PATHWAYS TO CARBON NEUTRALITY IN CALIFORNIA

Decarbonizing the Electricity Sector

March 2022

About

About the Stanford Center for Carbon Storage

Carbon Capture, Utilization, and Storage is a key technology for achieving net-zero greenhouse gas emissions. The Stanford Center for Carbon Storage (SCCS) uses a multidisciplinary approach to address critical questions related to flow physics, monitoring, geochemistry, geomechanics and simulation of the transport and fate of carbon dioxide stored in partially- to fully-depleted oil & gas fields and saline reservoirs. SCCS is an affiliates program associated with the Stanford University School of Earth, Energy and Environmental Sciences.

About the Stanford Carbon Removal Initiative

The Stanford Carbon Removal Initiative (SCRI) seeks to create science-based opportunities and solutions for gigaton-scale negative emissions and atmospheric carbon removal. The initiative helps to enable removal of atmospheric greenhouse gasses at scale by generating and integrating knowledge, creating scalable solutions, informing policies for technology deployment and governance, and demonstrating approaches and solutions with industry collaborators. All of this is done with a focus on social acceptance and equity, as well as environmental, economic, and social costs. SCRI is an affiliates program associated with the Precourt Institute for Energy and the Woods Institute for the Environment.

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International Brotherhood of Boilermakers

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List of Acronyms

AB	Assembly Bill
BECCS	Bioenergy with carbon capture and storage
BTM	Behind-the-meter
CARB	California Air Resources Board
CCS	Carbon capture and storage
CEC	California Energy Commission
CHP	Combined heat and power
CO_2	Carbon dioxide
CPUC	California Public Utilities Commission
DAC	Direct air capture
DR	Demand response
EV	Electric vehicle
Gas-CCS	Gas power plant with carbon capture and storage
GHG	Greenhouse gas
GW	Gigawatts
GWh	Gigawatt-hours
ICE	Internal combustion engine
IOUs	Investor Owned Utilities
IRP	Integrated Resource Planning process
kWh	Kilowatt-hours
LCOE	Levelized cost of electricity
MMBTU	Million British thermal units
mpge	Miles per gallon equivalent
MtCO2e	Million metric tonnes of CO_2 equivalent
MWh	Megawatt-hours
MW	Megawatt
PV	Photovoltaic
RPS	Renewable Portfolio Standard
SB	Senate Bill
TWh	Terawatt-hours
ZEV	Zero emissions vehicle

Key Findings

- The future electricity load is a significant driver of overall system costs. The size of the future grid will likely drive the total costs, regardless of the pathway chosen for decarbonization.
- The system cost of a grid does not scale linearly with the load size, meaning larger grids are more expensive on a $/MWh basis relative to smaller ones.
- For future systems that only expand intermittent generation resources with shorter duration energy storage (<10 hours), curtailment and overbuild will likely be a challenge, and the challenge increases with higher electricity load.
- The choices we make in technology options and pathways have a much larger impact for systems with higher electricity loads than smaller ones.
- Diversifying generation resources is the most effective way to reduce system generation capacity.
- PV and energy storage will be the mainstays of California's future energy system and experience the most growth in capacity relative to all other technologies.
- Gas generation will be needed for reliability in California's energy mix through 2040.
- By 2045, a clean source of dispatchable generation will be needed to maintain reliability.

Introduction

California is the largest state in the United States (U.S.) by population, and in 2019, was the fifth largest economy in the world, after only the United States, China, Japan, and Germany [1]. California has long been a leader in climate policy, which has inspired climate policies globally and in the U.S. California's early climate action stemmed from Assembly Bill (AB) 32 (2006), the California Global Warming Solutions Act of 2006. AB32 was the first program in the country to require a reduction of greenhouse gas emissions and take a comprehensive, long-term approach to doing so [2]. Since the passing of AB32, there have been several other policies to support California's ambition for climate action. Most notably, California has an executive order in place that calls for the state to achieve carbon neutrality economy-wide by 2045 [3].

Because of its ambitious climate goals, many energy systems models have been used to assess California's decarbonization policies. Scenario-based stock models assessing pathways for reaching California's AB32 goals emphasize that widespread electrification would be crucial, and decarbonized electricity would become the primary form of energy supply [4–6]. Wei et al. (2013) emphasized energy efficiency, electrification, and a shift from fossil fuel resources in meeting future greenhouse gas emissions targets [7]. Yang et al. (2015) found that while all low carbon resources are important, carbon capture and storage (CCS) would be a key technology for achieving the lowest mitigation costs [8]. Jacobson et al. (2014) considered an energy system for California utilizing only renewable resources and emphasized the role of energy efficiency in achieving the goals, assuming a 44% decrease in end-use power demands [9]. Overall, economy-wide studies of California's decarbonization have emphasized the importance of decarbonizing the grid, as well as the importance of a wide range of technologies including but not limited to renewable resources, energy efficiency, and carbon capture and storage (CCS). Similarly, more recent U.S.-wide studies that assess pathways for reaching economy-wide net-zero emissions by 2050 also commonly emphasize the need for 1) end-use energy efficiency, 2) electrification, 3) clean electricity, and 4) CCS [10,11].

In recognizing the importance of clean electricity, California passed Senate Bill (SB) 100, which established a 60 percent Renewable Portfolio Standard (RPS) goal for 2030 and a 100 percent clean electricity grid goal by 2045 [12]. In parallel, the California has established several policies encouraging electrification throughout the state. There is an executive order in place to reach 5 million sales of zero-emission vehicles (ZEVs) by 2030 [13], and an executive order that sets the goal of 100 percent of in-state sales of new passenger cars and trucks to be zero-emission by 2035 [14]. Concurrently, the state has several initiatives in place to encourage the development of infrastructure for transportation electrification around the state [15]. In the residential and commercial sectors, several cities have banned natural gas connections for new housing builds, fundamentally requiring electrification for those buildings [16–18]. California's 2022 Building Code reflects California's push for electrification with measures such as encouraging electric heat pump technology as well as establishing electric-ready requirements for new buildings when natural gas is installed [19]. As such, consistent with previous decarbonization studies, California already has implemented policies of electrifying, and concurrently decarbonizing the electricity grid.

Current Status of Electricity Sector Emissions and Generation

In 2019, the share of emissions from the electricity sector in California was 14%, which was lower than the national average of 25% [20,21]. In 2019, the total emissions from the electricity sector in California were 58.8 $MtCO_2e$, of which 37.2 $MtCO_2e$ (63%) were from in-state generation and 21.7 $MtCO_2e$ (37%) were from imports (Figure 1).

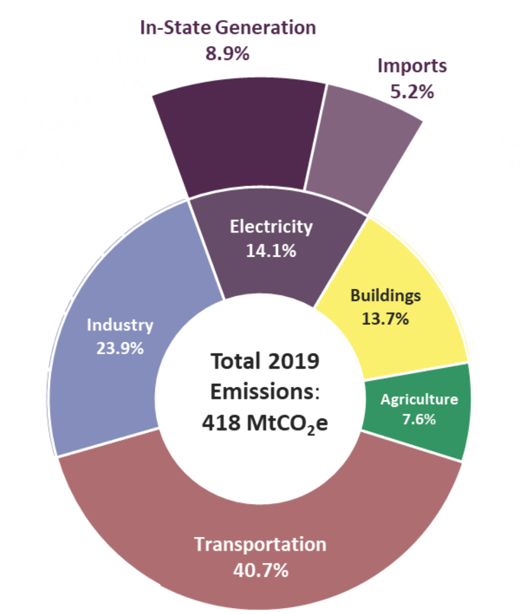


Figure 1: California 2019 Emissions. Adapted from CARB GHG Emissions Inventory (2021) [21].

California's electricity sector has seen continuously declining emissions (Figure 2). Since 2000, electricity sector emissions have decreased by 44%, while the total level of load has increased by 3% [21,22]. As a result, the greenhouse gas intensity of California's electricity sector has decreased significantly from 0.41 $MtCO_2e/MWh$ in 2000, to 0.21 $MtCO_2e/MWh$ in 2019 [21]. Notably, the decline in emissions from imports has been larger than the decline in in-state emissions, with the in-state emissions decreasing by 37% since 2000, and import emissions decreasing by 53%.

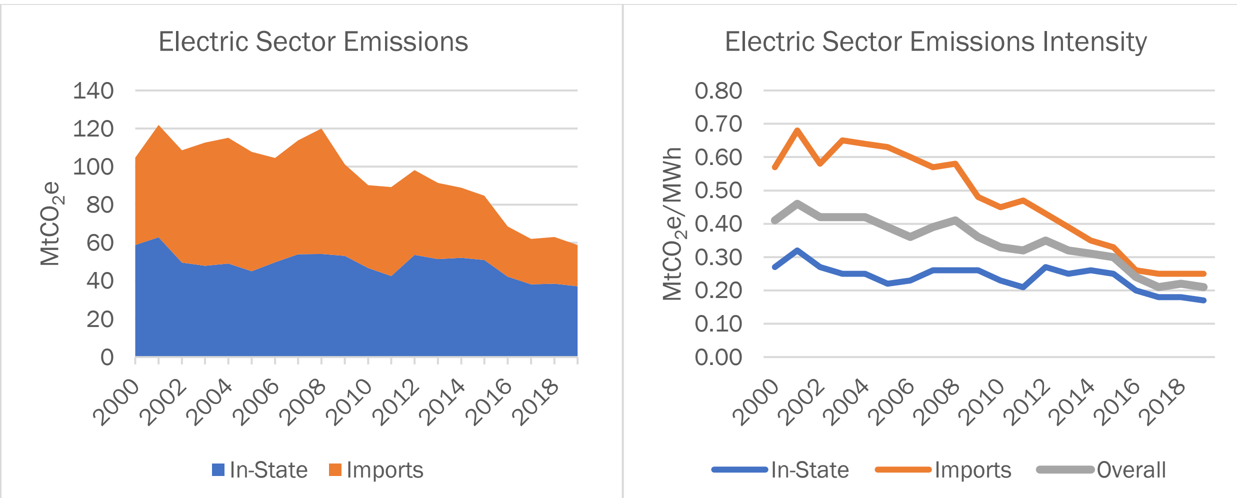


Figure 2: California historic electric power emissions and emissions intensity. California's electricity sector has seen continuously decreasing emissions, resulting in decreasing emissions intensity for both in-state generation and imported electricity. Adapted from CARB GHG Emissions Inventory (2021) [21].

Emissions from in-state generation in California have decreased largely by increasing the share of renewable resources in California's grid. Since 2010, combined solar and wind generation increased by seven-fold to reach 23% of total in-state generation shares in 2020 [21,23]. Wind generation in California has remained relatively constant since 2015, which indicates that solar PV has been responsible for much of the growth in renewable generation in the state (Figure 3).

Outside of the state, California's energy policies have helped replace imports from coal and natural gas generation with renewable resources from out of state [21]. Furthermore, regions outside of California have also generally seen decreases in emissions as coal plants have been replaced with natural gas generation.

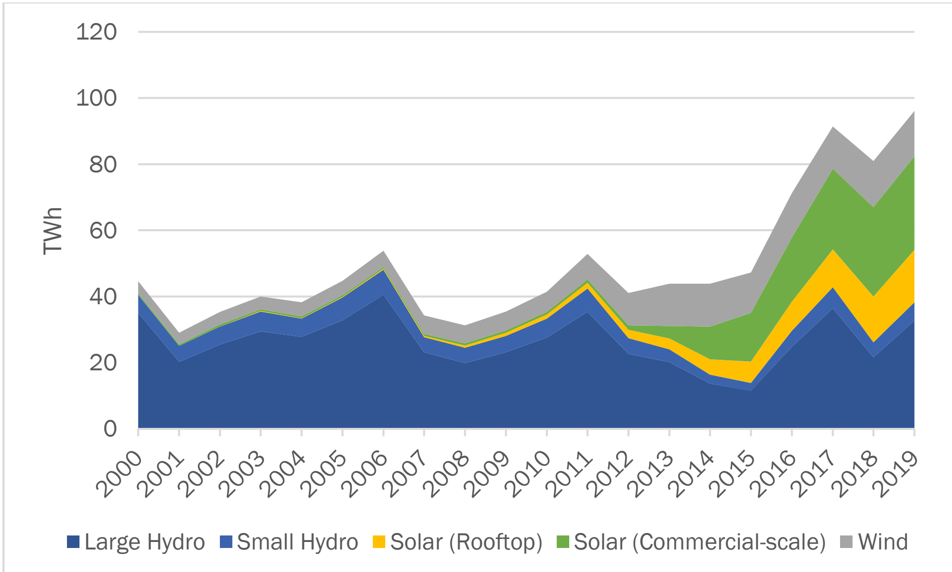


Figure 3: California in-state hydro, solar, and wind electricity generation. California's in-state renewable generation has increased over two-fold since 2000. In particular, PV generation has increased the most. Adapted from CARB GHG Emissions Inventory (2021) [21].

Current Electricity System

Figure 4 shows California's generation mix in 2019. Clean resources including wind, solar, geothermal, biomass, hydro, and nuclear generation account for 41% of the state's generation shares, while natural gas accounts for 31%. Imports account for the other 28% [24].

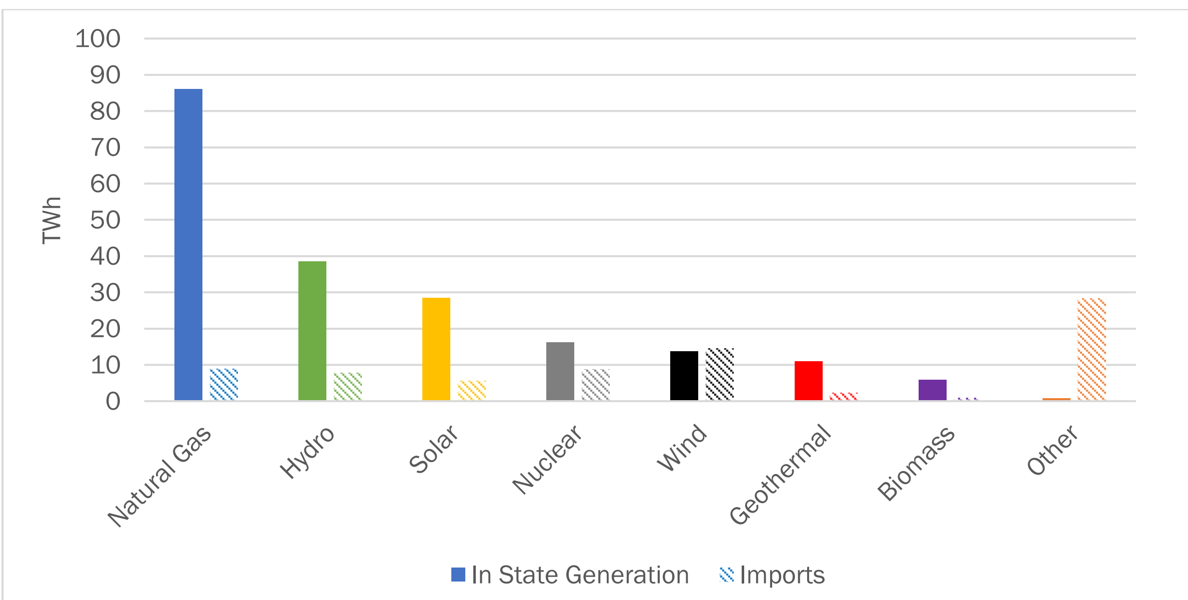


Figure 4: California 2019 electricity generation shares (in-state generation solid bar, imports hatched bar) . Clean resources including wind, solar, geothermal, biomass, hydro, and nuclear generation account for 41% of the state's generation shares. Source: California Energy Commission 2020 [23].

While there is a large share of renewable energy generation in the state, hydro generation varies significantly from year to year, accounting for anywhere from 7% (in 2015) to 21% (in 2011) of total in-state generation [24]. Year-to-year variations in hydro and other renewable generation is made up with natural gas generation (Figure 5). Furthermore, natural gas makes up for the sub-hourly and hourly fluctuation of intermittent resources on a daily basis (Figure 6). This underscores the important role that natural gas plays in California's electricity system as the marginal source of generation both on an hourly and seasonal basis in ensuring system reliability.

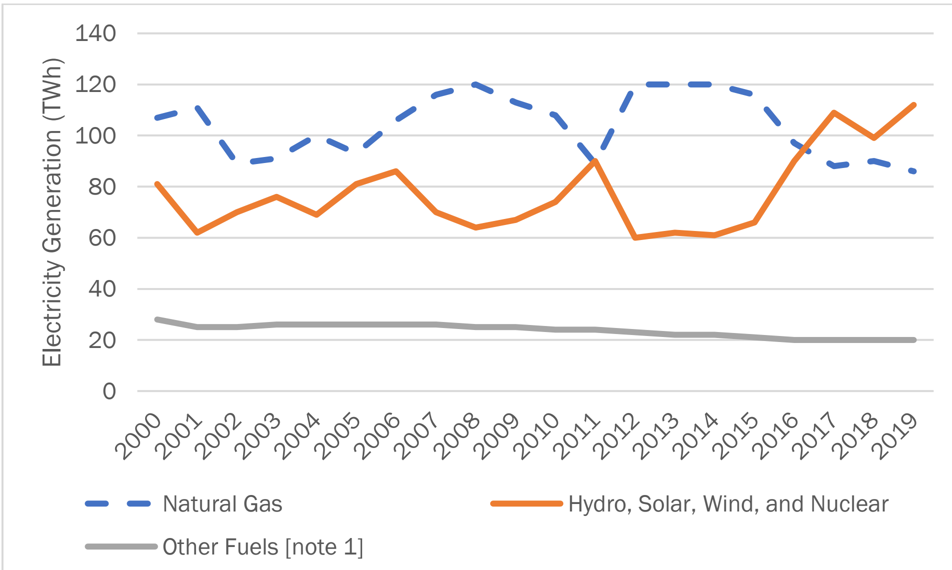


Figure 5: California 2019 in-state year-to-year generation. California's variation in year-to-year generation of gas and hydro, solar, wind, and nuclear generation. In-state natural gas generation complements the year-to-year fluctuations of variable resources. Note 1: "Other Fuels" include associated gas, biomass, coal, crude oil, digester gas, distillate, geothermal, jet fuel, kerosene, landfill gas, lignite coal, MSW, petroleum coke, propane, purchased steam, refinery gas, residual. Adapted from CARB GHG Emissions Inventory (2021) [21].

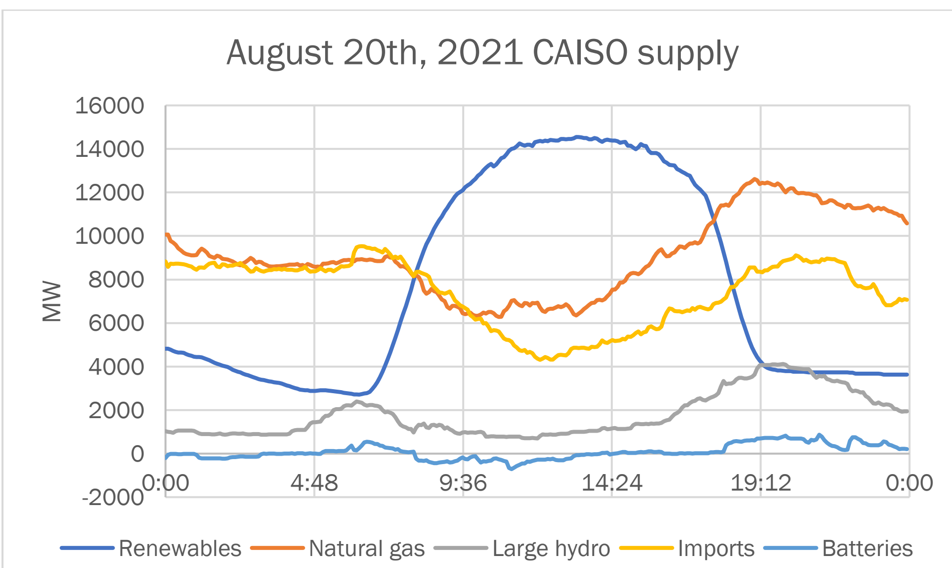


Figure 6: California hourly generation for random 2021 August day. California's variation in hourly generation of renewables, natural gas, hydro, imports, and batteries. Natural gas generation complements the hourly

fluctuations of renewable generation. The figure shows the supply of electricity on August 20th, 2021. Source: California Independent System Operator 2022 [25].

