DOCKETED

Docket Number:	21-ESR-01
Project Title:	Resource Planning and Reliability
TN #:	269658
Document Title:	Staff Report - Renewable and Firm Zero-Carbon Resources
Description:	N/A
Filer:	Mikayla Roberts
Organization:	California Energy Commission
Submitter Role:	Commission Staff
Submission Date:	4/28/2026 11:35:17 AM
Docketed Date:	4/28/2026

California Energy Commission

STAFF REPORT

Renewable and Firm Zero-Carbon Resources

April 2026 | CEC-200-2026-004

California Energy Commission

Chie Hong Yee Yang
Xieng Saephan
Justin Szasz
Justin Cochran
Primary Authors

Chie Hong Yee Yang
Project Manager

Liz Gill
Branch Manager
RELIABILITY ANALYSIS BRANCH

Aleecia Guiterrez
Director
ENERGY ASSESSMENTS DIVISION

Drew Bohan
Executive Director

ACKNOWLEDGEMENTS

The authors express appreciation to the staff at the California Energy Commission for their review and contributions to this report. The California Energy Commission would also like to acknowledge support from staff at Guidehouse, Inc. on the technical analysis.

California Energy Commission

Elise Ersoy

Liz Gill

Guidehouse, Inc.

Richard Shandross

Amul Sathe

Warren Wang

Darek Imadi

Kaavya Malhotra

Amy Wu

ABSTRACT

The Warren-Alquist State Energy Resources Conservation and Development Act establishes the California Energy Commission's responsibility to assess and plan for the state's energy needs to ensure a reliable, clean, and affordable electric system. The *Renewable and Firm Zero-Carbon Resources* report supports the Senate Bill 423 (Stern, Chapter 243, Statutes of 2021) report in the 2025 Integrated Energy Policy Report and supports the California Energy Commission's responsibilities under the Warren-Alquist State Energy Resources Conservation and Development Act. This requirement specifies that the California Energy Commission, in consultation with the California Public Utilities Commission, California Independent System Operator, and California Air Resources Board, must submit to the Legislature an assessment of emerging renewable energy and firm zero-carbon resources that support a clean, reliable, and resilient electrical grid in California and an update in each Integrated Energy Policy Report. The first SB 423 report was submitted to the Legislature in March 2025. An update was included in the 2025 Integrated Energy Policy Report. This report is a companion document to that update and contains additional technical details.

Keywords: Reliability, demand side resources, firm resources, zero-carbon resources, emerging resources, supply side resources, extreme events, climate change, reliability assessments

Yee Yang, Chie Hong, Xieng Saephan, Justin Szasz, and Justin Cochran. 2026. *Senate Bill 423: Renewable and Firm Zero-Carbon Resources Update*. California Energy Commission. Publication Number: CEC-200-2026-004.

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EXECUTIVE SUMMARY

Background

California's electricity system is undergoing significant transition with the overarching goal of achieving 100 percent clean electricity by 2045, as mandated by California Senate Bill 100 (De León, Chapter 312, Statutes of 2018). California's transition to renewable and zero-carbon electricity entails a strategic and phased transformation of its electric grid. The state's move from a fossil-based system has been characterized by widespread adoption of renewable power plants, while natural gas power plants continue to offer operational flexibility and reliability during the transition. The highlight of this transitional phase is the incremental addition of cleaner technologies, marking a significant departure from conventional fossil fuel sources. The ultimate objective is to create a 100 percent clean electricity system through gradually displacing carbon-intensive technologies with innovative, zero-emission solutions to provide the operational flexibility and reliability currently met by natural gas power plants. The 2025 Integrated Energy Policy Report addresses the requirement to assess emerging firm zero-carbon resources as per Senate Bill 423 (Stern, Chapter 243, Statutes of 2021). This staff report supplements the 2025 Integrated Energy Policy Report with additional technical detail on firm zero-carbon resources. These resources may be considered for deployment to address local reliability, system reliability, and emissions reductions within California.

This report provides a qualitative assessment of various firm zero-carbon resources, including long-duration energy storage, hydropower, geothermal, renewable natural gas, hydrogen, small modular fission reactors, fusion, and carbon capture. The report concludes by summarizing key barriers and providing recommendations to address challenges in the adoption and implementation of firm zero-carbon resources.

Resources

Within the context of this analysis, firm is defined as being an on-demand resource to ensure a consistent and stable power supply during multi-day extreme or atypical events. For consistency with the state's overarching SB 100 definitions, CEC includes renewable and zero-carbon resources consistent with the Renewables Portfolio Standard for this analysis. This means that some resources included here are not fully zero carbon but are being evaluated since they meet the requirements of the RPS program to support SB 100 goals. The resources reviewed in this assessment are geothermal, hydropower, generation with carbon capture, small modular reactors (fission), fusion, long-duration energy storage, hydrogen for power generation, and bioenergy. These are consistent with the 2025 *SB 423 Emerging Renewable and Firm Zero-Carbon Resources Report*.

Geothermal resources, both conventional and enhanced systems, can provide baseload power. California currently operates over 2.7 gigawatts of geothermal capacity, primarily in the Geysers and Imperial Valley regions. The conventional technology is mature, but expansion is hindered by high upfront exploration and drilling costs, regulatory and permitting delays, and transmission constraints. Enhanced geothermal systems, while still emerging, could unlock over 100 gigawatts (GW) of potential in the United States. In this space, federal demonstration projects such as the Frontier Observatory for Research in Geothermal Energy and commercial ventures are underway. Growth in this sector could yield steady low-emission energy well into the future.

Hydropower remains a foundational zero-carbon technology. California's large and small hydro systems are fully commercial, while pumped storage hydropower, including closed-loop configurations, are receiving attention for their grid-balancing capabilities. Environmental constraints, permitting, and high upfront costs limit expansion of new dammed resources. However, modernization of legacy plants through turbine upgrades, improved control systems and generator replacements can increase firm zero-carbon capacity. Federal infrastructure investments under the Bipartisan Infrastructure Law (BIL) and programs administered by the United States Department of Energy (DOE) help provide funding for plant upgrades and early-stage development of pumped storage hydropower, including proposed projects such as San Vicente Pumped Storage and Lake Elsinore Advanced Pumped Storage. These investments will help provide flexible, long-duration energy storage and reliability during peak demand periods.

Carbon capture technologies, while not strictly zero-carbon, provide a near-term solution to reduce emissions from natural gas power plants. Post-combustion absorption systems are commercially mature, while swing adsorption, membrane separation, and cryogenic capture are advancing through pilot stages. Policy incentives such as the federal 45Q tax credit and state programs like the Low Carbon Fuel Standard are advancing deployment. However, economic viability, public perception, and regulatory clarity remain key challenges. Carbon capture technologies are also limited to capturing CO_2 emissions and do not address other pollutants.

Small modular reactors (fission) and **nuclear fusion** have potential long deployment lead times. Factory-built fission systems are under active development, but deployment in California depends on reversing the state's nuclear moratorium. Fusion remains in the research stage, with recent breakthroughs at the National Ignition Facility and international labs. Although both technologies face technical, regulatory, and public acceptance hurdles, they have the potential to provide zero-carbon power starting in the 2030s and beyond if supported through coordinated policy and investment.

Long-duration energy storage technologies can help integrate variable and intermittent renewables and can help utilities meet electricity demand during periods with low renewable energy generation – including multiday extreme or atypical weather events. California is supporting commercialization through technology demonstration funding, as most long duration energy storage systems remain in pilot stages (typically 1–10 megawatts, with a duration of 8-12 hours, except for Form Energy's Iron Air technology, which has a duration of 100 hours). Additionally, the California Public Utilities Commission issued an order for load serving entities to procure 1,000 megawatts of net qualifying capacity of LDES technologies with durations of eight hours or more by 2031, and for the central procurement function at the Department of Water Resources to procure up to 2,000 megawatts of nameplate capacity of LDES technologies by 2037 -- 1,000 MW from LDES technologies with a duration of at least 12 hours and 1,000 MW from multi-day LDES technologies. Iron-air, flow batteries, and many other non-lithium battery chemistries offer the potential for longer storage durations and have little to no risk of thermal runaway-induced fire. However, cost competitiveness and lack of short-term market demand for longer duration storage remain barriers. Continued policy and financial support are essential to move long duration energy storage from concept to widespread deployment.

Hydrogen for power generation offers firm, zero-emission electricity through fuel cells or hydrogen turbines. Electrolytic hydrogen produced with renewable electricity is the most scalable pathway, though cost, infrastructure, and supply chain issues persist. The state's ARCHES initiative and the federal Hydrogen Hubs program were encouraging development of these systems. However, recent cuts in federal funding have resulted in a pause in ARCHES activities. Hydrogen's dual role as energy storage and immediate use positions it as a potential flexible solution.

Bioenergy, as used in this assessment, refers to electricity or hydrogen produced from biological feedstocks such as renewable natural gas, biogas, biomass residues, and other organic waste streams. Capital expenditures for these systems are moderate compared to the full range of resources evaluated in this report. However, fuel costs and production potential vary significantly by feedstock type, energy content, and conversion yield. In addition, the aggregation, collection, and transport of dispersed feedstocks, such as forest residues, agricultural waste, or thinned trees, introduce logistical and cost challenges that can materially affect project feasibility. While it can provide firm capacity and make use of waste streams, the role of bioenergy in California's electricity future will depend on sustainable resource availability, emissions performance, and market incentives.

Overall, California's path to a 100 percent clean electricity system will require a diverse portfolio of firm zero-carbon resources to ensure reliability as California transitions away from fossil fuel. Each technology presents unique strengths and challenges but collectively they offer solutions that can help California maintain reliability while achieving its decarbonization goals.

CHAPTER 1: Introduction

Background

California has long been a national leader in clean energy and climate policy, with a goal of achieving 100% clean electricity and net-zero economy-wide greenhouse gas emissions by 2045. Decarbonizing the electric grid is a foundational step toward this broader objective. The state's Renewables Portfolio Standard (RPS) has played a critical role in this transition, helping California exceed energy targets and placing it on track to reach 90% by 2035.

California's electricity system is undergoing significant transition to achieve 100 percent clean electricity by 2045, as mandated through Senate Bill 100 (De León, Chapter 312, Statutes of 2018). This transition involves a strategic and phased transformation of its electric grid – from one that was historically powered by fossil fuels to one increasingly supported by renewable and zero-carbon resources. As renewable and zero-carbon energy grows and fossil plants retire, these resources play a greater role in supporting all aspects of reliability. Achieving this goal will require not only continued expansion of wind, solar, and battery storage but also integration of diverse renewable and zero-carbon technologies to ensure reliability and resilience.

As demand increases due to electrification, economic development, and extreme heat events, maintaining reliability, particularly during peak and net-peak hours, presents significant challenges. These challenges include reduced firm capacity from retirement of existing dispatchable generation,[1] limited transmission capacity, and the risk of reserve margins falling below planning targets.[2] Some of these challenges could be addressed by the addition of firm zero-carbon resources.

Legislative Requirements

Senate Bill 423 (Stern, Chapter 243, Statutes of 2021) required the CEC, in consultation with the California Public Utilities Commission (CPUC), California Independent System Operator (California ISO), and California Air Resources Board, to submit to the Legislature an assessment of emerging firm zero-carbon resources that support a clean, reliable, and resilient electrical grid in California. This assessment is required to be updated in alignment with each major *Integrated Energy Policy Report* (IEPR) cycle, approximately every two years. In developing the report, the assessment identified available, commercially feasible and near-commercially feasible emerging renewable energy and firm zero-carbon resources, and

1 U.S. Department of Energy. 2025. *Resource Adequacy Report: Evaluating the Reliability and Security of the United States Electric Grid*. https://www.energy.gov/sites/default/files/2025-07/DOE%20Final%20EO%20Report%20%28FINAL%20JULY%207%29.pdf.

2 Watts, Brian and Maureen Quinlan. 2025. "With U.S. Electricity Demand Set to Skyrocket, the Call for Solutions Accelerates." The Pew Charitable Trusts. https://www.pew.org/en/research-and-analysis/articles/2025/09/12/with-us-electricity-demand-set-to-skyrocket-the-call-for-solutions-accelerates.

distinguished which resources could address system reliability needs, local reliability needs, and de-energization events. The assessment evaluated the potential needs for, and roles of these resources using a reasonable range of resource cost and performance assumptions. It also identified barriers to the procurement of these resources and possible pathways for additional procurement. The first SB 423 report was submitted to the Legislature on March 21, 2025. This staff report supplements the 2025 Integrated Energy Policy Report with additional technical detail on firm zero-carbon resources. These resources may be considered for deployment to address local reliability, system reliability, and emissions reductions within California.

Firm Zero-Carbon Resources

This report identifies and evaluates firm zero-carbon resources that are available in the market or in development for commercial use to help maintain a clean, reliable, and resilient electric grid. These resources can support both system-wide and local reliability.

Within the context of this analysis, firm zero-carbon resources are those that reliably produce zero-carbon or renewable electricity, as specified in PUC § 454.53, while producing consistent and stable power supply for extended periods on demand. To qualify, a resource must deliver steady power output. This excludes wind and solar due to their variability. Suitable technologies may include zero-carbon storage options like hydrogen or water reservoirs and must be able to operate for multiple days during extreme conditions. While some of these resources may not run continuously, they can be dispatched for grid needs. The list of resources reviewed in this report includes long duration energy storage (LDES), hydropower, geothermal, bioenergy, hydrogen, small modular reactors (fission), fusion, and carbon capture. These resources, along with a high-level synopsis, are described below:

- **Geothermal** technologies have historically relied upon natural geological conditions, but future deployments may include enhanced geothermal systems which can unlock resources previously deemed unsuitable due to limited permeability or fluid saturation.
- **Hydropower** resources are fully mature, but most viable sites for traditional (dammed) hydropower within California have been exhausted. Growth is expected within pumped storage hydropower, which is currently the least expensive, large-scale energy storage technology in terms of cost per megawatt hour.
- **Carbon capture** allows for existing fossil-fuel power generation assets, which are firm resources, to continue generating while significantly reducing carbon emissions. Carbon capture is still early in commercial deployment for natural gas power plants.
- **Small Modular Reactors** are largely in the demonstration phase and vary significantly in physical design, coolant type, and nuclear process.
- **Fusion** technologies offer transformative potential without the production of nuclear waste, but systems are far from commercial readiness and research to date has remained within a laboratory environment.
- **Long duration energy storage** via (1) electrochemical, (2) thermal, (3) mechanical, or (4) gaseous storage technologies must have durations of eight hours or more and can be zero-carbon when charged with clean resources. Some long duration energy storage

technologies have reached full maturity, while other long duration energy storage technologies are still emergent.

- **Hydrogen** power generation technologies can use renewable hydrogen fuel to produce low-to-zero emission electricity through both combustion and non-combustion processes. Several technology types are being explored. Hydrogen turbines may be better suited to large-scale plants than other hydrogen technologies such as fuel cells, which are better for distributed applications.
- **Bioenergy** can be utilized for direct power generation with biomass or stored as a fuel for energy storage applications.

Analysis and Characterization

To assess the potential role of emerging firm zero-carbon resources in supporting California's clean-energy and reliability goals, staff applied a consistent evaluation framework across all technologies. The framework allows for a clear and comparable assessment of technologies with different characteristics.

Each technology was evaluated across five areas: operational emissions, contribution to system reliability, ability to support local reliability in constrained areas, potential to improve resilience through distributed or restoring power service, and level of technology readiness and cost. Emissions characterization distinguishes between zero-emission and low-emission resources based on whether they produce greenhouse gases or criteria pollutants during power generation. Reliability and resilience characterization consider whether a technology can provide dependable capacity during net-peak periods and multiday events, and/or maintain service during disruptions. Technology readiness is measured using Technology Readiness Levels (TRLs), [3] which range from early laboratory research to full commercial deployment.

