%	REBN	11%
	REBCF	5%	REBC	8%
	REBNF	3%	REBF	17%
GenX	REBCN	4%	REBN	7%
	REBCF	6%	REBC	8%
	REBNF	not modeled	REBF	12%

3.2.2. *Sensitivity to technology costs*

The results of this analysis are based on the specific modeled costs of each of the resources. To determine robustness of findings to different cost assumptions, we modeled a range of technology sensitivities. We find that different capital cost assumptions for nuclear and CCS, as well as different variable cost assumptions for CCS and ZCF do not substantially affect the overall system costs, indicating that the overall value of clean firm resources is robust across a wide range of technology costs (SI Fig. A3).

However, depending on how the cost profiles of the technologies change, the resources may compete for being the most cost-effective source of generation for a wider range of operating regimes. For example, with lower variable costs for ZCF, the operating niche for ZCF might shift to higher annual capacity factors and take up generation shares from CCS. With lower capital costs for CCS, the operating niche of CCS will expand both into the territory where ZCF and Nuclear resources were previously more cost-effective. Finally, lower nuclear capital costs may compete directly with the operating niche of CCS. Figure A4 in the SI shows an illustration of changing screening curves depending on varying cost assumptions for different clean firm resources. While the screening curve method cannot determine the optimal grid portfolio *a priori*, it provides a way for assessing the optimal operating niche of each clean firm resource *ex post* after the cost-optimal net-load curve is known. Screening curves can be utilized to explain how the operating niche of different resources change with varying cost assumptions, and can be further developed to include more types of clean firm resources as well.

3.3. Differences across models

While the trends of the results are consistent across the three models, some differences persist based on the setup of each model. GenX optimizes for the entirety of WECC, and often shows higher PV build in California relative to RESOLVE and urbs. WECC-wide, California's solar resources are highly favored and so PV capacity built in California is also exported to surrounding states to reach WECC-wide emissions reductions. Similarly, because of this, GenX often builds less clean firm resources capacity because ample transmission and trade between the regions reduces the reliance on in-state clean firm resource capacity [38]. Additionally, GenX does not model a capacity reserve margin, instead modeling a high cost penalty on non-served energy, resulting in less capacity used solely to meet reserve requirements, which is generally supplied by the firm resource with lowest fixed costs (e.g. ZCF capacity). Between the two models that optimize for California, urbs tends to build more PV and consequently less clean firm capacity. This is because RESOLVE considers the incremental effective load carrying capacity (ELCC) of PV to meet the system's peak reserve margin (PRM) of 15% to be near-zero, while urbs utilizes average ELCC for PV to meet 15% PRM. As a result, more PV capacity is considered to satisfy the PRM requirement in urbs than in RESOLVE, resulting in overall higher PV build. As such, the differences in the models can be explained by the model setup. Regardless of the model set up, the models show fundamentally consistent results on the value and role of clean firm resources, further emphasizing the robustness of these results.

While all the models only simulate a single weather year, results from the RESOLVE model are also analyzed by an additional reliability model called RECAP [22]. E3's RECAP model combines loss-of-load-probability modeling with a capacity expansion heuristic, to identify additional wind, solar and battery resources needed to meet a 1-day-in-10-year Loss-of-Load Expectation standard that may occur from varying weather years. For scenarios with clean firm resources, the simpler reserve margin requirements produce portfolios that meet resource adequacy standards of RECAP. However, for the scenario without clean firm resources (ReB) more capacities of PV and storage need to be added to ensure meeting resource adequacy standards of RECAP. The higher storage and renewable capacity needs in RESOLVE's ReB results relative to that of urbs or GenX reflect the potential underestimation of the value of clean firm resources relative to a system without any clean firm resource for GenX and urbs.