Natural Gas Generation in California

Natural gas generation in California plays a critical role in California's grid. It provides the largest capacity for the state's required level of resource adequacy capacity and also is the marginal generator that often fills the gap left by intermittent or seasonal generation resources. However, in the absence of coal generation in California, and as one of the largest shares generation in-state, natural gas also accounts for over 90% of California's in-state emissions (Figure 7). Because of its critical role in ensuring reliability but associated emissions, the future of natural gas in California remains unclear.

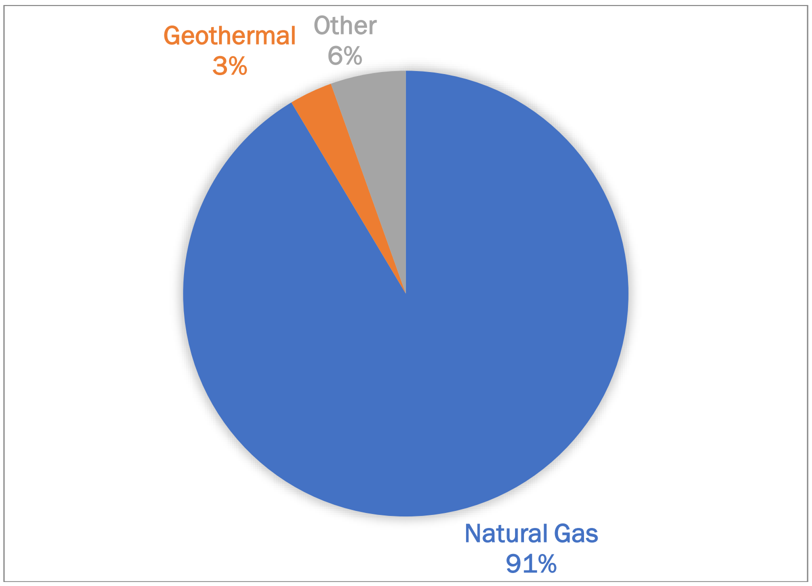


Figure 7: California 2019 in-state emissions share by source. Natural gas is responsible for over 90% of emissions in California's electricity sector. Source: 2019 Emissions & Generation Resource Integrated Database (eGRID) [26].

The California Public Utilities Commission (CPUC), California Energy Commission (CEC), and California Air Resources Board (CARB) published a Joint Agency report on meeting the SB100 goal of serving 100% of retail sales with clean energy sources, The report states that the continued use of natural gas generators will be necessary to maintain reliability through 2045. Most of the natural gas generation in 2045 is utilized to serve non-retail load or system losses, thus allowing compliance with SB100 in meeting 100% of retail sales with clean energy sources, while still having associated emissions. The report does not specify how the economy-wide carbon neutrality goal would be met with such a grid composition. However, the study does suggest that zero-carbon firm resources such as hydrogen fuel cells or CCS on natural gas power plants may reduce the need for unmitigated gas power plants. In a specific case, the Joint Agency report simulated a no-combustion scenario excluding natural gas combustion, which increased the annual costs by 12% and still had associated emissions from out-of-state imports.

As of today, there are 190 power plants in California dedicated to electricity generation where the primary fuel is natural gas. The 190 powerplants consist of 483 separate generators, of which 153 (32%) are combined cycle generators, 176 (36%) are combustion gas turbines, and 19 (4%) are steam turbines. Other types of generators include fuel cells and internal combustion engines.

Despite the relatively small number of generators, combined cycle generators account for more than 50% of the total gas generating capacity and nearly 90% of the total gas generation (Figure 8). Combined cycle generators are often larger and more efficient, given they utilize excess heat from combustion turbines to then operate a steam turbine. Such a role emphasizes the importance of decarbonizing combined cycle gas power plants in California.

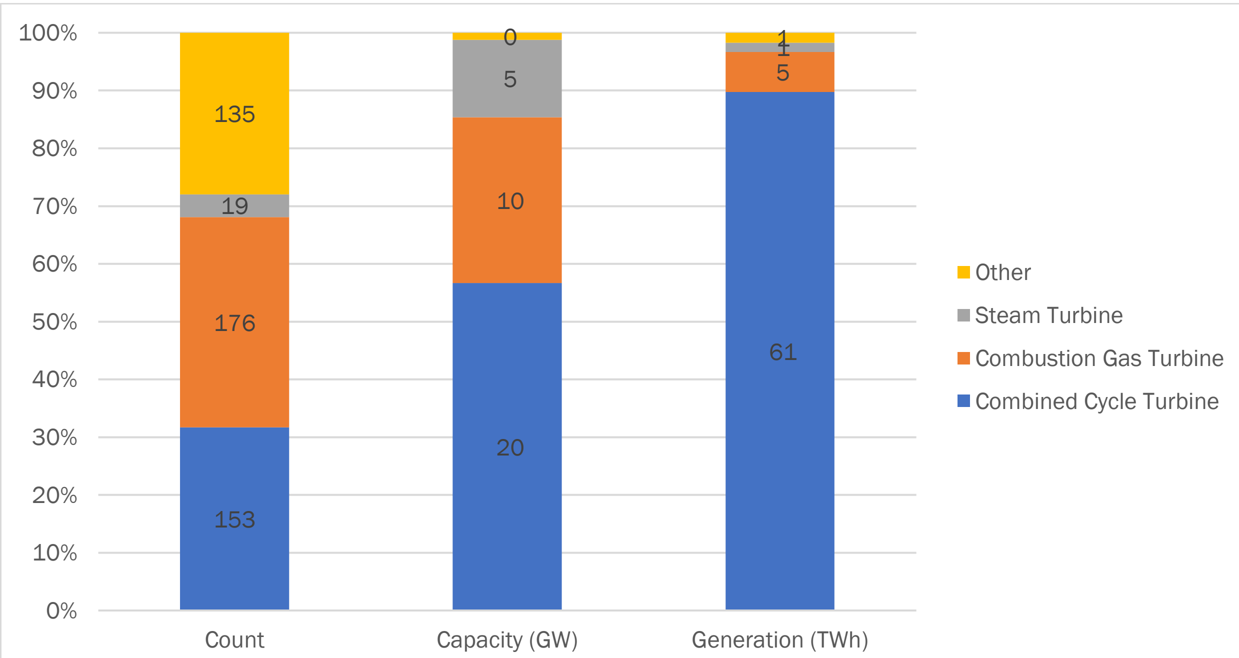


Figure 8: California 2019 natural gas generator count, capacity, and generation by type. Combined cycle gas turbines account for the largest capacity and generation. Source: 2019 Emissions & Generation Resource Integrated Database (eGRID) [26].

Decarbonization Opportunities

California has a wide range of potential resources that can be utilized to decarbonize its electricity sector. The following section includes a brief description of existing resources and technologies that would be available in California for future expansion.

Renewable Technology

Renewable resources have been the main focus of California's electricity sector decarbonization policies, and as a result, have seen the most significant growth in the past 5 years (Figure 9). Policies such as the Renewable Portfolio Standard (RPS), which establish required levels of renewable energy to serve a certain fraction of the load, have been key to California's decarbonization of the electricity sector while advancing renewable resources. In 2002, the first RPS was established by SB 1078, with an initial goal of meeting a 20% RPS by 2017. In 2015, SB 350 accelerated the goal to a 50% RPS by 2030, and recently, SB 100 increased the RPS goal to 60% by 2030.

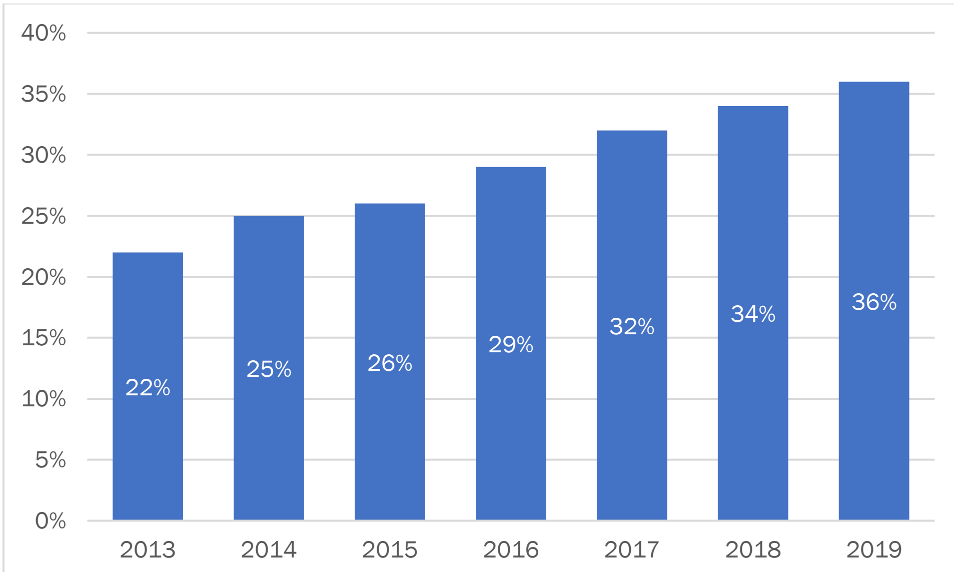


Figure 9: California estimated annual renewable percentage. Annual renewable percentage as estimated by the CEC has continued to increase. Source: CEC 2020 [27].

In California, eligible renewable resources for RPS include but are not limited to solar, wind (both onshore and offshore), biomass, geothermal, and small hydroelectric resources. Given limitations in expanding hydro resources, this section will focus on solar PV, onshore wind, and offshore wind resources.

Solar PV

Solar is the most abundant resource in California and has seen the most growth of any generation resource in California. In the past five years, solar generation has increased over 350%, and Behind-the-Meter (BTM) solar resources have increased by nearly 120% [27]. This can largely be attributed to decreasing costs of solar PV, as well as policies such as the RPS. As a result, solar PV is currently the most installed renewable capacity in the state.

Solar PV is abundant in the state, but most focused in the southeastern regions. Current capacity factors average 24% [24], but as more and more single or double axis tracking panels are installed, capacity factors may increase in the future. Solar PV potential is considered to be unlimited in state, and will likely be the mainstay of California's future electricity system. Scaling solar PV may face challenges such as development delays from land use constraints or regulatory hurdles, or the pace of energy storage or transmission line deployment.

Onshore Wind

Onshore wind energy accounted for nearly a third of California's renewable energy production in 2019 [27]. The majority of existing wind turbines in California are in six regions: Altamont, East San Diego County, Pacheco, Solano, San Gorgonio, and Tehachapi, operating with average capacity factors of approximately 26% in 2020 [24]. Given relatively moderate onshore wind potential in California, future expansion for onshore wind is likely limited in-state. However, California has future opportunities to import wind energy from surrounding regions that have higher capacity factor wind potential at lower costs. The potential for importing wind energy is largely limited by transmission capacity.

Offshore Wind

There are currently no deployed offshore wind plants in California. However, the Bureau of Ocean Energy Management–California Intergovernmental Renewable Energy Task Force was established in 2016 to help identify coastal regions in California that would be suitable for offshore wind energy. Since then, there have been studies outlining the costs and potential of offshore wind in California [28,29]. Five areas in particular have been studied in depth due to their widely dispersed geographic locations, as well as ongoing commercial-scale offshore wind projects that are under consideration. The five areas are: Morro Bay, Diablo Canyon, Humboldt, Cape Mendocino, and Del Norte [28].

The technical potential of offshore wind in California is abundant, with estimated average net capacity factors of approximately 49% [28]. Cost declines for offshore wind are also optimistic, where the levelized cost of electricity (LCOE) of offshore wind is estimated to decline by 44% between 2019 and 2032 [28]. However, given the deep waters off California's coast, offshore wind in the state will likely use floating wind platforms, which are currently still in pre-commercial phase. Continued technology advancement and deployment will likely be needed to scale offshore wind in a timely manner.

Energy Storage

Energy storage resources allow shifting intermittent generation to times when the generation is needed, such as times of high demand of low output from intermittent resources. Energy storage resources help integrate a larger share of intermittent resources while also helping reduce peak demand or defer investment in generation, transmission or distribution resources. Energy storage resources can also provide several grid services including frequency regulation, voltage support, and resource adequacy, thereby contributing to the reliable operation of the grid.

Given this important role, energy storage resources will be critical in California reaching its SB100 goals. The Senate Bill 100 Joint Agency report highlights that the future deployment rate of energy storage will have to reach 8 times the rate in 2020 [30], which emphasizes the urgency of action needed. There are a wide range of energy storage technologies including but not limited to pumped hydro, thermal, electrochemical, flywheel, and compressed air energy storage. Energy storage technologies also widely vary in discharge duration (energy to power ratio), from minutes to days. Short and Long duration storage technologies each play different roles in the grid and are briefly described below.

Short Duration Energy Storage

Short duration storage resources of less than 8 hours in duration often fill intermittencies on an hourly basis. There is legislation in place to advance the development and deployment of energy storage including but not limited to partnering with federal agencies in investing in demonstration projects, setting targets for utilities to procure grid-connected energy storage (AB 2514) and providing incentives for energy storage utilized for self-generation (Self-Generation Incentive Program).

With such efforts, California accounts for 40% of the total battery storage power capacity that is planned for installation between 2021 and 2023 in the US [31]. Recently, Pacific Gas and Electric proposed several new energy storage projects, amounting to 1,600 MW at 4 hours in duration. Short duration energy storage technology costs continue to decline significantly and will likely play a critical role in California's future energy grid.

Long Duration Energy Storage

Given its larger energy capacity and duration, long duration energy storage is able to fill intermittencies on a daily or weekly basis relative to short duration energy storage resources. Examples of long duration energy storage resources include pumped hydro, compressed air energy storage, and hydrogen storage. In California, there is currently 4.5 GW of pumped hydro storage operating, with 4,500 GWh of energy storage capacity. In addition, there have been planned long duration storage projects of compressed air energy storage amounting to 900 MW with 8 hours in duration [32].

In 2016, AB 33 required CPUC, in conjunction with the CEC, to evaluate and analyze the potential for long-duration energy storage. There is ongoing research on the potential value and role of long duration storage in future decarbonized grids. Recent analyses have highlighted that while long duration storage resources have value, the costs of long duration storage will have to decrease further for it to contribute in a meaningful way to cost-effective decarbonization [33].

Clean Firm Resources

Previous literature has highlighted the value that clean firm resources can have in decarbonizing electricity systems [34,35]. Firm resources provide reliable energy during times when intermittent generation output is low, or when load is high during peak times. Firm resources complement intermittent resources to provide cost-effective decarbonization in a reliable manner. Below are some examples of clean firm resource options that are available in California for future expansion.

Gas with Carbon Capture and Storage

Gas with carbon capture and storage (Gas-CCS) is a technology that captures CO_2 from natural gas power plants. While there are many options for capturing CO_2, post-combustion capture is a technology that is widely commercialized and utilized in the industrial sector today. Post-combustion capture typically captures 80-90% of the emitted CO_2, though research has shown that close to 99% can be captured with higher energy penalty and investment costs [36]. Post-combustion capture of CO_2 can be installed at existing gas power plants or in new builds. California also has significant and suitable geologic CO_2 storage sites [37].

However, there is currently no commercially operating Gas-CCS power plant, and the technology faces some public opposition because it utilizes fossil-fuel. If deployed, the technical potential of Gas-CCS is large compared to anticipated demand due to ample existing natural gas infrastructure and a variety of potential locations for CO_2 storage. Potential limitations of Gas-CCS may occur from limited gas availability during peak time due to limited pipeline import capacity or storage capacity of natural gas. Peak times for gas occur in the winter time for heating and in the summer due to high electricity usage for air conditioning.

Biomass

Currently, there are 87 operating biomass power plants in California, utilizing a wide range of biomass fuels including biomass residues, dairy digester gas, landfill gas, wastewater sludge, and municipal solid waste [38]. Biomass residues include but are not limited to forest slash, urban wood waste, lumber waste, and agricultural wastes. California's biomass power generation was at its peak in the early 1990s, but has consistently decreased since then largely due to the expiration of government subsidies and difficulty in competing on cost in the current energy market [39]. However, there is ongoing research and development in biomass energy given its value as a clean firm resource, as well as its contribution in better managing biomass waste from forests thereby reducing wildfire risks.

There is further potential for expansion for biomass resources for electricity production in the state. The potential for biomass combustion is relatively limited, and there are concerns of air pollution from combusting biomass that pose a challenge in biomass playing a significant role in a future decarbonized grid. Furthermore, while most landfill and dairy biogas projects are currently directed towards electricity production, more and more of the produced biogas is being pushed towards transportation liquid fuel production due to Low Carbon Fuel Standard credits. The companion study “Pathways to Carbon Neutrality in California: The Bioenergy Opportunity” [40] assesses biomass potential from agricultural residues, dairy manure, landfill gas, and wastewater sludge that could be available for the production of electricity, RNG and liquid fuels (e.g., renewable LNG), as well as potential for biofuels. Another companion study “Pathways to Carbon Neutrality in California: The Forest Management Opportunity” [41] highlights further opportunities and challenges for forest management for bioenergy as well.

Geothermal

California has the largest potential for geothermal resources in the United States, and accounts for more than 20% of the total geothermal energy production worldwide [42]. California’s ample geothermal potential is due to its location on the Pacific “ring of fire”. There are a total of 40 operating geothermal power plants in California, with approximately 2.7 GW in capacity [43]. The Geyser region located in Lake and Sonoma Counties currently have the most geothermal plants, while other production locations include the Salton Sea area in Imperial County, the Coso Hot Springs area in Inyo County, and the Mammoth Lakes area in Mono County [44].

There is ongoing research and development to further the deployment of geothermal resources within the state, including the Geothermal Grant and Load Program as well as state and federal partnerships [45]. In particular, enhanced geothermal technologies can help California access previously unavailable geothermal energy and expand the technical potential of geothermal resources in the state. However, in the near-term with existing technologies and resources, the potential of new geothermal energy is relatively limited to approximately 2 GW [46].

Zero Carbon Fuel

Zero carbon fuels include but are not limited to clean hydrogen or biofuels. Hydrogen or biofuels can serve as substitutes for storable or transferrable fuels that are currently utilized in the electricity system such as natural gas. Zero carbon fuels can be utilized to generate electricity via direct combustion or fuel cells. Hydrogen combustion turbines are currently in development, while commercially existing fuel cells can utilize hydrogen. Furthermore, clean hydrogen can be utilized to produce carbon neutral natural gas via methanation. Biofuels can be integrated into existing natural gas combustion turbines or utilized in fuel cells. As a versatile fuel source, the role of zero carbon fuels in the electricity sector will likely depend on how the fuels may be utilized in other parts of the economy as well. Further details on the future potential and use of clean hydrogen and biofuels can be found in the companion studies "Pathways to Carbon Neutrality in California: The BioEnergy Opportunity" [40] and "Pathways to Carbon Neutrality in California: The Hydrogen Opportunity" [47].