TRLs are a way to measure technology maturity. In Table 1, the scale goes from 1 to 9, starting with basic research and ending with full commercial operation. At the lowest TRL levels 1–3, scientists are studying and testing ideas in the lab. In the middle TRL levels 4–6, engineers build and test prototypes in controlled or realistic settings. At the highest TRL levels 7–9, the technology is proven to work in real situations and is ready for use or sale. This system, developed by NASA and now used by agencies like the U.S. Department of Energy and Department of Defense, helps track progress, reduce risk, and compare technology maturity.

Table 1: Technology Readiness Levels

TRL	Description
1	Basic principles observed
2	Technology concept formulated
3	Experimental proof of concept
4	Technology validated in laboratory

3 National Aeronautics and Space Administration (NASA). 2017. *Technology Readiness Level (TRL) Definitions*. https://www.nasa.gov/wp-content/uploads/2017/12/458490main_trl_definitions.pdf.

TRL	Description
5	Technology validated in relevant environment (industrially relevant environment for key enabling technologies)
6	Technology demonstrated in relevant environment (industrially relevant environment for key enabling technologies)
7	System prototype demonstration in operational environment
8	System complete and qualified
9	Actual system proven in operational environment (competitive manufacturing for key enabling technologies, or in space)

Source: U.S. Department of Energy. Technology Readiness Levels.
https://www.energy.gov/sites/prod/files/2016/07/f33/technology_readiness_levels.docx

In determining whether each resource can support local reliability or resiliency, staff asked the following questions:

1. **Local reliability**: Can the resource be deployed to reduce the amount of imported power into the local reliability area, at net peak hours?
2. **Resiliency**: Can the technology be deployed as a distributed resource to address system disruptions and localized outages?

If the answer to either question was yes, then staff assigned one or both roles to the respective resource.

System reliability encompasses the overall ability of the electricity grid in California to consistently provide a stable, adequate and secure supply of electricity. It involves meeting the demands of electricity consumers while adhering to established reliability standards.

In assigning the role of each resource on its emissions characteristics, staff asked the following questions:

1. **Zero emissions**: Does this resource category produce emissions, which include greenhouse gases or criteria pollutants, during power generation? If the answer is no, the resource was assigned a zero-emissions attribute.
2. **Low emissions**: If the answer to the zero-emission question is yes, then does the resource produce less emissions relative to fossil-fueled generation?[4] If so, the resource was assigned a low-emissions attribute.

It should be noted that lifecycle emissions were not included in this report analysis and some resource categories include technologies that can fall under either classification depending on their design or operational pathway. For example, the combustion of hydrogen can create nitrous oxides, a criteria pollutant at the point of use, while hydrogen fuel cells do not produce greenhouse gases or other criteria air pollutants. Similarly, certain bioenergy or carbon-capture configurations may span both categories.

4 U.S. Energy Information Administration. "Emission Annual Data."
https://www.eia.gov/electricity/data/state/emission_annual.xlsx.

CHAPTER 2: Geothermal Resources

Technology Overview

Conventional geothermal power plants utilize heat from the subsurface to generate electricity. Geothermal systems require favorable conditions for temperature, pressure, enthalpy, and permeability. The heated fluid is utilized to create steam, which is then used to generate electricity similar to other thermal plants.[5] These conditions do not vary with surface weather conditions, so geothermal power plants can reliably generate power at all times and can be used as baseload power.

An emerging geothermal technology, enhanced geothermal systems (EGS), has been in development for decades and has recently been deployed in successful demonstration projects. EGS sites start with just one of the many requirements for geothermal energy, hot rock. A working fluid is injected into these hot dry rock formations, where it absorbs heat, is brought to the surface, converted to steam, and used to drive turbines for electricity generation.[6] The potential advantage of EGS is its potential to vastly expand the amount of geothermal electrical capacity that can be developed. There is an enormous quantity of thermal energy stored in the subsurface. If a process can be developed and scaled to transfer this heat to a working fluid, EGS could enable large-scale, renewable baseload power generation.

Technology Maturity and Performance

Conventional Geothermal

In 2024, California had 2.715 GW of operational geothermal plants[7][8] – all of which are conventional, while the U.S. has roughly 4 GW of operational geothermal plants.[9] In other words, roughly two thirds of all installed geothermal capacity in the U.S. is in California.

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5 United States Department of Energy staff. n.d. "Geothermal: Electricity Generation." United States Department of Energy. https://www.energy.gov/eere/geothermal/electricity-generation.

6 Utah FORGE staff. 2021. "Frequently Asked Questions About Utah FORGE." Utah FORGE. https://utahforge.com/wp-content/uploads/2021/08/FAQs-Utah-FORGE-Final.pdf.

7 Nyberg, Michael. n.d. "Electric Generation Capacity and Energy." California Energy Commission. https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/electric-generation-capacity-and-energy.

8 California Energy Commission staff. 2025. "Electric Generation and Capacity 2024." California Energy Commission. https://www.energy.ca.gov/media/3757.

9 United States Department of Energy staff. N.d. "Geothermal: Electricity Generation." United States Department of Energy. https://www.energy.gov/eere/geothermal/electricity-generation.

Most geothermal power plants in California are in the Geysers region at the border of Sonoma and Lake counties, or in Imperial County near the California-Mexico border. There are currently 17 geothermal power plants in operation in the Geysers and 18 in operation in Imperial County. The plants in the Geysers began operation between 1971 and 1989, and roughly two thirds have a capacity of 110 to 120 MW. In Imperial County, 16 of the 18 geothermal plants began operation between 1985 and 2000 and are generally smaller than plants in the Geysers. Roughly three fourths of these plants have capacities of 18.5 to 55 MW. There are also three geothermal power plants in Inyo County, four in Mono County, and one in Lassen County.[10]

Enhanced Geothermal Systems

In 2014, the DOE launched the Frontier Observatory for Research in Geothermal Energy (FORGE) initiative to demonstrate and advance EGS technology. The DOE selected a site near Bearskin Mountain in Utah. Between 2018 and 2024, the FORGE project spent approximately $220 million constructing and testing an EGS system. FORGE staff anticipate that the federal government will continue to support the FORGE project during President Trump's second presidential term.

The FORGE approach to EGS is to drill multiple wells at least one mile deep, where the surrounding rock is at temperatures between 175°C and 225°C (between 347°F and 437°F). To create pathways underground connecting the wells, FORGE places a perforated pipe known as a perf gun in each well within the hot rock. The perf guns create fractures in the rock to allow for increased permeability. Water under pressure is then injected from the wells into the fractures to further expand them.[11] Once permeability has been established, a working fluid is injected through one well, absorbs heat from the rock, and is recovered through a separate production well. In August 2024, the FORGE project had demonstrated that it could inject 420 gallons of water each minute and recover more than 90% of this fluid at temperatures around 188°C (370°F) – sufficiently hot temperatures to generate electricity at commercially viable rates.[12]

Fervo Energy is aiming to commercialize EGS technology at a site located in the same county (Beaver County, Utah). Fervo Energy estimates their project will provide 500 MW of electrical

10 Loza, Erica. N.d. "California Known Geothermal Resource Areas, Geothermal Power Plants, and Funded Geothermal Program Projects." California Energy Commission. https://www.energy.ca.gov/programs-and-topics/programs/geothermal-grant-and-loan-program/california-geothermal-grant-and-0.

11 Utah FORGE staff. 2024. "Utah FORGE Successfully Completes Stimulation and Circulation Tests – Establishing Effective Communication." Utah FORGE. https://utahforge.com/press-release-stimcirc-tests/.

12 Utah FORGE staff. 2024. "Utah FORGE concludes successful extended circulation test." Utah FORGE. https://utahforge.com/utah-forge-concludes-successful-extended-circulation-test/.

nameplate capacity[13] -- 100 MW in 2026, and 400 MW more by 2028.[14] All of this capacity has been contracted, including 31 MW to Shell Energy North America,[15] 320 MW to Southern California Edison,[16] and 48 MW to the Clean Power Alliance.[17]

Policy and Regulatory Landscape

Multiple California state policies incentivize utilities to procure additional geothermal power. In 2021, the CPUC ordered the LSEs in its jurisdiction to collectively procure at least 1,000 MW from clean firm resources such as geothermal, measured in net qualifying capacity, to come online between 2023 and 2026.[18] The CPUC has since extended the deadline for these clean firm resources to come online to 2028 and has given LSEs the option to further extend the deadline to 2031.[19] Additionally, in 2024, the CPUC asked the California Department of Water

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13 Szymczak, Pat. 2024. "Fervo Energy inks world's largest geothermal power purchase agreements with Southern California Edison." Journal of Petroleum Technology. https://jpt.spe.org/fervo-energy-inks-worlds-largest-geothermal-power-purchase-agreements-with-southern-california-edison.

14 Fervo Energy staff. 2025. "Fervo Energy secures $206 million in new financing to accelerate Cape Station development." Fervo Energy. https://fervoenergy.com/fervo-secures-new-financing-to-accelerate-development/.

15 Fervo Energy staff. 2025. "Fervo Energy Announces 31 MW Power Purchase Agreement with Shell Energy." Fervo Energy.
https://fervoenergy.com/fervo-energy-announces-31-mw-power-purchase-agreement-with-shell-energy/.

16 Fervo Energy staff. 2024. "Fervo Energy Announces 320 MW Power Purchase Agreements with Southern California Edison." Fervo Energy. https://fervoenergy.com/fervo-energy-announces-320-mw-power-purchase-agreements-with-southern-california-edison/.

17 Clean Power Alliance staff. 2025. "Clean Power Alliance's expanded carbon-free geothermal supply will avoid 173 million pounds of greenhouse gas emissions annually: Renewable resource will provide 24/7 clean power to over 54,500 southern California homes each year." GlobeNewswire. https://www.globenewswire.com/news-release/2025/02/28/3034891/0/en/Clean-Power-Alliance-s-Expanded-Carbon-Free-Geothermal-Supply-Will-Avoid-173-Million-Pounds-of-Greenhouse-Gas-Emissions-Annually.html.

18 California Public Utilities Commission staff. 2021. "Fact sheet: Decision requiring clean energy procurement for mid-term reliability." California Public Utilities Commission. https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/integrated-resource-plan-and-long-term-procurement-plan-irp-ltpp/d2106035-mtr-decision-factsheet--07-01-2021.pdf.

19 California Public Utilities Commission staff. 2025. "California Public Utilities Commission (CPUC) Staff Review of Load-Serving Entities' (LSEs') Compliance with the Mid-Term Reliability (MTR, D.21-06-035) and Supplemental MTR (SMTR, D.23-02-040) Decisions." California Public Utilities Commission. https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/integrated-resource-plan-and-long-term-procurement-plan-irp-ltpp/compliance-status-reportmid-term-reliability-mtr-and-supplemental-mtr.pdf.

Resources (DWR) to consider procuring up to 1,000 MW nameplate capacity[20] of geothermal resources, to come online by 2037.[21]

In addition, California's sixteen largest Publicly Owned Utilities (POUs) are required to reduce their greenhouse gas emissions. In the most recent cycle of the Integrated Resource Plans, thirteen of these POUs forecasted new geothermal power procurement from 2026 onwards as a source of firm zero-carbon electricity will help meet emissions goals. 23 The sixteen largest POUs collectively forecasted that their owned and contracted dependable capacity from geothermal power would increase from 734 MW in 2026 to 1229 MW in 2030 – an increase of roughly 500 MW.

Challenges and Barriers

There has been only a small increase in net installed capacity from conventional geothermal power plants in California since the year 2000. This can partly be attributed to three factors. First, conventional geothermal power plants have high upfront costs, including high costs associated with resource characterization and drilling. Second, resources for conventional geothermal power plants are often located far away from load centers, in which case new transmission lines may be required to interconnect plants. Third, conventional geothermal projects go through long and complex processes to permit projects.[22]

Despite promising recent results, there are several potential issues with EGS technologies. EGS technologies have historically had higher costs per unit of electricity generated than many other sources of electricity generation.[23] Additionally, there are potential technical issues with EGS such as induced seismicity. These are small earthquakes caused by injecting fluid into dry formations.[24] The results from Fervo Energy's venture – whether the company is able to provide this power, for an extended period, while operating at a profit – will provide additional evidence and data about the commercial viability of EGS technology.

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20 California Public Utilities Commission staff. 2024. "CPUC Advances Clean Energy with Centralized Procurement Strategy." California Public Utilities Commission. https://www.cpuc.ca.gov/news-and-updates/all-news/cpuc-advances-clean-energy-with-centralized-procurement-strategy.

21 California Public Utilities Commission staff. 2024. "Fact Sheet: Decision Determining Need for Centralized Procurement of Long Lead-time Resources (R.20-05-003)." California Public Utilities Commission. https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/integrated-resource-plan-and-long-term-procurement-plan-irp-ltpp/ab1373/final_decision_-ab1373_factsheet_pdf.pdf.

22 Levine, Aaron, Ligia E.P. Smith, Jody Robins, Erik Witter, Caity Smith, and Clare Haffner. 2022. "Non-Technical Barriers to Geothermal Development in California and Nevada." National Renewable Energy Laboratory. NREL/TP-6A20-83133. https://www.nrel.gov/docs/fy23osti/83133.pdf.

23 Smith, Morgan. 2024. "Enhanced Geothermal Sytems (EGS): Frequently Asked Questions." Congressional Research Service. https://www.congress.gov/crs_external_products/R/PDF/R48090/R48090.2.pdf.

24 Ellsworth, William, and Josie Garthwaite. 2019. "Lessons from Pohang: A Stanford geophysicist discusses geothermal energy's earthquake problem – and possible solutions." Stanford Report. https://news.stanford.edu/stories/2019/05/lessons-south-korea-solving-geothermals-earthquake-problem.