4. Discussion

Cost-effective 100% decarbonization of the grid-and consequently the cost-effective decarbonization of the entire economy-appears to depend on the development and deployment of clean firm resources. This analysis has also demonstrated that having multiple clean firm resources provides more cost-savings than only developing a single clean firm resource. Furthermore, the analysis has shown that different clean firm resources with varying techno-economic abilities can provide similar cost savings value in decarbonizing the grid. However, the mechanism in which each resource operates to provide cost-savings varies, and each technology and its respective least-cost grid are shown to have different implications for California's system development. While not explicitly modeled, the results of the modeling imply that a system that relies heavily on high capacities of PV in-state (such as the scenario with ZCF) may encounter greater land-use and siting challenges that may potentially limit the development of PV, or may face higher system costs if expected cost declines in storage and PV do not materialize. On the other hand, CCS or nuclear generally face higher public opposition and may encounter siting challenges of their own that may slow the growth of clean firm capacity that is needed. The development of multiple clean firm resources thus provides a hedge against non-modeled risks associated with relying on technical and cost advances or social license for a single technology, especially if the risks associated with these technologies are not correlated. Furthermore, relying on multiple clean firm resources distributes the risk of system failure more broadly, by mitigating the risk of a system failure based on the failure of a single technology and increasing the flexibility of the system in adjusting to potential challenges.

In addition to reducing risk, utilizing multiple clean firm resources to decarbonize a grid is more cost-effective than solely relying on a single resource. While additional effort is required to develop more than one clean firm power option, the options are not limited to only the three technologies modeled in this analysis. There are also other clean firm resources that fit the identification of flexible base, intermediate, and firm cycler that can substitute for or supplement nuclear, CCS, or zero carbon fuels. Geothermal resources are also flexible base options that have high capital costs, but low variable costs when run. Allam cycle turbines are intermediate resources that are similar to natural gas with CCS. Biomass-fired power plants with CCS may also serve as intermediate resources. Firm cyclers can take the form of ZCF such as hydrogen with hydrogen turbines, or biogas or methanated hydrogen that run in conventional gas turbines. Running natural gas peakers that emit CO_2 with the use of negative emissions technologies or offsets can also be a form of firm cycler.

While long duration storage was also considered in this analysis, we find that long duration storage resources at current and future projects costs cannot serve as direct substitutes for clean firm resources, and the conclusion is consistent with recent literature [39]. This is because fully displacing firm generation with long duration storage requires very low marginal utilization rates for the final increments of storage capacity deployed. For this capacity to be economically competitive, energy storage capacity costs must be extremely low (on the order of $1 per kilowatt-hour of installed energy capacity) along with sufficient power cost and efficiency performance. A more detailed discussion on the long duration storage results can be found in the SI.

Regardless of the type, developing clean firm resources of any sort to scale by 2045 will likely require immediate action. Furthermore, recent policy signals have pointed to a possible goal to reach a net zero carbon grid by 2035 [40], greatly raising the urgency to take action. Planning and developing power system assets take multiple years, and the capacity installed in the next decade will likely persist through 2050. However, the development of clean firm resources explored in this analysis currently face a multitude of challenges in scaling up. Producing and distributing ZCF will likely require more affordable fuel production technologies and a wide range of fuel transport and storage infrastructure buildout. Similarly, CCS will require the development of CO_2 storage site development and protocols and pipelines, and nuclear will have to face public acceptance and siting challenges. Developing any clean firm technology at scale will require significant investment and a concerted effort to reduce barriers to deployment. Furthermore, all clean firm resources will need appropriate incentives or market mechanisms in place for them to participate and be profitable in the electricity system. Pursuing a broader range of possible clean firm resources, in addition to renewable technologies, will help build knowledge and experience, as well as encourage further investment across the energy sector to reach a net zero carbon grid sooner.

The result that having multiple clean firm resources within a decarbonized grid is more cost-effective than decarbonized grids with single clean firm resources is consistent across the three independent capacity expansion and dispatch models. This further emphasizes the robustness of the results and that the basis of the outcome was from the techno-economic characteristics of the resources instead of any unique set up of the models themselves. While this analysis focuses on California and the WECC, the techno-economic characteristics of flexible base, intermediate, and firm cycling resources imply that the results of this analysis will likely hold in any region with high share of renewable resources, and especially more so for regions such as the Northeast and Southeast US where the wind and solar resources may be of lower quality. Given the importance of affordably decarbonizing the electricity sector globally, this analysis highlights the integral role that multiple clean firm resources with varying techno-economic characteristics can play in decarbonizing the grid cost-effectively. Future work can be done to understand the role, value, and operation of clean firm resources in pathways for decarbonizing at less stringent emissions goals.

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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.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.egycc.2021.100046.

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