Transmission and Distribution

In addition to a wide range of generation resources, transmission and distribution resources can be utilized effectively to contribute to cost-effective and reliable decarbonization of the grid.

Interstate Transmission

California is already one of the largest importers of electricity in the United States. Further expanding interstate transmission enables California to source renewable energy from a wider geographic footprint, which includes resources with higher capacity factors, lower costs, or operational patterns that better complement California's energy load. Some examples include wind and hydro resources from Idaho, Wyoming, and the Pacific Northwest. Several studies show that expanding interstate transmission and enabling more energy exchange across regions to be a cost-effective method for decarbonization [10,48]. However, there are several challenges in expanding interstate transmission due to complex siting and permitting processes, as well as intersecting state, regional, and federal policies. Furthermore, building interstate transmission lines may take many years, which emphasizes the need to plan ahead of time in order to deploy the transmission lines in a timely manner.

Demand Side Management

As shares of intermittent renewable generation resources increase in the grid, there is a growing need for flexibility to maintain the balance of supply and demand. There are several forms of demand side management that can provide value to the grid including but not limited to load reduction, peak shaving, and load shifting capabilities. In recognizing the value and importance of demand side management, there are already voluntary programs in place in California, such as incentives for smart appliances, paying less normally but more for peak day pricing, or earning incentives for reducing energy consumption when needed [49]. Furthermore, CPUC ordered the state's three investor-owned utilities (IOUs) to transition to time of use rates for its customers by 2019, unless they opt out.

The growing presence of smart appliances, electric vehicles, and the internet-of-things can enable more demand side management to contribute to California's future decarbonized grid. Further research on programs that are needed and how they should be implemented is likely needed for wide-spread utilization of demand side management.

Distributed Generation

California leads the nation in distributed generation, with 1.4 million solar projects with nearly 12 GW of capacity. There are several policies in place to promote BTM solar PV including a mandate to include solar panels in new single-family and low-rise residential buildings (Building Energy Efficiency Standards – Title 24), as well as incentives for BTM PV and storage resources.

Increasing shares of distributed generation resources can be an effective way to increase the share of renewable generation in the grid, while also providing resiliency for individual customers. However, for the grid, the value of distributed generation can vary significantly based on the size, location, and feeder characteristics of the resource, and so strategically deploying distributed resources will be important [50]. Currently, there are challenges with scaling distributed generation resources based on assessing the right level of compensation and economic incentives for distributed generation resources. Furthermore, setting up the right regulatory structure will be needed to promote higher levels penetration of distributed generation.

Modeling: Potential Pathways to Decarbonizing California's Electricity Sector and the Impact of Electricity Demand

Future load growth is impacted by a wide range of factors. First, the level of electrification of the transportation, commercial and residential, and industrial sectors are the largest drivers of potential load growth in California. Electrifying end-uses of energy and cleaning the grid have often been found to be one of the most cost-effective ways of reducing emissions economy-wide cost-effectively [10]. The degree of electrification will drive the overarching load growth, but uncertainty remains on how much electrification will occur. Furthermore, electrification will likely impact the shape of the load in the future, largely depending on various charging times for electric vehicles, or energy usage in homes.

Second, the development and utilization of hydrogen may also impact the level of future electricity load. If large amounts of hydrogen are to be utilized in the future economy, and if the hydrogen is sourced via electrolysis, the electricity load will likely increase as well. However, increased utilization of hydrogen may also imply that end-uses of energy in the transportation, commercial and residential, and industrial sectors use hydrogen instead of electricity, thereby decreasing future potential electricity demand. Thus, the overarching impact of hydrogen usage on the electricity sector is a large uncertainty.

Finally, energy efficiency has long been an important pillar of California's reduction in emissions which will likely continue in the future. Similar to AB 32, California was the first state to implement electricity-usage efficiency standards, which have continuously tightened until today. Standards have also been supplemented by voluntary incentive programs that reward households, property managers, and developers for using appliances that exceed the state standards. These standards and programs have resulted in over 70 TWh of saved electricity from appliances, buildings, and other usage in the past 40 years [51]. Future energy efficiency measures may have an important impact on the level of future electricity loads.

Despite this wide range of uncertainty in assessing future electricity load levels, existing modeling literature on California's electricity sector have so far assumed a narrow range of electricity system loads into the future. In a state-sponsored study of economy-wide pathways to deep decarbonization (Mahone et al. (2018)), the range of electricity system load assumptions was 403-592 TWh by 2050, with the base assumption being a high electrification scenario resulting in 456 TWh of load in California by 2050 [6]. The SB100 Joint Agency Analysis report also took results from Mahone et al. (2018) as its default electricity demand scenarios. A study of decarbonizing California's electricity sector that utilized three independent models (Baik et al. (2021)) assumed 475 TWh of electricity load by 2045 in California as well.

No study has yet assessed the uncertainty of future load levels and its potential impact on the grid. Given that future California load demand will be the driving force of the total grid size, understanding its impact on the grid will be critical as California plans its future energy system. Further questions arise on how different technology mixes respond to changing load sizes, providing further insight into optimal technology mixes that are robust to future load uncertainty. This analysis addresses these questions using a detailed capacity expansion and dispatch model to assess future electricity systems in California over a wide range of electricity loads and across several technology scenarios.

Capacity Expansion and Dispatch Model urbs

In this analysis, a detailed capacity expansion and dispatch model, urbs, is used to assess various pathways for achieving a carbon neutral California grid by 2045. The model has previously been utilized in several studies and reports on decarbonizing California's electricity grid [35,52,53]. The open source model code and detailed mathematical description of the model is available on the urbs github page [54] [B].

Methods

For modeling electricity grid systems, generation expansion plans are the most widely used models to determine optimal portfolios to decarbonize the grid [55–57]. Comprehensive reviews of electricity grid models have commonly highlighted the importance of resolving details in time and space in the models [55,57], especially as the ratio of variable renewable resources increases as a solution to decarbonize energy systems. Models that combine capacity expansion and economic dispatch have the ability to consider not only the capital costs for developing different technologies, but also the ability to simulate detailed time-scale dynamics [56]. As both the load and supply of electricity become more dynamic, reflecting the temporal intermittency of variable renewable resources, the operational constraints of thermal resources, and the impacts of spatial distribution of generation have now become indispensable in energy systems modeling [58]. Consequently, capacity expansion and dispatch models are indispensable tools in informing future policies to decarbonize in a cost-effective and equitable manner.

[B] https://urbs.readthedocs.io/en/latest/

urbs is a dispatch and capacity expansion model that designs future large-scale power systems to meet policy standards while minimizing total costs. For capacity expansion, urbs determines what type and how much of generation, transmission, or storage capacities need to be added to each region to construct the optimal power system. For hourly dispatch, urbs utilizes generation, transmission, or storage resources from all regions cost-optimally to meet the hourly demand profiles in each region.

The optimization goal is to minimize the costs of the system which involves annualized capital costs for new capacities built, as well as fuel costs, and fixed and variable operational costs for a given year. The optimization is subject to operational constraints of generation, transmission, and storage technologies, as well as policies such as a RPS, a CO_2 tax, or a CO_2 regulation. The capacity expansion and dispatch model provides insight into the interaction of various resources within a system as opposed to assessing each technology individually. This method prioritizes the practicality of results while also allowing for analysis of complex investment decisions and operational behaviors within the model.

The main inputs into the model are hourly future electricity demand, technology costs and availability, as well as the policy assumptions. The following section describes the assumptions for this analysis.

Forecasts of Future Electricity Demand

Future electricity demand profiles are developed bottom-up from detailed data from companion studies on the Transportation, Industrial, Commercial, and Residential sectors [59–62]. For each sector, 2-3 future load profiles based on a range of decarbonization assumptions are provided. The individual load profiles and assumptions are then brought together to form the total electricity system demand. The three main cases are Low, Medium, and High electricity load.

The three scenarios are not meant to be precise estimates of what future load may be. Instead, the range is chosen to be representative of a wide range of electricity loads and peaks that the future electricity system might encounter. By showcasing a wide range of potential future loads under different scenarios for each sector, the modeling demonstrates the consequences of varying grid sizes on the level of capacity build needed, and range of resources that may be needed.

For the Low electricity load case, a baseline scenario is considered for all sectors, which mimics business as usual load growth without any drastic changes in electrification or hydrogen production. Note that in all sectors, the energy consumption has remained relatively constant as shown in Figure 10, with average change in load being less than 1% for all sectors since 2000.

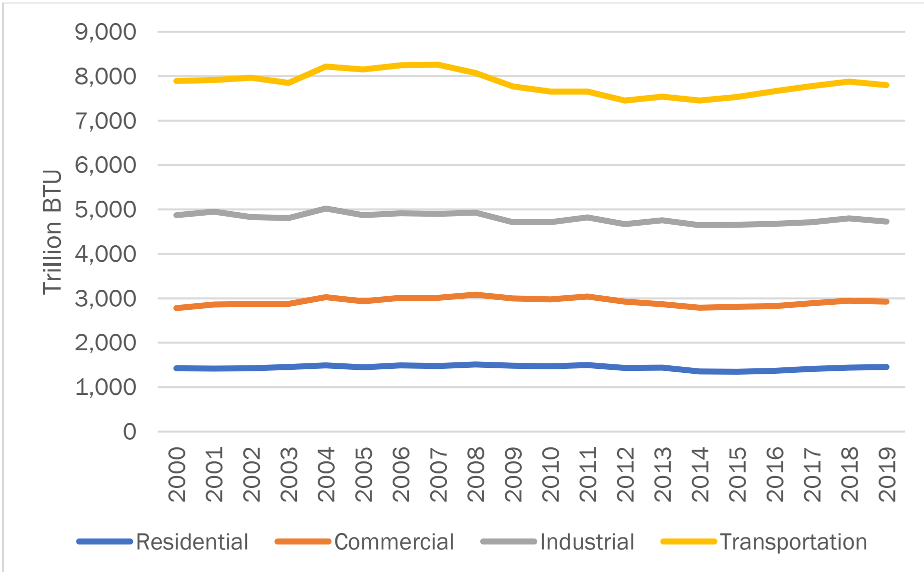


Figure 10: Historic energy consumption by sector in California. Historic energy consumption has remained relatively constant in California. Source: EIA 2021 [63].

Industrial Sector

In the industrial sector, the two major potential pathways of decarbonization are 1) CCS and 2) High Electrification. The two scenarios are informed by information from the companion study "Pathways to Carbon Neutrality in California: Decarbonizing the Industrial Sector" [62]. In both decarbonization scenarios, some level of CCS exists for hard to decarbonize industries such as cement and refineries. Overall, electrification levels are generally low in the industrial sector given challenges in electrifying and more cost-effective alternatives for decarbonizing the sector. Further details on decarbonizing the Industrial Sector can be found in the companion study mentioned above [62].

In the industrial sector, the incremental electrification shares were converted to electricity loads based on historic demand [64,65]. A constant load running for all 8760 hours is assumed for all industrial sector electricity loads. For the baseline case (Low electricity load case), 2020 levels of electricity usage is held constant through 2045. The details of the 2 additional cases are shown in Table 1.

Case		**2019 Total Energy Consumption (TBTU)**	**Incremental Electrification Levels %**				
	Subsector		2025	2030	2035	2040	2045
Carbon Capture and Storage Case	Oil and Gas	273	0%	0%	0%	0%	0%
	Refining and H2	606	0%	0%	0%	0%	0%
	Cement	49	0%	0%	0%	0%	0%
	Landfills	0	0%	0%	0%	0%	0%
	Manufacturing	530	5%	10%	13%	16%	19%
	Transmission & Distribution	22	0%	0%	0%	0%	0%
	Other	0	0%	0%	0%	0%	0%
	Total	1480					

High Electrification Case	Oil and Gas	273	10%	30%	50%	70%	90%
	Refining and H2	606	0%	0%	0%	0%	0%
	Cement	49	10%	35%	55%	80%	100%
	Landfills	0	0%	0%	0%	0%	0%
	Manufacturing	530	15%	30%	45%	65%	83%
	Transmission & Distribution	22	3%	6%	9%	11%	11%
	Other	0	0%	0%	0%	0%	0%
	Total	1480					

Table 1: Industrial sector electrification cases. Incremental electrification shares for two different future electricity load cases for the industrial sector.

Residential Sector

In the residential sector, space heating and water heating are collectively responsible for the majority of residential natural gas end use. As such, decarbonizing space and water heating will be the most important consideration in electrification of end-use energy. Electrification of residential end loads can predominantly be achieved with two families of technologies: electric resistance heating and heat pump heating. Resistance heating involves converting electricity directly into radiant heat. Heat pumps work by moving heat from the air or the ground rather than generating heat and are more energy efficient than resistance heaters, but often have higher costs. Residential electrification scenarios modeled also assume fully electrified cooking and clothes drying. More detail on the technologies can be found in the companion study “Pathways to Carbon Neutrality in California: Decarbonizing the Residential Sector” [60].

Decarbonization scenarios and corresponding load profiles are built using **ResLEAP**, which is detailed in “Pathways to Carbon Neutrality in California: Decarbonizing the Residential Sector” [60]. The first case is **Electrification Low Load**, where space and water heating are converted high levels of heat pump heating and low levels of electric resistance heating, thereby reducing the impact on the grid. The second decarbonization case is **Electrification Medium Load**, which assumes less heat pump heating and more resistance heating, given that ducted heat pump systems may not be suitable for all homes, whether for affordability reasons, physical/structural reasons, or others. Note that the scenarios used here are slightly different than those used in the companion study [60]. The baseline case for the residential sector assumes the addition of new homes based on population growth, without assuming any decarbonization. For highly electrified residential sectors, the electricity usage peaks in the wintertime (Figure 11) due to heating needs. The details of the baseline and 2 additional cases are shown in Table 2.

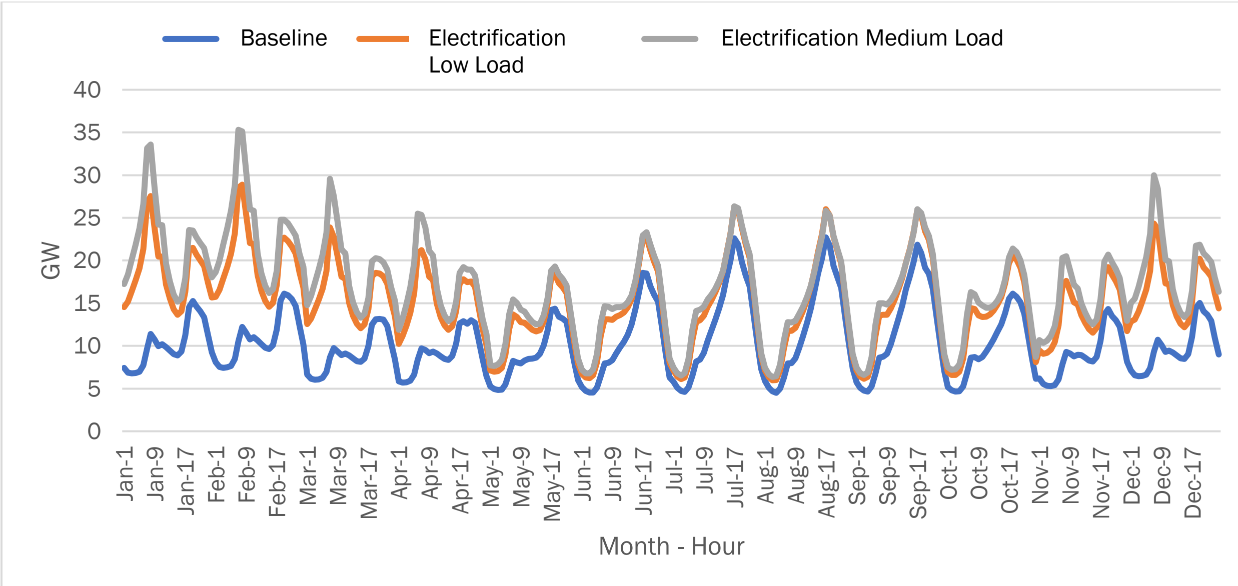


Figure 11: Daily load shapes by month in 2045 for residential sector. The figure shows average daily load curves for each of the 12 months in a continuous line. The residential sector becomes a winter peaking system due to high heating needs in the wintertime.

Case	2025	2030	2035	2040	2045
Baseline	87	87	88	89	90
Electrification Low Load	103	118	126	133	136
Electrification Medium Load	109	128	139	146	149

Table 2: Residential sector electricity demand by case in TWh. Electricity demand for the residential sector for three different electrification cases.

Commercial Sector

The main uses for natural gas in the commercial sector are heating, water heating, cooking, and combined heat and power plants (CHPs), while the main uses for electricity are cooling, fans, lights, and plug-in appliances. Heating is responsible for most of the direct emissions in the commercial sector. Decarbonizing heating and water heating will be relatively cost-effective and doable if utilizing heat pumps or electric boilers. However, cooking will be relatively difficult to decarbonize because there are a lot of small businesses that are unwilling or unable to electrify cooking.

As such, the future electrification scenarios in the commercial sector focus on electrifying heating and water heating needs. The scenarios are taken from the companion report "Pathways to Carbon Neutrality in California: Decarbonizing the Commercial Sector" [61]. One case, consistent with Scenario 1 in the companion report, assumes 100% decarbonization of the heating and water heating usage with 50% electric boilers and 50% heat pumps, while another case, consistent with Scenario 2 in the companion report, assumes decarbonization with 70% electric boilers and 30% heat pumps (Table 3). However, given the relatively low load and only a minor difference in efficiency between heat pumps and electric boilers, the total electrification levels between the two cases do not vary significantly. Existing historic shapes of commercial level sector are scaled for historic average daily load shapes (Figure 12). For the baseline case, 2020 levels of electricity usage is held constant through 2045.

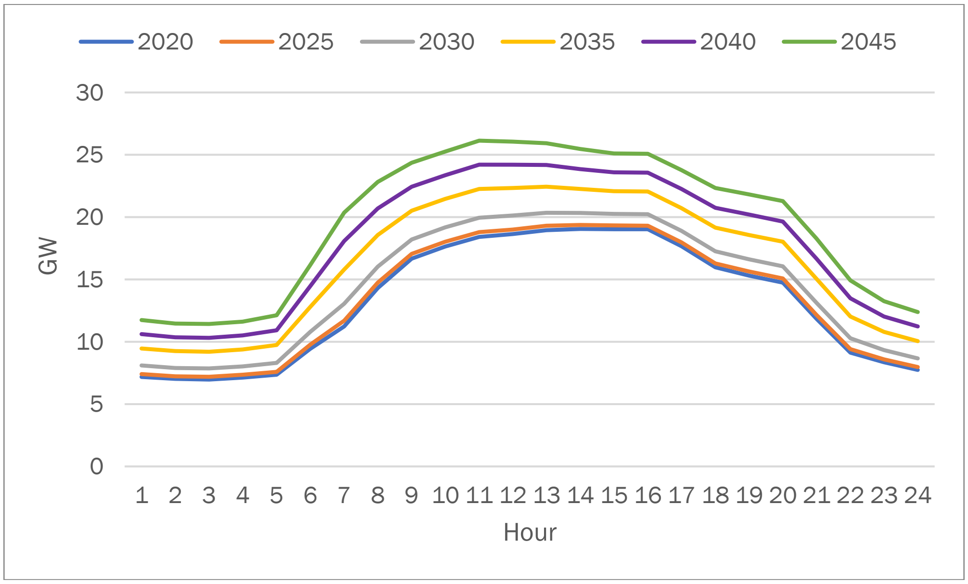


Figure 12: Average daily load shapes for commercial sector. The figure shows average daily load curves for each modeled year for the commercial sector assuming 50% electric boilers and 50% heat pumps. Source: "Pathways to Carbon Neutrality in California: Decarbonizing the Commercial Sector", 2022 [61].