Opportunities and Future Outlook

Electrical generation from conventional geothermal power plants could be increased in California. In 2024, the National Laboratory of the Rockies (NLR) estimated that there is 31.38 GW of remaining conventional geothermal potential in the U.S., mostly located across the western U.S. – 5.566 GW from identified resources and 25.810 GW from undiscovered resources.[25] The CEC curates data on known geothermal fields in California whose generation potential has been estimated by the federal government. In 2021, across all such geothermal fields in California, there was approximately 3.5 GW of undeveloped resource potential.[26]

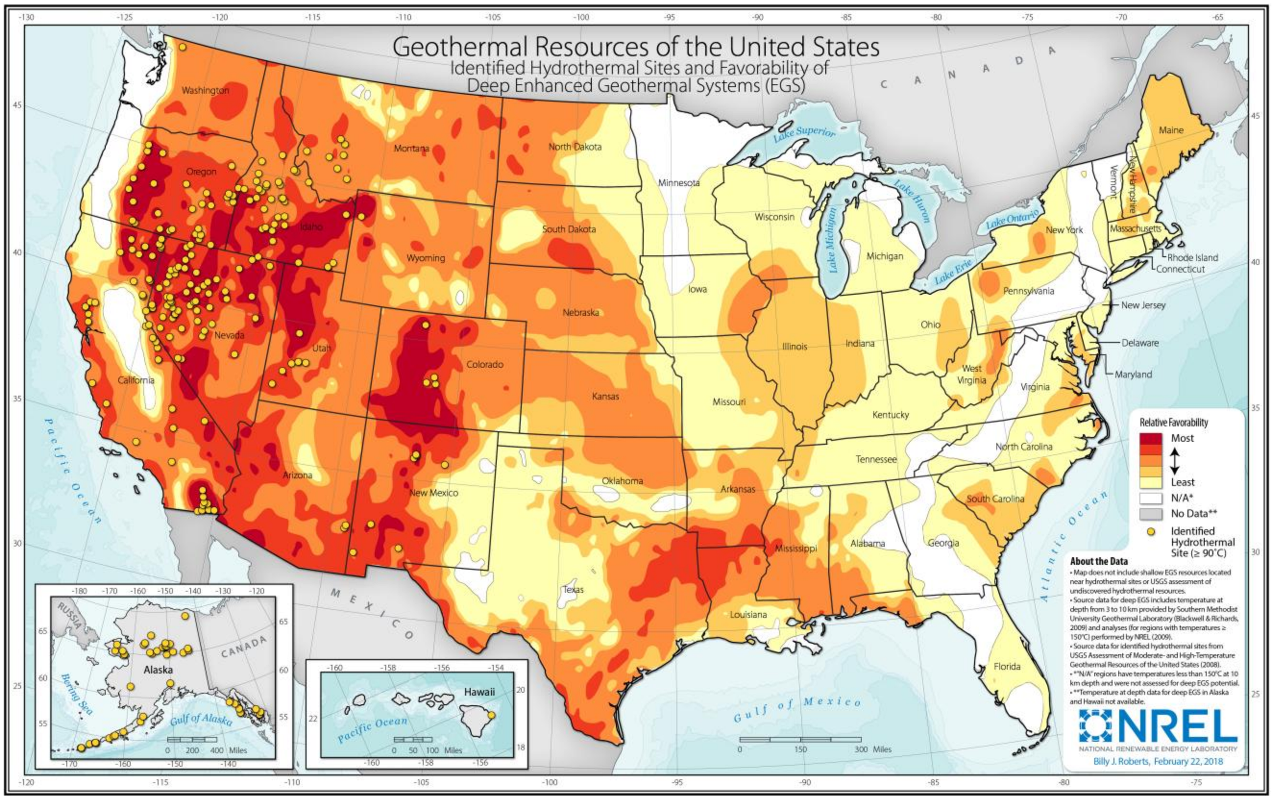
If EGS is successfully commercialized at scale, this technology could vastly expand the accessible geothermal resource base. NLR has estimated that the U.S. EGS resource potential exceeds 100 gigawatts (GW). Figure 1 illustrates the identified conventional geothermal sites (yellow circles) in the U.S. and the relative favorability of different locations to EGS (red).[27]

25 National Laboratory of the Rockies staff. 2025. "Annual Technology Baseline: Geothermal." National Laboratory of the Rockies. https://atb.nrel.gov/electricity/2024/geothermal.

26 California Energy Commission staff. 2024. "Geothermal Resource Potential by Field." State of California Open Data. https://lab.data.ca.gov/dataset/geothermal-resource-potential-by-field.

27 National Laboratory of the Rockies staff. 2025. "Annual Technology Baseline: Geothermal." National Laboratory of the Rockies. https://atb.nrel.gov/electricity/2024/geothermal.

Figure 1: Map of Identified Hydrothermal Sites and Favorability of Deep EGS in the United States



Source: NLR ATB, 2025.

CHAPTER 3: Hydropower Resources

Technology Overview

Hydropower remains a valuable zero-carbon resource helping California meet electricity demand and maintain grid reliability. While new conventional hydropower development is limited by environmental and geographic constraints, the technology continues to provide steady and reliable generation across the state.

California hosts over 12 GW of conventional hydroelectric capacity, including large dam-based and run-of-river facilities that can provide flexible generation and water management benefits. In the past year, most new activity has focused on pumped storage hydropower (PSH), which offers large scale energy storage that can help balance variable resources such as solar and wind and improve grid reliability. California currently has an estimated 3.9 GW[28] of PSH in operation and an estimation of more than 2.7 GW of proposed PSH projects in various stages of development.

Because opportunities for new development are limited due to siting constraints and environmental permitting requirements, current efforts are focused on upgrading existing infrastructure and advancing new forms of hydropower-based energy storage. Efficiency upgrades, such as modern turbine replacements, are being deployed to boost generation capacity at legacy plants.

Interest in pumped storage hydropower is also growing, particularly in closed loop systems that use two isolated reservoirs. These projects can utilize excess solar or wind energy to pump water to higher elevations and dispatch it when grid demand is higher or renewable output drops.[29]

Figure 2 to Figure 5 below illustrate how conventional hydropower and pumped storage hydropower operate, showing the basic schematic and how each system produces and stores energy.

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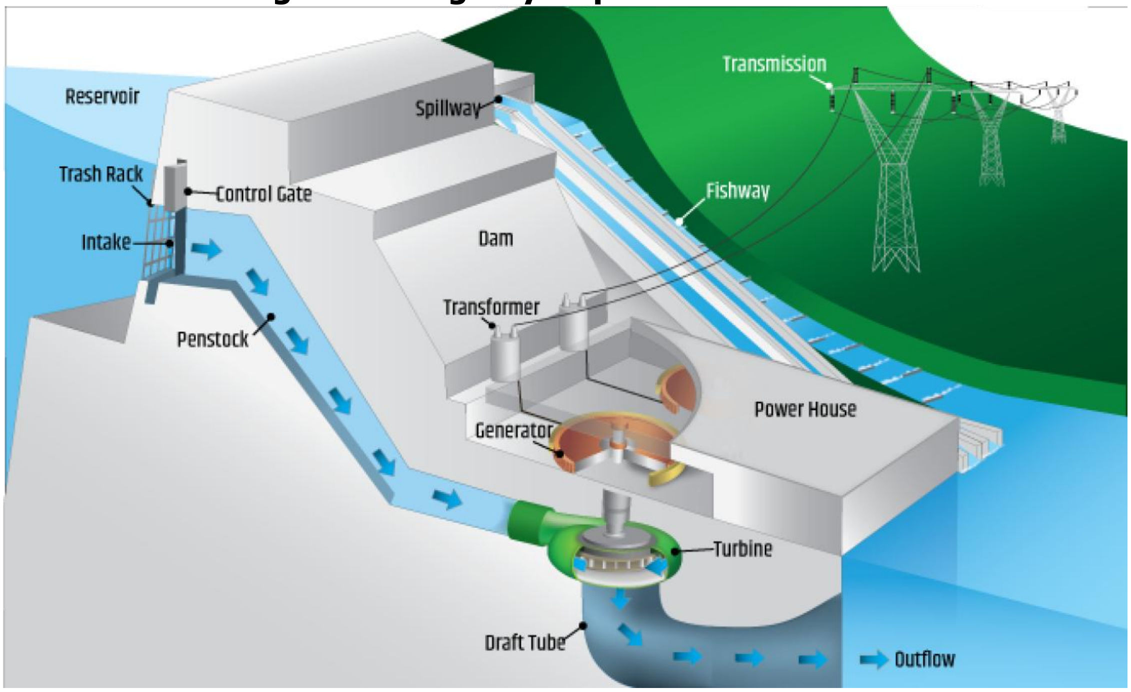
28 U.S. Energy Information Administration (EIA), *Natural gas-fired generation increases in the Southwest Power Pool*. https://www.eia.gov/todayinenergy/detail.php?id=41833

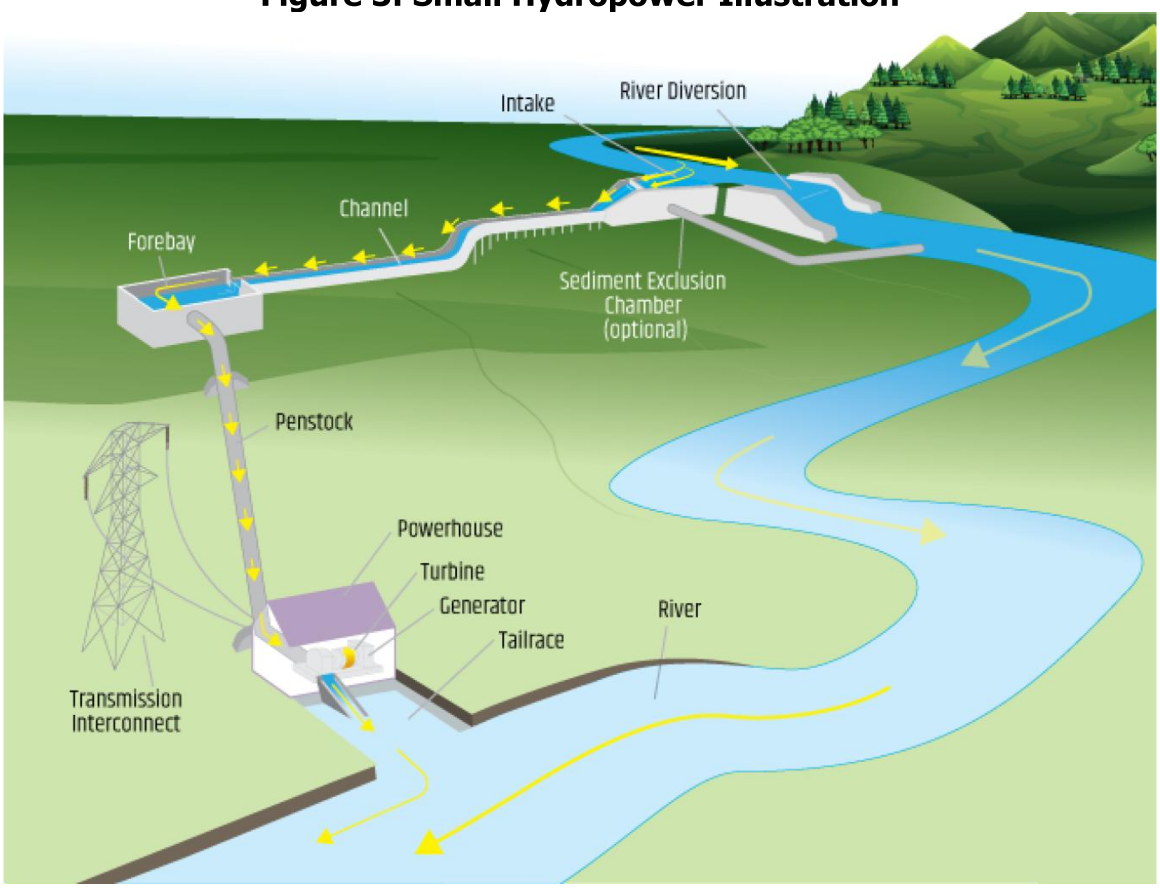
29 U.S. Department of Energy, *Pumped Storage Hydropower*. https://www.energy.gov/eere/water/pumped-storage-hydropower.

Figure 2: Large Hydropower Illustration



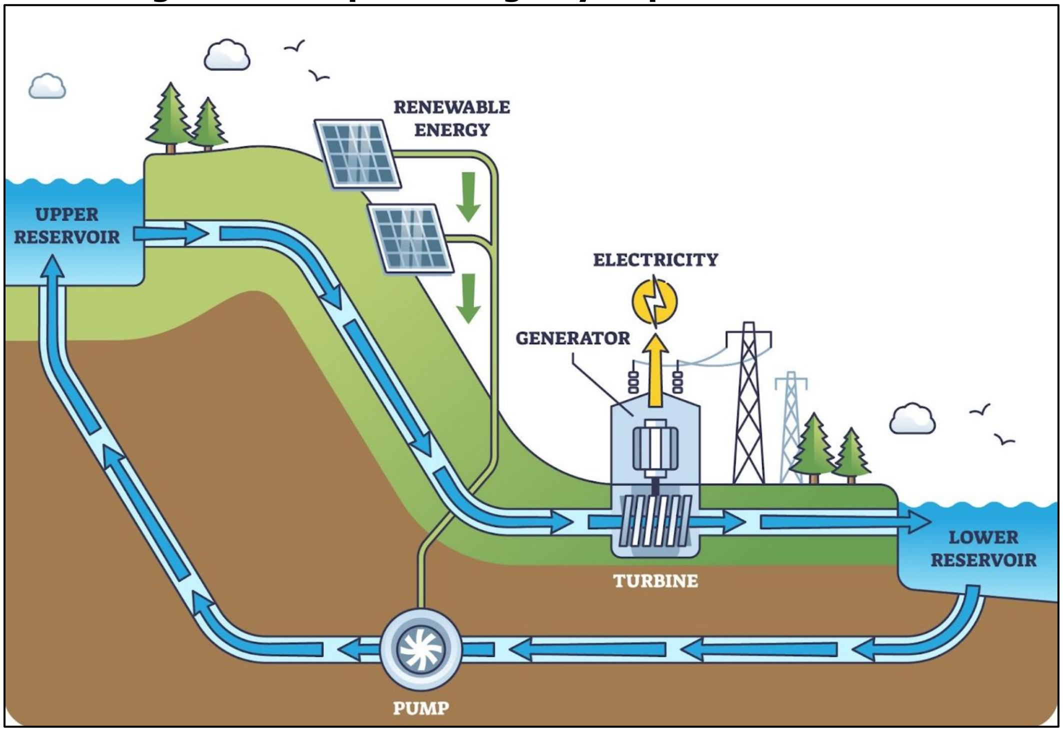
Source: Department of Energy

Figure 3: Small Hydropower Illustration



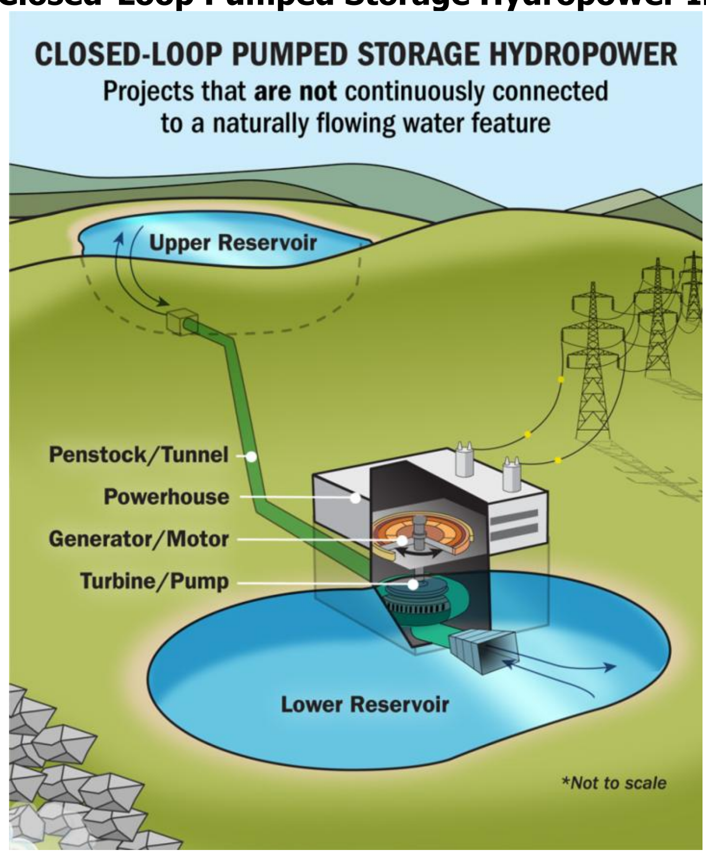
Source: Department of Energy

Figure 4: Pumped Storage Hydropower Illustration



Source: Department of Energy

Figure 5: Closed-Loop Pumped Storage Hydropower Illustration



Source: Department of Energy

Table 2: Hydropower Technological Profile

Criteria	Unit	Large Hydropower	Small Hydropower	Pumped Storage Hydropower
Typical Power Output	MW	> 30 MW	< 30 MW	100–1,000+
Net Capacity Factor	%	41%	66%	N/A
Annual Energy Production	kWh/kW	3,680	5,430	N/A
Round-Trip Efficiency	%	N/A	N/A	70–87[30]
Discharge Duration	Hours	N/A	N/A	8–12+
Lifetime	Years	~100	~100	~100

Source: 2024 NLR ATB. https://atb.nrel.gov/electricity/2024/data

Technology Maturity and Performance

Hydropower technologies in California range from fully commercialized systems to mature but less widely deployed configurations. Large and small hydropower facilities are well established, with most systems in operation for several decades and a technology readiness level (TRL) of 9. These technologies are proven and continue to provide essential, zero-carbon electricity across the state.