Case	2025	2030	2035	2040	2045
Scenario 1 50% electric boilers 50% heat pumps	119	127	144	158	171
Scenario 2 70% electric boilers 30% heat pumps	119	128	145	160	174

Table 3: Commercial sector electricity loads in TWh. Electricity demand for the commercial sector for two different electrification cases. Source: "Pathways to Carbon Neutrality in California: Decarbonizing the Commercial Sector", 2022 [61].

Transportation Sector – Light Duty Vehicles

The light duty transportation sector includes passenger cars, light duty trucks, and T3 trucks that can all be electrified. Future projections of electricity consumption in the light duty transportation sector are derived from a fleet turn-over model which explicitly sets sales and retirement regimes such that net-zero emissions from the fleet is achieved by 2045 (i.e., no Internal Combustion Engine (ICE) vehicles by 2045). More details on the model can be found in the companion study "Pathways to Carbon Neutrality in California: Decarbonizing the Transportation Sector" [59]. Fresh vehicle sales, which are more efficient and have higher mpge (miles per gallon equivalent), are assumed through the fleet-turnover, which result in a reduction in the energy required for transportation each year. For instance, the mpge of a new battery electric vehicle is 110-130 mpge compared to average gasoline vehicles (27-34 mpg), which reduces the amount of total fuel in million gasoline gallon equivalent from 14,000 to 2,705. Electrification reduces not only emissions but also net primary energy requirements for transportation.

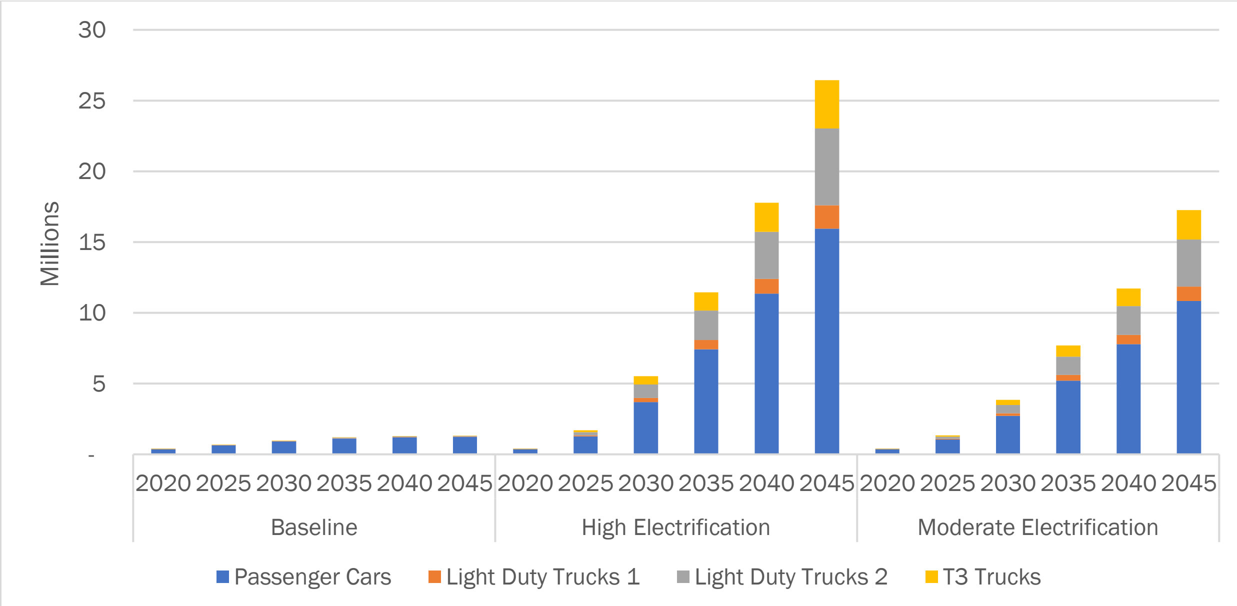


Figure 13: Number of light duty electric vehicles by electrification cases. Source : "Pathways to Carbon Neutrality in California: Decarbonizing the Transportation Sector", 2022 [59].

The **Baseline** case assumes current sales fraction of different fuel types to continue until 2045. The **High Electrification** case assumes 100% electrification of passenger vehicles in California starting 2035, and the **Moderate Electrification** case, with 100% ZEV sales by 2035, assumes a sales ratio of 2:1 for Battery Electric Vehicles/Fuel Cell Vehicles in passenger cars starting in 2035 until 2045, while assuming sales ratios for trucks (T1, T2, T3) at 1.5:1. The resulting number of electric vehicles over the years for each case is shown in Figure 13. Charging profiles are derived from National Household Transport Survey 2017's vehicle and trip level data, with the assumption that vehicles will be fully recharged each week [66].

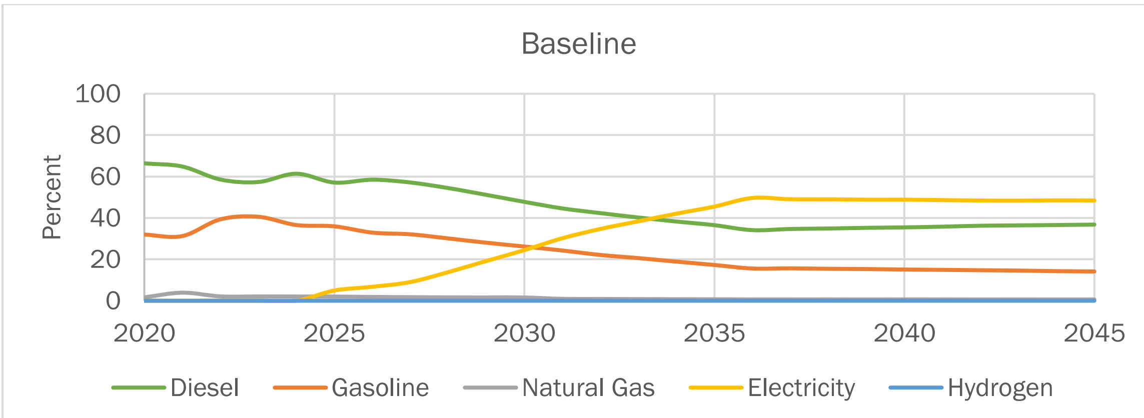
Across all sectors, electrification of light duty vehicles is the largest contributor to electricity growth and drives the overall load in the final economy-wide demand scenarios.

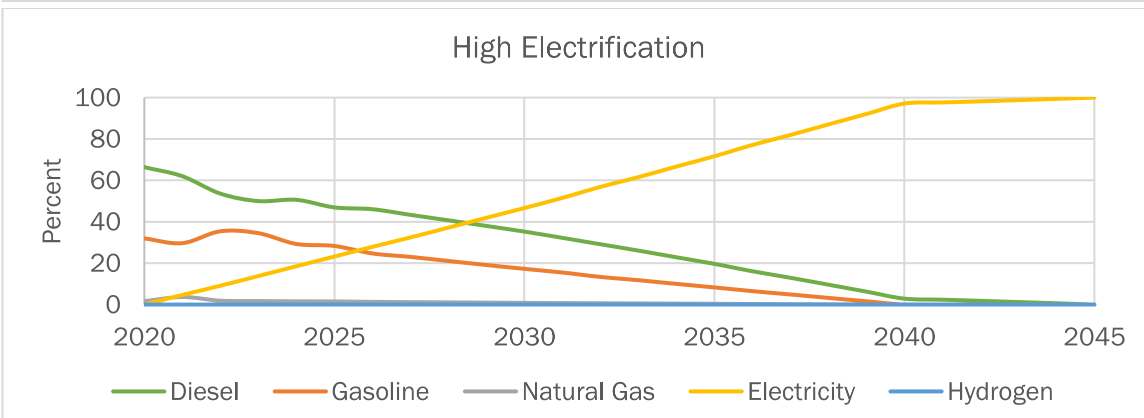
Transportation Sector – Heavy Duty Vehicles

Heavy-duty vehicle types include heavy duty pickup trucks, delivery vans, short-haul trucks, long-haul trucks (semis), port vehicles, buses, motorhomes, etc. The existing fleet information for heavy duty vehicles is taken from the California Air Resources Board's EMission FACtor (EMFAC) 2021 Emissions Inventory [67].

Similar to the light duty vehicle assumptions, future projections of electricity consumption in the heavy-duty transportation sector are also derived from a fleet turn-over model which explicitly sets sales and retirement regimes. For the heavy-duty vehicles, adjusting sales alone is not sufficient to reach zero ICE vehicles, as older ICE vehicles will remain on the road even after sales are entirely electric. To account for this, early retirement of older ICE vehicles is forced in the model. In the heavy-duty model, a ban of ICE vehicles greater than fifteen years old is implemented starting in 2035, and a ban of all ICE vehicles is implemented in 2045. Rather than assuming that all vehicles meeting these criteria's will be retired at once, a five-year phase-in period is assumed in which a fraction of vehicles that will be impacted by the ban are retired each year. To make up for the large number of early retirements, each vehicle that is retired early is replaced by a new ZEV vehicle.

The **Baseline** case assumes a moderate increase in total vehicle sales, and moderate electrification of the heavy-duty fleet. This is based on EMFAC 2021 Fleet Database projections of California's heavy-duty fleet. The **Moderate Electrification** case assumes a mix of hydrogen and electric vehicles that ultimately reaches net zero emissions by 2045. The share of vehicles sales by fuel type is shown in Figure 14. The **High Electrification** case assumes net-zero emissions from heavy-duty vehicles by 2045 utilizing only electric vehicles. Charging profiles are derived from the 2017 National Household Transport Survey [66].





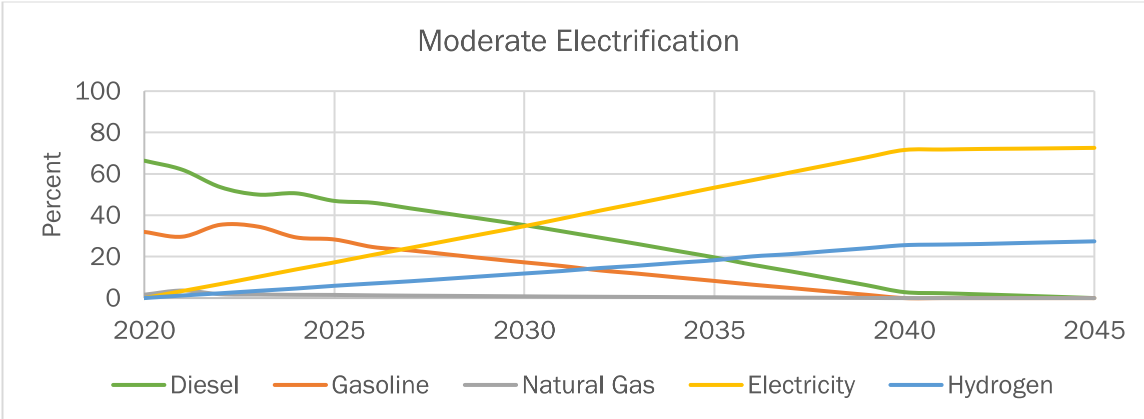


Figure 14: Share of light duty electric vehicles by electrification cases. Source : "Pathways to Carbon Neutrality in California: Decarbonizing the Transportation Sector", 2022 [59].

Three Electricity Demand Cases

The individual electrification cases from each sector are brought together to form three electricity demand cases: **Low**, **Medium**, and **High** electricity loads. Overall, the **High Electricity Load** case is consistent with a future in which all end-use of energy uses in the transportation, residential, and commercial sectors are electrified. The **Medium Electricity Load** case is consistent with moderate levels of electrification in the transportation sector, given the potential use of other technologies such as fuel cell vehicles for decarbonization of the transportation sector. The **Medium Electricity Load** case also assumes more optimistic electrification profiles of residential and commercial sector with more efficient technologies, while the industrial sector assumes more use of carbon capture and storage for decarbonization relative to electrification. The **Medium Electricity Load** case is most consistent with electricity loads modeled in previous literature. Finally, the **Low Electricity Load** case assumes baseline or constant load growth for all sectors, regardless of the potential for full decarbonization in other economic sectors. Details for the 3 cases are outlined in Table 4 below.

Sector	High Load Case	Medium Load Case	Low Load Case
Transportation – heavy	High Electrification	Moderate Electrification	Baseline
Transportation – light	High Electrification	Moderate Electrification	Baseline
Residential	75% Heat Pump 25% Resistive Heating	100% Heat Pump	Baseline
Commercial	70% Electric Boilers 30% Heat Pumps	50% Electric Boilers 50% Heat Pumps	Constant (no change from today)
Industrial	High Electrification (with some CCS)	Carbon Capture and Storage	Constant (no change from today)

Table 4: High, Medium, and Low Electricity load cases and the corresponding cases for each sector.

This analysis aims to demonstrate the impacts of varying levels of electrification of a range of sectors on the electricity grid in California by assessing a wide range of future load possibilities. A plot of historic load growth and the three different projections of load are shown in Figure 15. The **High Electricity Load** case exceeds 2.5 times the load in 2020, while the **Medium Electricity Load** case approximately doubles the electric load of 2020. The **Low Electricity Load** case corresponds to approximately a 13% increase in load relative to 2020. The **High Electricity Load** case also shows much higher daily peaks than the **Low** or

Medium Electricity Load cases as shown in Figure 16. Table 5 summarizes the load growth from each sector.

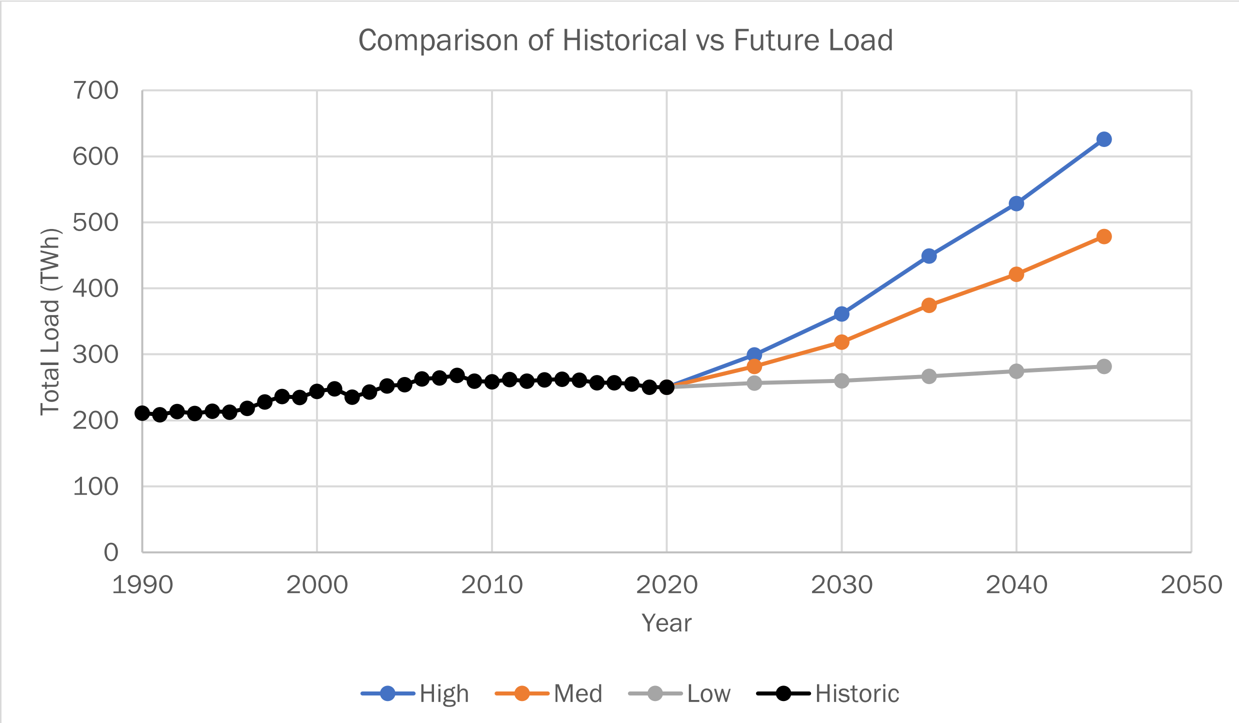


Figure 15: High, medium, and low electricity load projections with historic load growth. Comparison of historic electricity loads with future load growth scenarios show the wide range of future load projections. Source: EIA 2021 [63].

		transport - heavy	transport - light	residential	commercial	industrial	Total
Low	2025	0	3	87	116	50	**256**
	2030	2	4	87	116	50	**259**
	2035	7	5	88	116	50	**267**
	2040	14	6	89	116	50	**275**
	2045	19	6	90	116	50	**282**
Medium	2025	1	6	103	119	53	**282**
	2030	4	15	118	127	55	**319**
	2035	21	27	126	144	56	**374**
	2040	33	40	133	158	58	**421**
	2045	54	59	136	171	59	**479**
High	2025	2	7	109	119	62	**299**
	2030	7	21	128	128	78	**362**
	2035	33	40	139	145	92	**449**
	2040	54	61	146	160	108	**528**
	2045	90	91	149	174	121	**626**

Table 5: Table summarizing the electricity load contribution from each sector by electricity load case in TWh.

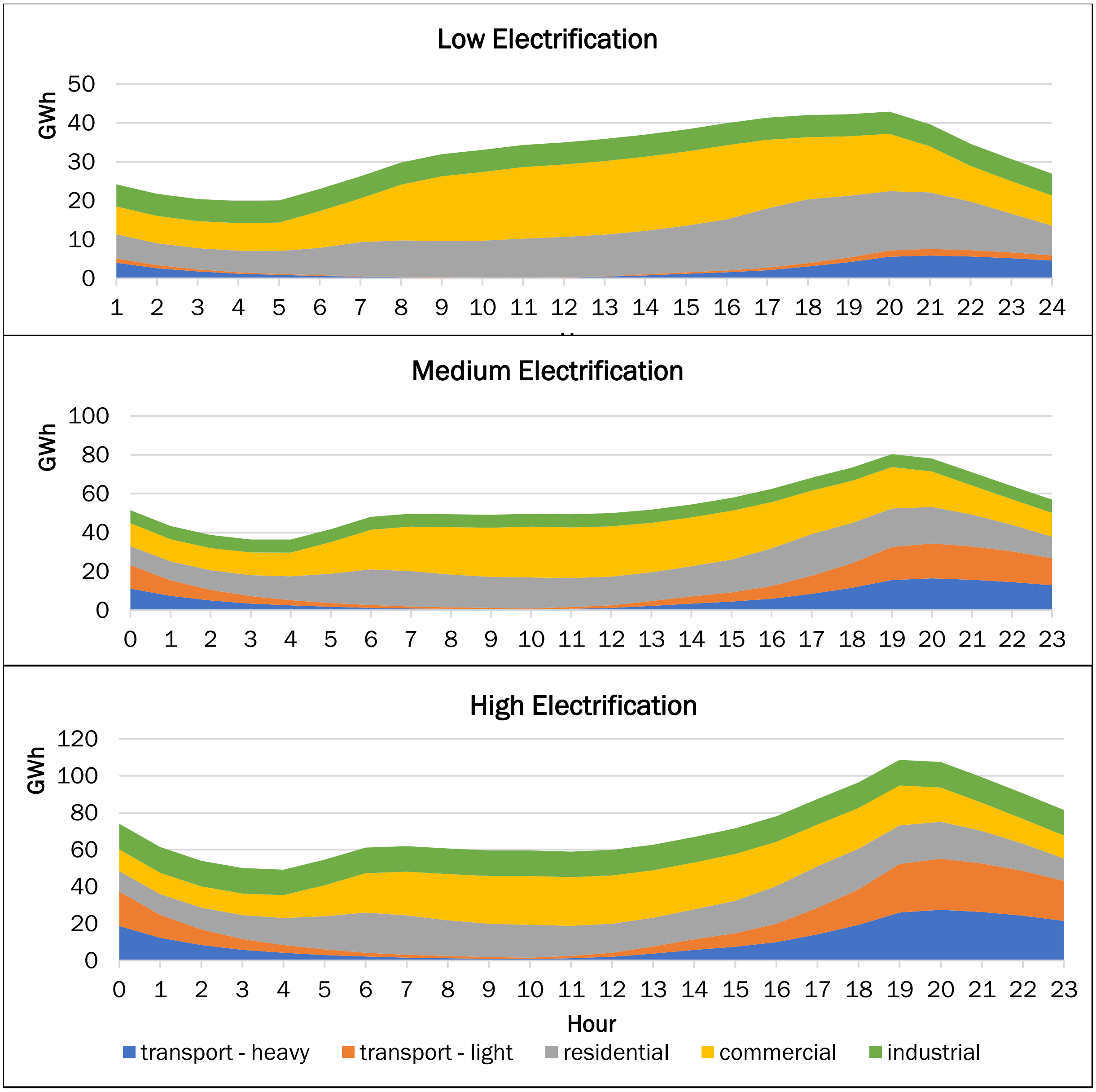


Figure 16: Daily average electricity load by sector. High Electrification case shows a daily system with higher peaks relative to the Low or Medium Electrification cases.

Model Assumptions

In addition to electricity demand assumptions, technology availability and expansion capacity assumptions for the modeling are also taken from California's Senate Bill 100 Joint Agency Report [30] and shown in Table 6.

	Additional Capacity
Solar PV	No limit
Onshore Wind	+11 GW in-state and out-of-state
Offshore Wind	+10 GW
Storage (li-ion batteries)	No limit
Storage (Pumped Hydro)	+4 GW

Biomass	+1.1 GW
Geothermal	+2.4 GW
CCGT	No limit
Peaker	No limit
Gas with Carbon Capture and Storage (Gas-CCS)	No limit
Fuel Cell	No limit
Demand Response (DR)	+ 3 GW

Table 6: Additional expansion capacity allowed through 2045. Limited potential of onshore wind, offshore wind, biomass, geothermal, and pumped hydro resources. But unlimited potential of solar PV and li-ion energy storage, as well as clean firm resources such as Gas-CCS or Fuel Cells. Source: 2021 SB100 Joint Analysis Report (CEC, CPUC, and CARB) [30].

Technology Cost Assumptions

Technology cost assumptions for generation and storage technologies are taken from mid future price projections from NREL's 2021 Annual Technology Baseline [68] (Figure 17). Intermittent renewable resources such as solar PV, onshore wind, and offshore wind show decreasing capital costs through 2050. Clean firm generation technologies such as Biomass, Geothermal, and Gas-CCS technologies have high capital costs relative to intermittent renewable resources. Note that li-ion batteries are modeled with a $/kWh energy capacity capital cost and $/kW power capacity capital cost, and the energy to power ratio is optimized within the model. Prices for hydrogen fuel cells are taken from Senate Bill 100 Joint Agency study assumptions. Demand Response (DR) is modeled at $114/kW and $600/MWh, which is consistent with the SB 100 Joint Agency study assumptions as well. Natural gas costs are assumed to be $4.3/MMBTU in 2025 and linearly increase to $4.6/MMBTU in 2045. Clean hydrogen price is assumed to linearly decrease from $3.5/kg in 2025 to $1/kg in 2045.

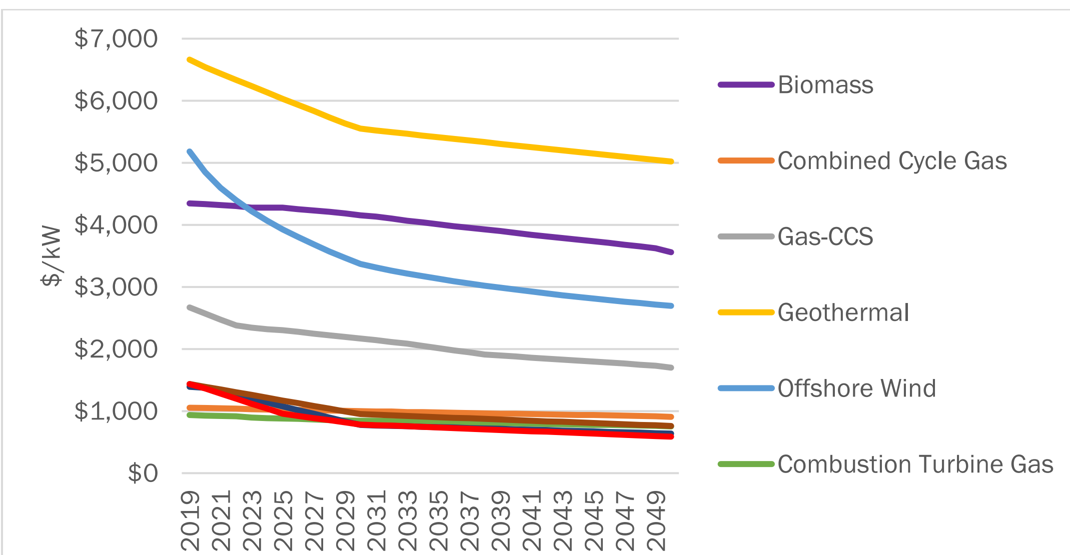


Figure 17: Capital costs for modeled resources ($/kW). Mid future price projections for modeled technologies taken from NREL's 2021 ATB. Li-ion battery prices are in $/kWh. Source: 2021 NREL Annual Technology Baseline [68].

Policy Assumptions

In order to comply with a carbon neutral economy by 2045 in California, the electricity sector will have to reach net zero emissions by 2045 as well. Therefore, a linearly decreasing annual CO_2 emissions constraint that reaches zero in 2045 is applied to the grid (Figure 18). Note that this assumption differs from the SB100 Joint Agency Analysis that allows residual emissions in 2045, as long as 100% of the retail load is met with clean energy sources. In California, natural gas generation has associated CO_2 emissions. In addition, un-specified, or non-dedicated imports from external regions to California are taxed at a carbon emissions rate of 0.428 t CO_2/MWh, which is consistent with California Air Resources Board's accounting of unspecified electricity imports into the state [69].

In addition to an emissions constraint, an increasing price of carbon, consistent with medium projections of future prices of carbon shared in the Senate Bill 100 Joint Agency Report is utilized for this analysis and shown in Figure 18. Note that the price of carbon likely has limited impact on the optimization process or grid design due to the emissions constraint that is binding. However, for scenarios that utilize negative emissions, no emissions constraint is imposed and the price of carbon is highly relevant. The price of carbon represents the price at which residual emissions can be offset using negative emissions technologies with a carbon removal price equivalent to the modeled cost of CO_2.

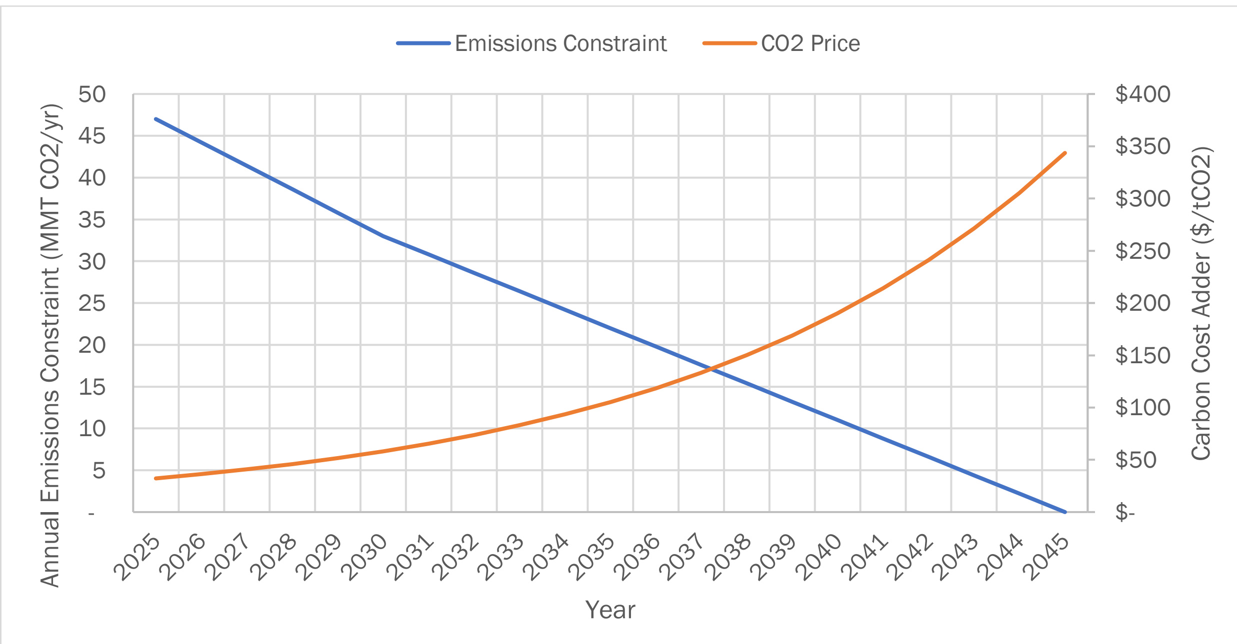


Figure 18: Modeled price of carbon. Mid future price projections for a carbon price taken from Senate Bill 100 Joint Agency Report. Source: 2021 SB100 Joint Analysis Report [30].

Variable Generation Patterns

For intermittent resources such as solar PV, onshore wind, and offshore wind, a time series that governs the exact operation of the generation process is provided, leaving the capacity to be optimized by the model. For example, in the case of a solar resource, a time series of 8760 hours that indicates solar energy generation normalized from 0 to 1 (with 1 being generation at full capacity) at a given site is provided. Within California, multiple solar, onshore wind, and offshore wind profiles are considered to reflect the diversity of generation profiles across the state. Furthermore, the weather profile is varied for each modeled year. Various locations for each resource are modeled to ensure that the geographic diversity of generation in California is captured. The solar PV, onshore wind, and offshore wind generation data are taken from 2015-2019 weather year data from renewables.ninja [70,71] for various locations within California (Figure 19).

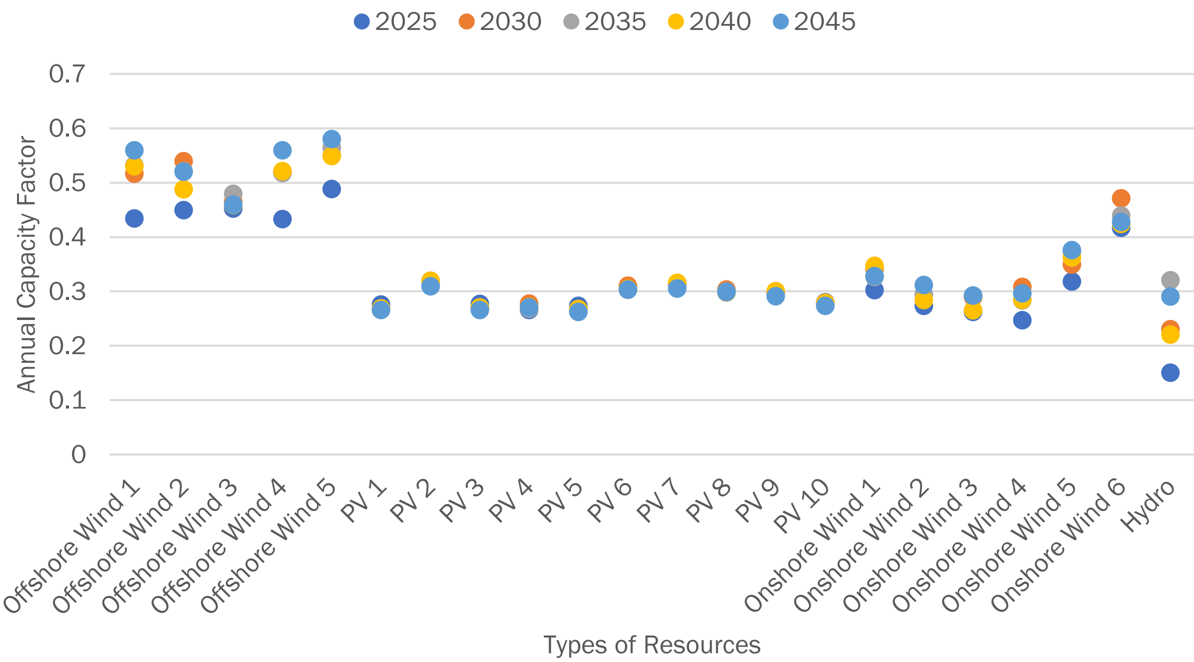


Figure 19: Assumed capacity factors for modeled intermittent resources across the years for different locations. PV shows relatively low variation across weather years relative to onshore wind. Offshore wind and hydro show the most variation across different weather years. Note that some resources modeled are resources outside of California that are assumed to be importable. Source: renewables.ninja 2021 [70,71].

Hydro is a resource that is dispatchable on a limited basis. Some hydro generation is dictated by varying seasonal occurrences, as well as limited on a daily basis. For this reason, hydro is modeled in two ways. 70% of the capacity is modeled as an intermittent resource based on historic operating patterns, which reflects seasonal and daily levels of operation, while 30% of the capacity is left as a fully dispatchable resource only limited by an annual capacity factor of 30%. Historic hydro generation in California is taken from EIA-930, Hourly and Daily Balancing Authority Operations Report [72].

Modeling Scenarios

In addition to the **High, Medium**, and **Low Electricity Load** cases modeled, additional scenarios of technology availability are considered to assess the impact of different technologies on grids of varying sizes. Five scenarios are considered: 1) Base, 2) Clean Firm, 3) Flexible Load, 4) Unmitigated Gas with Negative Emissions, and 5) All, which combines all of the previous scenarios. The scenarios vary what types of resources are allowed to expand in a future grid. The descriptions of the scenarios are listed in Table 7.

The scenarios are organized to demonstrate how clean firm power, flexible load, and utilizing unmitigated gas with negative emissions can each be effective methods to balance the grid with high shares of intermittent renewable resources. Assessing each scenario independently shows how the different resources operate and contribute to building a more reliable and affordable grid.

Scenario	Description
Base	Allows expansion of Solar PV, Onshore Wind, Offshore Wind, Biomass, Geothermal, Gas generation, as well as Energy Storage Resources
Clean Firm	In addition to resources allowed in Base, allows further expansion of Fuel Cells utilizing clean hydrogen and Gas-CCS
Flexible Load	In addition to Base scenario, allows 50% of the light and heavy duty electrification load each year to be shiftable
Unmitigated Gas with Negative Emissions	From Base assumptions, no emissions cap is set, allowing unmitigated emissions assuming negative emissions technologies at the assumed price of carbon in 2045 of approximately $340/ton.
All	Allows all the technologies above

Table 7: Descriptions for the modeled scenarios used in this study.

For the flexible load scenario, instead of assuming historical charging profiles for all electrified load, approximately 50% of the light and heavy duty vehicles are assumed to be charged optimally as determined by the model. The resulting load profiles from flexible load shifting can be achieved by policy driven charging behaviors or integration of smart charging technologies. Each load that is shifted is allowed to be delayed by 3 days, while the shift can only occur once a week. The shiftable load in each hour is limited to 50% of the annual peak of light and heavy-duty vehicle charging.

Negative emissions technologies are not explicitly modeled in the scenarios. Rather, by setting a high cost on CO_2, the resulting energy system and residual emissions can be considered cost-effective assuming that the residual emissions would be removed with a negative emissions technology with a carbon removal price equivalent to the modeled cost of CO_2.

Modeling Results and Insights

Across all scenarios, load is a significant driver of overall system costs. The drastically increasing present value of system costs with increasing load shown in Figure 20 indicate that the level of future investments and operating costs needed to maintain a grid will depend significantly on the level of future electricity demand. This trend is consistent across all scenarios, implying that the size of the grid will likely drive the total costs, regardless of the pathway chosen for decarbonization.

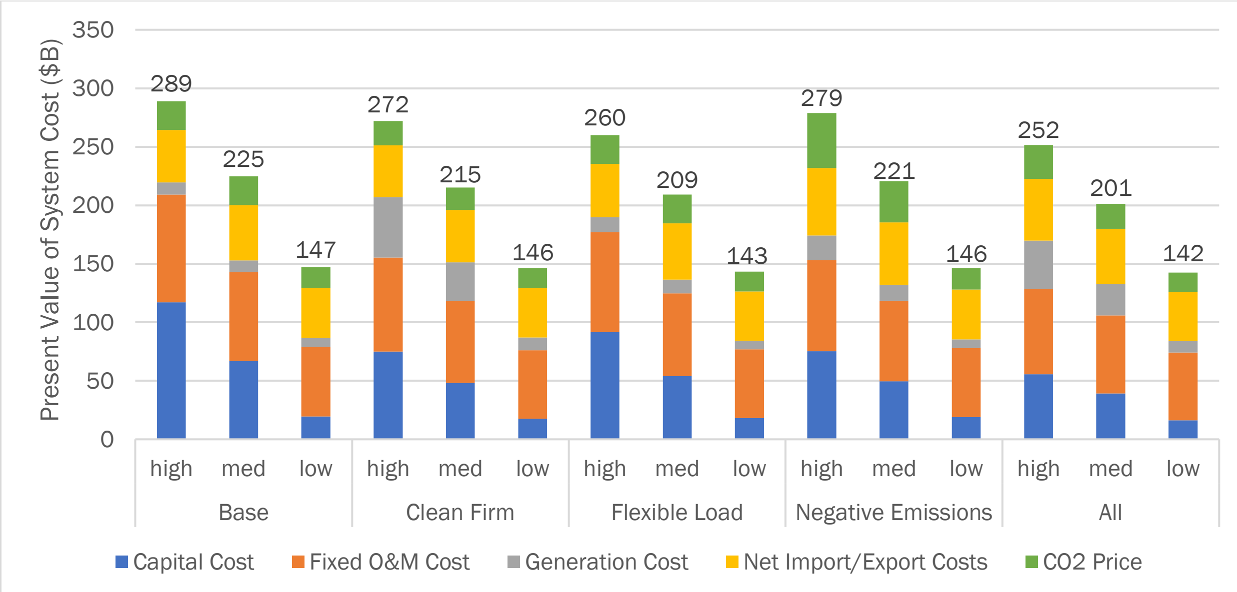


Figure 20: Present value of cumulative system costs between 2025-2045. Generation costs include fuel costs and variable O&M costs. Net Import/Export costs are calculated by assessing the marginal price of electricity at the time of import/export. The numbers on the bars are the cumulative costs. CO_2 price is the modeled price of carbon multiplied by the emissions.

To assess the impact of scale, the modeled present value of system costs is divided by the average load size for each case. These normalized costs indicate that larger systems with higher loads have higher costs per MWh than smaller systems. This implies that the increase in costs due to the level of load does not increase linearly. This is driven by the fact that the investments in technologies do not grow linearly with load. With the decreasing marginal contribution of capacity and energy by intermittent renewable resources, and particularly solar PV, system capacity must increase more than the incremental capacity needs from increasing load. This results in a non-linear increase in investments with increasing load.