Pumped storage hydropower, including closed-loop variants, also holds a TRL of 9 and has been successfully deployed in multiple locations. However, deployment has slowed in recent years due to permitting, cost, and siting challenges.[31]

Closed-loop PSH, which is isolated from natural waterways, has gained renewed interest as California seeks long-duration energy storage solutions to support its clean energy goals. Although technically mature, these systems have seen limited deployment to date due to long development timelines, high upfront costs and complex permitting.[32]

31 U.S. Department of Energy. 2023. Technology Strategy Assessment – Pumped Storage Hydropower. https://www.energy.gov/sites/default/files/2023-07/Technology%20Strategy%20Assessment%20-%20Pumped%20Storage%20Hydropower_0.pdf

32 U.S. Department of Energy, Office of Scientific and Technical Information (OSTI). 2019. Pumped Storage Hydropower: Advanced Concepts for Improved Reliability, Integration, and Sustainability. https://www.osti.gov/servlets/purl/1546512.

Table 3 summarizes the main hydropower technologies, their basic operating mechanisms, and corresponding TRLs.

Table 3: Hydropower Technologies

Technology Type	Mechanism	TRL
Large Hydropower (> 30 MW)	Releases stored water from dams through turbines to generate electricity	9
Small Hydropower (< 30 MW)	Generates power from low-head flows, canals, or pipelines using compact turbine systems	9
Pumped Storage Hydropower	Moves water between two reservoirs to store and release electricity based on grid needs	9
Closed-Loop PSH	Uses two artificial reservoirs not connected to a river to store and discharge energy	6–8

Source: CEC

While these technologies are well established, their operational characteristics and performance metrics vary depending on scale and configuration. Table 4 provides a comparison of hydropower technological profiles.

Table 4: Hydropower Technological Profile

Criteria	Unit	Large Hydropower	Small Hydropower	Pumped Storage Hydropower
Typical Power Output	MW	> 30 MW	< 30 MW	100–1,000+
Net Capacity Factor	%	41%	66%	N/A
Annual Energy Production	kWh/kW	3,680	5,430	N/A
Round-Trip Efficiency	%	N/A	N/A	70–87[33]

33 National Laboratory of the Rockies. Pumped Storage Hydropower – 2024 Annual Technology Baseline. https://atb.nrel.gov/electricity/2024/pumped_storage_hydropower.

Criteria	Unit	Large Hydropower	Small Hydropower	Pumped Storage Hydropower
Discharge Duration	Hours	N/A	N/A	8–12+
Lifetime	Years	~100	~100	~100

Source: 2024 NLR ATB. https://atb.nrel.gov/electricity/2024/data

Recent Innovations and Future Improvements

Hydropower modernization efforts have focused on increasing efficiency, reducing environmental impacts, and improving grid integration. For large hydropower, key innovations include high-efficiency turbine replacements,[34] digital sensors, and real-time automation systems that reduce outages[35] and improve operational flexibility. Forecast-informed reservoir operations have also been adopted to optimize water releases[36] using weather and runoff models.

In small hydropower, modular and prefabricated turbine systems have streamlined installation and reduced costs. Advanced control systems improve performance in remote or off-grid settings, and new designs, such as low-head and fish-friendly turbines, have minimized ecological impacts.

In the pumped storage segment, closed-loop configurations have emerged as a key innovation, offering energy storage without direct river connection. These systems benefit from advanced tunneling techniques, faster construction timelines through modular components, and flexible turbines that respond quickly to grid needs. Coupling with renewables and the use of real-time optimization tools further enhances the value and responsiveness of pumped storage systems. [37]

Policy and Regulatory Trends

Hydropower technologies benefit from policy frameworks aimed at enhancing grid reliability, supporting zero-carbon generation, and expanding energy storage.

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34 National Hydropower Association. Modernizing America's Hydropower. https://www.hydro.org/waterpower/modernizing/.

35 Arxiv. 2025. Battery Storage as a Grid Reliability Resource: Evidence from CAISO Market Participation. https://arxiv.org/abs/2504.15483.

36 California Department of Water Resources. 2025. Report Shows Forecast-Informed Reservoir Operations Can Increase Region Resilience. https://water.ca.gov/News/News-Releases/2025/Mar-25/Report-Shows-Forecast-Informed-Reservoir-Operations-Can-Increase-Region-Resilience.

37 U.S. Department of Energy. 2023. Predicting Grid and Market Trends to Maximize Pumped Storage Hydropower. https://www.energy.gov/eere/water/articles/predicting-grid-and-market-trends-maximize-pumped-storage-hydropower.

Federally, the Bipartisan Infrastructure Law[38] provides funding for dam repairs, modernization projects,[39] and grid-scale storage, including pumped storage hydropower. The DOE supports hydropower through multiple programs, including the Water Power Technologies Office and the Long-Duration Storage Shot initiative, which funds advanced energy storage development. The Hydropower Regulatory Efficiency Act[40] streamlines the licensing process for small hydropower projects under 10 MW.

Additionally, the Water Resilience Portfolio promotes integrated water energy planning, while Clean Energy Financing Programs[41] assist local governments in funding small-scale hydropower development. These policy tools help reduce project costs, simplify permitting, and incentivize technology upgrades across the hydropower sector.

Challenges and Barriers

Despite its many benefits, hydropower development in California faces a range of persistent challenges. Drought and climate variability have a direct impact on hydropower output, reducing water availability and limiting generation when it is often needed most. Many of California's large hydropower assets are aging and require significant investment to maintain operational reliability and safety. Environmental regulations, while essential for protecting aquatic ecosystems, can constrain water release timing and reduce operational flexibility. Pumped storage and closed-loop systems face additional hurdles such as long permitting timelines, complex regulatory review processes involving multiple agencies, and high capital costs. Financing remains a key barrier, especially for projects requiring extended development timelines without guaranteed long-term revenue streams. Furthermore, siting limitations, due to terrain, land use conflicts, and water sourcing requirements, can constrain the deployment of new closed-loop pumped storage facilities.

Opportunities and Outlook

Despite these challenges, hydropower remains a strategic asset in California's transition to a clean and reliable electricity grid. Significant opportunities exist to enhance the value and performance of existing facilities through modernization efforts such as turbine and capacity upgrades, digital monitoring, and improved coordination with water agencies. Small hydropower offers untapped potential through the installation of turbines in irrigation canals, pipelines, and dam outlets, often requiring minimal new construction. Pumped storage hydropower, especially in closed-loop configurations, can provide long-duration storage that is critical for balancing variable solar and wind generation. These systems offer up to 12 or more

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38 U.S. Congress. Infrastructure Investment and Jobs Act (H.R.3684 - 117th Congress). https://www.congress.gov/bill/117th-congress/house-bill/3684.

39 U.S. Department of Energy. 2024. U.S. Department of Energy Invests Nearly $15 Million to Enhance Hydropower's Ability to Support a Reliable and Resilient Power Grid. https://www.energy.gov/eere/articles/us-department-energy-invests-nearly-15-million-enhance-hydropowers-ability-support.

40 U.S. Congress. Hydropower Regulatory Efficiency Act of 2013 (H.R. 267). https://www.congress.gov/bill/113th-congress/house-bill/267.

41 California Public Utilities Commission. Clean Energy Financing Programs. https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/demand-side-management/energy-efficiency/clean-energy-financing.

hours of discharge, making them uniquely suited to meet peak demand and support grid stability. When paired with hybrid renewable projects, closed-loop PSH can reduce integration costs and expand siting flexibility. With continued policy support, interagency collaboration, and innovation in design and permitting, hydropower technologies can continue to provide zero-carbon energy while supporting California's evolving reliability and decarbonization needs.

CHAPTER 4:
Carbon Capture

Technology Overview

Carbon capture remains an important tool for reducing carbon emissions from existing fossil fuel power plants, especially natural gas combined cycle (NGCC) plants. While these systems do not make a power plant completely carbon free, they can remove most carbon dioxide (CO_2) emissions, helping the state meet climate goals while keeping the electricity grid reliable.

Post-combustion carbon capture, where CO_2 is removed from the exhaust of power plants, remains the most commonly used method for capturing emissions from natural gas combined cycle plants. Other approaches, such as oxy-fuel combustion, pre-combustion capture, and direct air capture are also under development but remain less widely deployed. This chapter focuses on post-combustion capture technologies as it is the most commercially mature and widely applied method for capturing emissions from natural gas combined cycle facilities.

Technology Maturity and Performance

Post-combustion carbon capture remains the most commercially mature and widely demonstrated approach for removing CO_2 from power plants. These systems have achieved capture rates above 90 percent in some installations and continues to advance, with emerging techniques aimed at improving CO_2 capture efficiency, system modularity, and energy performance. Several commercial players and research institutions are developing new materials, modular systems, and hybrid processes to overcome cost and performance barriers. Table 5 summarizes the major post-combustion carbon capture technology types, their mechanisms, technology readiness levels (TRL), and key stakeholders actively developing or piloting these systems.

Table 5: Post-Combustion Carbon Capture Technologies

Technology Type	Mechanism	TRL	Key Stakeholders
Absorption	Chemical solvent (usually amines) absorbs CO_2	8–9	Mitsubishi Heavy Industries, Shell
Swing Adsorption	Solid sorbents adsorb CO_2 and release it during pressure/temperature swing	6–9	Nuada, Svante, Carbon Clean
Membrane Separation	Selective membranes filter CO_2 based on size or solubility	5–8	Membrane Technology & Research, GTI Energy, Air Liquide

Technology Type	Mechanism	TRL	Key Stakeholders
Cryogenic Capture	CO_2 is condensed by extreme cooling (desublimation)	4–6	Chart Industries, Carbon America

Source: CEC

Absorption

Amine absorption is the most developed method for removing CO_2 from flue gas in power and industrial settings, with a TRL of 8 to 9, indicating it is fully commercial and widely demonstrated. The approach uses chemical solvents, primarily amines, to bind CO_2 from exhaust streams. Current development focuses on reducing energy consumption during solvent regeneration and improving solvent durability to lower operating costs. Key stakeholders that are leading the development of these technologies include, but are not limited to:

- Mitsubishi Heavy Industries, which has deployed over a dozen commercial systems globally using its KS-1 and KS-21 solvents,[42] achieving capture rates of 90 to 95 percent.
- Shell's CANSOLV system has been used in coal and industrial applications.[43]

Swing Adsorption

Swing adsorption systems use solid materials to capture CO_2 from flue gas and then release it by changing pressure or temperature. These technologies are well suited to smaller installations due to their lower heat requirements and smaller size. Most swing adsorption systems for post-combustion applications are at a TRL of 6 to 8, meaning they have progressed beyond lab testing and are now being demonstrated at pilot and near commercial scale. Current research focuses on making the sorbents last longer, speeding up the capture-release cycle, and lowering costs. Key developers include the following.

- Nuada, which employs metal-organic frameworks in a vacuum swing adsorption process to improve CO_2 capture efficiency. Their pilot plant in Italy began operations in mid-2024 at a cement facility in Monselice and captures approximately one ton of CO_2 per day.[44]
- Svante, which uses structured solid sorbents coated with metal-organic frameworks. Their new gigafactory in British Columbia can manufacture filters to capture as much as

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42 Mitsubishi Heavy Industries. *CO_2 Recovery Plants (Post Combustion)*. https://www.mhi.com/products/engineering/co2plants_process.html.

43 Shell. *CANSOLV CO_2 Capture System Fact Sheet*. https://catalysts.shell.com/hubfs/Shell%20Cansolv%20CO2%20Capture%20System%20Fact%20sheet.pdf.

44 Nuada. 2024. *Nuada Starts Carbon Capture Trials to Accelerate Decarbonisation of Cement Industry*. https://nuadaco2.com/nuada-starts-carbon-capture-trials-to-accelerate-decarbonisation-of-cement-industry/.

10 million tons of CO_2 annually.[45] The company aims to deploy these filters in rotary adsorption machines at industrial sites.

- Carbon Clean, which is creating compact adsorption units tailored for gas and industrial plants. These modular units simplify installation and operation in existing facilities.[46]

Membrane Separation

Membrane separation systems use specialized filters that allow CO_2 to pass through while blocking other gases based on molecular size or chemical properties. These systems operate without solvents or regeneration heat, which can lower operational complexity, energy use, and water consumption. Most membrane technologies for post-combustion carbon capture are at a TRL of 5 to 8, meaning they are moving from laboratory validation to pilot and demonstration stages. Current development focuses on improving membrane selectivity, durability, and reducing the pressure or vacuum requirements needed to move gas through the system. Key developers include the following.

- Membrane Technology & Research (MTR), which is developing polymer-based membrane systems for post-combustion capture. Their platform is designed for scalability and is being tested in demonstration projects with natural gas and coal plants.[47]
- GTI Energy, which is piloting compact membrane systems integrated with other low-carbon technologies to reduce the cost and footprint of CO_2 capture.[48] GTI Energy is also exploring electrified membrane systems that use voltage rather than pressure, offering opportunities for integration with renewable electricity.
- Air Liquide, which has developed advanced gas separation membranes and is deploying them in various industrial settings for partial CO_2 separation and conditioning.[49]

Cryogenic Capture

Cryogenic carbon capture uses extreme cooling to separate CO_2 from flue gas by condensing or freezing it. This method does not use solvents or sorbents, which helps reduce chemical handling and waste. It produces high-purity liquid CO_2 with little need for further processing. Most cryogenic systems for carbon capture are at a TRL of 5 to 7, meaning they are in pilot-scale testing but not yet widely demonstrated in commercial power settings. Current development focuses on improving system efficiency and lowering energy consumption.

Key developers include:

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45 Svante. 2025. *Svante Launches World's First Commercial Gigafactory for Carbon Capture Removal Filters*. https://www.svanteinc.com/press-releases/svante-launches-worlds-first-commercial-gigafactory-for-carbon-capture-removal-filters/.

46 Carbon Clean. *Modular CO_2 Capture Technology*. https://www.carbonclean.com/technology/modular.

47 Membrane Technology and Research (MTR). *Carbon Capture Technology*. https://mtrccs.com/technology/.

48 GTI Energy. *Carbon Capture with Facilitated Transport Membrane (FTM) Technology*. https://www.gti.energy/carbon-capture-with-facilitated-transport-membrane-ftm-technology/.

49 Air Liquide. *Our Membranes*. https://usa.airliquide.com/innovation-technology/membrane-technology/our-membranes.

- Carbon America, which is piloting its FrostCC system to test cryogenic capture performance in various industrial settings.[50]
- Chart Industries, which developed the Cryocap system for commercial and industrial carbon capture.[51]

Performance Characteristics

Performance metrics, CO_2 capture efficiency, energy input, cost per ton captured, emissions intensity, and system lifetime, remain central to evaluating carbon capture technologies. Although no major changes have been identified in core performance metrics since the previous report,[52] recent pilot projects and laboratory scale demonstrations continue to support earlier estimates. Amine based systems continue to lead with capture efficiencies ranging from 90 to 97 percent. Cryogenic and swing adsorption technologies are showing potential for lower energy consumption in specific settings. Membrane and cryogenic systems are still in earlier stages of use but are advancing through improvements in materials and system integration, particularly for natural gas power plant retrofits.

Policy and Regulatory Trends

Carbon capture technology depends heavily on supportive policies, financial incentives, and regulatory clarity to advance. Without ongoing federal and state backing, many existing and planned projects would likely stall or shut down. Public funding and clear permitting pathways are essential for reducing risk, attracting private investment, and moving projects from pilot to commercial scale. The following sections outline key federal and California state policies that have shaped the growth of this sector.