Furthermore, the degree of non-linear increase in normalized system costs also vary across the different scenarios assessed, as shown in Figure 21. This means when system size is small, the range of resulting normalized system costs are lower than when the system size is large. This implies that as electricity load increases, the choice in technology option and pathway has a much larger impact than when the electricity load is small.

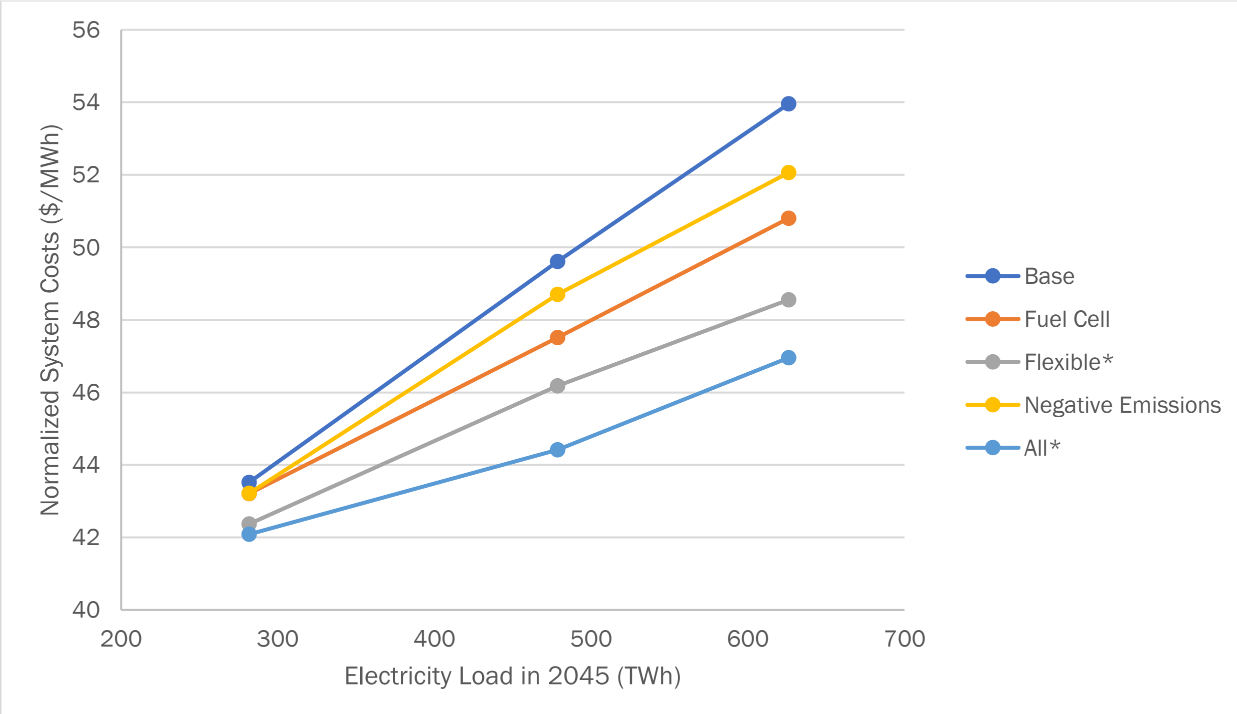


*Figure 21: Normalized system costs by scenario. Normalized system costs are calculated by dividing the present value of cumulative system costs between 2025-2045 by the cumulative load modeled between 2025-2045. Note that the normalized prices should not be compared to current electricity prices, as normalized prices do not represent a specific time frame in which the price can be compared to. *The costs of operating or implementing flexible load resources are not modeled, and thus are not included in the resulting system costs.*

Overall, the scenarios from most to least cost-effective are All, Flexible Load, Clean Firm, Negative Emissions and Base scenario. Note that while the costs of clean firm technologies and negative emissions were considered, the cost of flexible load is not reflected in the system costs. Therefore, depending on the cost of achieving such a load shape, the cost and optimal composition of the total system may change. Regardless, the cost-effectiveness of the flexible load scenario means that while the size of the overall load is a large driver of system cost, the shape of that load is a critical consideration that has potential to reduce system cost significantly. Furthermore, the difference in cost composition across the scenarios indicate that each pathway can uniquely help reduce system cost and work together to bring the most value to the system.

The following section takes a deeper look into each scenario to assess the impact of each technology or resource on the grid.

Base Scenario

In the Base Scenario, across all load cases, solar PV is the dominant resource that is responsible for 55-88% of total electricity generation by 2045 (Figure 22). This is driven by the low cost of solar PV and the relatively limited expansion potential of other clean resources including onshore wind, offshore wind, biomass, and geothermal. That said, in all cases, the maximum available potential of onshore wind, biomass, and geothermal resources are invested in and built, which demonstrates the value of a diverse range of generation resources if available.

In the Base scenario, the average annual PV capacity addition increases non-linearly for the High Electricity Load case. Furthermore, the average annual utility-scale solar PV capacity addition is 1 GW, 9 GW, and 17 GW for the Low, Medium, and High Electricity Load cases respectively (Figure 23), another indication that the PV capacity does not scale with the load. As a result, 2045, the total system capacity is 340%, 540%, and 630% of the peak for the Low, Medium, and High Electricity Load cases respectively. The non-linear trends in capacity build with load growth indicates the importance of managing future load growth as the risk of limited deployment rates can hinder meeting decarbonization goals significantly more.

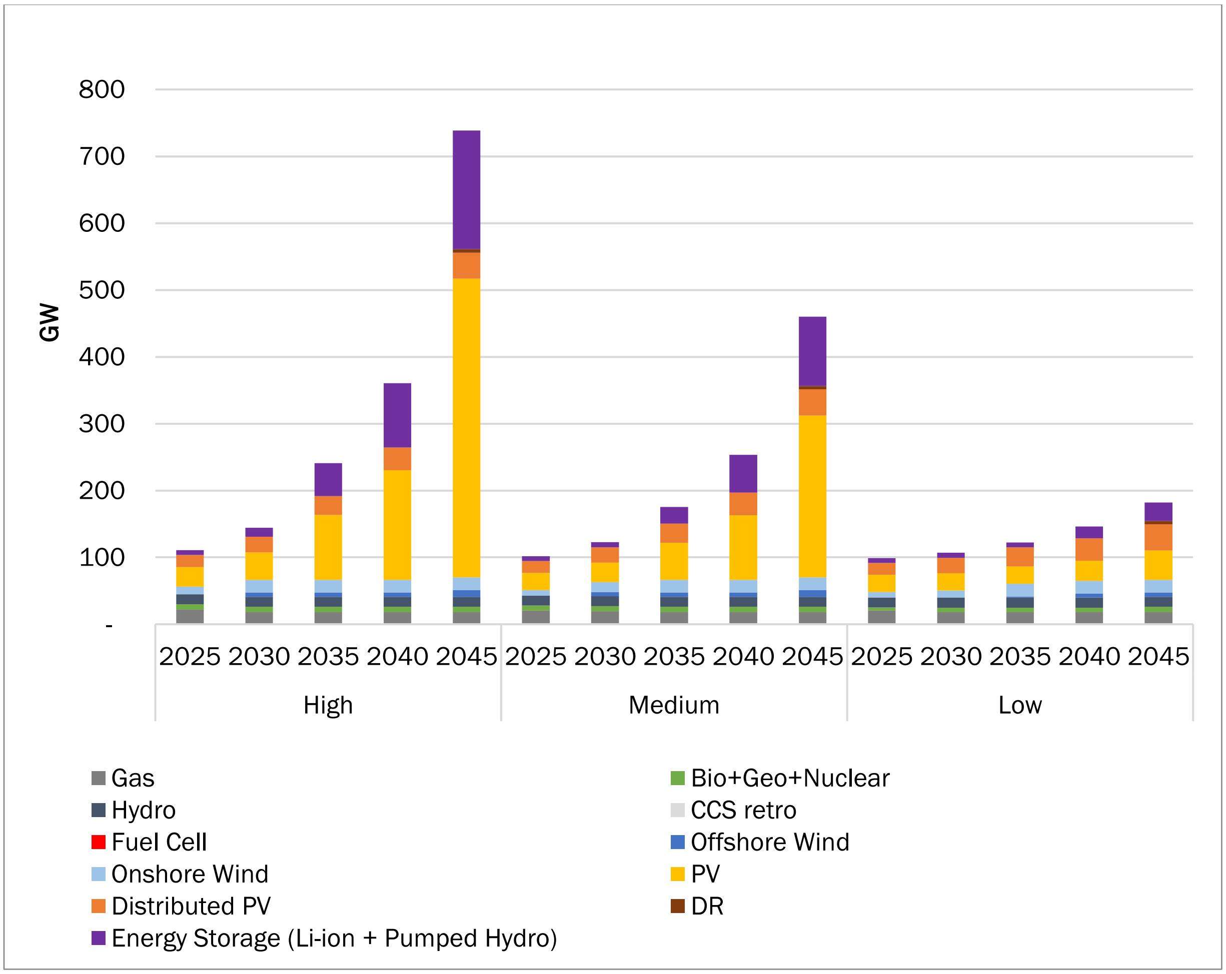


Figure 22: California system capacity for Base scenario. Significant capacity growth for High Electricity Load cases for the Base scenario.

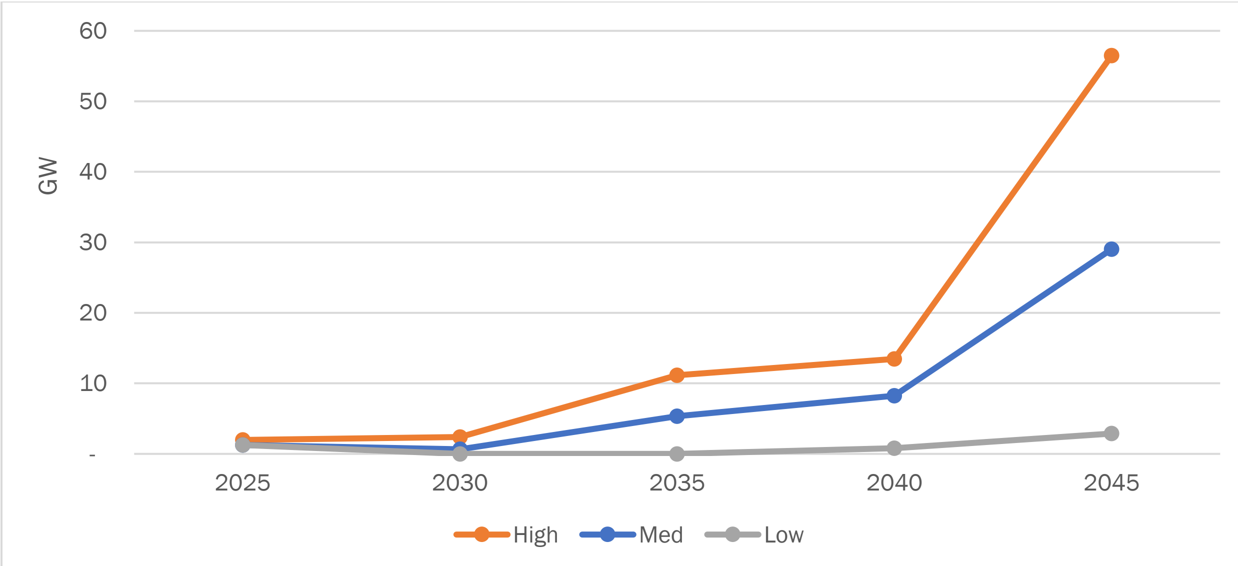


Figure 23: California average annual solar PV capacity addition. Non-linear growth in PV capacity additions for the High Electricity Load case.

Consistent with capacity build, overall excess generation, or curtailment of energy, also increases drastically as the total load increases (Figure 24). In the High Electricity Load case, by 2045, approximately 46% of total generation is curtailed, while in the Medium case by 2045, approximately 32% of total generation is curtailed. However, in the Low case, curtailment only is approximately 6% of total generation. This highlights that when only expanding intermittent generation resources with shorter duration energy storage (<10 hours), curtailment and overbuild will likely be a challenge, and the challenge only grows with larger grid sizes.

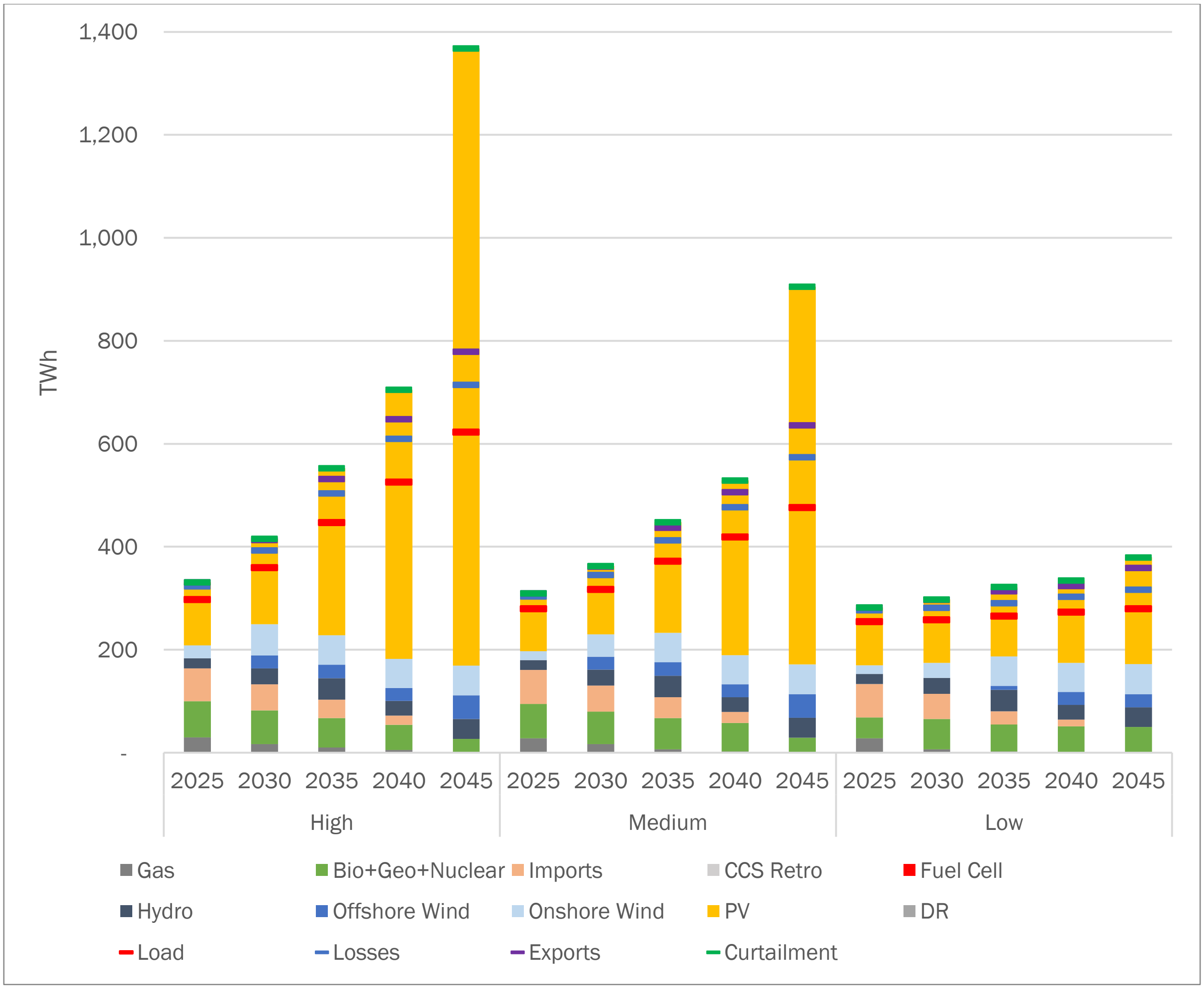


Figure 24: California system generation for Base scenario. Non-linear growth trends in generation and curtailment for the High Electricity Load case.

Clean Firm Scenario

For all levels of loads, allowing the expansion of clean firm resources, such as Gas-CCS and hydrogen fuel cells reduces the costs and resulting system capacity, which is consistent with previous literature highlighting the value of clean firm resources [34,35]. Clean firm resources help reduce the overbuild of intermittent resources and energy storage by providing energy during days and weeks when variable renewable energy output is low. In California, this typically happens during the wintertime when PV generation decreases for some weeks at a time.

In the High Electricity Load case with Clean Firm resources, the system capacity decreases by more than half relative to the Base scenario (Figure 25). While for the Low Electricity Load case, the system capacity decreases only by 18% relative to the Base scenario. Unlike the Base scenario, the growth rate of system capacity over the years is relatively constant across the three different load scenarios with clean firm resources. The average annual utility-scale solar PV capacity addition is at most 6.5 GW, with an average of 2 GW across all load cases. Furthermore, by 2045, the total system capacity is 260-290% of the peak across the load scenarios, which suggests that with clean firm resources, the drastic overbuild of capacity can be decreased significantly.

With clean firm resources, the level of curtailment is moderate across all scenarios and years, reaching at most 2% of total generation (figure 26). By preventing overbuild of generation resources, clean firm resources allow for a grid with significantly less curtailed generation overall. Given the low levels of excess generation, the Clean Firm Scenarios show less exports relative to the export case across all years and load cases. Furthermore, having clean firm resources in the generation mix reduces California reliance on imports for energy generation.

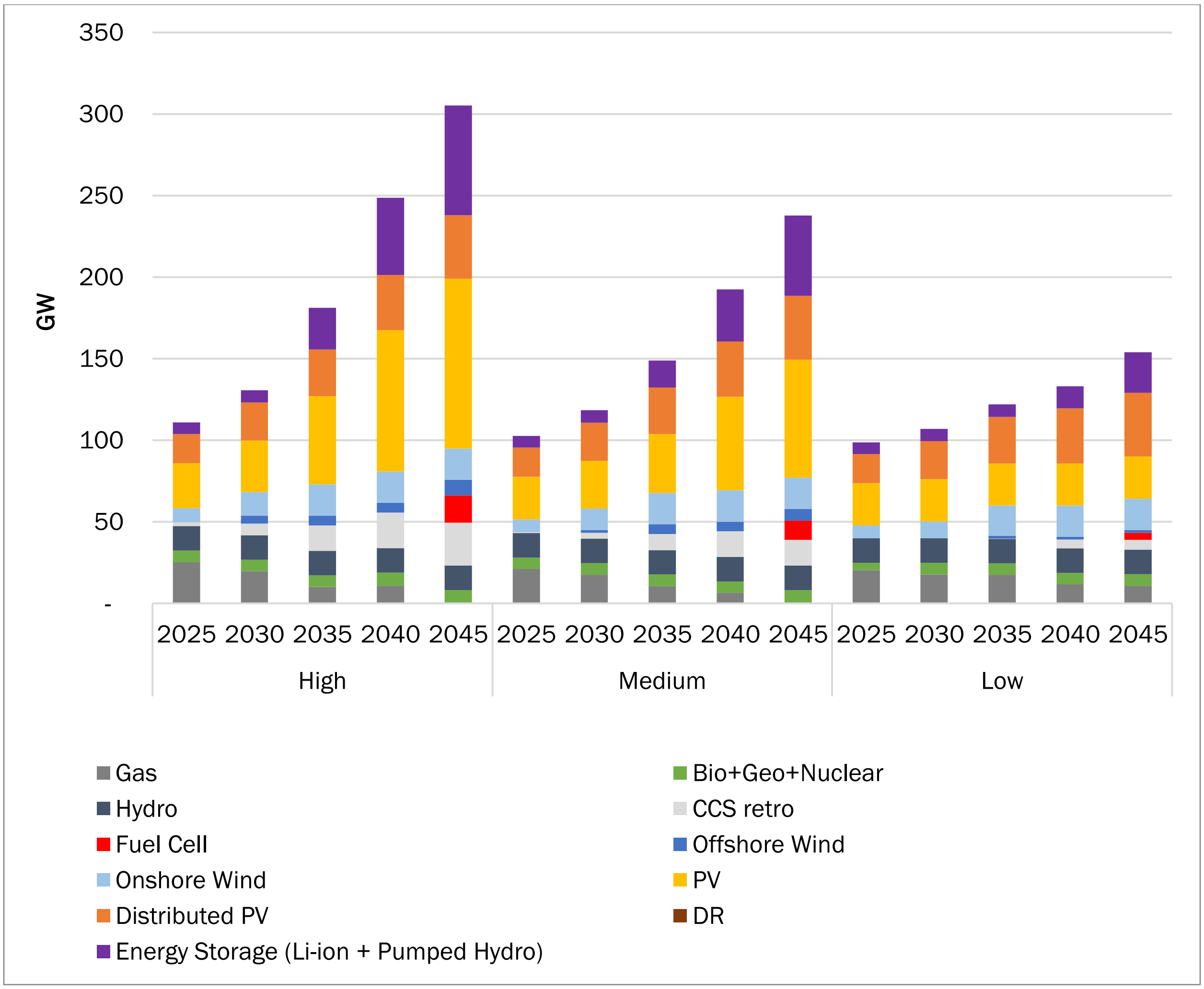


Figure 25: California system capacity for Clean Firm scenario. Linear growth trends in capacity growth for all electricity load cases.