Federal Policies

Federal policy has become the main driver of carbon capture development in the U.S., providing the financial support needed to scale early-stage technologies.

- The Inflation Reduction Act (IRA) significantly increased the Section 45Q tax credit. For point-source capture, it now provides up to $85 per metric ton of CO_2 permanently stored in secure geologic formations.[53] The law also lowered the minimum capture thresholds, making more facilities eligible, and allows direct pay for nonprofit or public entities, reducing barriers to participation.[54]

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50 Carbon America. *Carbon Capture Technology*. Available at: https://www.carbonamerica.com/technology.

51 Chart Industries. *Carbon Capture Solutions*. Available at: https://www.chartindustries.com/Products/Carbon-Capture.

52 California Energy Commission. *Senate Bill 846 Implementation Update*. Available at: https://efiling.energy.ca.gov/GetDocument.aspx?tn=262264&DocumentContentId=98778.

53 U.S. Department of Energy. *IRA and Carbon Management Opportunities in Tribal Nations*. Available at: https://www.energy.gov/sites/default/files/2023-03/IRA-and-Carbon-Management-Opportunities-in-Tribal-Nations.pdf.

54 U.S. Department of Energy. *Qualifying Advanced Energy Project Credit (48C) Program*. Available at: https://www.energy.gov/infrastructure/qualifying-advanced-energy-project-credit-48c-program.

- The Bipartisan Infrastructure Law (BIL) provides significant federal investment in carbon management technologies. It includes dedicated funding for carbon dioxide transportation infrastructure, and large-scale pilot and demonstration projects in both industrial and power generation sectors.[55]

The combined effect of the IRA and BIL has improved project economics and increased private investment in early deployment efforts, especially for post-combustion.

California State Policies

In California, carbon capture policy is guided by climate goals and environmental justice considerations:

- Senate Bill 1314 (Limon, Chapter 336, Statutes of 2022) bans the use of captured CO_2 for enhanced oil recovery, limiting the economic options for sequestration projects that had previously relied on oil production revenue.[56]
- The Low Carbon Fuel Standard provides financial credits for carbon capture and sequestration when used in fuel pathways or associated with eligible electricity production. This credit system helps offset capital costs and can support long-term project financing.[57]
- Assembly Bill 617 (C. Garcia, Chapter 136, Statutes of 2017),[58], requires additional air quality monitoring and public engagement for projects near disadvantaged communities. These requirements increase transparency but also extend permitting timelines for capture and storage infrastructure.

Recent Policy Developments and Outlook

On the balance, these federal and California policies have helped reduce economic and regulatory barriers, improve project finance viability, and drive new investment into carbon capture deployment. However, ongoing challenges remain, including lengthy permitting processes, public opposition in some communities, and uncertainty around long-term liability and storage oversight.

At the same time, recent federal actions have introduced new uncertainty for the future of carbon capture. In 2025, the Trump administration terminated more than $7 billion in

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55 U.S. Department of Energy. *FECM Infrastructure Factsheet*. Available at: https://www.energy.gov/sites/default/files/2021-12/FECM%20Infrastructure%20Factsheet.pdf.

56 California Legislature. *Senate Bill 1314*. Available at: https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220SB1314.

57 California Air Resources Board (CARB). 2018. *Carbon Capture and Sequestration (CCS) Protocol Under LCFS*. Available at: https://ww2.arb.ca.gov/sites/default/files/2020-03/CCS_Protocol_Under_LCFS_8-13-18_ada.pdf.

58 California Legislature. *Assembly Bill 617*. https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180AB617.

Department of Energy grants, including several projects supporting CCS.[59] Alongside grant cancellations, the EPA has proposed to repeal GHG emissions standards for fossil fuel power plants. These steps could reduce regulatory incentives and oversight supporting CCS deployment. Collectively, these policy shifts risk slowing project development, reducing private investment, and weakening momentum toward commercial scale carbon capture deployment.

59 U.S. Department of Energy, Energy Department Announces Termination of 223 Projects, Saving Over $7.5 Billion Available at https://www.energy.gov/articles/energy-department-announces-termination-223-projects-saving-over-75-billion.

CHAPTER 5: Fission

Technology Overview

Advanced or Generation IV reactors use new designs that enhance safety, efficiency, and versatility compared to traditional reactor designs.[60] Small modular reactors (SMRs), are a class of advanced fission nuclear reactors. SMRs are characterized by a power capacity up to 300 MW and the ability of the unit to be factory-assembled and installed on-site. Currently, the U.S. Nuclear Regulatory Commission (NRC) has only approved two SMR designs for U.S. commercial deployment.

Beyond size and modularity, SMR technologies vary widely in the physical design, coolant type, and nuclear process applied. The current approved SMR designs are based on the widely deployed conventional light water cooled thermal-spectrum fission reactors, as they are one of the more technologically mature types of SMRs under development.[61]

TerraPower's Natrium reactor is a 345-MW sodium-cooled fast reactor[62] with a coupled molten salt-based energy storage system.[63] The NRC has accepted TerraPower's construction permit application for a Natrium reactor demonstration project in in Kemmerer, Wyoming.[64] This is the nation's first commercial advanced reactor. The project began construction on the non-nuclear portion in June 2024 and the nuclear elements are targeting 2026.

Research and development of thorium-based nuclear reactors has been or is now being done in the United States, United Kingdom, Germany, Brazil, India, Indonesia, China, France, the Czech Republic, Japan, Russia, Canada, Israel, Denmark and the Netherlands. Interest in the thorium fuel cycle is based on several potential advantages over the more traditional uranium fuel cycle; including easier mining access to the more abundant element thorium, superior physical and nuclear fuel properties around efficiency, safety and reduced nuclear waste production. Thorium fuel also has a lower weaponization potential because it is difficult to weaponize uranium-233 and there are lower levels of plutonium-239 production. By 2019, China had two prototype thorium reactors under construction in the Gobi Desert. In October 2023, a 2 MW_t (megawatt thermal) prototype molten salt reactor went critical and in June

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60 U.S. DOE. (n.d.). Advanced Reactor Technologies. https://www.energy.gov/ne/advanced-reactor-technologies.

61 McGarry, James, John Stevens, Mengyao Yuan, Bill Wheatle, Aaron Burdick, Nick Schlag, Roderick Go, Oluwafemi Sawyerr. 2022. CPUC IRP Zero-Carbon Technology Assessment Final Report. Energy and Environmental Economics, Inc. https://www.ethree.com/wp-content/uploads/2023/03/CPUC-IRP-Zero-Carbon-Technology-Assessment.pdf.

62 Fast reactors are a type of nuclear fission reactor that uses fast-moving neutrons to sustain a chain reaction, without using a neutron moderator. Key benefits may include enhanced fuel efficiency, reduced long-lived nuclear waste, and the option to use recycled nuclear waste as fuel.

63 TerraPower. 2025. Natrium. https://www.terrapower.com/natrium/.

64 U.S. NRC. 2025. TerraPower, LLC -- Kemmerer Power Station Unit 1 Application. https://www.nrc.gov/reactors/new-reactors/advanced/who-were-working-with/applicant-projects/terrapower.html

2024, the reactor reached full power.[65] China expects to put thorium reactors into commercial use by 2030.

Technological Maturity and Performance

Both pressurized water reactors and boiling water reactors, as small modular reactor technologies, have a Technology Readiness Level (TRL) of 7-8, representing that validation of the technology through prototypes and models have been demonstrated in relevant environments. Anticipated improvements for both technologies include improved economies of scale and supply chain optimization as more SMRs are deployed.

The TerraPower Natrium reactor is more difficult to assign a TRL since it has elements that are well developed and based on established technologies, but other aspects are still engaged in testing and validation programs to assess the performance and safety of various components. China's 60 MW_t thorium reactor, TRL 6-7, is scheduled to be completed in 2029. Approximately 10 MW will be used to create electrical power with the remainder used to evolve hydrogen from water.[66]

Recent Innovations and Future Improvements

Research and development of thorium-based nuclear reactors has been or is now being done in the United States, United Kingdom, Germany, Brazil, India, Indonesia, China, France, the Czech Republic, Japan, Russia, Canada, Israel, Denmark, and the Netherlands. Interest in the thorium fuel cycle is based on several potential advantages over the more traditional uranium fuel cycle; including easier mining access to the more abundant element thorium, superior physical and nuclear fuel properties around efficiency, safety and reduced nuclear waste production. Thorium fuel also has a lower weaponization potential because it is difficult to weaponize uranium-233 and there are lower levels of plutonium-239 production. By 2019, China had two prototype thorium reactors under construction in the Gobi Desert. In October 2023, a 2 MW_t (megawatt thermal) prototype molten salt reactor went critical and in June 2024, the reactor reached full power.[67] China expects to put thorium reactors into commercial use by 2030.

Policy and Regulatory Trends

On May 23, 2025, the Office of the President of the United States issued four executive orders as part of the administration's effort to increase U.S. nuclear generating capacity by 2050.[68]

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66 Stephen Chen. 2024. 'China sets launch date for world's first thorium molten salt nuclear power station. Available at: https://www.scmp.com/news/china/science/article/3271978/china-sets-launch-date-worlds-first-thorium-molten-salt-nuclear-power-station.

67 TMSR-LF1 liquid fuel thorium-based molten salt experimental reactor. Available at: https://en.wikipedia.org/wiki/TMSR-LF1.

68 Executive Order 14302 – Reinvigorating the Nuclear Industrial Base, (https://www.federalregister.gov/documents/2025/05/29/2025-09801/reinvigorating-the-nuclear-industrial-base.) Executive Order 14299 – Deploying Advanced Nuclear Reactor Technologies for National Security, (https://www.federalregister.gov/documents/2025/05/29/2025-09796/deploying-advanced-nuclear-reactor-

The administration and allies claim that the executive orders promote deployment of advanced nuclear technologies, build out nuclear fuel supply chains, expedite the licensing process, and increase U.S. nuclear exports. Others have raised concerns that the orders if implemented could undermine the very objective they intend to promote. Furthermore, opponents have expressed concern that reducing the NRC's staff, curtailing its political independence, compromising its technical integrity, scaling back its community engagement role or outright bypassing the NRC and its regulations could undermine the national and international credibility of the U.S. nuclear sector.

Aside from the recent executive orders, recent nuclear fission policy and regulatory trends have focused on modernizing licensing and regulations to speed up deployment, providing financial incentives, and supporting advanced reactor technologies. These efforts have been driven by goals for carbon-free energy, increased electricity demand from AI and data centers, and enhancing energy security. Key policy developments include the U.S. ADVANCE Act of 2024 to reform the Nuclear Regulatory Commission's (NRC) processes, the Inflation Reduction Act's tax credits for nuclear power, and a global push from world leaders that see nuclear as a potential cornerstone for climate and energy goals.

Challenges and Barriers

The primary challenges and barriers for nuclear fission have not changed in the last 40 years: production of long-lasting radioactive waste, high upfront costs, long construction times, public perception around safety concerns, and the risk of nuclear proliferation. Over the last decade additional challenges have evolved to include the availability of advanced uranium fuels, ensuring water supply for cooling, and safety concerns around digital and drone technologies.

Since 1976, California has had a moratorium on the construction and licensing of new nuclear fission reactors until the federal government implements a long-term solution for the disposal of radioactive waste.[69] The use of SMRs or any fission reactor in California is contingent on policy change at the state level or a long-term disposal solution implemented at the federal level. However, this does not preclude electricity procurement from out-of-state resources.

Uranium Fuel Supply Chain

The U.S. has historically imported uranium as yellowcake or triuranium octoxide (U_3O_8) equivalents, shown in Figure 6.[70] Imports accounted for 99% of the U_3O_8 used in 2023 to make nuclear fuel. In 2023, these imports where primarily from Canada, Australia, Russia,

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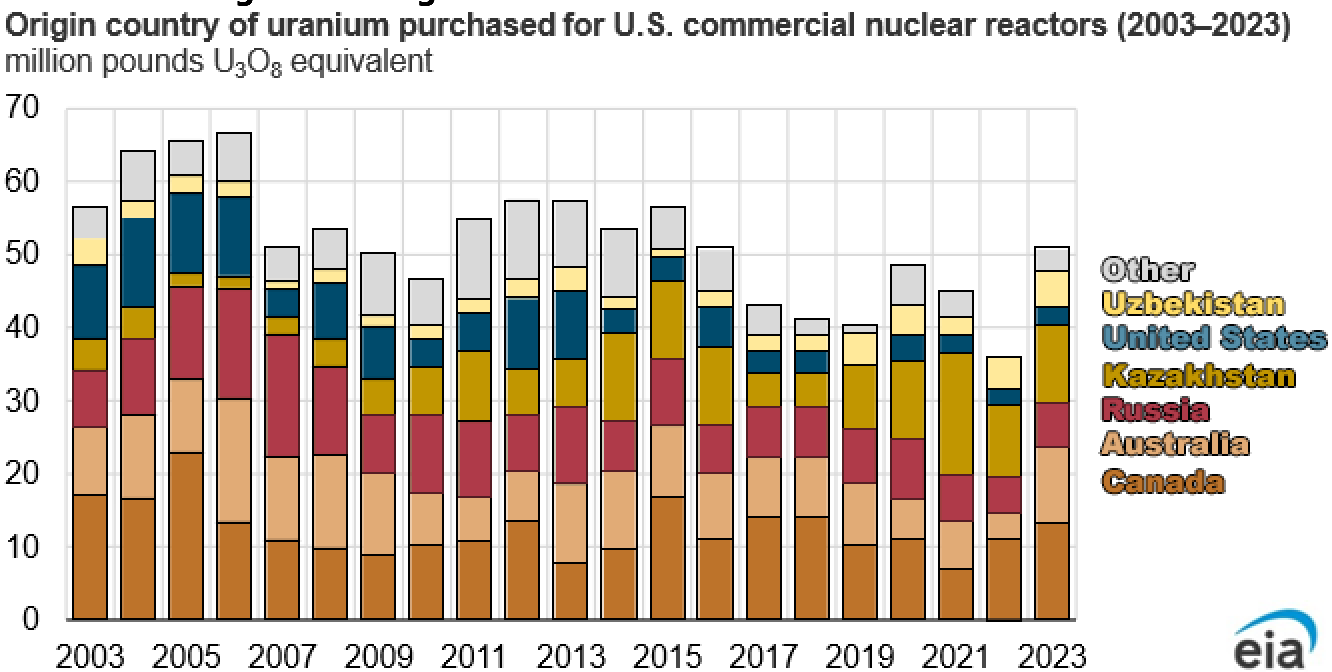
technologies-for-national-security). Executive Order 14300 – Ordering the Reform of the Nuclear Regulatory Commission, (https://www.federalregister.gov/documents/2025/05/29/2025-09798/ordering-the-reform-of-the-nuclear-regulatory-commission) Executive Order 14301 – Reforming Nuclear Reactor Testing at the Department of Energy, (https://www.federalregister.gov/documents/2025/05/29/2025-09799/reforming-nuclear-reactor-testing-at-the-department-of-energy)

69 California Energy Commission staff. 2020. Nuclear Power Reactors in California. California Energy Commission. https://www.energy.ca.gov/sites/default/files/2020-03/Nuclear_Power_Reactors_in_California_ada.pdf.

70 Uranium quantities are expressed in the unit of measure U_3O_8e (equivalent). U_3O_8e is triuranium octoxide (or uranium concentrate) and the equivalent uranium-component of uranium hexafluoride (UF_6) and enriched uranium.

Kazakhstan, and Uzbekistan. In May 2024, the U.S. banned imports of uranium products from Russia, although companies may apply for waivers. Federal policies have recently been implemented to build out the U.S. domestic nuclear fuel supply chain, but this will likely have limited near term impacts to imports.