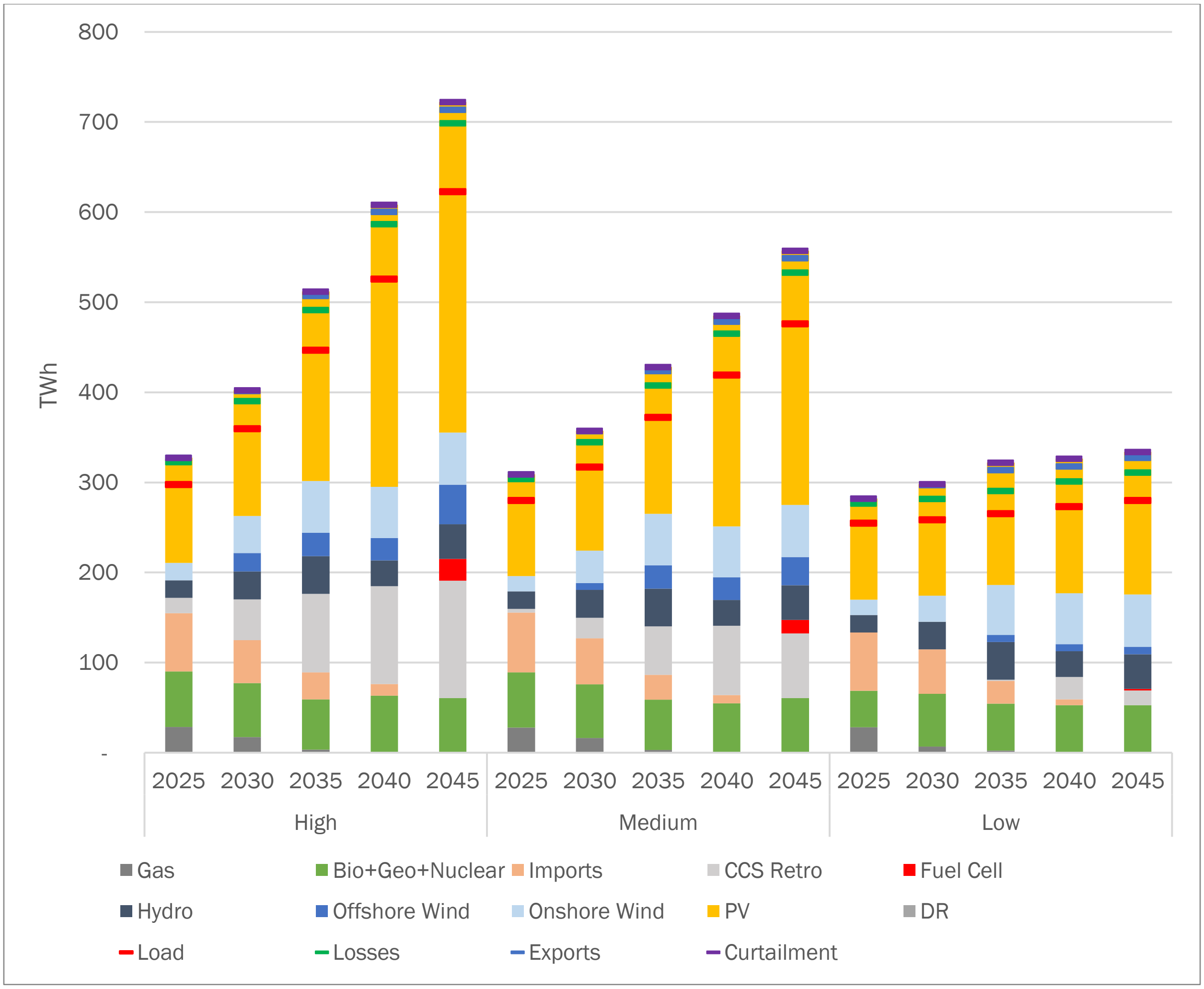


Figure 26: California system generation for Clean Firm scenario. Clean Firm scenario shows lower imports and exports, as well as curtailment relative to the Base scenario.

Gas-CCS is the primary clean firm resource that is invested in with relatively consistent capacity additions each year, while hydrogen fuel cells are invested in between 2040 and 2045. The later deployment of hydrogen fuel cells is likely driven by high clean hydrogen prices prior to 2040.

Gas-CCS and fuel cells utilizing clean hydrogen have different cost structures that lead to different utilization and roles in future grids [35]. Gas-CCS is an intermediate resource filling energy needs on a diurnal basis, while hydrogen, due to its high variable costs, is largely used for filling seasonal peaks. As a result, Gas-CCS has an average of 62% annual capacity factor across all load shapes and years, while fuel cells have an average annual capacity factor of 12%.

For the High Electricity Load case, the scale and pace of deployment of clean firm technologies are accelerated relative to the Low and Medium load cases (Figure 27). This implies that if California anticipates significant levels of electrification and increase in future load, clean firm energy resources will have to be deployed sooner and faster. For the medium and high load cases, before 2040, the rate of build for clean firm resources is largely consistent with historic rates at which California added natural gas capacity between 2001 and 2013 [73] (Figure 27).

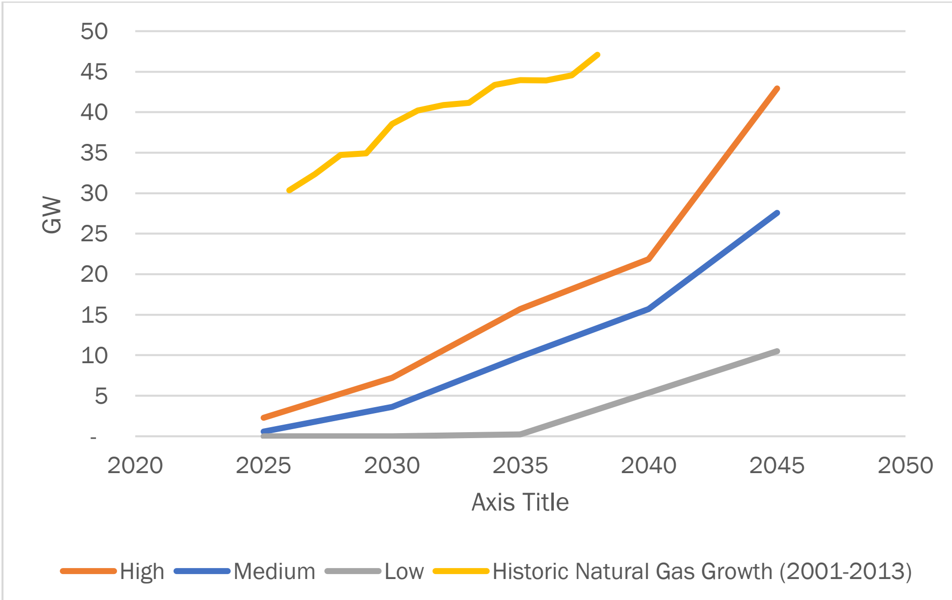


Figure 27: Cumulative clean firm capacity for Clean Firm scenarios. Combined capacity of Gas-CCS and hydrogen fuel cells between 2025-2045 for all three electricity load scenarios. The growth rate is relatively consistent with historic growth of natural gas capacity in California. Source: CEC 2019 [73].

Flexible Load Scenario

Flexible load is modeled to assess the impact of different load shapes, with particular emphasis on being able to optimize charging profiles of electric vehicles in the transportation sector. Instead of assuming historical charging profiles for all electrified load, the flexible load scenario allows 50% of the light and heavy-duty vehicles to be charged optimally as determined by the model. Note that the costs of operating or implementing flexible load resources are not modeled, and thus are not included in the resulting system costs. Figure 28 demonstrates how the average daily load profile changes over the years with flexible load.

The overall trend shows night-time and peak loads shifted towards the daytime when there is ample sun available. While this results in increased load ramping in the mornings, the ramp coincides with the sun rising, thereby decreasing the impact on the overall net load. The trend is consistent regardless of the load size scenarios, and is likely indicative of a grid that is dominated largely by PV generation. The shape of the grid provides insight for how incentives for charging should be designed to optimize integration of high levels of intermittent renewable resources.

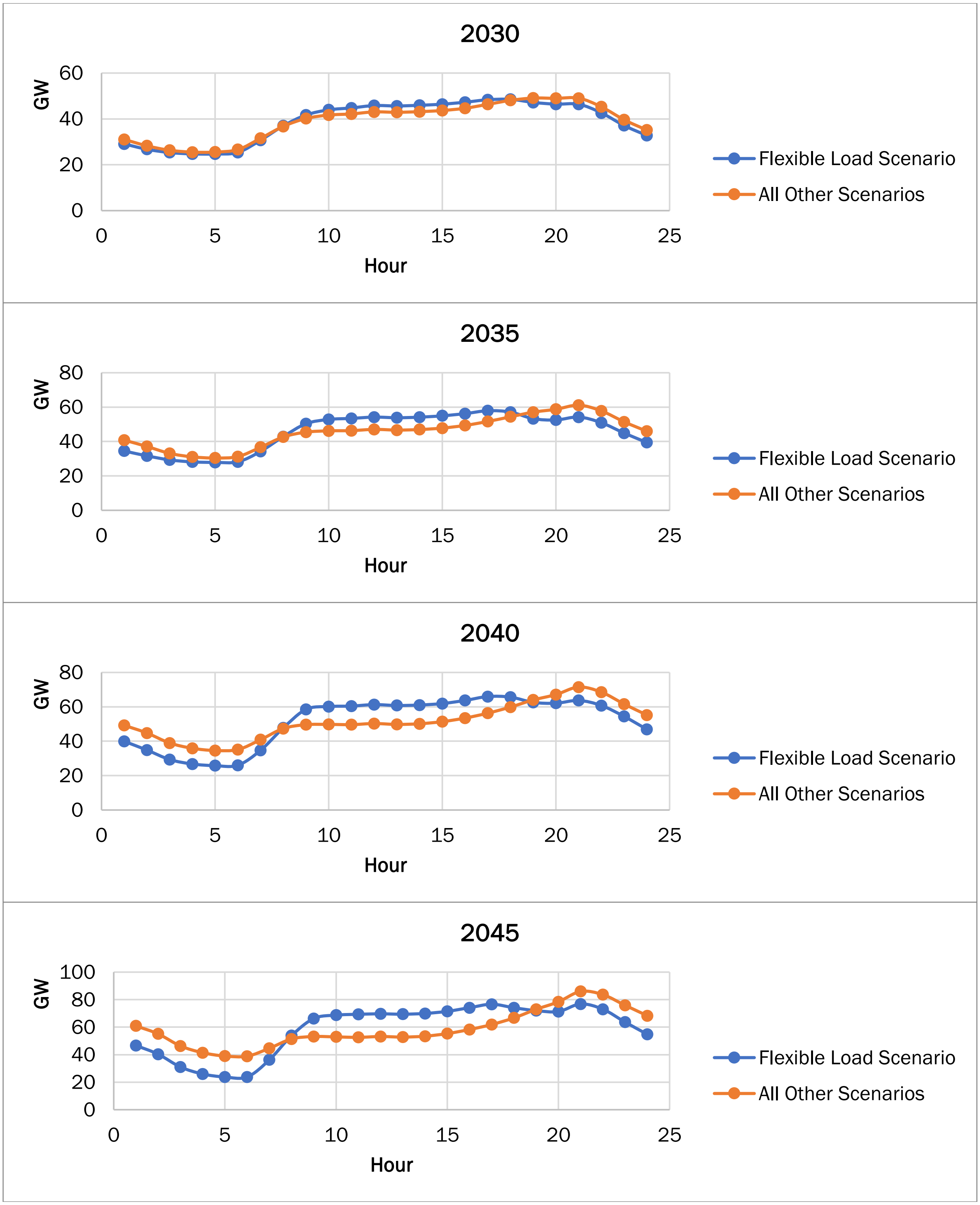


Figure 28: Average daily load profile for the Medium Load case for all other scenarios and the resulting profile for the Flexible Load scenarios. More load is shifted to the daytime when more solar PV generation is available.

While the general grid composition and energy generation shares in the Flexible Load scenarios are similar to the Base scenarios, cost savings are driven by not having to overbuild the system as much as the Base scenarios to maintain system reliability. With more flexible load in the system, system capacity as well as associated curtailment by 2045 decreases significantly relative to the Base scenario. By 2045 in the Medium Electricity Load case, the peak solar PV capacity decreases by 29% from 242 GW in the Base scenario to 172 GW in the Flexible Load scenario. As a result, curtailment by 2045 also decreases from 32% of total generation curtailed in the Base scenario relative to 20% curtailed in the Flexible Load scenario for the Medium Electricity Load cases.

Notably, the divergence in system capacity between the Flexible Load and Base scenarios occur largely between 2040 and 2045 (Figure 29). This means that the value of flexible load is most pronounced in 2045 and beyond, when the utilization of natural gas or unspecified imports as a source of reliable energy is limited due to stringent emissions constraints. This points to the fact that while flexible load is valuable, its value is greatest when there are no other sources of back up generation available.

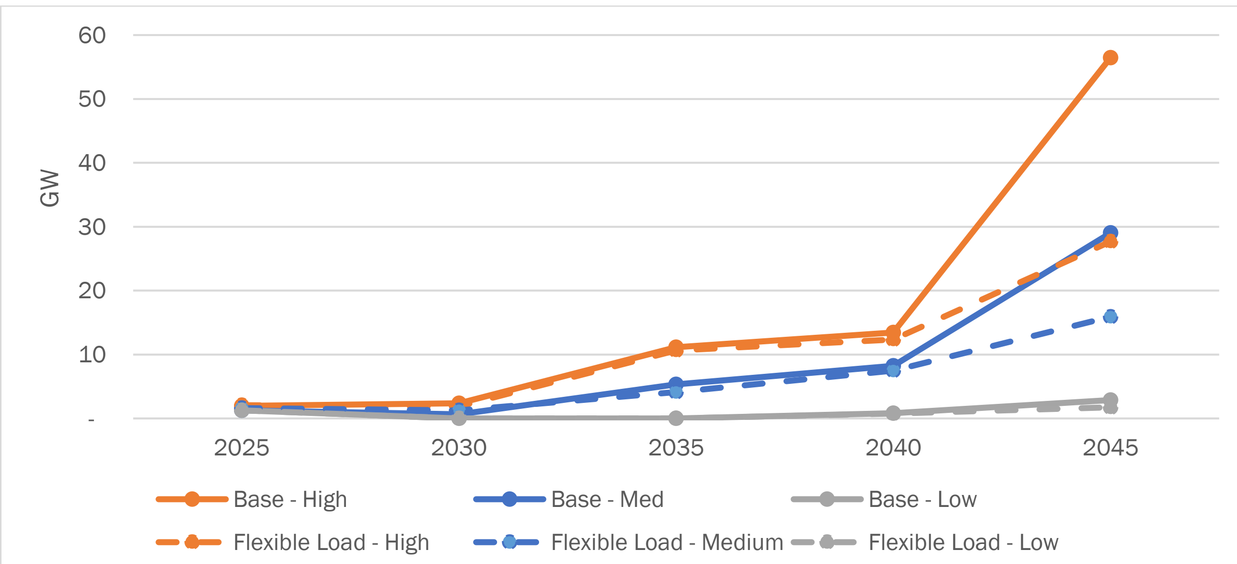


Figure 29: Average annual solar PV capacity addition for Base and Flexible Load scenarios. For the Flexible Load scenarios, solar PV capacity growth remains relatively consistent with the Base scenario until 2045. In 2045, the presence of flexible load drastically decreases the solar PV capacity build.

Negative Emissions Scenario

Negative emissions technologies such as direct air capture (DAC) or biomass with carbon capture and storage (BECCS) can contribute to cost-effective and reliable decarbonization of the electricity system by providing more flexibility to the system. In all three load cases modeled, the use of natural gas decreases consistently over the years. However, with negative emissions allowed, by 2045, there are residual emissions from the use of natural gas and unspecified imports that are needed during times of low intermittent generation. The emissions are then offset by negative emissions technologies. By allowing utilization of natural gas or unspecified imports as backup generation sources, negative emissions technologies prevent overbuilding the system for reliability, which allows for more cost-effective decarbonization.

Similar to the Flexible Load scenarios, the grid composition and generation shares in the Negative Emissions scenarios are largely consistent with the Base scenarios. Notably, a reliance on negative emission technologies is more effective at reducing overall system capacity relative to the relying on flexible load resources. This is because negative emissions enable the operation of natural gas plants or imports, which serve as generation sources that can help offset generation needs from intermittent resources. However, flexible load resources largely replace energy storage technologies instead of generation resources, which then requires larger capacity of the other generation resources to ensure reliable operation.

By 2045, negative emissions needed to reach net-zero varies significantly with system load, from 2-16 MtCO_2 (Figure 30). Overall, more negative emissions are needed to reach net-zero emissions as the electric loads grow. With lower prices of negative emissions, more residual emissions may be economic, but may also simultaneously raise challenges of scaling negative emissions infrastructure.

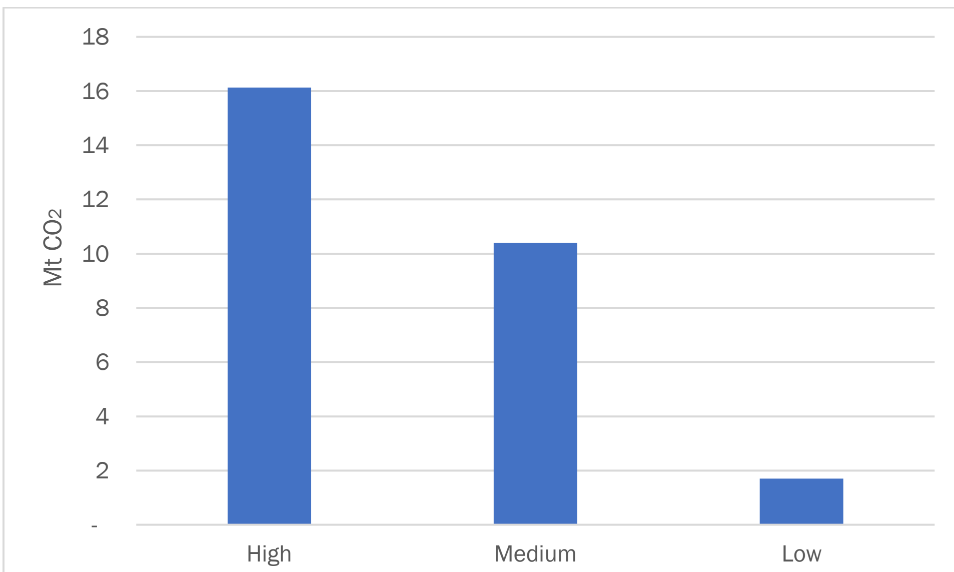


Figure 30: Negative emissions amount for different electricity load cases. For the Flexible Load scenarios, solar PV capacity growth remains relatively consistent with the Base scenario until 2045. In 2045, the presence of flexible load drastically decreases the solar PV capacity build.