Figure 6: Origin of Uranium for U.S. Nuclear Power Plants



Source: U.S. Energy Information Administration, *Monthly Energy Review*, *Domestic Uranium Production Report*, and *Uranium Marketing Annual Report*

CHAPTER 6: Fusion

Technology Overview

Nuclear fusion offers a potential long-term energy source and a path to producing medical and commercial isotopes.[71] Compared to nuclear fission, fusion could generate four times more energy per kilogram of fuel while not producing long-lived nuclear waste.[72] Achieving controlled fusion requires maintaining a sustained high-temperature, high-density plasma. Table 6 displays the characteristics of the most mature fusion technology types.

Table 6: Fusion Reactor Technology Overview

Fusion Resources	Characteristics
Inertial Confinement Fusion (ICF)	Initiates nuclear fusion reactions through compressing and heating small pellets of fuel (deuterium-tritium). Energy is deposited via a system of high intensity laser beams or laser-produced X-rays to create a plasma envelope that compresses the fuel until the capsule implodes.
Magnetic Confinement Fusion (MCF)	Uses a magnetic field to confine the movement of the fuel particles in plasma. The most common magnetic configuration is a tokamak, a toroid-shaped apparatus used for producing controlled fusion in hot plasma. Many of the new designs include other configurations such as field-reversed models. Tokamaks commonly use deuterium-tritium fuel while in-development field-reversed configuration technologies use hydrogen-boron fuel in an aneutronic reaction.

Source: International Atomic Energy Agency.

Technological Maturity and Performance

Given its potential as a zero-carbon energy source, significant investment in the field of nuclear fusion has continued through early 2025. Both ICF and MCF are still at a TRL of 4, with fusion technology making iterative improvements in a laboratory environment. These efforts continue to demonstrate the capabilities and current limitations of the technology. The next significant step will be deployment of a more advanced reactor prototype by either a public or private entity.

71 Clark, Stuart. 2024. Fusion power might be 30 years away but we will reap its benefits well before. The Guardian.

72 International Atomic Energy Agency (IAEA). *"What Is Nuclear Fusion"*. 2023. Available at: https://www.iaea.org/newscenter/news/what-is-nuclear-fusion.

Manufacturing and Supply Chain

Most nuclear fusion reactions use fuel made up of deuterium and tritium, both isotopes of hydrogen. Deuterium is naturally occurring and can be separated from seawater while tritium must be produced by fission reactors or high energy accelerators.[73,74] Tritium is a scarce resource that will require increased production and supply chains to meet expected needs. Alternative isotopes to tritium such as helium-3 are also a scarce resource, facing similar issues as the tritium supply. Many of the proposed reactor designs require significant quantities of high-performance conductors, capacitors, magnetic systems, computer control systems, and high-performance materials for reactor components. Many of these components are custom built or have limited availability, likely necessitating a more robust supply chain in the future.

Performance Characteristics

The primary performance metrics applied to fusion reactors is the fusion energy gain factor, Q, which measures the ratio of fusion power released in the reaction to the power inputted to maintain the plasma in a steady state.[75] In order to be economically and technologically viable, projects are expected to have a Q value of 10 or greater.[76]

When commercially viable, fusion technology may be more attractive than fission given the reduced risks of radiation from long-lived isotopes. The potential benefits of fusion are currently driving both private sector investment and legislative actions. In California, there are multiple private sector startups, university programs, and local and state legislative interest in the development of fusion technologies. Assembly Bill 1172 (Calderon, 1172 Chapter 360, Statutes of 2023) requires the CEC to include an assessment of the potential for fusion energy to contribute to California's power supply as part of the 2027 edition of the *IEPR*.[77]

Recent Innovations and Future Improvements

Before nuclear fusion reactor technology can reach the market, significant engineering and logistical barriers still need to be resolved. Though the fusion industry has seen recent successes in funding, technology development, and policy development, further effort is needed to overcome technical challenges associated with creating a sustained energy source.[78] Some important updates impacting the fusion sector since the 2024 *SB 423 Emerging Renewable and Firm Zero-Carbon Resources Report* include:

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73 Tritium Breeding. ITER. https://www.iter.org/mach/TritiumBreeding.

74 2005. Fact Sheet: Tritium Production. U.S. Nuclear Regulatory Commission. https://www.nrc.gov/docs/ML0325/ML032521359.pdf.

75 Wurzel, Samuel, Scott Hsu. 2022. Progress Toward Fusion Energy Breakeven and Gain as Measured Against the Lawson Criterion. Phys. Plasmas 29. https://pubs.aip.org/aip/pop/article/29/6/062103/2847827/Progress-toward-fusion-energy-breakeven-and-gain.

76 Facts & Figures. ITER. https://www.iter.org/factsfigures.

77 2023. AB-1172 Integrated energy policy report: fusion energy. https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202320240AB1172.

78 2009. How NIF Works. Lawrence Livermore National Laboratory. https://lasers.llnl.gov/about/how-nif-works.

- The National Ignition Facility at the Lawrence Livermore National Laboratory have achieved doubling the input energy on February 12, 2024 (5.2 megajoules (MJ) yield from 2.2 MJ input), and a record-breaking 8.6 MJ yield on April 7, 2025.
- Scientists at the Max Planck Institute for Plasma Physics in Germany achieved a record for stellarator energy turnover, 1.8 gigajoules over a six-minute run, in May of 2025.
- The nuclear fusion industry has continued to see private funding investments and formation of new public-private partnerships.
- U.S. Department of Energy established a national hub for Inertial Fusion Energy (IFE) research (IFE-STARFIRE), linking expertise from national labs, academia, and industry.
- Senate Bill 80 establishes the Fusion Research and Development Innovation Initiative to accelerate fusion energy development in California. Signed by Governor Newsom in October 2025, the bill allocates $5 million to provide financial incentives for fusion research with the goal of a pilot fusion project in California.

Policy and Regulatory Landscape

The nuclear fusion landscape is evolving with a focus on developing a streamlined framework that builds on existing nuclear regulations but is separate from the more stringent rules for fission facilities. This is supported by the U.S. NRC adopting a framework based on its byproduct material regulations (10 C.F.R. Part 30) and the recent ADVANCE Act to support advanced nuclear technologies. Internationally, sovereign states like the UK are creating specific laws to ensure regulations are proportionate to fusion's lower risks. State-level policies are also being developed to support fusion research, development, and deployment.

CHAPTER 7: Long Duration Energy Storage

Technology Overview

For the purposes of this chapter, LDES refers to technologies other than lithium-ion batteries or pumped storage hydropower which can store electricity and which have a discharge duration of more than eight hours. LDES technologies are not currently commercially deployed at scale in the U.S and are currently in the pilot or demonstration phase. These technologies have received public and/or private funding for test and demonstration projects.[79] Broader adoption will depend on LDES technologies proving their technical and market viability.

There are multiple different LDES technologies with different chemistries. Table 7 lists the LDES technologies that will be referenced later in this chapter, their mechanisms, and their TRL.

Table 7: LDES Technologies

Technology Type	Mechanism	TRL
Compressed Air Energy Storage	Air is compressed, then later allowed to expand to spin a turbine.	8-9
Iron-Air Batteries	Rechargeable battery or energy storage that uses an iron anode and oxygen from air as the cathode, operating on a principle of "reversible rusting".	8-9
Lead Acid Batteries	The positive electrode, cathode, is Lead Dioxide, and the negative electrode, anode, is Lead usually in a sulfuric acid electrolyte.	9
Thermal Energy Storage	A material is heated. The material can remain heated, the heat can cause a phase change, or the heat can be used in a chemical reaction. Later, the heat can be removed, either from the material directly, from converting the material to its previous phase, or from reversing the previous reaction.	4-8

79 The CEC is not aware of any non-lithium-ion storage projects in California with sizes greater than 1 MW that were built without public funding.

Technology Type	Mechanism	TRL
Vanadium Redox Flow Batteries	A battery that stores energy in two liquid electrolytes held in separate tanks. The electrolytes are acidic solutions containing vanadium ions in different oxidation states: the anolyte, negative half-cell, and catholyte, positive half-cell.	8-9
Zinc-Air Batteries	The anode is zinc paste, the electrolyte is potassium hydroxide (KOH), and cathode is water and atmospheric Oxygen (O_2).	7
Zinc Hybrid Batteries (e.g., Zn-Ni, Zn-MnO_2)	The anode is zinc, and the electrolyte is aqueous potassium hydroxide (KOH). The cathode is manganese dioxide (MnO_2) or nickel hydroxide (NiOOH).	6-7

Source: CEC Energy Assessments Division staff. Mechanisms described based on sources from Pacific Northwest National Laboratory[80] [81], Form Energy[82], and Sandia National Laboratories.[83] [84]

The LDES technologies in Table 7 do not have the same fire safety risks associated with lithium-ion batteries. Due to the materials used in conventional lithium-ion batteries, when these batteries are overheated, overcharged, or damaged, their temperature steadily increases (thermal runaway), resulting in a fire or explosion.[85] In recent years, there have been multiple instances of lithium-ion batteries igniting, such as the battery fire at Moss Landing in January 2025.[86] The likelihood of thermal runaway can be reduced – for example, by monitoring

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80 Descriptions of Compressed Air Energy Storage and Lead Acid Battery technologies are based on descriptions in: Pacific Northwest National Laboratory staff. N.d. "Energy Storage Cost and Performance Database: Cost and Performance Estimates." *Pacific Northwest National Laboratory*. https://www.pnnl.gov/projects/esgc-cost-performance/estimates.

81 Wang, Wei. 2012. "Vanadium Redox Flow Batteries: Improving the performance and reducing the cost of vanadium redox flow batteries for large-scale energy storage." *Pacific Northwest National Laboratory.* https://www.energy.gov/sites/prod/files/VRB.pdf.

82 Jackson, Sarah, Rachel Wilson, and Justin Adamson. 2024. "Breakthrough low-cost, multi-day energy storage." *Form Energy*. https://www.iso-ne.com/static-assets/documents/100017/2024-10-29_etwg_a05_iron-air_battery_technology_and_applications_overview_final_2.pdf.

83 Sandia National Laboratories. *Energy Storage Handbook: Chapter 12 – Thermal Energy Storage*. September 2021. Available at: https://www.sandia.gov/app/uploads/sites/163/2021/09/ESHB_Ch12_Thermal_Ho.pdf

84 https://www.sandia.gov/app/uploads/sites/163/2021/09/ESHB_Ch5_Zinc_Lim.pdf

85 BatteryDesign.Net staff. N.d. "Thermal Runaway." BatteryDesign.Net. https://www.batterydesign.net/safety/thermal-runaway/.

86 Rodriguez, Olga, and Isabella O'Malley. 2025. "Smoke from fire at California lithium battery plant raises concerns about air quality." Associated Press. https://apnews.com/article/battery-storage-plant-fire-california-moss-landing-7c561fed096f410ddecfb04722a8b1f8.

batteries' temperatures.[87] Nonetheless, some communities have responded to recent instances of thermal runaway-caused battery fires with temporary moratoriums on the permitting of utility-scale lithium-ion batteries.[88] Most LDES technologies are composed of materials which have little to no risk of thermal runaway-induced fire.[89]

There are ongoing field demonstrations for multiple LDES technologies to assess whether they store energy as intended. Consistent with an emerging technology area, demonstration projects for LDES are currently orders of magnitude smaller than the amount of storage California may need to help meet state requirements. For example, current LDES demonstration projects supported by the California Energy Commission are mostly in the 1-10 MW range.

LDES technologies could be deployed alongside variable renewable resources such as solar and wind. In this scenario, excess energy generated by the renewable resources could be stored for use when the grid demands which could help California meet its renewable and zero-carbon electricity goals.

Both advanced lithium-ion and non-lithium-ion energy storage technologies may be needed to meet the goals of California's clean energy transition. While lithium-ion batteries currently have most of the market share for energy storage in the U.S. – and may continue to be the more cost-effective option in some cases for shorter durations – LDES technologies have several potential desirable attributes which may make LDES technologies a more affordable, or otherwise more feasible option to store energy in some cases.

The following sections discuss the policies California is pursuing to commercialize LDES technologies, the issues impeding the commercialization of LDES technologies, and the potential advantages of these technologies.

Policy and Regulatory Landscape

The CEC is funding demonstration projects to help reduce system costs for multiple LDES technologies. In 2020, the CEC's Electric Program Investment Charge grant program awarded grants to eleven LDES demonstration projects with a duration of at least 10 hours.

Subsequently, in 2022, the California Legislature created an LDES Program at the CEC to provide grant funding for LDES demonstration projects that are 1 MW or larger with a

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87 Ufine Battery staff. 2025. "What is thermal runaway lithium ion battery?" *Ufine Battery.* https://www.ufinebattery.com/blog/what-is-thermal-runaway-lithium-ion-battery/.

88 Orange County Board of Supervisors. 2025. "OC Board of Supervisors Vice Chair Katrina Foley releases statement following U.S. government funding freeze, BESS moratorium, and Board of Supervisors meeting actions." *Fullerton Observer*. https://fullertonobserver.com/2025/01/30/oc-board-of-supervisors-vice-chair-katrina-foley-releases-statement-following-us-government-funding-freeze-bess-moratorium-and-board-of-supervisors-meeting-actions/.

89 For example, flow batteries have a significantly lower risk of thermal runaway, compared with lithium-ion batteries. See Scott, Alex. 2023. "Flow batteries, the forgotten energy storage device: They may soon emerge from the shadow of lithium ion to store renewable energy." Chemical & Engineering News. https://cen.acs.org/materials/energy-storage/Flow-batteries-forgotten-energy-storage/101/i25.

discharge duration of at least 8 hours. CEC's budget is over $270 million for this program,[90] and the CEC has allocated almost all of the program budget to 10 LDES demonstration projects. Nine of these projects demonstrate zinc-air, zinc hybrid, or vanadium redox flow battery technologies, are sized between 1 MW and 40 MW, and plan to have a duration of 8-12 hours. The LDES Program is also funding a 1.5 MW project using iron-air technology. This project plans to store electricity with a duration of 100 hours. The CEC LDES Program expects the ten demonstration projects to be operational in 2026 to 2028.

Through demonstration projects, LDES companies may identify opportunities to decrease costs and scale the technology. Increasing LDES system sizes from 1.5-40 MW to 50-100 MW would likely decrease the cost of LDES technologies due to economies of scale. Decreases in LDES technologies' costs in turn, would likely increase market demand for these technologies.

In 2021, as part of its Integrated Resource Planning proceeding, the CPUC ordered CPUC-jurisdictional LSEs to collectively procure at least 1,000 MW (net qualifying capacity) of long duration storage resources (eight hours or greater),to come online between 2023 and 2026.[91] Subsequent decisions have changed the deadline for LDES resources to come online by 2028 and have given LSEs the option to further extend the deadline to 2031.[92]

In 2024, the CPUC requested DWR procure up to 1,000 MW of nameplate capacity from multi-day LDES technologies, as well as up to 1,000 MW of capacity from LDES technologies with a duration of at least 12 hours, to come online between 2031 and 2037.[93] CPUC requested that DWR hold the first round of solicitations in 2026 and evaluate bids based on quality, cost, and

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90 California Energy Commission staff. N.d. "Long Duration Energy Storage Program." *California Energy Commission*. https://www.energy.ca.gov/programs-and-topics/programs/long-duration-energy-storage-program.

91 California Public Utilities Commission staff. 2021. "Fact Sheet: Decision Requiring Clean Energy Procurement for Mid-Term Reliability." *California Public Utilities Commission*. https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/integrated-resource-plan-and-long-term-procurement-plan-irp-ltpp/d2106035-mtr-decision-factsheet--07-01-2021.pdf.

92 California Public Utilities Commission staff. 2025. "California Public Utilities Commission (CPUC) Staff Review of Load-Serving Entities' (LSEs') Compliance with the Mid-Term Reliability (MTR, D.21-06-035) and Supplemental MTR (SMTR, D.23-02-040) Decisions." *California Public Utilities Commission*. https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/integrated-resource-plan-and-long-term-procurement-plan-irp-ltpp/compliance-status-reportmid-term-reliability-mtr-and-supplemental-mtr.pdf.

93 California Public Utilities Commission staff. 2024. "Fact Sheet: Decision Determining Need for Centralized Procurement of Long Lead-time Resources (R.20-05-003)." *California Public Utilities Commission*. https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/integrated-resource-plan-and-long-term-procurement-plan-irp-ltpp/ab1373/final_decision_-ab1373_factsheet_pdf.pdf. California Public Utilities Commission staff. 2024. "CPUC Advances Clean Energy with Centralized Procurement Strategy." California Public Utilities Commission. https://www.cpuc.ca.gov/news-and-updates/all-news/cpuc-advances-clean-energy-with-centralized-procurement-strategy.

risk.[94] DWR may decide to not procure if costs to ratepayers are too high.[95] DWR will then submit selected bids to the CPUC for review, and CPUC may also veto bids based on cost.

Challenges and Barriers

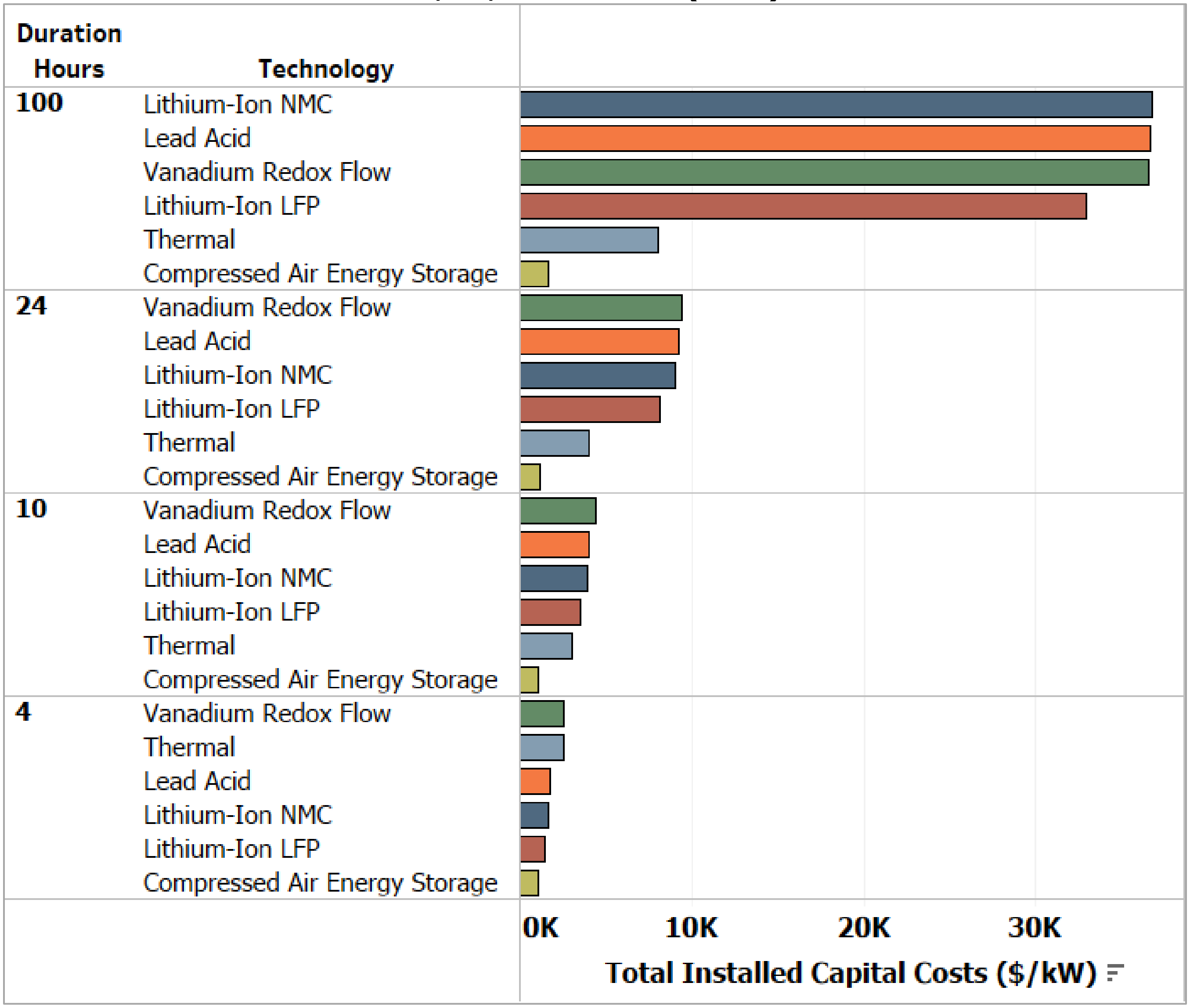
Currently, the need for storage is to meet evening summer peaks and is met primarily met by four hour lithium ion technologies, which is typically the least cost non-fossil capacity resource.

Lithium-ion batteries are generally less expensive than long duration storage technologies. In 2023, the Pacific Northwest National Laboratory (PNNL) estimated the total capital costs for 100 MW storage systems using the lithium-ion batteries with lithium iron phosphate (LFP) and nickel manganese cobalt (NMC) chemistries, as well as lead acid batteries, vanadium redox flow batteries, compressed air energy storage, and thermal energy systems. PNNL estimated these costs for 4-, 10-, 24-, and 100- hours (**Error! Reference source not found.**). PNNL estimated that for durations of four hours, 100 MW lithium-ion batteries had lower installed capital costs than 100 MW vanadium redox flow, thermal, or lead acid systems.

94 California Public Utilities Commission staff. 2024. "CPUC Advances Clean Energy with Centralized Procurement Strategy." California Public Utilities Commission. https://www.cpuc.ca.gov/news-and-updates/all-news/cpuc-advances-clean-energy-with-centralized-procurement-strategy.

95 California Public Utilities Commission staff. 2024. *Fact Sheet: Decision Determining Need for Centralized Procurement of Long Lead-time Resources (R.20-05-003)*. California Public Utilities Commission. https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/integrated-resource-plan-and-long-term-procurement-plan-irp-ltpp/ab1373/final_decision_-ab1373_factsheet_pdf.pdf.

Figure 7: Total Installed Capital Costs for 100 MW Systems with Durations of 100, 25, 10, and 4 Hours (2023)



Source: CEC Energy Assessments Division, based on PNNL Energy Storage Cost and Performance Database.[96]

NLR has examined all new battery storage projects with a storage capacity of at least 1 MW, for the years 2021 and 2022, which list the battery type. Excluding thermal storage for heating/cooling or concentrated solar plants, more than 99% of new projects were lithium ion,[97] presumably due to the significantly lower costs.

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96 Pacific Northwest National Laboratory staff. N.d. "Energy Storage Cost and Performance Database." *Pacific Northwest National Laboratory*. https://www.pnnl.gov/projects/esgc-cost-performance/estimates.

97 Denholm, Paul, Wesley Cole, and Nate Blair. 2023. *Moving Beyond 4-Hour Li-Ion Batteries: Challenges and Opportunities for Long(er)-Duration Energy Storage*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A40-85878. https://www.nrel.gov/docs/fy23osti/85878.pdf.

Opportunities and Future Outlook

As storage penetrations increase and the need shifts to overnight hours and winter months with the electrification of heating and vehicles, there may be increased market demand for storage durations longer than four hours. At storage durations of 10 hours or more, some LDES technologies – for example, compressed air energy storage, thermal storage systems,[98] or iron air batteries[99] – may have lower installed capital costs per kW of capacity than lithium-ion batteries. So, market demand for LDES technologies may increase in the future. However, LDES technologies will need to continue to see reductions in cost.

98 See Figure 8 for PNNL estimates of installation costs for 100 MW systems with durations of ten hours or more.

99 Form Energy staff. N.d. "Battery Technology." Form Energy. https://formenergy.com/technology/battery-technology/.

CHAPTER 8:
Hydrogen for Electricity Generation

Technology Overview

Hydrogen for electricity generation is increasingly viewed as a potential resource for decarbonizing California's electricity sector, providing a zero-carbon alternative for dispatchable power generation. Technologies that utilize hydrogen to generate electricity include fuel cells, hydrogen combustion turbines, and integrated hybrid systems. Lifecycle emissions analysis was not part of the scope of this report. A detailed analysis of hydrogen fuel production scenarios and cost estimates can be found in the hydrogen chapter of this IEPR.

Technology Maturity and Performance

Technologies that utilize hydrogen to generate electricity include fuel cells, hydrogen combustion turbines, and integrated hybrid systems. Both proton exchange membrane (PEM) and alkaline electrolyzers are commercially available and widely deployed with a Technology Readiness Level (TRL) of 9.

Hydrogen can generate electricity through two primary mechanisms: electrochemical conversion in fuel cells and direct combustion in gas turbines. Fuel cells—especially PEM and solid oxide fuel cells (SOFC) provide consistent and emissions-free power suitable for distributed or backup generation. These systems can achieve electrical efficiencies between 40 and 60 percent and, when configured for combined heat and power (CHP), can reach total system efficiencies above 80 percent.

Hydrogen combustion turbines, either retrofitted from existing natural gas infrastructure or newly built, are emerging technologies capable of providing firm, grid-scale power. While combustion-based systems currently operate with lower efficiency (around 40 percent), they benefit from compatibility with existing generation fleets and may be easier to integrate at scale for peak and reserve capacity needs. Hydrogen can also serve as a medium for long-duration energy storage in power-to-gas-to-power systems. In these systems, electricity is converted to hydrogen via electrolysis, stored, and then converted back to electricity when needed, although with a round-trip efficiency of roughly 30 to 40 percent, this approach trades efficiency for duration and scalability.

Recent Innovations and Future Improvements

Innovation in hydrogen-based power generation is occurring across several dimensions. Technological advancements have improved electrolyzer responsiveness, enabling PEM units to follow variable renewable generation more effectively. Projects integrating hydrogen turbines, such as those developed by Siemens Energy and GE, are exploring retrofits for hydrogen and natural gas blends, and in some cases, 100 percent hydrogen combustion. Hydrogen storage technologies, including salt caverns, lined rock caverns, and above-ground tanks, are being evaluated for their role in balancing intra-day and seasonal demand fluctuations.

Policy and Regulatory Trends

Senate Bill 100 and SB 423 model hydrogen as a candidate for meeting California's firm zero-carbon electricity requirements. Senate Bill 1075 mandates evaluation of hydrogen's role in the electricity and transportation sectors. California's Hydrogen Market Development Strategy, administered by California Governor's Office of Business and Economic Development (GO-Biz) in collaboration with ARCHES, seeks to coordinate investment, workforce development, and equity considerations in the buildout of the hydrogen economy. These efforts are supported by the Infrastructure Investment and Jobs Act and Inflation Reduction Act, which collectively allocate billions in funding for clean hydrogen production, infrastructure, and end use. However, in October 2025 the U.S. Department of Energy announced the cancellation of approximately $1.2 billion in federal funding for California's hydrogen hub (ARCHES) and over $7.5 billion across clean-energy programs, introducing significant uncertainty for the state's hydrogen strategy.[100].

Challenges and Barriers

Despite these favorable conditions, significant challenges remain. Cost remains a major hurdle, with electrolytic hydrogen ranging from $3.50 to $6.00 per kilogram, compared to approximately $2.00 per kilogram for steam methane reforming hydrogen without carbon capture and even lower for conventional fossil fuels. Regulatory uncertainty, including delays in incentive guidance and permitting complexity, has led to the cancellation of some high-profile projects. For example, recent uncertainty around IRA incentives has affected major facilities proposed by Air Products and Nel.

Supply chain risks are also notable. Electrolyzers are primarily manufactured in China, and key components rely on imported critical minerals such as platinum, cobalt, and graphite. Recent tariffs and trade tensions may increase capital costs. Moreover, producing electrolytic hydrogen at scale will require substantial electricity, potentially requiring new generation and transmission capacity. Biogenic hydrogen pathways, such as reforming renewable gas or gasifying biomass, are potential methods for producing hydrogen for long duration applications and dispatchable generation but conversion losses, transportation, and feedstock may challenge economic viability.

Opportunities and Outlook

Hydrogen presents a critical opportunity for California's clean energy transition. It may be a viable solution for firm, dispatchable capacity and enables decarbonization of the power sector. When integrated with renewables, hydrogen can absorb surplus solar generation to create a long duration storage solution for excess electricity and help mitigate curtailment, though site-specific analyses are required to evaluate cost-effectiveness.

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100 https://www.reuters.com/business/energy/us-energy-department-cancels-76-billion-funding-meant-projects-2025-10-02/?

Stationary and mobile[101] fuel cells can provide resilient, emissions-free backup power to critical facilities, including hospitals and data centers. Hydrogen turbines can support the grid during high-demand periods as a peaking or reserve resource, and hybrid CHP systems can increase overall system efficiency. To develop these resources, California must invest in large-scale hydrogen storage, potentially out of state, and develop pipeline infrastructure to support strategic delivery. Policymakers should consider implementing market mechanisms that value flexibility and reliability, rather than focusing solely on commodity pricing.

101 Kaizen Clean Energy. https://kaizencleanenergy.com/.

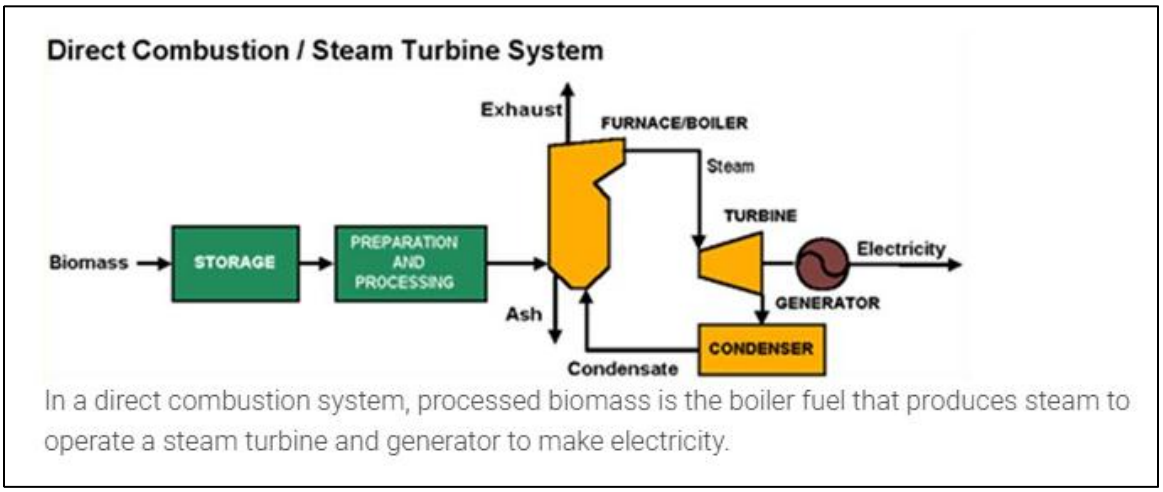
CHAPTER 9: Bioenergy

Technology Overview

Bioenergy technologies generate electricity by converting organic feedstocks, including biomass and waste-derived methane, through both direct combustion and thermochemical processes. Direct combustion of biomass such as wood waste or agricultural residue is the most established method which produces heat to drive steam turbines, but also emits criteria pollutants and greenhouse gases unless paired with carbon capture systems to create a carbon-negative system.