All Scenario

The All scenario allows the model to utilize clean firm, flexible load, and negative emissions technologies to design the most cost-effective grid across the three different Electricity Load cases modeled. The All Scenario shows that all three technologies are utilized through 2045, and each contribute to cost-effective decarbonization. This means that there is not one technology that dominates or is the most-effective. Instead the combination of technologies working together results in the least-cost system.

Notably, relative to each individual scenario, less of each technology is utilized or deployed in the All scenario (Figure 31). For example, for the Medium Electricity cases, the Clean Firm scenario shows 28 GW of clean firm resources (Gas-CCS and hydrogen fuel cells) by 2045, while in the All scenario, only 18 GW was deployed. In the Flexible Load scenario, approximately 62 TWh of load was shifted in 2045 while in the All scenario, 61 TWh of load was shifted. And finally, relative to 10 Mt CO_2 removed via negative emissions in the Negative Emissions scenario, only 1 Mt CO_2 is removed in the All scenario. This shows that at the modeled price of negative emissions of approximately $340/ton, negative emissions technologies are not deployed as much if other decarbonization options are available. Furthermore, the system capacity in the All scenario is the lowest relative to all other scenarios. This shows that having a diverse mix of technologies for decarbonization can reduce the burden of deploying large amounts of a single technology, and also reduce the systemic risk relying on limited number of technologies that may or may not materialize at scale as expected.

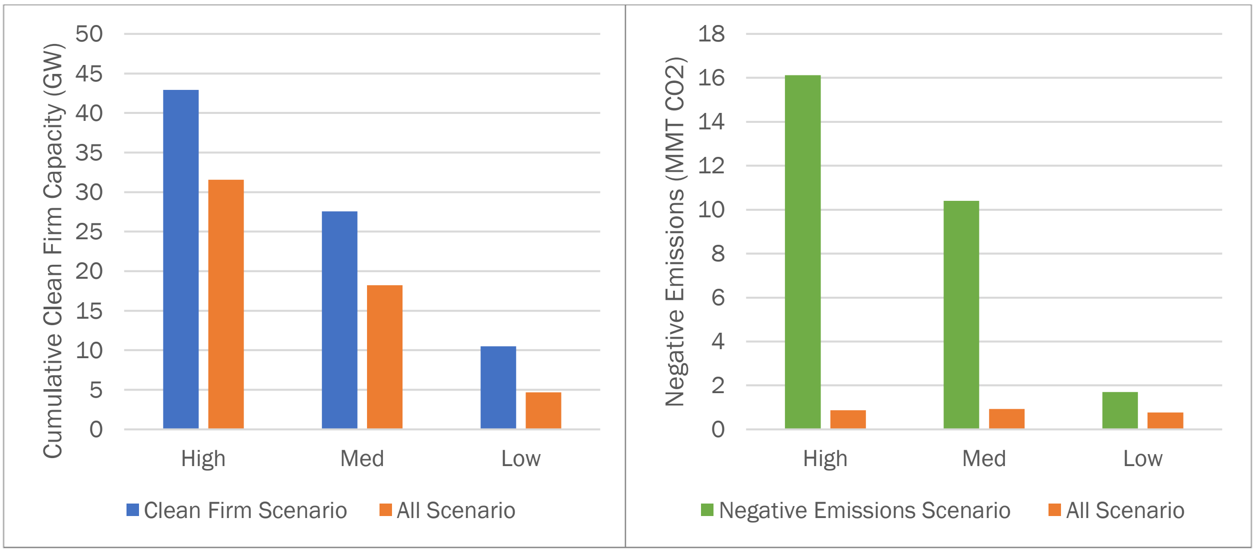


Figure 31: Cumulative clean firm capacity (gas-CCS and fuel cell) by 2045 for Clean Firm and All scenario; Negative emissions levels needed for net-zero emission by 2045 for Negative Emissions and All scenario. All scenario requires both less clean firm capacity and negative emissions.

Key Takeaways from Modeling Results

Electricity system load is a key driver of system costs and size.
The system cost of a grid does not scale linearly with the load size, meaning larger grids are more expensive on a $/MWh basis relative to smaller ones. Overall, the value and benefits of technologies such as clean firm resources, flexible load, and negative emissions technologies increase with larger grid sizes. This also indicates that if California fails to prepare adequately for a large grid, costs will increase significantly more than if it is better prepared. When the system is small, decarbonization pathways remain relatively consistent across all scenarios and technologies that are available.

Gas capacity is maintained in all scenarios through 2045.
In all scenarios across all load cases, gas generation is included in California's energy mix through 2040.By 2045, gas generation reaches zero due to carbon constraints, but the model chooses to maintain its capacity for reliability. The only scenario in which gas capacity decreases significantly is the Clean Firm Scenario, in which other firm generation resources such as Gas-CCS and hydrogen fuel cells are available for generation. The presence of either clean firm resources or natural gas capacity indicates that dispatchable capacity is needed

in 2045 for reliability purposes. However, in reality, maintaining unmitigated gas power plants that do not generate any electricity will likely be a challenge. In 2045, natural gas power plants can still be utilized effectively as a dispatchable resource if the fuel that sustains it is transitioned to natural gas with CCS, renewable natural gas, or clean hydrogen.

PV and energy storage are the mainstays of California's future energy system

In all scenarios and load cases, solar PV and energy storage experience the most growth in capacity relative to all other technologies. As a result, solar PV generation accounts for more than 50% of generation across all scenarios and load cases modeled. This can largely be attributed to decreasing costs of solar PV and energy storage technologies, as well as California's abundant solar resources. However, scaling solar PV and energy storage at the rate needed may also pose challenges, and is discussed further in the next section.

In all scenarios, investment in offshore wind is made by 2030

Despite the higher capital cost of offshore wind relative to onshore wind or solar PV, offshore wind is a technology that is consistently valuable and invested in regardless of the scenario and load case. Notably, investments in offshore wind consistently happens by 2030, which indicates the importance of the resource well before 2045. However, as noted earlier, floating offshore wind platforms needed for California are still in the pre-commercial stages, an indication that additional development of that technology at a rapid pace will be required.

Clean Firm resources and diverse generation resources are the most effective way to reduce system capacity build

Regardless of the costs of the resulting system, scenarios with clean firm resources, including Clean Firm and All scenarios, show the lowest system capacity across all load cases. Furthermore, the Negative Emissions scenario that allows unmitigated natural gas generation or imports results in lower system capacity than the Base or Flexible Load scenarios as well. Overall, having diverse sources of generation decreases required system capacity, as it decreases the reliance on overbuilding intermittent renewable resources to maintain reliability throughout the entire year.

Decarbonization Challenges

A grid system is fundamentally a network of infrastructure that includes distribution lines, transmission lines, substations, and power plants. Increasing the size of the grid will involve not just increasing generation capacity, but all the infrastructure that supports the entire system. Based on the significant potential for electrification across the transportation, residential, commercial, and industrial sectors, the future grid size in California may be unprecedented. Growing the grid to an unprecedented extent will likely require accelerating the pace of deployment of distribution lines, transmission lines, substations, and generators alike, all the while maintaining affordable rates of electricity. Furthermore, deploying each technology faces unique challenges, including potential land use limitations and regulatory hurdles. The following section discusses these challenges in more detail.

Unprecedented Pace of Growth

Several studies have shown that California will have to expand new generation resources, and particularly solar PV and energy storage resources, at unprecedented rates. Even the

Senate Bill 100 Agency report stated that solar PV growth will have to be 2-3 times historic deployment rates, while energy storage growth will have to reach 8 times historic rates [30]. While this analysis shows that the rate of deployment of solar PV needed to meet net-zero emissions goals depends heavily on the level of electricity load as well as presence of other technology options, by the 2040s, the average annual deployment rate of solar PV ranges from 1-57 GW every year, with an average of 10 GW. As a reference, historic deployment levels of solar PV has averaged 1.3 GW in the past 5 years [24]. It remains to be seen whether this needed rate of deployment can be reached.

Despite the growth needed, a recent report shows that the pace of renewable generation growth in California has been slowing in recent years [74]. The state will need to accelerate its pace of deployment to ensure meeting its goals on time. Furthermore, in addition to renewable and energy storage capacity, this analysis has shown how a wide range of clean firm technologies, flexible load resources, or negative emissions technologies can help achieve cost-effective decarbonization with more moderate growth in system capacity relative to a system without. However, all of the above technologies will have to scale in order to have a meaningful impact on future grid systems. Further research and development, as well as pointed efforts for deployment will be needed in a timely manner.

Generation and Transmission Land Use

Solar PV capacity will be critical in California reaching net-zero emissions in the electricity sector. Furthermore, with the increasing size of the grid, more transmission lines will have to be built to support the growing grid as well. Both resources are land intensive, and their unprecedented pace of growth and level of deployment needed raises challenges in siting and implementing them in a timely and sustainable manner.

While California has lots of land mass that may be available for developing energy resources, there are several steps that are needed construct a plant, each of which may pose a risk for project development (Figure 32) [75]. Some limitations or risks include the fact that land availability is limited by areas that are reserved for conservation or physically unsuitable for siting plants. Once a site is chosen, there may be additional limitations in leasing the land or confronting public opposition for development. Stakeholders have expressed the importance of considering equity, environmental, and social justice factor for planning the buildout of new resources. One suggestion is to ensure equitable indicators are considered in the planning process, such as modeling not only economic cost and benefits, but also environmental cost and benefits [75].

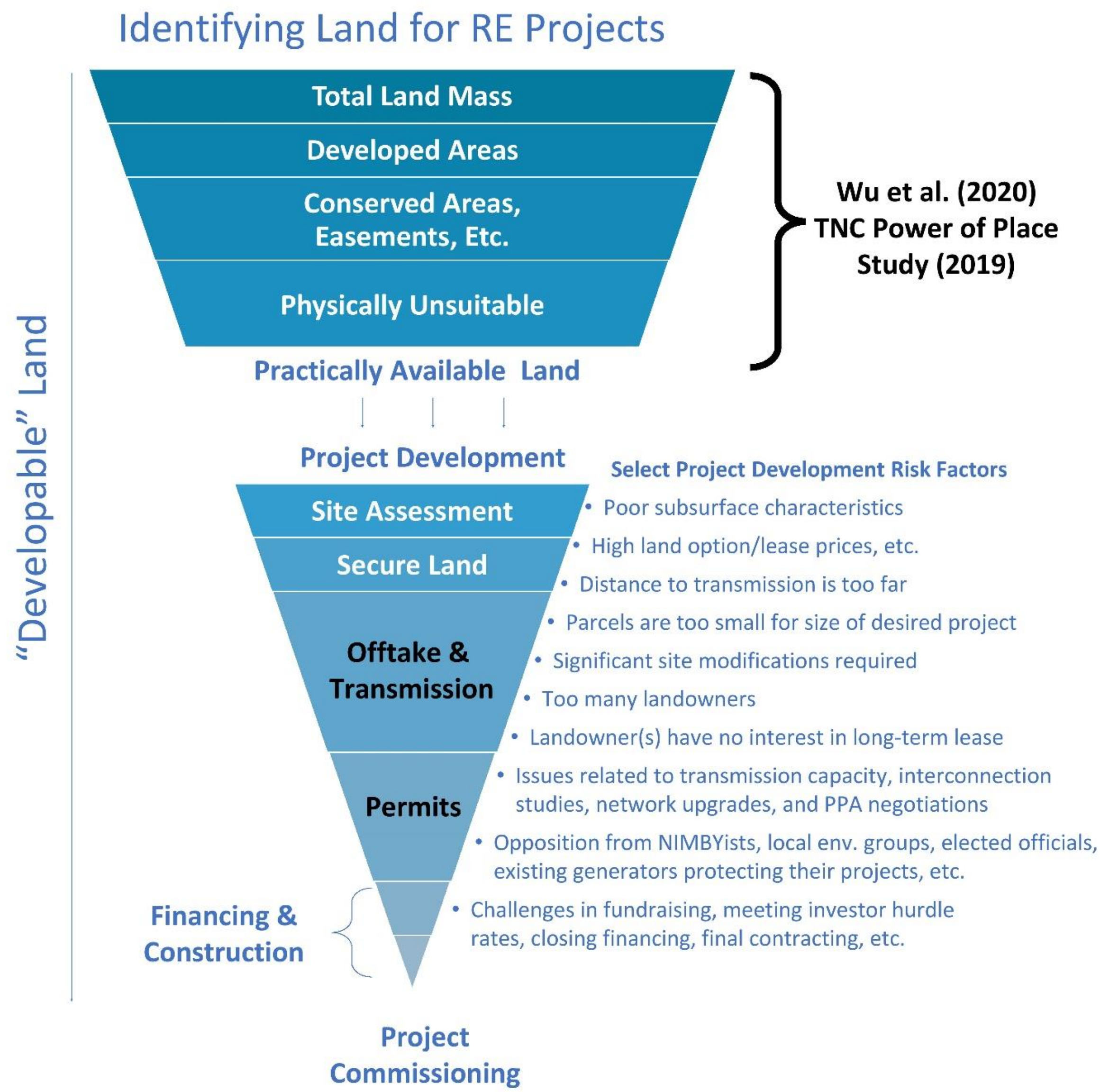


Figure 32: Outline of process for developing generation projects. Large areas of available land face several steps in finally being chosen for a project. Figure taken from: Clean Air Task Force and Environmental Defense Fund, "Building a Zero Carbon California Grid: Moving From Models to an Implementable Plan", 2021 [75].

Deploying Clean Firm Resources

Deploying clean firm resources such as gas-CCS, fuel cells, geothermal, and biomass resources face challenges due to their high capital costs relative to intermittent renewable resources. Higher capital costs often discourage investment, and without strong market or policy signals that might ensure a profitable return on investment, their deployment is often limited. Furthermore, clean firm resources often have associated variable costs that make it difficult for them to compete in an energy market that is filled with zero marginal cost resources such as solar PV and wind. Despite these economic challenges, clean firm resources have system value that would make decarbonization much more cost-effective and reduce the challenges of scaling a grid. Such value may warrant targeted policy support for deploying and scaling clean firm technologies.

Each clean firm resource also faces unique challenges that may be overcome with more pointed support and policy measures. For example, gas-CCS requires not only building a CO_2 capture plant but also CO_2 storage sites as well as potential transportation networks for CO_2. This would require overcoming regulatory barriers as there is no commercially deployed carbon storage in California. Developing significant capacities of geothermal resources beyond the near-term potential will require further exploration of resources, as well as development of technologies that can access them. Similarly, further cost reductions on green or blue hydrogen production technologies will be needed for fuel cells to operate cost-effectively. As such, while there are a wide range of clean firm resources that provide value, each technology will need more tailored development for the resource to be deployed and scaled in a timely manner.

Offshore Wind Deployment

Offshore wind will be an important resource in California's energy future. However, floating offshore wind resources are still in the pre-commercial stages, and deploying offshore wind on California's coast comes with challenges that involve a wide range of stakeholders and environmental impacts.

A report published by the CEC on opportunities for offshore wind energy in California highlighted that offshore wind technology has not been deployed in marine conditions and water depths similar to that of California, which limits availability of data to fully assess technology performance or costs [76]. Furthermore, there are concerns of limited information on the environmental impacts of floating wind turbines in the California coast [76]. Additional challenges include untested permitting processes both on a federal and state-level, with additional complications of potential conflicts with military training and operations [76]. With a wide range of challenges facing offshore wind deployment, California must take action soon to ensure timely deployment of offshore wind, including additional research and addressing stakeholder concerns.

Affordability

The CPUC is tasked with ensuring the delivery of clean, reliable, and affordable electricity. As California continues to decarbonize its grid to achieve a clean grid, affordability has become a significant challenge. Currently, the electricity rate for the three IOUs in California are 45-80% higher on a dollar per kWh basis than the national average [77].

The high electricity prices are driven by California's cost structure, where 66-77% of the costs are fixed [77]. The fixed costs include not only the fixed costs of the generation, transmission, and distribution system, but also public purpose programs and wildfire recovery costs. This fixed cost structure is then translated to electricity rates for residents, meaning electricity costs do not change significantly based on how much electricity the residents consume. This puts a much higher burden on lower income families who end up pay a larger share of their income for energy services.

In understanding this challenge, CPUC has rulemakings in place to measure and assess affordability of essential utility services [78]. However, state-led analysis of future electricity prices has already shown that in the coming decade, energy prices for sensitive households will outpace inflation [79]. The report finds that the issue can be exacerbated by cost shifts to lower-income households that cannot afford BTM generation and storage resources. As California expands and moves more of its energy usage to electricity, keeping electricity prices affordable will be critical to ensuring that the goals will be met.

Conclusions

California has goals to reach net-zero emissions economy-wide by 2045, and a clean grid and electrification of the transportation, industrial, residential, and commercial sectors are critical components of meeting those goals. Electrifying such a large share of the economy's energy usage has the potential to increase electricity load and the associated grid size to an unprecedented size. Several technologies including but not limited to clean firm resources, flexible loads, or negative emissions resources can help reduce the cost of decarbonization as well as the overall size of the grid. However, the challenges and costs of decarbonization do not scale linearly with the size of the grid – larger grids are more expensive to decarbonize. If California is going to rely heavily on electrification, then planning for the decarbonization of a larger grid will be critical to ensure timely decarbonization of not only the electricity sector, but also the economy as a whole, in an affordable and reliable manner. Recognizing the challenges and preparing for them will also help California stay ahead as a leader in climate action.

Appendix – Method for assessing powerplants

For the electricity sector, the US Environmental Protection Agency's 2019 Emissions & Generation Resource Integrated Database (eGRID) was utilized to analyze existing natural gas power plants in California. The eGRID database contains emissions, emission rates, generation, heat input, resource mix, and many other attributes for all U.S. electricity generating plants that provide power to the electric grid and report data to the U.S. government [26].

The dataset is utilized to identify natural gas power plants currently operating in California. The Plant-level and Generator-level aggregated datasets are used, and the plants are identified utilizing the following metrics.

File Name	PLNT			GEN		
Variable Name	Plant state abbreviation	Plant-level sector	Plant primary fuel	Generator planned or actual retirement year	Generator annual net generation (MWh)	Generator status
Identifying Category	CA	IPP Non-CHP IPP CHP Electricity Utility	NG	Empty or beyond 2022	>0	OP; OA; SB

CA – California; IPP – Independent Power Producer; CHP – Combined Heat and Power; NG – Natural gas; OP – operating- in-service; OA – Out of service (returned or will be returned to service); SB – stand-by (long term storage)

Once the plants and generators are identified, only the plants that meet all of the criteria above are chosen for analysis. The list of generators is matched to each plant utilizing the variable 'DOE/EIA ORIS Plant or Facility Code (ORISPL)', which contains unique codes for each plant. From there, emissions levels are analyzed based on 'Plant annual CO_2 equivalent emissions (tons)' reported in the dataset.

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