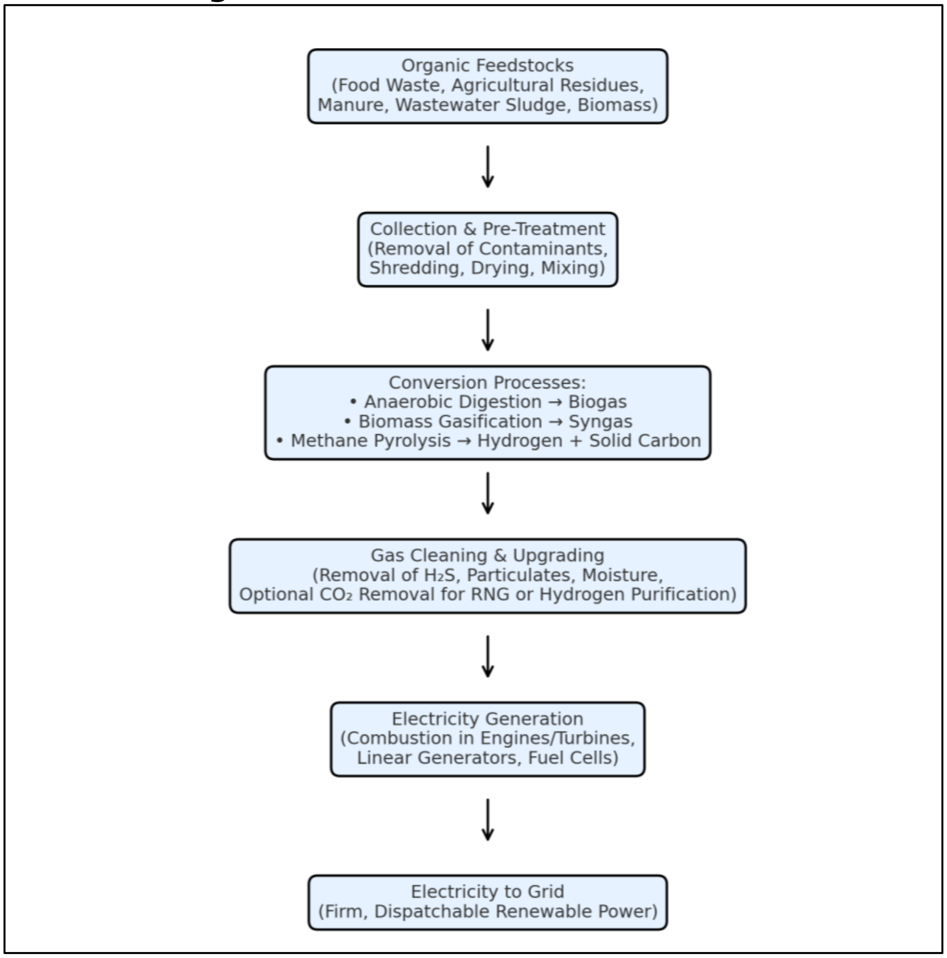
Alternatively, thermochemical conversion pathways such as gasification and pyrolysis produce intermediate fuels like hydrogen and syngas, which can be combusted in turbines or used in fuel cells for electricity generation.

Figure 8: Biomass Direct Combustion



Source: Whole Building Design Guide. [Biomass for Electricity Generation](https://www.wbdg.org/resources/biomass-electricity-generation). https://www.wbdg.org/resources/biomass-electricity-generation.

Figure 9: Thermochemical Processes



Source: Yee Yang, Chie Hong and Kristen Widdifield. December 2024. *SB 423 Firm Zero-Carbon Resources Report*. California Energy Commission. Publication Number: CEC-200-2024-012. https://www.energy.ca.gov/publications/2024/sb-423-emerging-renewable-and-firm-zero-carbon-resources-report-assessment-firm.

Technology Maturity and Performance

Although bioenergy power generation technologies are commercially available (TRL 9), the availability of feedstock, processing costs, and the size and complexity of the production facility pose challenges. renewable natural gas (RNG)-based steam methane reforming facilities in California are few and typically small in scale, which reduces their economic viability compared to larger fossil-based counterparts. Likewise, biomass gasification, though technologically feasible, remains mostly in the demonstration or planning stages, with firms like Mote and Torrgas advancing toward commercial deployment.[102]

Recent Innovations and Future Improvements

Recent innovations in bioenergy for power generation and fuel production focus on increasing efficiency, reducing emissions, and overcoming feedstock-related variability. Some steam methane reforming systems now include improved CO_2 capture solutions, targeting up to 96%

102 Guidehouse. CEC LCF GH Subtask 1 - Biogenic Only - DRAFT v2.

capture efficiency. These advancements are important for low-carbon electricity applications and could reduce the levelized cost of hydrogen to $2.61/kg H_2 with efficient CCS systems.[103]

Methane pyrolysis innovations include the use of molten salt, plasma, and catalytic reactors to increase hydrogen yields while capturing valuable carbon byproducts like carbon black. Companies such as Monolith, C-Zero, and Ekona Power are exploring these advanced designs to commercialize low-emissions hydrogen. Similarly, biomass gasification systems are incorporating modular reactor designs and optimized feedstock pre-processing systems. The concept of regional biomass aggregation hubs has also emerged as an innovation to manage dispersed biomass resources while improving scale and cost-effectiveness.

Policy and Regulatory Trends

Bioenergy for electricity production is supported by a mix of state and federal policies aimed at reducing emissions and supporting technology development. Programs such as the Low Carbon Fuel Standard (LCFS) incentivize production and use of renewable hydrogen through carbon intensity (CI) credits.

At the federal level, the Inflation Reduction Act's 45V Production Tax Credit offered up to $3/kg for clean hydrogen, including that produced from RNG and biomass, provided it meets stringent lifecycle emissions thresholds. Additional policy drivers include the Bipartisan Infrastructure Law (BIL), which funds hydrogen infrastructure and clean power technologies, and the DOE's ongoing investments in bioenergy research and regional feedstock aggregation strategies. However, as discussed in the Hydrogen section, recent federal actions have introduced new uncertainty. The 45V credit eligibility window has been shortened (requiring construction starts before the beginning of 2028) and the DOE has announced cuts to several regional hydrogen-hub awards, which together raise questions about the trajectory of federal support.

Challenges and Barriers

Despite technical promise, bioenergy faces multiple deployment challenges. RNG production from sources such as landfills, dairies, and wastewater treatment plants is often small-scale and geographically dispersed. Guidehouse estimates that roughly 90 percent of California landfills could supply less than 15.4 tons of hydrogen per day (or 2.43 TBtu RNG/day), with 80 percent producing 10 tons per day or less. Most sites are limited to around 7.8 tons per day. For context, 15.4 tons of hydrogen per day could generate approximately 300 MWh of electricity at a 50 percent conversion efficiency, demonstrating that even small-scale landfill resources can provide a meaningful amount of firm, zero-carbon energy. Variability in gas composition and the presence of contaminants like siloxanes complicate steam methane reforming, which is an issue when converting from RNG or biogas, operations and increase purification costs.

Pyrolysis and gasification technologies, while advancing, remain cost-intensive and face limited economies of scale. In addition, the logistics of biomass collection, transport, and processing, particularly for agricultural residues and wood waste, pose economic and environmental

103 Monolith Materials, C-Zero, Ekona Power: Company websites and technology briefs.

barriers. Seasonal availability, decentralized supply, and the need for high volumes of dry, uniform biomass further complicate operations. Long permitting timelines and environmental compliance also slow progress.

Opportunities and Outlook

California's large and diverse bio-waste streams present an opportunity to expand low-carbon electricity generation using hydrogen from biogenic sources. Steam methane reforming with high carbon capture rates, when paired with low-leakage RNG, can deliver hydrogen at moderate cost while leveraging existing gas infrastructure. However, direct use of RNG onsite for power generation continues to be viable use of the fuel without going through additional steps to convert to hydrogen. Methane pyrolysis offers the potential for near-zero emission hydrogen with co-product value, especially if carbon black markets expand with demand for electric vehicle batteries and sustainable materials.

Gasification, though less mature, is particularly promising in producing carbon-negative hydrogen for electricity or industrial use. Projects like Mote's proposed California plant and Torrgas'[104] high-efficiency systems demonstrate commercial potential. Regional biomass hubs could mitigate logistical challenges by centralizing processing and improving feedstock reliability. These hubs could enhance rural economic development, reduce wildfire risks, and support the circular economy by turning organic waste into electricity, hydrogen, and valuable byproducts.

104 Mote and Torrgas project announcements and technical documentation.

CHAPTER 10: Conclusion and Findings

California's transition to a clean and reliable electric grid requires a diverse portfolio of zero-carbon resources, particularly those capable of providing firm and dispatchable capacity. This report provides a market update on a range of technologies, including geothermal, hydropower, long-duration energy storage, carbon capture, hydrogen, small modular reactors, fusion, and bioenergy; through a common framework that assesses technology readiness, innovation trends, policy trends, and implementation challenges.

While each technology faces unique barriers, they also offer specific strengths that can complement variable renewables and help meet system-wide and local reliability needs. Continued innovation, investment, and regulatory coordination will be essential to scale these technologies and reduce deployment risks. As California pursues its SB 100 goals, firm zero-carbon resources will play a key role in maintaining grid stability, supporting decarbonization, and ensuring equitable outcomes across communities. Figure 10 highlights the broad conclusions of this report. CEC developed the cost estimates in Figure 10 using data from NLR ATB, Pacific Northwest National Laboratory, the Department of Energy, the Environmental Protection Agency, the International Energy Agency, the Oxford Institute for Energy Studies, the International Renewable Energy Agency, and interviews with developers and manufacturers, among other sources.[105]

This analysis was done prior to the passing of the federal One Big Beautiful Bill Act (OBBBA) on July 4, 2025. However, impact on costs may be minimal for the resources analyzed as the OBBBA excluded non-variable renewable energy sources as well as energy storage projects from accelerated construction timelines and tax credit terminations. New policies, such as OBBBA, will however be considered for future analysis.

105 The cost estimates in Figure 10 come from the following report: Yee Yang, Chie Hong and Kristen Widdifield. December 2024. *SB 423 Firm Zero-Carbon Resources Report*. California Energy Commission. Publication Number: CEC-200-2024-012. https://www.energy.ca.gov/publications/2024/sb-423-emerging-renewable-and-firm-zero-carbon-resources-report-assessment-firm.

Figure 10: Firm Zero-Carbon Resources

Resources	Role			Technology Readiness	2025 Avg. CAPEX $/kW
Long Duration Energy Storage (LDES)	◐	●	●	5-9	1,280-7,000
Hydropower	●	●	●	9	8,000 – 10,000
Geothermal	●	●	◐	7-9	6,800 - 16,000
Bioenergy	◐	●	◐	9	5,000
Hydrogen	◐	●	◐	5-9	1,500 – 2,500
Modular Fission Reactors	◐	●	●	6	8,500 – 9,400
Generation with Carbon Capture	●	●	◐	4-9	2,700 - 3,400

Local Reliability
Resiliency
System Reliability
Zero Emissions
Low Emissions

Source: CEC staff with 2024 NLR ATB/SB 423 Final Report data

Findings

Based on the market analysis and research presented, the following recommendations are offered to support the expanded consideration and adoption of firm zero-carbon resources in California.

- **Align Market and Contracting Mechanisms with Reliability Attributes** - Support efforts to develop market mechanisms such as central procurement, or long-term contracting structures that value the unique operational characteristics of firm zero-carbon resources, including their contributions to system adequacy, flexibility, and resilience.

- **Continue Public Investment in Demonstration and Early Deployment** – continue to support current state-funded programs that support demonstration, pilot, and early-stage deployment of firm zero-carbon technologies, including LDES, hydrogen, carbon capture, fusion energy, and advanced geothermal systems. Funding may include support for emerging technologies to overcome the innovation valley of death.[106]

- **Continue to Improve Permitting Coordination for Existing and Emerging Technologies** – Continue to identify opportunities to improve coordination, increase permitting transparency, and reduce process-related uncertainty for projects involving firm zero-carbon infrastructure.

Looking ahead, the next update to this assessment, conducted under Senate Bill 423, will align with the 2027 Integrated Energy Policy Report cycle. The next update will build on the findings of this report, incorporating new market data, technology developments, and policy trends to ensure that California's planning and procurement strategies for firm zero-carbon resources remain current and effective. These continued efforts will help California advance toward its SB 100 goal of achieving a 100 percent clean electricity system.

106 Nick Skillicorn. 2021. "The Innovation Valley of Death." https://www.ideatovalue.com/inno/nickskillicorn/2021/05/the-innovation-valley-of-death/.

APPENDIX A: Abbreviations

Acronym	Definition
AB	Assembly Bill
ATB	Annual Technology Baseline
BIL	Bipartisan Infrastructure Law
CARB	California Air Resources Board
CAISO	California Independent System Operator
CCS	Carbon Capture and Storage
CEC	California Energy Commission
CEQA	California Environmental Quality Act
CHP	Combined Heat and Power
CI	Carbon Intensity
CO_2	Carbon Dioxide
CPUC	California Public Utilities Commission
DOE	United States Department of Energy
DWR	Department of Water Resources
EGS	Enhanced Geothermal Systems
FERC	Federal Energy Regulatory Commission
FORGE	Frontier Observatory for Research in Geothermal Energy
GW	Gigawatt
IEPR	Integrated Energy Policy Report
ICF	Inertial Confinement Fusion
IFE	Inertial Fusion Energy
IRA	Inflation Reduction Act

Acronym	Definition
ISO	Independent System Operator
LCFS	Low Carbon Fuel Standard
LDES	Long Duration Energy Storage
LFP	Lithium Iron Phosphate
LSE	Load Serving Entity
MCF	Magnetic Confinement Fusion
MJ	Megajoule
MTR	Membrane Technology & Research
MW	Megawatt
MWt	Megawatt Thermal
MWh	Megawatt-hour
NEPA	National Environmental Policy Act
NGCC	Natural Gas Combined Cycle
NLR	National Laboratory of the Rockies
NRC	Nuclear Regulatory Commission
PEM	Proton Exchange Membrane
PNNL	Pacific Northwest National Laboratory
POU	Publicly Owned Utility
PPA	Power Purchase Agreement
PSH	Pumped Storage Hydropower
RNG	Renewable Natural Gas
RPS	Renewables Portfolio Standard
SB	Senate Bill
SMR	Small Modular Reactor
SOFC	Solid Oxide Fuel Cell
TRL	Technology Readiness Level

Acronym	Definition
U_3O_8	Triuranium Octoxide

APPENDIX B: Glossary

For additional information on commonly used energy terminology, see the following industry glossary links:

- California Air Resources Board Glossary, available at https://ww2.arb.ca.gov/about/glossary
- California Energy Commission Energy Glossary, available at https://www.energy.ca.gov/resources/energy-glossary
- California Energy Commission Renewables Portfolio Standard Eligibility Guidebook, Ninth Edition Revised, available at: https://efiling.energy.ca.gov/getdocument.aspx?tn=217317
- California Independent System Operator Glossary of Terms and Acronyms, available at: http://www.caiso.com/Pages/glossary.aspx
- California Public Utilities Commission Glossary of Acronyms and Other Frequently Used Terms, available at https://www.cpuc.ca.gov/glossary/
- Federal Energy Regulatory Commission Glossary, available at https://www.ferc.gov/about/what-ferc/about/glossary
- North American Electric Reliability Corporation Glossary of Terms Used in NERC Reliability Standards, available at: https://www.nerc.com/pa/Stand/Glossary%20of%20Terms/Glossary_of_Terms.pdf
- US Energy Information Administration Glossary, available at: https://www.eia.gov/tools/glossary/